Minutes of Meeting of Joint Coordination Committee #2 of Technical Cooperation to Promote Energy Efficiency in Caribbean Countries among MPI, NIA, NEVLEC, SKELEC, JICA, and JICA Expert Team

November 22, 2021

Ministry of Public Infrastructure, Post, Urban Development, and Transport (MPI)

Dr. Bertill Browne

Nevis Island Administration (NIA)

Ms. Michelle Walters

St. Kitts Electricity Company Limited (SKELEC)

Mr. Jonathan Kelly, Engineering Manager

Nevis Electricity Company Limited (NEVLEC)

Mr. Albert Gordon, General Manager

Japan International Cooperation Agency (JICA), Tokyo

Dr. Katsuya KUGE, Director, Team 2, Energy and Mining Group

Japan International Cooperation Agency, St. Lucia Office

Mr. Hiroyasu TONOKAWA, Chief Representative

JICA Expert Team (JET)

Mr. Ryosuke OGAWA, Team Leader

Date and Time:

November 22, 2021 9:00am (in St. Kitts and Nevis), 10:00pm (in Japan)

Location:

Online (Virtual Meeting by Zoom)

Participants:

1) Ministry of Public Infrastructure, Post, Urban Development, and Transport (MPI)

- Dr. Bertille Browne, Director of the Energy Unit (absent)

2) Nevis Island Administration (NIA)

- Ms. Michelle Walters, Energy Commissioner (absent)

3) St. Kitts Electricity Company (SKELEC)

- Mr. Jonathan Kelly, Engineering Manager
- Mr. Kenrod Roberts, Maintenance Engineer

4) Nevis Electricity Company (NEVLEC)

- Mr. Albert Gordon, General Manager
- Mrs. Roma Merchant, Financial Controller
- Mr. Jervan Swanston, System Planning and Projects Manager
- Mr. Ian Ward, Chief Engineer
- Mr. Naftalie Errar, Planning Engineer
- Mr. Starett France, Planning Officer
- Mr. Nelson Stapleton, T&D Manager

5) Japan International Cooperation Agency (JICA), Tokyo

- Mr. Takeshi NAITO

6) Japan International Cooperation Agency (JICA), St. Lucia Office

- Mr. Hiroyasu TONOKAWA, Chief Representative
- Ms. Hitomi URUSHIHATA
- Mr. Terumasa MATSUZAKI

7) JICA Expert Team (JET)

- Mr. Ryosuke OGAWA, Team Leader

- Mr. Masaaki EBINA, Sub Team Leader/Power System
- Mr. Yasuhiro SAKAMOTO, Energy Efficiency
- Ms. Yuka NAKAGAWA, Renewable Energy
- Mr. Tomoaki TSUJI, Grid Stabilization/Coordinator
- Ms. Anna MIYAURA, Human Resource Development
- Mr. I-Ronn Audain, Technical Assistant

Discussions:

<Looking Back the Current Status of Project>

- JET explained the summary of current project status by presentation material. (Attachment 1).
- JET has plans to visit the region in 2022 up to four (4) times each for EE and RE if possible, for a duration of five working days each visit. The Project is expected to wrap-up in early 2023.
- JET also explained about the further activities of EE and RE both in presentation slides.

<Resuming Onsite Visit to St. Kitts and Nevis>

- JICA indicated this project was planned to finish by the end of March 2022 originally, but JICA would like to extend 1 more year. The procedure to extend the project will be informed later by email. MPI, NIA, SKELEC and NEVLEC agreed with this proposal for this project extension.
- JICA indicated JET cannot visit St. Kitts & Nevis, due to JICA restriction, until March 2022 or later, and JICA cannot say when JET can resume field activities at the moment.
- JICA also indicated that specific conditions, especially medical information, and institutions, must be met for the visits to occur. Although there is no JICA office or Embassy of Japan in St. Kitts & Nevis, JICA St. Lucia office has started information collection. They will gather more information and make an assessment on whether to approve visits to St. Kitts and Nevis going forward.
- No objection to the visits in 2022 was raised by the St. Kitts and Nevis participants. However, NEVLEC local team propose that, in order to keep the project moving toward completion, assistance from JET remotely for a while would be greatly appreciated.

<Update on Activities in St. Kitts and Nevis>

- NEVLEC and SKELEC have procured the Generation Software PLEXOS and NEVLEC has procured the grid modeling software, ETAP. Both utilities have procured software at a significant discount for the first few years. SKELEC intends to procure grid modeling software within Q1 of 2022.

- NEVLEC is in the process of purchasing an asset management software, ESRI. SKELEC will also be acquiring this software within Q1 of 2022.
- Both NEVLEC and SKELEC have base models in PLEXOS to commence learning remotely with JET's supports. Both utilities can prepare for the basic knowledge for the effective use of the software.
- Both NEVLEC and SKELEC are ready to receive training on power system design and implementation using JET's training platforms and software tools
- Nevis' geothermal project will receive equity from a private developer and CDB (Caribbean Development Bank) will provide funding for the first phase. Contracts will be signed on December 2021. Funding will be needed for the second phase, which will involve the production of hydrogen and ammonia.
- St. Kitts: the Leclanche 35MW PV project is to be installed and commissioned in the second quarter of 2023, with the specifications remaining the same as before COVID-19. Battery installation is also planed the second quarter of 2023.

<Area for Technical Assistance >

- JET agreed to the following items.

  1) To assist in capacity building in relation to grid modeling and simulation, explanation of asset management and "QGIS" software, which is open source one.
  2) To share the basic knowledge about how to use software, hydrogen project and future possibilities remotely. JET has an expert to explain the use of system to students for education purpose.
  3) To provide fundamental training in high voltage submarine cable installation and maintenance. JET can give basic level lecture for plans to place high voltage submarine cable between St. Kitts and Nevis.
  4) To evaluate whether a study can be conducted in relation to the production of hydrogen and/or ammonia from the Nevis geothermal site.

- NEVLEC mentioned the deliberative of hydrogen as below.

  1) NEVLEC is looking to develop 90 MW of geothermal energy source in the medium term. Peak electricity demand is just over 9 MW. Excess capacity would be used for export and production of hydrogen and/or ammonia.
  2) Looking to develop additional capacity for manufacturing, agriculture tourism and other areas of the economy based on geothermal resources. Application is being

made for 15 million Euros of financing to support the production of hydrogen and/or ammonia.

3) Mixture of energy sources and hydrogen projects also need to be supported. For hydrogen, looking for offshore opportunities for export.

List of Attachments:

1) Presentation Slides on November 22, 2021(PowerPoint)

End of the MoM

Joint Coordinating Committee (JCC) #2 for Technical Cooperation to Promote Energy Efficiency in Caribbean Countries [St. Kitts and Nevis]

November 22, 2021
JET (JICA Expert Team)
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Contents and Timetable

3 min.	• Opening Remarks from JICA
5 min.	• Introduction of Participants
3 min.	• Project Outline and Current Status
10 min.	• Further Activity
5 min.	• Relevant Restrictions against the Implementation of the Project
15 min.	• Constrains in Project Schedule and Discussion
3 min.	• Closing Remarks from St. Kitts and Nevis Side

Today’s Participants

Today’s Participants (1/2) (St. Kitts and Nevis)

St. Kitts and Nevis
- Ministry of Public Infrastructure, Post, Urban Development, and Transport (MPI)
- Nevis Island Administration (NIA)
- SKELEC
- NEVLEC

JICA
- JICA HQ
- JICA Office (JICA St. Lucia Office)

JET
- Japanese Experts
- Local Expert

Today's Participants (2/2) (St. Kitts and Nevis)

St. Kitts and Nevis

Organization	Name and Title
MPI	Mr. Daryll Lloyd- Permanent Secretary Dr. Bertille Browne- Director of Energy Mr. Denasio Frank- Energy Officer
NIA	Mr. Wakely Daniel- Permanent Secretary Ms. Michelle Walters- Energy Officer
NEVLEC	Mr. Albert Gordon – General Manager Ms. Roma Merchant - Financial Controller Mr. Jervan Swanston - Strategic Planning Manager Mr. Ian Ward – Chief Engineer Mr. Naftalie Errar - Planning Engineer Mr. Starett France - Planning Officer Mr. Nelson Stapleton - T&D Manager
SKELEC	Mr. Clement Williams – General Manager Ms. Pearl Williams- Financial Controller Ms. Inga Rogers – Human Resource Manager Mr. Jonathan Kelly – Engineering Manager Mr. Kenrod Roberts – Maintenance Engineer

JICA

Organization	Name
JICA (Tokyo)	Dr. Katsuya KUGE, Director, Team 2, Energy and Mining Group Mr. Takeshi NAITO
JICA (St. Lucia Office)	Mr. Hiroyasu TONOKAWA, Chief Representative Mr. Terumasa MATSUZAKI Ms. Hitomi URUSHIHATA

JICA Expert Team Member

JET

Name and Position
Mr. Ryosuke OGAWA, Team Leader Mr. Masaaki EBINA, Sub Team Leader/Power System Mr. Yasuhiro SAKAMOTO, Energy Efficiency Ms. Yuka NAKAGAWA, Renewable Energy Dr. Hiroshi SUZUKI, Electrical Grid Expert Dr. Hisao TAOKA, Electrical Grid Expert (additional) Mr. Hiroaki NIIMI, Grid Stabilization/Coordinator (former) Mr. Tomoaki TSUJI, Grid Stabilization/Coordinator (new) Ms. Anna MIYAURA, Human Resource Development Mr. I-Ronn Audain, Technical Assistant

Project Outline and Current Status

Project Outline

This project is a technical cooperation project by Japan International Cooperation Agency (JICA), which is a governmental agency of Japan.

Duration

- Originally 3 Years from March 2019 to March 2022.

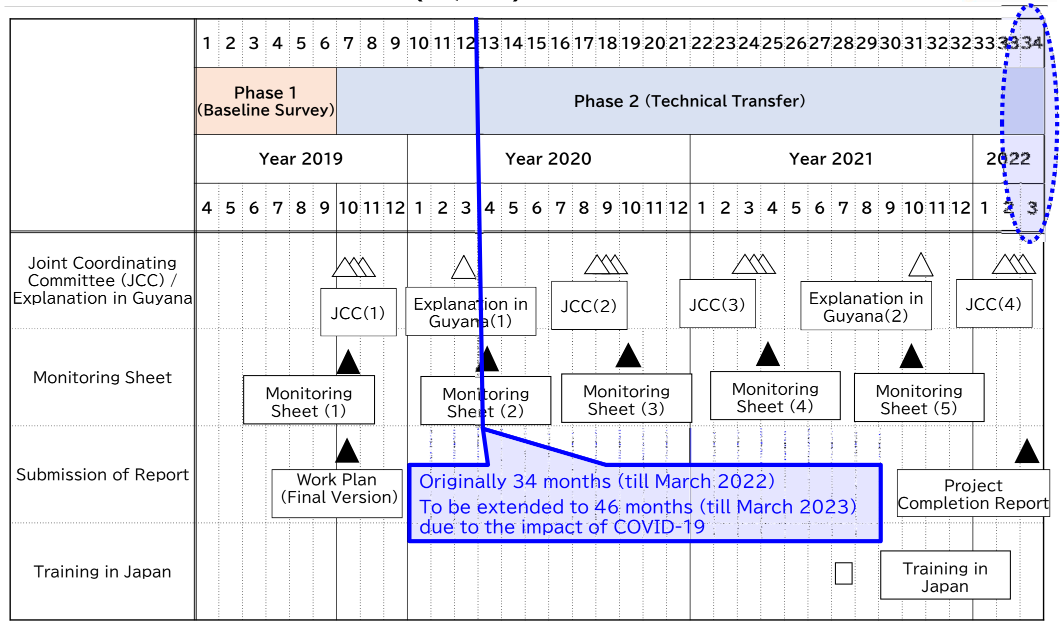
Purpose

- Human and institutional capacities are enhanced for the introduction of Renewable Energy (RE) and the promotion of Energy Efficiency (EE).

Output

- The basic information is confirmed for the capacity building for the introduction of RE and for the promotion of EE.
- The human and institutional capacities are enhanced for the introduction of RE and the promotion of EE.

Current Status (1/5)



Current Status (2/5) (St. Kitts and Nevis)

Baseline Survey (EE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

- In EE, in addition to JET's original activities plan, the importance and necessity to collect energy consumption data by end-use/equipment basis has been shared and confirmed with the counterparts toward the formulation of future EE policies.
- Power consumption data collection device (logger, software) are to be provided through this project.

Current Status (3/5) (St. Kitts and Nevis)

Baseline Survey (RE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

RE Installation:
- 100% RE by 2020 target
- 0.7+0.5 MW PV (St. Kitts)
- 2MW wind operated at 1.1 MW (Nevis)
- Bellevue 5.4MW wind, Leclanche 35MW PV to be installed
- Nevis Geothermal plan (10-30 MW + potential

Grid Stability:
- 6MW-34MWh BESS planned for 35MW PV
- Output suppression conducted in NEVLEC

Needs for:
1) Modeling for existing transmission and distribution network
2) Provision of grid simulation software and training and grid analysis with 35 MW PV
3) Proposal for grid code revision
4) Introduction of network asset management
5) Additional request of hydrogen utilization study (from NEVLEC, 2021)

Current Status (4/5)

Current Status

- Activities at the site are suspended from March 2020, due to restrictions caused by COVID-19.
- All remained activities are postponed for one year and online (remote) activities are to be added.
- "Baseline Survey" has been completed and currently the initial stage of "Technical Transfer".

- JICA and JET considers that it takes some more time to resume the activities due to the restrictions (till the end of Year 2021 or March 2022).
- *It is not realistic to implement the activities for "Technical Transfer" by online (remote).*

Current Status (5/5)

Further Schedule

- Now, JICA and JET seeking possibilities to resume the site activity to complete the project within the extended project duration (46months) since the restrictions have been slightly relaxed.

- With necessary revision of R/D (for extension of the project duration and any other issue if necessary), we would like to reach a consensus of the new timeline of this project.

Further Activity

Outline of Further Activity (EE)

Year 2021 ● Online Activity

- ◆ Additional activities:

  Current & future situation on energy efficiency & conservation in Japan & the world including effects derived from COVID-19.

  - ➢ EE policy, Outlook of power demand, CO_2 reductions ,etc.
- ◆ Activities originally planned at site:
  - ➢ Collaboration activities to draft EE activities/roadmap based on energy balance in each country.

Year 2022 ● Site Activity (Technical Transfer)

Review of S&L program	On site energy auditing	Preparation of EE roadmap
Possibilities of ESCO business	Energy auditor / manager	Delivery of power consumption measurement device (data logger)
Review of building code	Examination of EE pump system	

Outline of Further Activity (RE)

	Year 2021 Online Activity	Year 2022 Site Activity
Additional Activity	● COVID19 impact on RE plan, operation, investment ● RE tends after COVID-19, fuel price forecasts	
Grid Stability	● Lecture on grid simulation (basic, concept, methodology) ● Simulation model ● Energy storage and equipment	● Exercise on grid simulation using software ● RE scenario setting
Microgrid	● Microgrid examples and Japanese experiences (system component, benefit, cost, challenges)	● Data collection and concept formulation
Resilience, Asset Management	● Mitigation measurement for RE to enhance resilience ● Introduction of asset management concept	● Demonstration of asset management
Policy Recommendation	● Example of grid code with large RE penetration (frequency/voltage stability, Inertia, speed regulation, etc.)	● Discussion/recommendation for future application of grid code ● Hydrogen utilization possibility with Geothermal

Relevant Restrictions against the Implementation of the Project

Restrictions (General)(1/2)

Flights

- There is some difficulty for scheduling due to limited number of routes and flights, and availability of air tickets with reasonable price.

Quarantine

- Depending on the country, however negative certificate of COVID-19 is generally required "home quarantine" is also required after arriving a country in some country.

Restrictions (General)(2/2)

Previously …

- Day 1-2(Sat, Sun): from Japan via Canada(Toronto)
- Day 3-7(Mon to Fri): Barbados
- Day 10-14(Mon to Fri): St. Kitts and Nevis
- Day 17-21 (Mon to Fri): Jamaica
- Day 22-24 (Sat to Mon): to Japan
- Mainly travel days are Saturday and Sunday.

Currently …

Flight Schedule as of January 2022

- Between Barbados and St. Kitts and Nevis by LIAT Twice a week (daily flight in 2019)
- Between Barbados and Jamaica by Caribbean Air Twice a week (previously 5 flights/week (direct or one-stop flights) in 2019)

Restriction (Country Specific)

Barbados

- No quarantine for <u>fully vaccinated traveler</u>. (Selected traveler are to be tested upon arrival.)

Jamaica

- In case of business travel (Category 3), no quarantine for <u>fully vaccinated traveler</u> after obtaining negative test result of test conducted upon arrival

St. Kitts Nevis

- Quarantine till obtaining negative result test conduced within 24 hours after arrival in case of <u>fully vaccinated traveler</u>
- However, there is a travel restriction by JICA.

Constrains in Project Schedule and Discussion

Constrains in Project Schedule

Schedule

- Four (04) times each in 2022 are expected for EE and RE. (05 working days/time)
- Wrap-up is expected in early 2023.

↓

Constrains

- Possibility of availability for project activity
- Preferred timing (season)
- Program in Japan

Thank you.

Minutes of Meeting of Joint Coordination Committee #3 of Technical Cooperation to Promote Energy Efficiency in Caribbean Countries among MSET, JICA, and JICA Expert Team

March 30, 2023

Ministry of Science, Energy and Technology (MSET)

Mrs. Olive Wilson Cross, Chief Technical Director, Programme Implementation

Japan International Cooperation Agency, Jamaica Office

Mr. Mitsuyoshi KAWASAKI, Resident Representative

JICA Expert Team (JET)

Mr. Tomoyasu FUKUCHI, Team Leader

Date and Time:

March 30, 2023, 10:00 a.m. (in Jamaica), 12:00 a.m. (in Japan)

Location:

Virtual Meeting by Zoom

Participants:

1) **Ministry of Science, Energy and Technology (MSET)**

- Mrs. Olive Wilson Cross, Chief Technical Director, Programme Implementation
- Mr. Horace Buckley, Project Engineer
- Mr. Steve Dixon, IRP Consultant (T&D Expert)
- Mr. Todd Johnson, Principal Director, Energy Division
- Ms. Leneka Rhoden, Director of Energy Systems and Conservation

2) **Japan International Cooperation Agency (JICA), Tokyo**

- Mr. Kentaro KUNIKATA, Special Advisor, Team 2, Energy and Mining Group

3) **Japan International Cooperation Agency (JICA), Jamaica Office**

- Mr. Mitsuyoshi KAWASAKI, Resident Representative
- Mr. Hiroyuki OKAZAKI, Project Formulation Advisor

4) **Caribbean Community (CARICOM), Guyana**

- Mr. Tatsuya MORITA, CARICOM Advisor (Dispatched from JICA)

5) **JICA Expert Team (JET)**

- Mr. Tomoyasu FUKUCHI, Team Leader/Power System
- Mr. Yasuhiro SAKAMOTO, Energy Efficiency
- Ms. Yuka NAKAGAWA, Renewable Energy
- Dr. Hisao TAOKA, Electrical Grid Expert
- Ms. Anna MIYAURA, Human Resource Development
- Mr. Tomoaki TSUJI, Grid Stabilization/Coordinator
- Ms. Christina Francis (Representing Mr. Kevin Douglas, Technical Assistant)

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Discussions

<Looking Back Over all the Project>

- JICA Expert Team (JET) explained the project was originally from March 2019 to March 2022, however, due to the COVID-19 pandemic, it was extended to May 2023.

<Activities of Phase 1 for Renewable Energy (RE)>

- JET explained that the Phase 1 baseline survey indicated that before 2019 the former RE target in Jamaica was 35% by 2030 and 40% by 2037. This was accelerated to 50% RE by 2030. The fluctuation due to Variable RE such as PV and wind had caused issues on the grid, but the Jamaica Public Service (JPS) installed hybrid energy storage systems which improved the fluctuation conditions.
- JET mentioned that to achieve the 50% RE, additional grid stability measurements will be necessary. In addition, enhancement of resilience for climate change is an issue. Accordingly, JET summarized that the parties had agreed that the technical transfer stage will mainly focus on grid stability and microgrid concept to enhance resilience.

<Activities of Phase 1 for Energy Efficiency (EE)>

- Baseline survey was conducted on Phase 1 as planned while the additional activity was proposed through Phase 1 to hand over the data collection devices (data logger and its software) to figure out the energy consumption ratio at households, etc. to formulate effective EE policies/regulations. Two data loggers were provided to Jamaica (MSET and BSJ).

<Achievement of Phase 2 "Technical Transfer">

- Activities of Phase 2 for RE:
  - JET explained that Seminars on Large RE and Grid Stability were conducted in three sessions (1st seminar on 12 Oct 2022, 2nd seminar on 30 Nov 2022, and 3rd seminar on 8 Feb 2023). The key focus was on Grid Stability and how this is affected by large amounts of VRE on the grid as this is of high importance for the government, JPS, and other key stakeholders to enable 50% RE target.
  - JET stated that the load flow analysis was conducted and that the grid model comprising of the open data of Jamaica's grid system was prepared. A simplified model has been prepared for exercise in the seminar making it easier for participants to understand the concept.

- JET also stated that a simulation scenario was developed based on seminar feedback for trial, and JET highlighted the importance of grid simulation with one example that a line section was overloaded according to PV increase in future.
- A concept for microgrid was also prepared with the selection criteria of target location based on remote, high transmission loss, area with voltage drop and fluctuation and area with high solar and wind potential. JET stated that, Hagley Gap in St. Andrew, meets the criteria. JET noted that all information presented on the area is based on desktop survey and detailed design will be necessary based on actual site data.
- JET stated that a grid model was created for the Hagley Gap microgrid, and grid analysis was conducted, and indicated that grid forming inverter (GFM) will be necessary when PV and wind percentage is increased. A provisional cost estimation for Hagley Gap microgrid was also done based on assumptions.
- JET made some recommendations for grid stability and revision of grid code:
  1. Spinning reserve to compensate variable RE (VRE) fluctuation should be kept.
  2. Reactive power compensation should be provided according to VRE installation.
  3. For grid stability, the Short Circuit Ratio (SCR) (= AC power in grid / Power from inverter based resource (PV and wind) should be kept more than 3.0.
  4. In case SCR will be less than 3.0, Grid Forming Inverter (GFM) should be applied, once GFM becomes available in the market.
  5. If the VRE will be installed more than 1 MW, a BESS with minimum 80% capacity and 4hrs duration should be installed.
- JET summarized policy recommendations for future RE for Jamaica, such as approval of investment for grid stability, sharing responsibility of grid stability with IPP and consumers, and promotion of microgrid.

- Activities of Phase 2 for EE
  - JET explained the workshops that were conducted, and that stakeholders were receptive to the knowledge shared.
  - JET stated that data loggers were handed over to Jamaica, BSJ: 1 (November 2022) and MSET: 1 (March 2023).
  - Major contents presented from JET are as follows.
    1. Energy Management & Energy Audit (International Standards and introduction of successful practices).

2. EE&C Roadmap with Country Energy Balance and efficient technologies (residential & commercial sector integration).
3. EE Building Code including Okinawa & Hawaii Situation and EE&C Evaluation Study.
4. Report on Energy Audits Results including Walk Through Survey.
5. Demonstration: Data Logger and its Software.
6. EE policy in Japan.

<Confirmation of Project Design Matrix (PDM)>

- To confirm the achievement of Overall Goal in PDM, JET stated that the first indicator is the energy self-dependency and confirmed current percentage of the total RE generation as of March 2023 in GWh. MSET indicated that at present it is 12.4%.
- JET also asked for data on the imported amount of fossil fuel in energy base for March 2023 as the indicator. MSET will provide the data by the time of training in Japan in April 2023.
- To confirm the achievement of Project Purpose, JET requested the provision of data about the total capacity MW of distributed PV, utility scale PV and battery as of March 2023. MSET will also provide the data before the training in Japan.
- JET also asked for data on the number of public buildings which were implemented or introduced in EE programs including BEMS introduction as of March 2023. The information was not available at the time but would be provided. With regard to BEMS, JET requested data covering all public buildings from MSET. MSET stated that there are several projects under other institutions that are implementing similar programs and that it would not be possible to provide an answer at the time; however, MSET confirmed that as far as possible, any data available will be provided.
- As for the Achievement for other Project Purpose and Outputs, Mr. Horace Buckley of the MSET reconfirmed the ones which were confirmed in the 1st JCC in 2019 and agreed. Mrs. Olive Wilson Cross of MSET stated that some achievements from the activities done after 2019 should be confirmed later.

<Training in Japan>

- JET gave a brief overview of the training program that will be held in Japan from departure to arrival.
- JET also mentioned the necessities to carry, ideal clothing, the procedure of purchasing a sim card and immigration entry procedures.

List of Attachment:

Attachment – 1: Presentation Material for 3rd JCC

Attachment – 2: Presentation Material for Training in Japan

End of the MoM

Joint Coordinating Committee (JCC) #3 for Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

March 30, 2023
JET (JICA Expert Team)
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Contents and Timetable

5 min.	Opening Remark from JICA
5 min.	Introduction of Participants
5 min.	Project Outline and Recap of Project
30 min.	Detail of Activities in Phase 2
30 min.	Confirmation of PDM (Project Design Matrix)
10 min.	Discussion
5 min.	Closing Remark from Jamaica Side

Opening Remarks from JICA

Today’s Participants

Today's Participants (1/4)

Jamaica
- MSET

JICA
- JICA HQ in Tokyo, Japan
- JICA Jamaica Office

JET
- Japanese Experts
- Local Expert

Today's Participants (2/4)

Jamaica

Organization	Name and Title
MSET	Dr. Olive Wilson Cross, Director Programme Management

Today's Participants (3/4)

JICA

Organization	Name
HQ, Tokyo	Mr. Kentaro KUNIKATA, Special Advisor, Team 2, Energy and Mining Group, Infrastructure Management Department
Jamaica Office	Mr. Mitsuyoshi KAWASAKI, Resident Representative Mr. Hiroyuki OKAZAKI, Project Formulation Advisor

CARICOM

Organization	Name
HQ	Mr. Tatsuya MORITA, CARICOM Advisor (Dispatched from JICA)

Today's Participants (4/4)

JET

Name	Position
Mr. Tomoyasu FUKUCHI	Team Leader/Power System
Mr. Masaaki EBINA	Sub Team Leader/Power System
Mr. Yasuhiro SAKAMOTO	Energy Efficiency
Ms. Yuka NAKAGAWA	Renewable Energy
Dr. Hisao TAOKA	Electrical Grid Expert
Ms. Anna MIYAURA	Human Resource Development
Mr. Tomoaki TSUJI	Grid Stabilization/Coordinator
Mr. Kevin DOUGLAS	Technical Assistant

Project Outline and Recap of Project

Project Outline

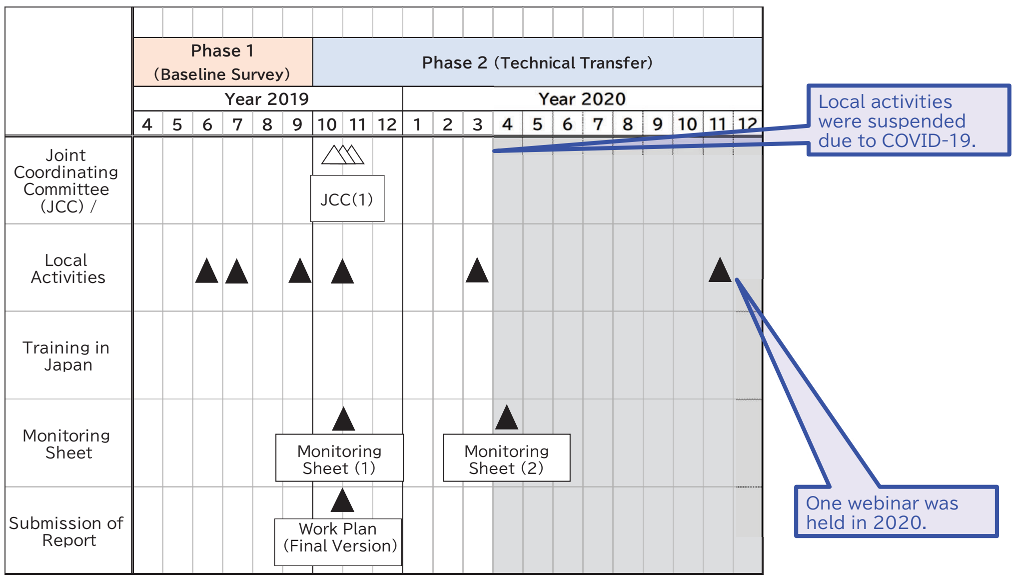
This project is a technical cooperation project by Japan International Cooperation Agency (JICA), which is a governmental agency of Japan.

Duration
- Originally 3 Years from March 2019 to March 2022.
- >>> Extended until Jun 2023.

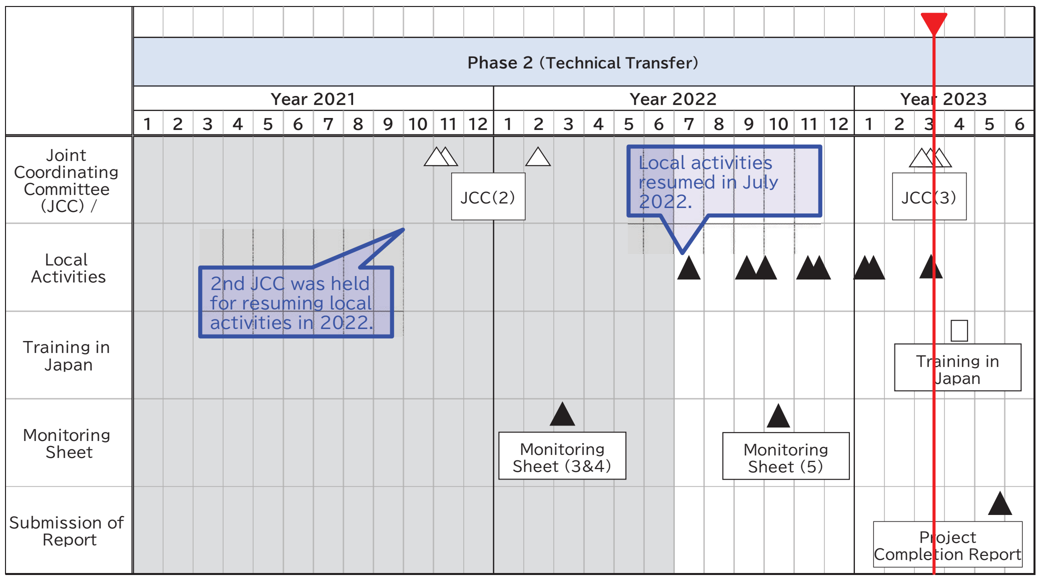
Purpose
- Human and institutional capacities are enhanced for the introduction of Renewable Energy (RE) and the promotion of Energy Efficiency (EE).

Output
- The basic information is confirmed for the capacity building for the introduction of RE and for the promotion of EE. (Phase 1: from Mar to Sep 2019)
- The human and institutional capacities are enhanced for the introduction of RE and the promotion of EE. (Phase 2: from Oct 2019 to Jun 2023)

Recap of Project (1/6)



Recap of Project (2/6)

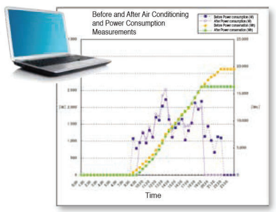


Recap of Project (3/6)

Phase1 Baseline Survey (EE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

- In addition to JET's original activities plan, the importance and necessity to collect energy consumption data by end-use/equipment basis has been shared and confirmed with the counterparts toward the formulation of future EE policies.
- Power consumption data collection device (data logger, software) are to be provided through this project.



Source: Data logger catalogue of HIOKI E.E. CORPORATION

Recap of Project (4/6)

Phase1 Baseline Survey (RE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

RE Installation (2020):
- 50% RE penetration target by 2030,
- 35% RE in 2030, 40% in 2037 (IRP2020)

→ Target acceleration, 50% RE by 2030
- Current RE: 14% (hydro 28.7MW, VRE 179MW)
- Roof-top 20MW? Need statistics.
- Wind in valley place
- IRP additional 513.5MW by 2025

Grid Stability:
- Capacity 1,071MW, Peak demand 654.5 MW
- Sales 4,227MWh (JPS2020AR)
- 0.31 UScent/kWh, 26.9% loss (JPS2020AR)
- JPS 21.5MW/16.6MWh Li BESS +3MW Flywheels
- Fuel increase for spinning reserve. Feeder cut at 49.5 Hz. "VRE is a Nightmare"

Challenges:
- RE gap of present vs target(15% vs 50%)
- Voltage/frequency fluctuation → Grid stability needed with 50% VRE
- Cost of energy → Rooftop PV increase
- RE project implementation plan
- Wind and PV potential unevenly distributed → Less smoothing

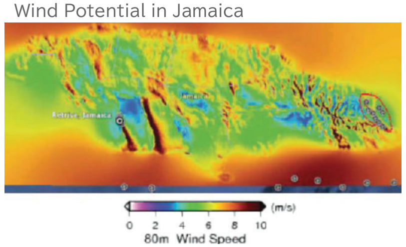
Needs:
- Capacity building of grid planning Proposal for grid code revision
- Enhancement of resilience → Microgrid concept

Recap of Project (5/6)

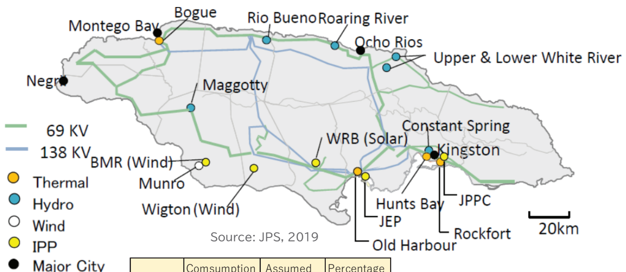
Challenges for RE:

- ✓ Increasing RE capacity >20%, RE generated energy >14%.
- ✓ Future increase of RE with stability
- ✓ System losses 26.3% (2018) →28.3% (2021)
- ✓ Large number of distributed PV → need database management
- ✓ Wind & PV potential unevenly distributed →less smoothing

Wind Potential in Jamaica



Source: Sustainable Energy Roadmap 2013



Source: JPS, 2019

Year	Comsumption (MWh)	Assumed RE (MWh)	Percentage of RE
2020	4,227	564	14%
2030	5,453	1,913	35%
2037	5,939	2,435	41%

Source:
2020: Assumed from table below.
2030/2037: IRP2020 draft

Location/Project	Type	Capacity MW	Generation GWh estimated	Year	Tariff USc/kWh	Investment mil USD	USD/ MW
Wigton I	Wind	20.7	52	2004	10.21	26	1,256
Wigton II	Wind	18	45	2010	10.723	45	2,500
Wigton III	Wind	24	60	2016	13.4	46.5	1,938
Munro	Wind	3	10.5	2010	(JPS)		
BMR Wind	Wind	36.3	120	2016	12.9	90	2,479
Content Solar (WRB)	PV	20	34	2016	18.8	65	3,250
Eight River (EREC)	PV	37	59.2	2019	8.5		
Hydro	Hydro	28.67	152.2				
Independent roof-top	PV	20?	30.6		--		
Wigton IV	Wind	34		?			
RE under operation		**207.67**	**564**				

Source: Prepared by JET with several data sources

Recap of Project (6/6)

Phase 2 Technical Transfer

- JET conducted capacity building related to RE and EE based on baseline survey.
- Seminar or Workshop were held online
  - 3 RE and Grid Stability Seminar
  - 2 EE Workshop
- The following equipment was also provided from JET
  - EE: Data Loggers
- The only remaining activity is the training in Japan, April 2023.

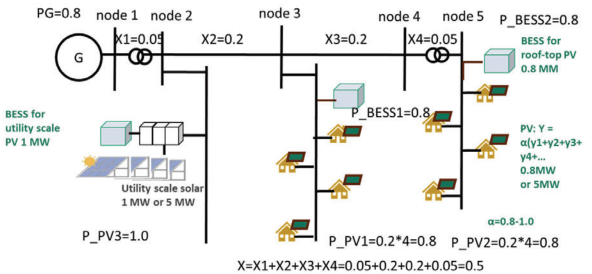
Detail of Activities in Phase 2

Activity and Achievement (RE)

Basics of Load Flow Analysis with simplified model

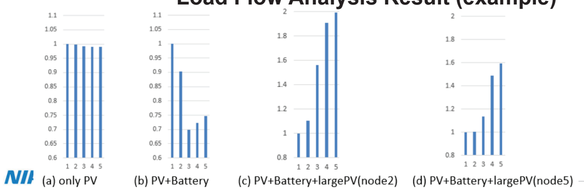
Load Flow Analysis with Grid Model for Exercise

- Case study: 1 or 5 MW PV's, 1 MW BESS, total 0.8 or 5 MW roof-top PV + 0.8 MW BESS per a feeder
- Unbalanced voltage will be problem BESS capacity/ location is suggested from the result.



Y axis : P.U. Voltage

Load Flow Analysis Result (example)

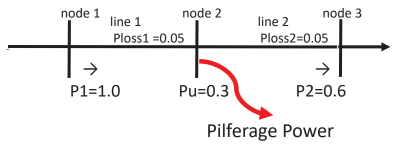


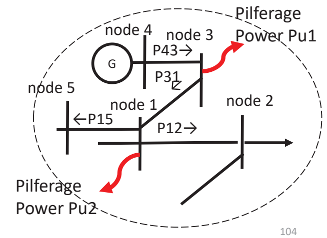
State Estimation method

- System loss:

26.5% in 2018 → 28.3% in 2021

- State Estimation in the grid analysis, method to specify the location and amount of stolen electric energy, was introduced in seminars

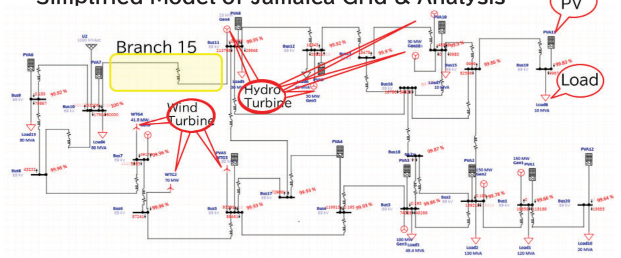




Activity and Achievement (RE)

Grid Modeling and Analysis with Future Scenario

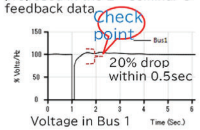
Simplified Model of Jamaica Grid & Analysis



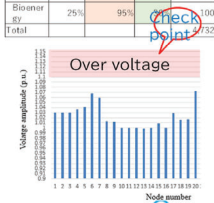
Category	Capacity factor 2020 Jamaica	Capacity factor IRP2020	Capacity factor IRENA	2021 GWh	GWh target %	2030 GWh	2030 MW	2030 MW %
Fossil Fuel	44%	54%	41%	4,092	50%	2,689	748.6	33%
Total RE				640	50%	2,689	1,537	67%
Hydro	37%	61%	52%	136	10%	538	118.0	5%
Solar	11%	21%	15%	124	30%	1,613	1,227.6	54%
Wind	23%	38%	32%	280	10%	538	191.8	8%
Bioenergy	25%	95%	[illegible]	100	0%	0	0.0	0%
Total				4,732	100%	5,377	2,286	100%

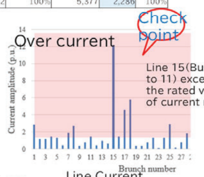
Check point

This is the typical case proposed in the 2nd seminar's feedback data

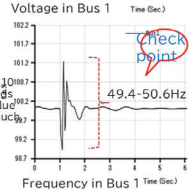


Voltage in Bus 1





Line Current



Frequency in Bus 1

Load and at generation at nodes

Node ID	Fossil Fuel	Hydro	Bioenergy	Load	PV	Battery	Wind	
(Up to 4 characters)	(pu)	(pu)	(pu)	(pu)	(pu)	(pu)	(pu)	1pu= 100MW
1	1.5			1.2	1.5			
2	1.5			1.3	1.5			
3	1			0.494	1			
4					1			
5	1				1		0.8	
6							0.7	
7		0.3					0.418	
8								
9				0.8	1			
10	2			0.8	1			
11		0.28		0.3	1			
12		0.3		0.3	1			
13								
14	0.486	0.3		0.1	1			
15								
16								
17								
18								
19				0.1	0.276			
20				0.2	1			
(Total pu)	7.486	1.18	0	5.594	12.276	0	1.918	

Simulation scenario case prepared based on seminar feedback for trial

- 69kV as base voltage
- GWh Energy base: 30%PV, 10%Wind, 10% hydro, 50% thermal.

→ Output 54%PV, 8% wind, 5% hydro (capacity factor need to be reviewed)

- Over current at low demand area at Feeder 15 (Rio Bueno)

→ Depends on scenario, it needs to re consider PV location and/or line enhancement

Activity and Achievement (RE)

Microgrid Concept: Hagley Gap

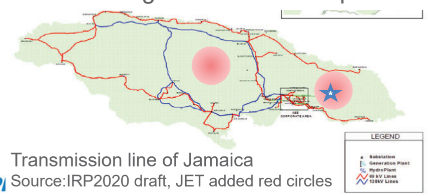
The data used in this plan is based on assumption, and it needs site confirmation and review .

Hagley Gap and Perlyne Castle

Wind Speed of the Area

Selection Criteria:

- Remote, high transmission loss
- Area with voltage drop and fluctuation
- Area with high solar and wind potential



Transmission line of Jamaica

Source:IRP2020 draft, JET added red circles

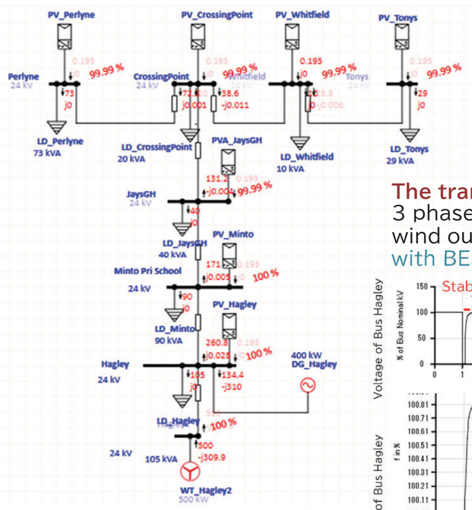
→ Target area: around Hagley Gap in St. Andrew

Total residential consumer	166	hh*1
Max daily energy consumption	7,029	kWh/day*2
Peak load	367.2	kW*2
Hagley Gap mean wind speed	7.6	m/s @10mH*3
Wind rated output	500	kW
Wind average output	301	kW
Hagley Gap solar irradiation	4314	kWh/kWp/day
Total Solar PV output	105	kWp
Diesel Generator	400	kW

*1 This count is not accurate and need to be reviewed.
*2 Assumed from 1.5 kW /hh, 30kW/facility. It needs to be reviewed by accrual data of the area. *3 Wind speed at available road. Better wind speed may be obtained at hilltop, but road construction will be necessary.

Activity and Achievement (RE)

Transient Stability Analysis of Hagley Gap Micro Grid

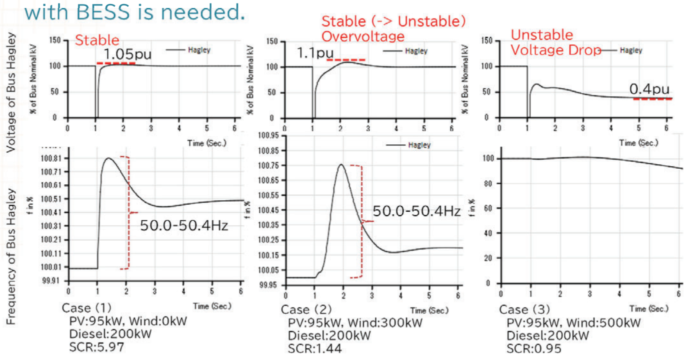


Model of Hagley Gap Microgrid

Source: Prepared by JET with ETAP

Load Flow Analysis:
(a) PV95kW, Wind500kW, Diesel400kW
(b) PV95kW, Wind500kW (c) Wind500kW (d) Wind500kW, Diesel400kW (e)Wind500kW, Diesel100kW
→ Case (a)-(e): Load flow analysis has no problem about voltage and load.

The transient stability analysis : with condition of 100 msec 3 phase grounding fault at Hagley Node→ unstable when wind output is more than 300 kW → Grid forming inverter with BESS is needed.

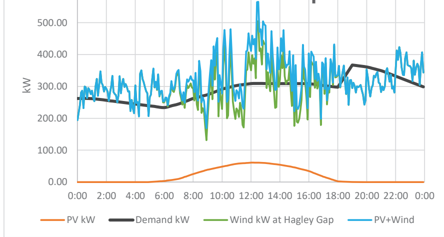


Activity and Achievement (RE)

Provisional Cost Estimation for Hagley Gap Micro Grid

This is NOT Feasibility Study. The data used in this plan is based on assumption, and it needs site confirmation and review.

Case: Wind 500 kW + Rooftop PV 95 kW



- The estimation is just trial, based on assumptions, which need to be reviewed.
- Feasibility is much depending on wind speed.
- Both PV & wind has fluctuation. BESS or DG is necessary to absorb fluctuation and levelized output.
- Initial cost : DG < BESS
- GFM is necessary for stability.
- Cost of DG needs fuel cost. BESS needs consideration of replacement and cycle life.

With BESS, 260 kW-1.05 MWh

Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	95	kW	
Cost of PV installation	94,700	USD	
Unit cost of Wind	2,500	USD/kW	
Rated output of Wind	500	kW	
Cost of Wind	1,250,000	USD	
Unit cost of 24 kV system	400,000	USD/km	
Length of 24 kV	0.3	km	
Cost of 24 kV system	120,000	USD	
Requirement of SCO	149	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	29,735	USD	
Unit cost of Diesl Generator	300	USD/kW	
Capacity of Diesel Generator	400	kW	
Cost of Diesel Generator	120,000	USD	
Total Cost	**1,913,918**	**USD**	

With Diesel Generator, without BESS

Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	95	kW	
Cost of PV installation	94,700	USD	
Unit cost of Wind	2,500	USD/kW	
Rated output of Wind	500	kW	
Cost of Wind	1,250,000	USD	
Unit cost of 24 kV system	400,000	USD/km	
Length of 24 kV	0.3	km	
Cost of 24 kV system	120,000	USD	
Requirement of SCO	149	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	29,735	USD	
Unit cost of Diesl Generator	300	USD/kW	
Capacity of Diesel Generator	400	kW	
Cost of Diesel Generator	120,000	USD	
Total Cost	**1,614,435**	**USD**	+ Fuel Cost

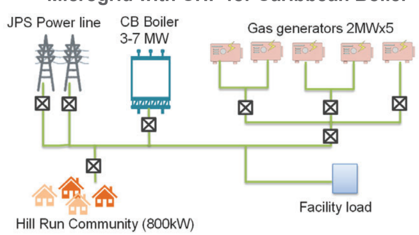
Activity and Achievement (RE)

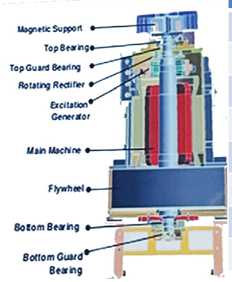
Sharing of Good Practice of Jamaica in Caribbean Countries

To cope with ＞140MW VRE for 650 MW peak grid in 2016, JPS took following measurement:

1. Application of 24.5 HESS Demand projection >99% accuracy → base for efficient operation in System Control Center
2. AWS installed for weather projection and output forecast of PV and wind, utilizing satellite image → 90% accuracy. Remaining 10% is covered by spinning reserve.
3. Microgrid with CHP for Caribbean Boiler and Hill Run community (800kW)
4. Establishment of **training school for Caribbean countries**

Microgrid with CHP for Caribbean Boiler



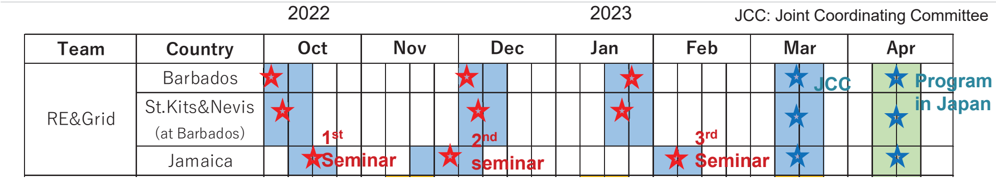


HESS for Stabilization

Item	Flywheel
System integrator	ABB RE+
Manufacturer	Pillar Germany
Capacity	3MW, 16.5 MWs
Speed	1800-3600 rpm
Bearing life	8yrs
Response speed	100 ms
Efficiency	>96%
BESS	LG Chem, 21 MWh

Activity and Achievement (RE)

Seminars on Large RE and Grid Stability



Title	Date	Objective	Contents
1st Seminar	12 Oct 2022	To share basic technical knowledge for grid analysis with large RE	Overview of Power system, per unit method, modeling, asset management, load flow analysis, introduction of method, software and tools
2nd Seminar	30 Nov 2022	To conduct and exercise grid modeling and analysis	Grid modeling, Microgrid, example, Load flow analysis and stability analysis, evaluation
3rd Seminar	8 Feb 2023	Review and exercise of grid analysis with scenario cases	Detailed system and countermeasures, protection, Exercise of tools for grid analysis with various RE scenarios
Final JCC	Mar 2023	To confirm outcome of project and way	Review of TC activity output, policy recommendation, Program in Japan

Activity and Achievement (RE)

Seminars on Grid Stability and Large RE (1)

Seminar	Agenda of 1st Seminar	Participants
1st Seminar 12 Oct 2022	**Overview if challenges of large RE and Grid analysis** 1. Activity and overall project schedule 2. RE target, challenges, and activity of Technical Assistance 3. Grid with large RE penetration& Microgrid Concept for resilience 4. Proposed Contents for Workshop No.1 and No.2 5. Suggestion for countermeasure to non-technical loss	32 nos in total (MSET: 3, OUR 4, JPS and other: 25)
2nd Seminar 30 Nov 2022	**Grid Stability, Grid Analysis, and Microgrid** 1. Project Outline, RE and Microgrid Concept 2. Review and Feedback of 1st seminar 3. Why Grid Stability is necessary - Grid Modelling for Jamaica - Basics of Power System Engineering for Grid Stability Simulation 4. Load Flow Analysis and its Evaluation 5. Transient Stability Analysis and Evaluation of Stability 6. State Estimation for Multi-point Pilferage 7. Discussion for future grid and RE in Jamaica	45 nos in total (MSET:6, OUR:2, JPS and other: 57)

Activity and Achievement (RE)

Seminars on Grid Stability and Large RE (2)

Seminar	Agenda of 1st Seminar	Participants
3rd Seminar 8 Feb 2023	1. Opening Remark 2. Project outline, Review and Feedback of 2nd Seminar 3. Grid Scenario proposed and stability analysis 4. Development Status of Grid Forming Inverter and its Safety : Current Status, Blackout with GFM & Black Start using BESS 5. Transmission lines and Remedial Action Schemes : Special Protection System, PV/Wind Turbine Trip 6. Microgrid planning 7. Technology options 8. Policy recommendation 9. Discussion, sharing good practice of Jamaica, and way forward	29 nos in total (MSET:6, OUR:3, JPS and other: 20)

Activity and Achievement (RE)

Recommendations for Grid with Large RE

Need of Spinning Reserve:
- stand-by thermal generation source should be kept to absorb output fluctuation of VRE

Reactive Power Compensation:
- Reactive power is necessary to establish and maintain the electromagnetic field in the grid and keep voltage. VRE can lead to voltage fluctuations and instability. Reactive power compensation should be installed.

Provision of Sufficient Synchronous generator and Inertia in grid:
- In case VRE generates more than 1/3 of the grid capacity, insufficient synchronous generator and inertia will be a problem.

SCR (short circuit ratio):
- SCR = AC in grid / IBR power. Keep SCR>3.0

IEEE Std 1204-1997(R2003) IBR: Inverter based resource (PV & wind)

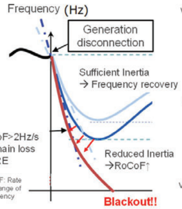
BESS: VRE more than 1 MW should mandate to install BESS, more than 80% of VRE, 4hrs

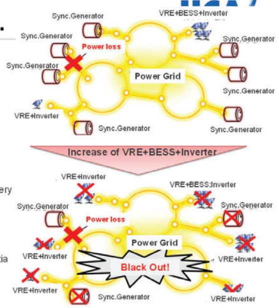
Application of Grid Forming Inverter (GFM):
- To keep SCR >3.0 with VRE, apply GFM with BESS and PV and wind as soon as it can be procured in the market

→ Discussion with Fair Trade Commission (FTC) will be important

Black-out when insufficient Sync. Gen.

If synchronous generator is reduced and inertial is not sufficient, power loss
→ Frequency drop, with no recovery
→ Chain reaction of loss of VRE
→ Black out

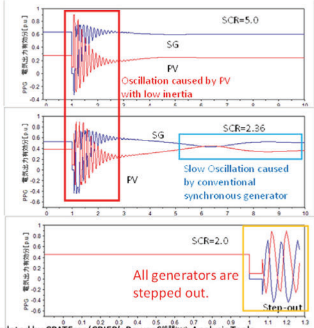




Difference of SCR value

Red: PV (Low Inertia)
Blue: Synchronous Generator (SG) (High Inertia)

70 msec 3 line ground fault by lightning at 1 of 2 circuit transmission line close to SG.



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Activity and Achievement (RE)

Recommendation for Future RE and Grid for 50%RE by 2030

Item	Description
Energy Storage for smoothing &peak shift	- Mandatory installation of BESS, for example, more than 80% of Peak MW and 4hrs storage for utility scale VRE
Investment to secure inertia and spinning reserve for grid	- Maintaining sufficient synchronous generator for spinning reserve - Introduction of Grid Forming Inverter (GFM) for VRE once available, application of Weather projection system
Investment for voltage and reactive power compensation	- Capacitor bank/ STATCOM / Synchronous condenser where needed. - Mandatory application of inverter with reactive power compensation for Wind/Solar IPP
Sharing responsibility of grid stability among utility, IPP, consumers	- **Utility:** maintaining transmission and distribution line frequency and voltage stability, ancillary service, -**VRE IPP:** installation of inverter with reactive power compensation & energy storage - **Consumer:** demand response, ToU setting& EV charging, peak shift
Option for storage (especially with inertia)	- In addition to BESS, options for future ex. consideration of V2G, hydrogen, pumped storage, Compressed Air Energy Storage (CAES) and Gravity Storage to be considered
Microgrid	- To promote microgrid to strengthen resiliency
Data management	- GIS for distributed PV, Database management, Asset management
Recycle/disposal	- Consideration for disposal/recycling of battery &PV panel
Finance	- Use of climate finance, international finance cooperation for RE&stability
"Best-Mix" Energy	- Gas for fluctuation mitigation as intermittent measurement. - Multiple alternative for RE and storage, not a single source (Solar/CSP/Wind/Biomass, BESS/Thermal/new storage, etc.)

Activity and Achievement (EE): #1 Workshop

Year 2022

1. Dates and venue

Feb.9-10 (2days), Zoom

2. Participants

Participated relevant entities(Jamaica)		
Name of entity		# of participants (3 persons in total)
MSET	Ministry of Science, Energy and Technology	1 persons
OUR	Office of Utilities Regulation	2 persons

Activity and Achievement (EE): #1 Workshop

3. Workshop program

Day-1 Feb. 9 (Thu)

Time	Contents	Speaker	Session Time (min.)
9:00	<Presentation> Energy Management & Energy Audit (International Standers and introduction of successful practices)	JET	90
10:30	<Presentation> Battery VS Hydrogen Storage	JET	30

Day-2 Feb. 10 (Fri)

Time	Contents	Speaker	Session Time (min.)
9:00	<Presentation> Report on Energy Audits Results	JET	60
10:00	<Presentation> Market Study of EV	JET	60

Activity and Achievement (EE): #2 Workshop

1. Dates and venue

Mar.28, ZOOM

2. Participants

Participated relevant entities(Jamaica)		
Name of entity		# of participants (8 persons in total)
MSET	Ministry of Science, Energy and Technology	5 persons
BSJ	Bureau of Standards, Jamaica Technology	3 persons

Activity and Achievement (EE): #2 Workshop

3. Workshop program

Time	Contents	Speaker	Session Time (min.)
10:00	<Presentation> Organizational Management and Q&A	JET	50
10:50	Break Time	-	10
11:00	<Presentation> Energy balance, energy efficiency and conservation roadmap	JET	30
11:30	<Presentation> Energy Efficiency Policy in Japan	JET	20
11:50	Q&A	-	10
12:00	Lunch Time	-	60
13:00	<Presentation> Part-1 Energy Efficiency Building Code (Including Okinawa Situation and EE&C Evaluation Study)	JET	50
13:50	Break Time	-	10
14:00	<Presentation> Part- Energy Efficiency Building Code (Including Okinawa Situation and EE&C Evaluation Study)	JET	50
14:50	Q&A	-	10
15:00	Closing	-	-

Activity and Achievement (EE): Workshop Summary

1. Summary of Workshops Contents

	Contents of Workshops	WS, etc.
I	Energy Management & Energy Audit (International Standards and introduction of successful practices)	#1WS
II-a	EE Roadmap with Country Energy Balance and efficient technologies (residential sector)	#2WS
II-b	EE&C Roadmap with Country Energy Balance and efficient technologies (Res & Com sector integration)	#2WS
III-a	Introduction of EE Building Code in Japan	#2WS
III-b	EE Building Code (Including Okinawa & Hawaii Situation and EE&C Evaluation Study)	#2WS
IV	Report on Energy Audits Results including Walk Through Survey	#1WS
V-a	Demonstration: Data Logger & Software	To BNSI: Pre-Conducted
V-b	Demonstration: Software	To MSET: #1WS
V-c	Demonstration: Data logger	To MSET: #2WS
VI	EE policy in Japan	#2WS

Activity and Achievement (EE): Workshop Summary

2. Feedback from Participants of #1 EE Workshop

On a 5-point scale, participants were asked to rate the content of the workshop.

✓ Was JICA experts' explanation clear and easy to understand?	5
✓ Were training materials well organized and easy to understand?	5
✓ Was the content of lecture enough to understand?	4
✓ Were JICA experts maximize participants' opportunities?	4

Activity and Achievement (EE): Workshop Summary

2. Feedback from Participants of #2 EE Workshop

On a 5-point scale, participants were asked to rate the content of the workshop.

✓ Was JICA experts' explanation clear and easy to understand?	3.5
✓ Were training materials well organized and easy to understand?	3.5
✓ Was the content of lecture enough to understand?	3.5
✓ Were JICA experts maximize participants' opportunities?	5

Activity and Achievement (EE): Data Loggers

- **Demonstration was conducted and data loggers were handed over to Jamaica**
  - MSET: 1 data logger (This mission)
  - BSJ: 1 data logger (Mission in last November)

Demonstration using a kettle @ BSJ

Demonstration using a fan @ MSET

Confirmation of PDM (Project Design Matrix)

Overall Goals & Achievement

Description	Verifiable Indicator	Achievement
Overall Goal Energy security is ensured through introduction of renewable energy	**1.** Energy self-dependency Target Value: **50%** **(50% RE by 2030)** **2.** Imported amount of fossil fuel Target Value: **To 80%** **(20% by RE in energy base)**	**1.** As of March 2023, RE generation accounts for 12.4% of total generation. **2.** As of March 2023, imported amount of fossil fuel is ??% in energy base. (MSET will inform to JET)

Project Purpose & Achievement (1)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**1.** Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant Target Value: **To be set according to IRP**	**1.** As of Mar 2023, Utility Scale PV Total ?? MW, Distributed PV Total ?? MW, (If possible) Wind Total ??MW, Battery Total ??MW etc. (MSET will inform to JET)

Project Purpose & Achievement (2)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**2.** Number of public buildings with EE program including BEMS Target Value: **EE program in total for 44 facilities in next 4 years)**	**2.** As of Mar 2023, number of public buildings which are implemented or introduced EE program is ??. (MSET will inform to JET)

Project Purpose & Achievement (3)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**3.** Number of trained staffs for introduction of RE Target Value: - **Domestic trainings: 20-30 personnel** - **Training in Japan: 1-4 personnel**	**3.** In total, number of participants (accumulated total) was 115 personnel **Average (Domestic):** 115/3 = 38.9 personnel/time - 1st Seminar in Oct 2022 was 31 personnel - 2nd Seminar in Nov 2022 was 45 personnel - Final (3rd) Seminar in Feb 2023 was 39 personnel 1 officer engaged in RE will participate in the training in Japan.

Project Purpose & Achievement (4)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**4.** Number of trained staffs for promotion of EE Target Value: - **Domestic trainings: 20-30 personnel** - **Training in Japan: 1-4 personnel**	**4.** In total, number of participants (accumulated total) was 19 personnel **Average:** 19/3 = 6.3 personnel/time - Demonstration on EE roadmap program etc. in Feb 2020 was 8 personnel - 1st Workshop in Feb 2023 was 3 personnel - Final (2nd) Workshop in Mar 2023 was 8 Personnel 1 officer engaged in EE will participate in the training in Japan.

Output 1 & Achievement

Description	Verifiable Indicator	Achievement
Outputs Output 1 (to be achieved in Phase 1) The basic information is confirmed for the capacity building for the introduction of RE	**1-1.** Assessment of number and qualification of staffs responsible for RE **1-2.** Human resource development plan for the introduction of RE **1-3.** Number of training courses for the introduction of RE **1-4.** Total capacity of RE	**1-1.** Confirmed **1-2.** Confirmed **1-3.** Confirmed **1-4.** Confirmed *** Achievement of Output 1 was already confirmed when 1st JCC which was held in Nov 2019**

Output 2 & Achievement

Description	Verifiable Indicator	Achievement
Outputs Output 2(to be achieved in Phase 1) The basic information is confirmed for the capacity building for the promotion of EE	**2-1.** Assessment of number and qualification of staffs responsible for EE **2-2.** Human resource development plan for the introduction of EE **2-3.** Number of training courses for the promotion of EE **2-4.** Number of facilities conducted energy audit	**2-1.** Confirmed **2-2.** Confirmed **2-3.** Confirmed **2-4.** Confirmed *** Achievement of Output 2 was already confirmed when 1st JCC which was held in Nov 2019**

Output 3 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-1.** Number of trained staffs Target Value: **MSET/PCJ: 6 personnel** **3-2.** Textbooks/ manuals Target Value: **3 programs** (2 domestic trainings and 1 training in Japan)	**3-1.** In total, number of participants (accumulated total) was **115 personnel** **Average: 38.9 personnel/time** **3-2.** In total, **3 (4) materials** were prepared. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Nov 2022 and Feb 2023. - 1 training material for training in Japan (Available next month)

Output 3 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-3.** Number of participants of workshops to disseminate introduction of RE to the relevant organizations Target Value: - **Kick-off workshop: 15 personnel** - **Final workshop: 20 - 30 personnel**	**3-3.** - Kick-off workshop in Nov 2019 was **8 personnel** - 1st Seminar in Oct 2022 was 31 personnel - 2nd Seminar in Nov 2022 was 45 personnel - Final (3rd) Seminar in Feb 2023 was **39 personnel**

Output 3 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**3-4.** In total, **4 times** - Kick-off workshop was conducted in Nov 2019 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Nov 2022 - Final (3rd) Seminar was conducted in Feb 2023

Output 4 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-1.** Number of trained staffs Target Value: **MSET/PCJ: 4 personnel** **4-2.** Textbooks/ manuals Target Value: **3 programs** (2 domestic trainings and 1 training in Japan)	**4-1.** In total, number of participants (accumulated total) was **19 personnel** **Average: 6.3 personnel/time** **4-2.** In total, **2 (3) materials** were prepared. - 2 training materials about 'Energy Efficiency Workshop' for domestic training in Feb and Mar 2023. - 1 training material for training in Japan in Apr 2023. (Available next month)

Output 4 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-3.** Number of participants of workshops to disseminate promotion of EE to the relevant organizations Target Value: - **Kick-off workshop: 15 personnel** - **Final workshop: 20 -30 personnel**	**4-3.** - Kick-off workshop in Nov 2019 was **8 personnel** - 1st Workshop in Feb 2023 was 3 personnel - Final (2nd) Workshop in Mar 2023 was **8 personnel**

Output 4 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**4-4.** In total, **3 times** - Kick-off workshop was conducted in Nov 2019 - 1st workshop was conducted in Feb 2023 - Final (2nd) workshop was conducted in mar 2023

Output 5 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-1.** Number of trained staffs Target Value: **MSET/PCJ: 6 personnel** **5-2.** Textbooks/ manuals Target Value: **2 programs** (1 domestic trainings and 1 training in Japan)	**5-1.** In total, number of participants (accumulated total) was **115 personnel** **Average: 38.9 personnel/time** **5-2.** In total, **3 (4) materials** were prepared. - **3 training materials** about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - **1 training material** for training in Japan (Available next month)

Output 5 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-3.** Number of participants of workshops to disseminate promotion of power network resiliency to the relevant organizations Target Value: - **Kick-off workshop: 15 personnel** - **Final workshop: 20 - 30 personnel**	**5-3.** - Kick-off workshop in Nov 2019 was **8 personnel** - 1st Seminar in Oct 2022 was 31 personnel - 2nd Seminar in Nov 2022 was 45 personnel - Final (3rd) Seminar in Feb 2023 was **39 personnel**

Output 5 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**5-4.** In total, **4 times** - Kick-off workshop was conducted in Nov 2019 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Nov 2022 - Final (3rd) Seminar was conducted in Feb 2023

Discussion

Closing Remarks

Thank you.

Minutes of Meeting
of
Joint Coordination Committee #3
of
Technical Cooperation to Promote Energy Efficiency in Caribbean Countries
among
MEB, JICA, and JICA Expert Team

March 27, 2023

Ministry of Energy and Business (MEB)	**Japan International Cooperation Agency, St. Lucia Office**
Ms. Debra Dowridge, Deputy Permanent Secretary	Japan International Cooperation Agency, St. Lucia Office

JICA Expert Team (JET)

Mr. Tomoyasu FUKUCHI, Team Leader

Date and Time:

March 27, 2023, 10:00am (in Barbados), 11:00pm (in Japan)

Location:

Hybrid: Face to Face and Online (Virtual Meeting by Zoom)

Participants:

1) Ministry of Energy and Business (MEB)

- Ms. Debra Dowridge, Deputy Permanent Secretary
- Mrs. Frances Scantlebury, Administrative Officer
- Mr. William Hinds, Chief Energy Conservation Officer
- Mr. Horace Archer, Senior Technical Officer
- Mr. Frank Branch, Technical Officer
- Mr. Terry Neblett, Licensing Officer

2) Japan International Cooperation Agency (JICA), Tokyo

- Mr. Kentaro KUNIKATA, Special Advisor, Team 2, Energy and Mining Group

3) Japan International Cooperation Agency (JICA), St. Lucia Office

- Mr. Ichiro MIMURA, Chief Representative
- Ms. Hitomi URUSHIHATA, Programme Formulation Advisor
- Dr. Ayodele Hippolyte, Project Officer

4) Caribbean Community (CARICOM), Guyana

- Mr. Tatsuya MORITA, CARICOM Advisor (Dispatched from JICA)

5) JICA Expert Team (JET)

- Mr. Tomoyasu FUKUCHI, Team Leader/Power System
- Mr. Yasuhiro SAKAMOTO, Energy Efficiency
- Ms. Yuka NAKAGAWA, Renewable Energy
- Dr. Hisao TAOKA, Electrical Grid Expert
- Ms. Anna MIYAURA, Human Resource Development
- Mr. Tomoaki TSUJI, Grid Stabilization/Coordinator
- Mr. Alex Harewood, Technical Assistant

Discussions:

<Looking Back at the Overall Project>

- JICA Expert Team (JET) explained the project was originally from March 2019 to March 2022, however, due to the COVID-19 pandemic, it was extended to June 2023.
- Activities of Phase 1 for Renewable Energy (RE)
  - Baseline survey was conducted, and JET summarized RE potential in Barbados, existing/planned RE projects, and challenges for achieving 100% RE including grid stability resilience.
  - Accordingly, JET modified the capacity building program to be conducted in Phase 2 to include training for grid stability analysis and microgrid concept.
- Activities of Phase 1 for EE
  - Baseline survey was conducted.
  - JET also recapped Energy Efficiency (EE) background and potential for Barbados as the reduction of energy consumption is fundamental to achieve the 100% RE by 2030.
  - JET revealed with their analysis that approximately half of primary energy is used by residential and commercial sector; and the bulk of EE measures should target these areas in Barbados. The energy saving potential utilizing the proposed JET EE Roadmap with increasing MEPS is estimated to be over 50% by 2036.

<Achievement of Phase 2 "Technical Transfer">

- The activities of JET in the Caribbean region were resumed in July 2022 for Phase 2.
- The capacity building activities were conducted through seminars and workshops based on the baseline survey in the areas of RE and EE.
- JET expressed appreciation for the continuous attendance from MEB and other organizations. Four seminars on Large RE and Grid Stability and two workshops on EE were conducted by a combination of face to face and online methods from Oct 2022 to Jan 2023.
- JET reported about the equipment provision that (i) the power flow analysis software "Microgrid Designer" were handed over to Barbados, and (ii) the power

consumption data collection device (logger, software) was handed over to MEB and BNSI.

- Activities of Phase 2 for RE:
  - JET explained the hybrid seminar series in four sessions where the key focus was on Grid Stability and how this is affected by large amounts of RE on the grid as this is of high importance for the government, the BLPC, and other key stakeholders.
  - JET explained the training sessions were well attended, and the information shared will assist the policy makers and engineers as they seek to achieve 100% RE. JET indicated that the need for spinning reserve, reactive power compensation, and inertia are crucial to ensure grid stability with large penetration of RE in the grid.
  - JET made some recommendations for grid stability and revision of grid code:
    1. Spinning reserve to compensate variable RE (VRE) fluctuation should be kept.
    2. Reactive power compensation should be provided.
    3. For grid stability, the Short Circuit Ratio (SCR) (= AC power in grid / Power from inverter based resource (PV and wind)) should be kept more than 3.0
    4. In case SCR will be less than 3.0, Grid Forming Inverter (GFM) should be applied, once GFM is available in the market.
    5. If the VRE will be installed more than 1 MW, a BESS with minimum 80% capacity and 4hrs duration should be installed.
  - JET summarized recommendations for future RE and grid plans for Barbados.
  - For the enhancement of resilience, JET recommended microgrid application, and reported on case study of Microgrid at Coverley with 100% RE including EV demand. The proposed system includes 3 MW rooftop PV, 7 MW utility scale PV, and 16 MW wind in Long Bey with 33 MWh BESS for135 MWh/day demand, and recommended to apply GFM for stable supply by RE.
- Activities of Phase 2 for EE
  - JET demonstrated data logger and software use to BNSI before handing over.
  - JET demonstrated the data logger and set up the refrigerator to collect power consumption data at the MEB following the request of MEB after handing over.

- JET explained the workshops that were conducted, and stakeholders were receptive to the knowledge shared. The participants voiced the need for a battery standard for safety and performance, along with EE standards for housing in Barbados for cooling.
- Major contents presented from JET are as follows.
    1. Energy Management & Energy Audit (International Standards and introduction of successful practices).
    2. EE&C Roadmap with Country Energy Balance and efficient technologies (residential & commercial sector integration).
    3. EE Building Code including Okinawa & Hawaii Situation and EE&C Evaluation Study.
    4. Report on Energy Audits Results including Walk Through Survey.
    5. Demonstration: Data Logger and its Software.
    6. EE policy in Japan.

<Confirmation of Project Design Matrix (PDM)>

- JET explained the goals of the projects and discussed the achievements in terms of the number of personnel trained in RE and EE, the number of training sessions and the number of training manuals.
- For achievement items of Overall Goal (energy self-dependency and imported amount of fossil fuel), MEB indicated that they will provide the updated data in early April 2023 and will discuss during training in Japan.
- As for the achievement of Project Objective, for RE, JET requested MEB to review the existing project list presented in JCC. MEB will provide the result in early April 2023. For EE, MEB indicated that there are two public buildings with EE program including BEMS (one is National Insurance and the other is regional university (UWI)).
- MEB was in agreement with the result of activities by JET, except the part of under confirmation above.

<Training in Japan>

- JET presented the content of the training experience in Japan, including what to wear, the places that will be visited and any pertinent information key to the visit. MEB asked about sim cards and JET stated that additional information, including any other questions, can be sent forward by 06 April for clarification.

- Participants were also informed about the immigration entry procedures for entering Japan.

List of Attachment:

Attachment-1 Presentation Material for 3rd JCC

Attachment-2 Presentation Material for Training in Japan

End of the MoM

Joint Coordinating Committee (JCC) #3 for Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

March 27, 2023
JET (JICA Expert Team)
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Contents and Timetable

5 min.	• Opening Remark from JICA
5 min.	• Introduction of Participants
5 min.	• Project Outline and Recap of Project
30 min.	• Detail of Activities (Phase 2)
30 min.	• Confirmation of PDM
10 min.	• Discussion
5 min.	• Closing Remark from Barbados Side

Opening Remarks

Today’s Participants

Today's Participants (1/4)

Barbados
- MEB

JICA
- JICA HQ
- JICA Office (JICA St. Lucia Office)

JET
- Japanese Experts
- Local Expert

Today's Participants (2/4)

Barbados

Organization	Name and Title
MEB	◆ **Administration** - Mr. Andrew Gittens, Permanent Secretary - Mrs. Debra Dowridge, Deputy Permanent - Mrs. Frances Scantlebury, Administrative Officer I ◆ **Energy Conservation and Renewable Energy Unit** - Mr. William Hinds, Chief Energy Conservation Officer - Horace Archer, Senior Technical Officer - Frank Branch, Technical Officer - Terry Neblett, Licensing Officer

Today's Participants (3/4)

JICA

Organization	Name
HQ, Tokyo	Mr. Kentaro KUNIKATA, Special Advisor, Team 2, Energy and Mining Group, Infrastructure Management Department
Saint Lucia Office	Mr. Ichiro MIMURA, Chief Representative Ms. Hitomi URUSHIHATA, Programme Formulation Advisor Dr. Ayodele HIPPOLYTE, Project Officer

CARICOM

Organization	Name
HQ	Mr. Tatsuya MORITA, CARICOM Advisor (Dispatched from JICA)

Today's Participants (4/4)

JET

Name	Position
Mr. Tomoyasu FUKUCHI	Team Leader/Power System
Mr. Masaaki EBINA	Sub Team Leader/Power System
Mr. Yasuhiro SAKAMOTO	Energy Efficiency
Ms. Yuka NAKAGAWA	Renewable Energy
Dr. Hisao TAOKA	Electrical Grid Expert
Ms. Anna MIYAURA	Human Resource Development
Mr. Tomoaki TSUJI	Grid Stabilization/Coordinator
Mr. Alex HAREWOOD	Technical Assistant

Project Outline and Recap of Project

Project Outline

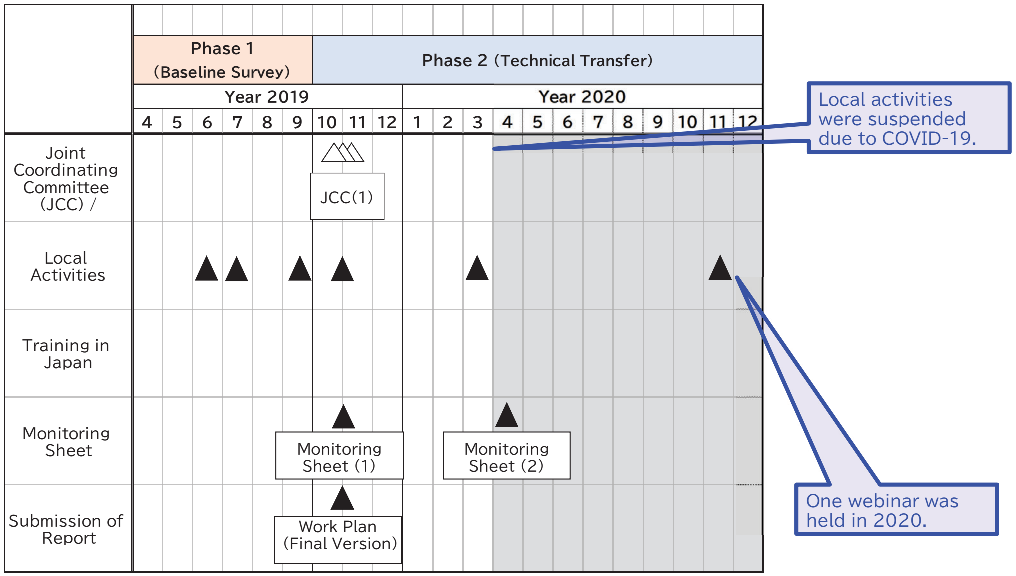
This project is a technical cooperation project by Japan International Cooperation Agency (JICA), which is a governmental agency of Japan.

Duration
- Originally 3 Years from March 2019 to March 2022.
- >>> Extended until Jun 2023.

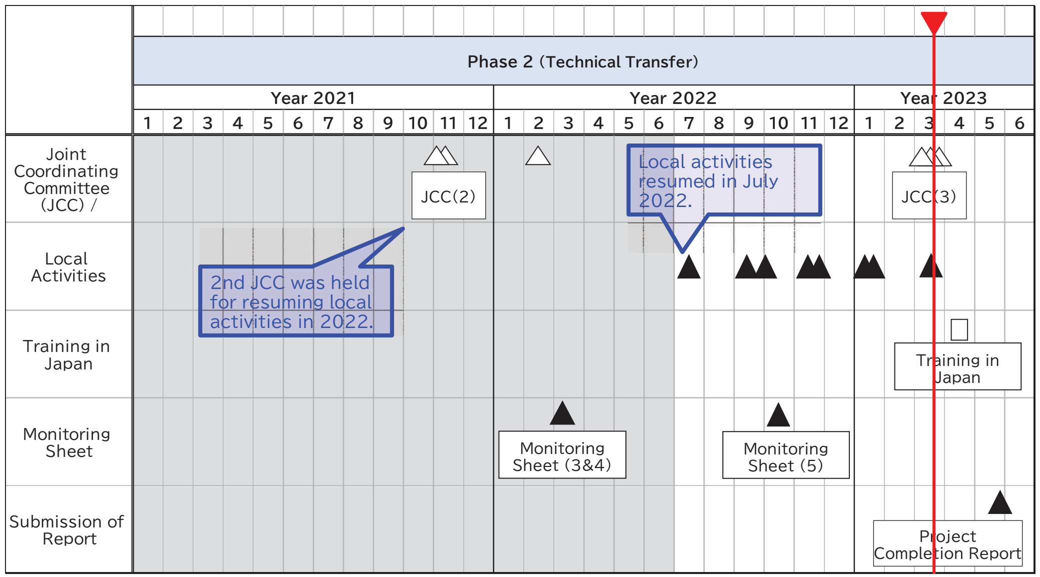
Purpose
- Human and institutional capacities are enhanced for the introduction of Renewable Energy (RE) and the promotion of Energy Efficiency (EE).

Output
- The basic information is confirmed for the capacity building for the introduction of RE and for the promotion of EE. (Phase 1: from Mar to Sep 2019)
- The human and institutional capacities are enhanced for the introduction of RE and the promotion of EE. (Phase 2: from Oct 2019 to Jun 2023)

Recap of Project (1/5)



Recap of Project (2/5)



Recap of Project (3/5)

Phase1 Baseline Survey (EE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

- In EE, in addition to JET's original activities plan, the importance and necessity to collect energy consumption data by end-use/equipment basis has been shared and confirmed with the counterparts toward the formulation of future EE policies.
- Power consumption data collection device (logger, software) are to be provided through this project.

Recap of Project (4/5)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

Baseline Survey and Challenges

Fields	Baseline Findings
RE	• 100% RE target incl. fuel by 2030 • 14% RE (generation), 2% of RE (energy) in 2018 • Good RE potential, but project plan not concrete • 10MW Trents PV + Rooftop PV 12 MW (2018) →>70 MW (Jan 2023)
Grid Stability	• Annual Peak Demand: about 150MW • 5MW, 20 MWh BESS • PV curtailment required • VRE Fluctuation → stability issue • Fuel increase for spinning reserve

Barbados National Energy Policy (BNEP) 2019-2030

- 52% RE by 2030
- 100% RE by 2030 (energy base)
- 10 Visionary goals: Diversity, Efficiency, Affordability, Reliability, Capacity&Collabolation, Entrepreneurship, Environment, Regulation, Innovation, Economic enfranchisement

Importance on Resilience, Integrated Resource and Resilience Plan (IRRP)

RE and Grid Stability activity is to:
- propose the way to enhance resiliency → Microgrid
- introduce micro-grid concept in one of the agreed areas and develop modelling
- introduce computer modelling for grid analysis and examine issues associated with a large penetration of VRE
- consider and propose the technologies for achieving the RE goals, including grid stabilization,
- consider and propose additional policy and legal system for achieving RE goals
- Prepare training (seminar) plan
- provide recommendations on design of the policy/ legal system

Recap of Project (5/5)

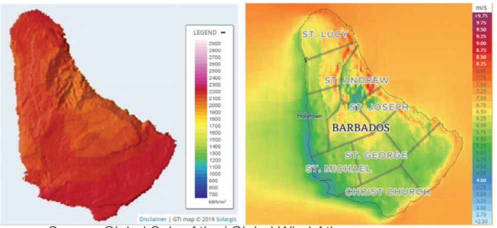
Phase 2 Technical Transfer

- JET conducted capacity building related to RE and EE based on baseline survey.
- Seminar or Workshop were held online or face to face in Barbados
  - 4 RE Seminars on Large RE and Grid Stability
  - 2 EE Workshops
- The following equipment was also provided from JET
  - RE: Grid Analysis Software
  - EE: Data Loggers
- The only remaining activity is the training in Japan, April 2023.

Detail of Activities (Phase 2)

Activity and Achievement (RE)

RE Potential and Plan



Source: Global Solar Atlas/ Global Wind Atlas

Solar and Wind Potential in Barbados

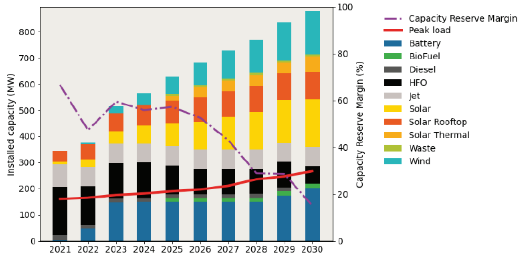
Barbados has overall high solar and local wind potential

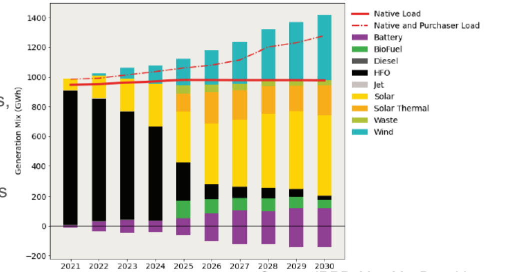
- High Solar potential :2,000-2,200 kWh/m2 (5.5-6.2 kWh/m2/day)
- Rapid increase of distributed PV
- Wind potential is relatively high in the eastern part , 6-8 m/s, due to winds from the east of the Atlantic Ocean
- Wind potential of 472 MW, estimated by UWI

IRRP Scenario-3 plans to install:

- PV: 100.13 MW distributed, 176.75 MW IPP, 9.4 MW Trents
- Biomass: 23 MW + 34 MW MSD (biofuel?)
- Wind166.35 MW, CSP: 60 MW
- BESS: 203.37MW

→ Detailed location of VRE is not clear. Grid capacity and stability according to VRE location needs to be assessed.





Source: IRRP, Mott MacDonald

Capacity and Generated Energy in IRRP Scenario-3

Activity and Achievement (RE)

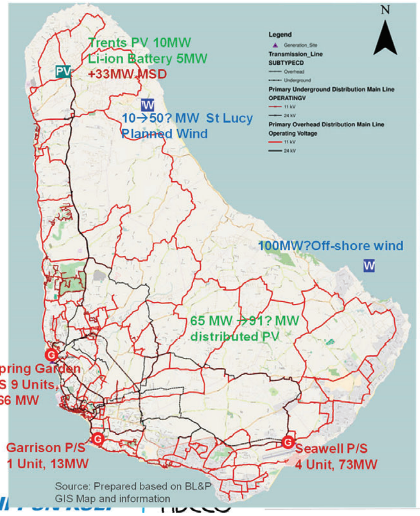
VRE Mapping and Grid Modeling

Challenges:

- Grid capacity enough for Feeder Wise PV / Wind location ?
- Necessary measurement for Grid stability with VRE fluctuation?

→ GIS Mapping of planned PV location and feeder arrangement was done

→ Modeling and grid analysis was conducted.

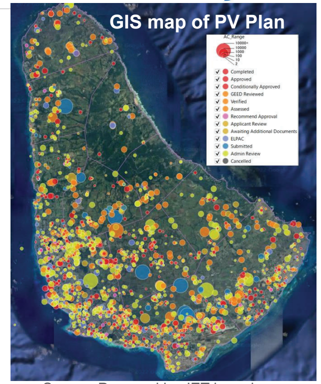


Source: Prepared based on BL&P GIS Map and information

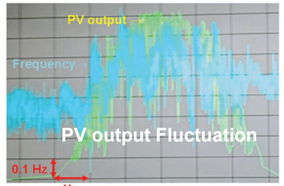
Grid and Generation of Barbados

	Location	MW/u	Qy	MW	Remark
Existing					
Total thermal power				**225**	
	Spring Garden Total		9	166	LDS, ST, GT
	Garrison	13	1	13	Gas Tubine
	Seawell	13	1	13	Gas Tubine
	Seawell	20	0	0	GT (Retire)
	Trents	8.3	4	33	MSD Engine
Total PV				**75.6**	
	Trents	10	1	10	PV
	Distributed PV		LS	65.6	PV
Total Wind				**1**	
	Ashford	1	LS	1	Wind
Total Battery				**5**	
	Trents	1	LS	5	BESS
Planned					
Total Planned RE				**248.5**	
	St Lucy	50	1	50	Wind Planned
	Northeast	100	1	100	Off-shore wind
	St Tomas	30	1	30	Vaucluse Biomass
	PV	13	1	13	PV 52 MW+hydrogen
	Distributed PV		LS	25.5	Licensed yet installed
	PV IPP's		LS	30	IPP's by 2025

Source: Based on information from MEB and BLPC, as of Jan 2023



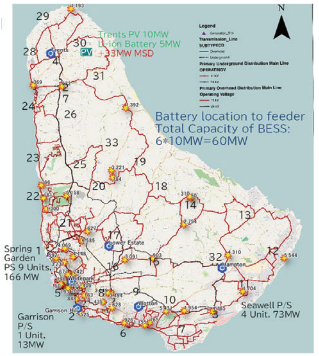
Source: Prepared by JET based on MEB database



Source: BLPC

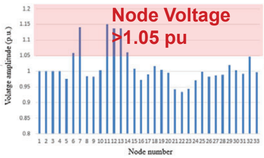
Activity and Achievement (RE)

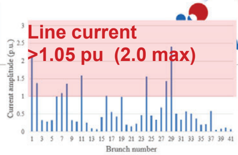
Grid Model and Analysis



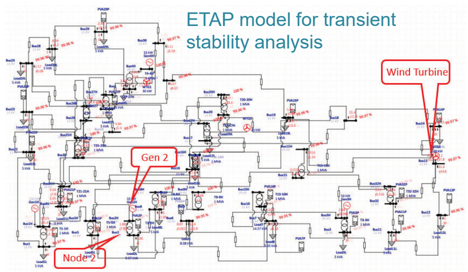
(1) Power flow analysis (Load flow analysis) result with discharge of BESS Discharge (10MW x 6 nos BESS + 143.37MW BESS at new PV/Wind site)

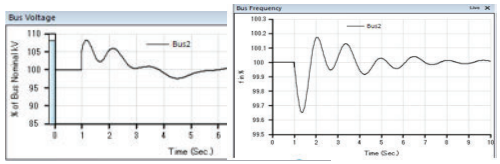
(2) Transient stability analysis with a case 100 MW wind trips





→ Need to enhance grid by such as larger conductor material constructing 2 circuits, voltage upgrade,





- Capacity in 2030 from IRRP Report

Power Resources	Capacity [MW]	Node
– Thermal Generator	102.7*	1,2,3,4
– WH	3.7*	2
– Distributed Solar	100.13	1~33
– Utility Scale Solar	186.16	3,7,11
– Biomass and WtE	57.04*	25
– Onshore Wind	166.35	29
– Solar CSP	60.00*	11
– Battery	203.37	2, 4, 5, 9, 17, 32 +others
• Total	879.45	

Source: Prepared by JET

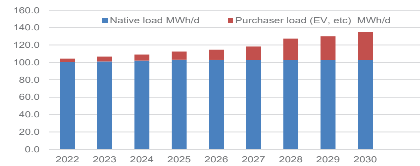
→No problem found in transient stability analysis

Activity and Achievement (RE)

Microgrid Study in Coverley Village

Coverley Village Microgrid Plan with:

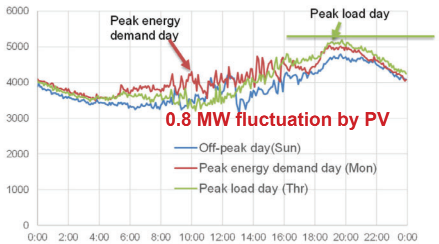
- 99MWh→135 MWh/d demand with EV in 2030
- 3 kW rooftop PV/hh
- 5-7 MW additional utility PV BESS and EMS
- 8-16 MW wind at Long Bey



Demand Increase of Coverley Village

Source: Prepared by JET using Google Earth

Location of Coverley Village



Load Curve of Coverley Village (kW)

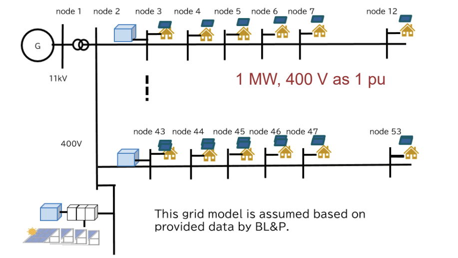
Source: Prepared by JET based on BLPC data

Example of system

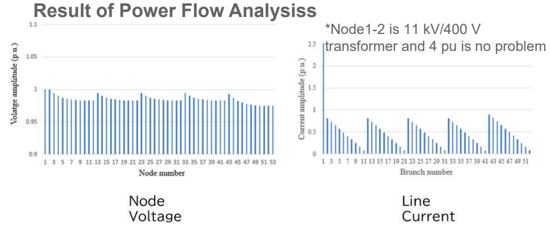
Nos of houses	1026	nos
Roof area for PV	30	m2/house
Commercial/official roof	300	m2 (6 facilities)
Total rool area	31080	m2
Rooftop PV Capacity	3108	kWp
Specific PV Generation	4.917	kWh/kW/day
PV Generation by Rooftop	15,282	kWh/day
Current peak demand	5191	kW
Current energy demand	99,637	kWh/day

Source: Prepared by JET with Global Solar Atras

Coverley Village Microgrid Modeling and Analysis

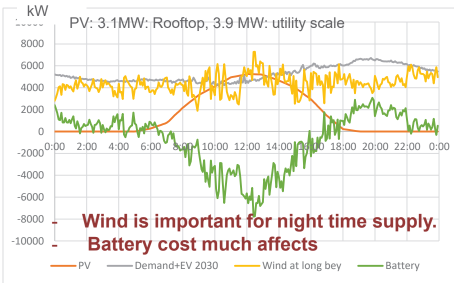


Source: Prepared by JET



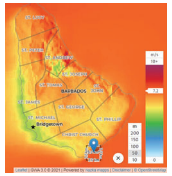
→ No problem in node voltage and line current, since current is small with PV at each house and BESS. Small current from generator (wind or grid)

Case: PV 7 MW + Wind 16 MW, 33 MWh BESS



Provisional Cost Estimation

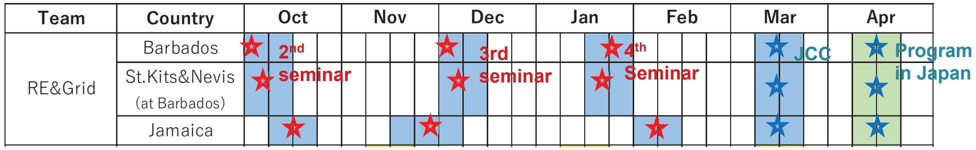
Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	7,000	kW	
Cost of PV installation	7,000,000	USD	
Unit cost of Wind	1,500	USD/kW	
Rated output of Wind	16,000	kW	
Cost of Wind	24,000,000	USD	
Unit cost of 22 kV system	400,000	USD/km	
Length of 22 kV	5	km	
Cost of 22 kV system	2,000,000	USD	
Requirement of SCO	5,750	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	1,150,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	32.9	MWh	8 MW, 4.1 hr
Cost of Battery	13,158,725	USD	
Total Cost	**47,308,725**	**USD**	



Source: Prepared by JET

Plan for Seminars on Large RE and Grid Stability

JCC: Joint Coordinating Committee



Title	Date	Objective	Contents
1st Seminar	27 Jul 2022	To confirm present situation and needs for seminar	• RE target and challenges, revise of activity, general issues of grid with large RE penetration • Microgrid Concept for resilience
2nd Seminar	3-5 Oct 2022	To share basic technical knowledge for grid analysis with large RE	Overview of Power system, per unit method, modeling, load flow analysis, introduction of method, software and tools
3rd Seminar	6-7 Dec 2022	To conduct and exercise grid modeling and analysis	Grid modeling, Microgrid, example, Load flow analysis and stability analysis, evaluation
4th Seminar	25-26 Jan 2023	Review and exercise of grid analysis with scenario cases	Detailed system and countermeasures, protection, Exercise of tools for grid analysis with various RE scenarios
Final JCC	Mar 2023	To confirm outcome of project and way forward	Review of TC activity output, policy recommendation, Program in Japan

Seminars on Grid Stability and Large RE (1)

Seminar	Agenda of 1st Seminar	Participants
1st Seminar 27 Jul, 2022	(On-line/Off-line hybrid) **Overview of Large RE Challenge and needs update** 1. Activity and overall project schedule 2. RE target, challenges, and activity of Technical Assistance 3. Grid with large RE penetration 4. Microgrid Concept for resilience 5. Grid Stability: General Session 6. Grid Stability: Special Session	25 nos in total (MEB:3,GEED:1 BLPC:3CCREEE: 2 UWI:1 Other: 15)

Seminars on Grid Stability and Large RE (2)

Seminar	Agenda of 1st Seminar	Participants
2nd Seminar 3, 4, & 5 Oct 2022	<Day-1 on-line only> **Basics of Power System Engineering for Grid Stability** 1. What is Power System?, Three-phase AC, Single line network description 2. Per Unit Method 3. Modeling of Power System Equipment: Transmission Line, Transformer, Generator & Load 4. Active Power & Frequency: Frequency control, Area requirement 5. Reactive Power & Voltage: P-V Curve, Reactive power resource 6. Practice of Modeling of Grid	Day-1: 61 nos in total (Day-1: 61 nos in total (joint with St. Kitts & Nevis) MEB:7, GEED:2, BPLC:1 BREA and other: 51
	<Day2 online/off-line hybrid > **Basics and Exercise for Load Flow Analysis** 1. Overview of Load Flow Analysis: Purpose, Methods, Modeling of grid 2. Newton-Raphson Method: Theory, Characteristics 3. DC Flow Method: Theory, Simple method to solve load flow manually 4. Exercise of DC Flow Method 5. Practice on Microgrid/VPP Designer 6. Load Flow Analysis & Evaluation of sample Grid	Day-2: 44 nos (joint with St. Kitts & Nevis) MEB:11, GEED:1, CCREEE:3, BLPC:2, BREA:1, Other:26
	<Day-3 on-line/off-line hybrid> **Analysis of Grid Stability and LFC/ELD** **Overview of Stability: Definition, Methods, Swing equation** 1. Stability Model: Simplified grid model, Equivalent circuit of synchronous generator 2. Equal Area Criterion: Theory, Simple method to solve stability manually 3. Available Transmission Capacity & Spinning Reserve 4. Exercise of Equal Area Criterion 5. Practice on Microgrid/VPP Designer and LFC/ELD 6. Discussion for Interconnection, RE and Grid Stabilization in St. Kitts&Nevis	Day-3: 48 nos (joint with St .Kitts & Nevis) MEB:11, GEED:1, CCREEE:3 BLPC:2 BREA:1, Other:26

Activity and Achievement (RE)

Seminars on Grid Stability and Large RE (3)

Seminar	Agenda of 2nd Seminar	Participants
3rd Seminar 6 Dec (full day)	<Day-1 on-line >: **Preparation for Exercise and Grid Modeling** 1. Opening Remarks. 2. Project Outline, Feedback of 2nd seminar, Microgrid, Why Grid Stability is necessary 3. Grid Modeling 4. Basics of Power System Engineering, 5. Load Flow Analysis and its Evaluation 6. Transient Stability Analysis and Evaluation of Stability. 7. Discussion	Day-1: 45 nos (joint with St. Kitts & Nevis) MEB:9 GEED:2, CCREEE:3 BLPC:5 BREA:4, Other: 22
8, Dec 2022 (Half day	<Day-2 on-line/off-line hybrid >**Exercise for Grid Analysis** 1. Evaluation of Load Flow Analysis by Microgrid Designer 2. Evaluation of Load Flow Analysis & Transient Stability by ETAP 3. Discussion for 100% RE achievement 4. Closing Remarks	Day-2:11 nos MEB:4 CCREEE:2 BLPC:1 BREA:2, Other: 2

Team for exercise of grid analysis

Power Flow analysis tool "Microgrid Designer" was handed over to MEB.

Activity and Achievement (RE)

Seminars on Grid Stability and Large RE (4)

Seminar	Agenda of 3rd Seminar	Participants
4th Seminar 24-25, Jan 2023 (All full day)	<Day-1 on-line only> **Scenario Cases, Protection, and Technologies** 1. Introduction for the Seminar, Power system, Review &feedback 2. Microgrid Planning with Large RE 3. Development Status of Grid Forming Inverter and its Safety: Current Status, Blackout with GFM & Black Start using BESS 4. Battery & Hydrogen as an Electricity Storage, cost comparison 5. Special Protection System including Load Shedding, PV/WT Trip 6. Scenario cases of modified IRRP, Simulation Cases for Exercise 7. Cost of stability and Sharing Responsibility for stability 8. Harmonics and filtering 9. Inverter, Grid Code 10. A Sample of Other Countries Situations of Grid and RE 11. Investment of MW and MWh of Energy Storage for VRE	Day-1:13 nos MEB:3 UWI:1 CCREEE:3 GEED:2 BLPC:2 BREA:2
	<Day-2 on-line/off-line hybrid > **Exercise for analysis with Microgrid** 1. Introduction of Microgrid Designer and Transient Analysis 2. - Role of Tools for Power System Analysis, - Load Flow Analysis 3. - Transient Stability Analysis for Operation and Control 4. Microgrid model with Coverley Village example 5. Exercise on simple model and Microgrid : Design &Operation Planning, Load Flow Analysis, Transient Stability Analysis 6. Exercise on Future Grid and IRRP Scenario: Design and Operation Planning, Load Flow Analysis, Transient Stability Analysis 7. Analysis Result and Countermeasure of Grid Stability 8. Discussion and Way forward 9. 9. Conclusion and Closing Remarks	Day-1:8 nos MEB:3 GEED:1 BLPC:2 BREA:2

Activity and Achievement (RE)

Recommendations for Grid with 100%RE

Need of Spinning Reserve:

- stand-by thermal generation source should be kept to absorb output fluctuation of VRE

Reactive Power Compensation:

- Reactive power is necessary to establish and maintain the electromagnetic field in the grid and keep voltage. VRE can lead to voltage fluctuations and instability. Reactive power compensation should be installed.

Provision of Sufficient Synchronous generator and Inertia:

- In case VRE generates more than 1/3 of the grid capacity, insufficient synchronous generator and inertia will be a problem.

SCR (short circuit ratio):

- SCR = AC in grid / IBR power. Keep SCR>3.0

IEEE Std 1204-1997(R2003) IBR: Inverter based resource (PV & wind)

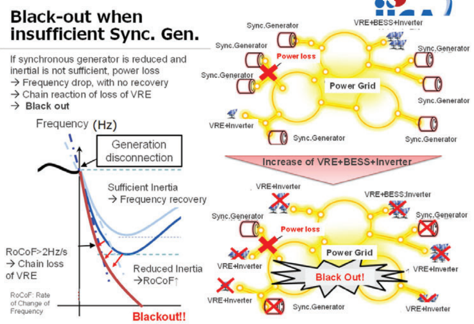
BESS: VRE more than 1 MW should mandate to install BESS, more than 80% of VRE, 4hrs

Application of Grid Forming Inverter (GFM):

- To keep SCR >3.0 with VRE, apply GFM with BESS and PV and wind as soon as it can be procured in the market

→ Discussion with Fair Trade Commission (FTC) will be important

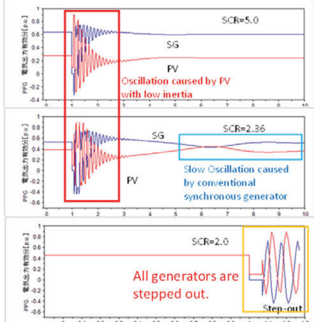
Black-out when insufficient Sync. Gen.



Difference of SCR value

Red: PV (Low Inertia)
Blue: Synchronous Generator (SG) (High Inertia)

70 msec 3 line ground fault by lightning at 1 of 2 circuit transmission line close to SG.



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Activity and Achievement (RE)

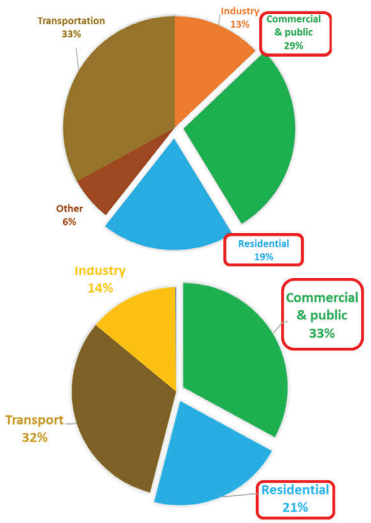
Recommendation for Policy and Regulation

Item	Description
Storage for smoothing output and peak shift	- Mandatory installation of BESS, for example, more than 80% (or 100%) of Peak MW and 4hrs storage for utility scale VRE
Investment to secure inertia and spinning reserve for grid	- Maintaining sufficient synchronous generator for spinning reserve - Introduction of Grid Forming Inverter (GFM) for VRE once available, application of Weather projection system
Investment for voltage and reactive power	- Mandatory application of Inverter with reactive power compensation for Wind/Solar IPP
Microgrid	- To promote microgrid to strengthen resiliency
Sharing responsibility of grid stability among utility, IPP, consumers	- Utility: maintaining transmission and distribution line frequency and voltage stability, ancillary service - IPP of VRE: installation of inverter with reactive power compensation and energy storage - Consumer: demand response, ToU setting& EV charging, peak shifting
Option for storage (especially with inertia)	- In addition to BESS, consideration of V2G, hydrogen, (pumped storage), Compressed Air Energy Storage (CAES) and Gravity Storage based on cost analysis and future development
Data management	- Database management, update plans based on implementation status
Recycle/disposal	- Consideration for disposal and recycling of battery and PV panel
"Best-Mix" Energy	- Multiple alternative for RE and storage, not a single source (Solar/CSP/Wind/Biomass, BESS/Thermal/new storage, etc.)

Year 2022

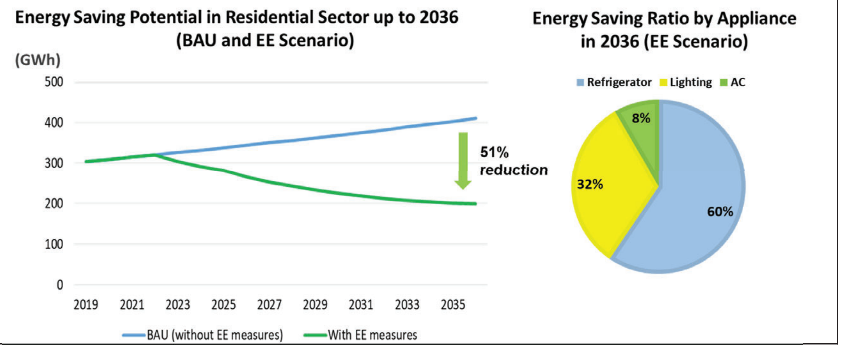
Activity and Achievement (EE): Visits in Sep.2022

Items	Technology transfer/sharing contents in Sep.2022
E&CE roadmap／MEPS & labeling program (S&L)	▪ Reported Primary Energy (PE) consumption analysis based on national energy balance. [Barbados] ➢ 48% of PE is used for non-industrial sector (Res&Com). ➢ PE consumption has been reduced by approx. 6% in last 10 years. [SKN] ➢ 54% of PE is used for non-industrial sector (Res&Com). ➢ PE consumption has increased by approx. 6% in last 10 years. ▪ Based on above analysis, EE&C should be promoted with **priority given to non-industrial sector.**



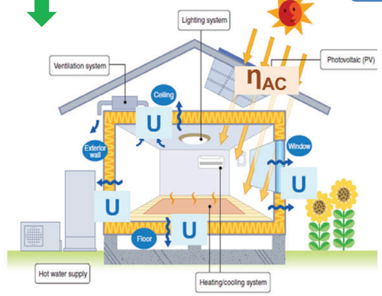
Activity and Achievement (EE): Visits in Sep.2022

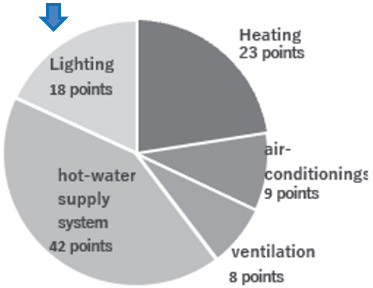
Items	Technology transfer/sharing contents in Sep.2022
EE&C roadmap／MEPS & labeling program (S&L)	▪ Introduced the method of creating EE&C roadmap. ▪ Reported the developed roadmap for residential sector assuming MEPS introduction as well as periodical increasement of MEPS targeting to refrigerators, air conditioners, and lighting). ➢ Energy saving potential was estimated to be 51% in 2036. ➢ Refrigerator has the highest energy-saving potential (60%).



Activity and Achievement (EE): Visits in Sep.2022

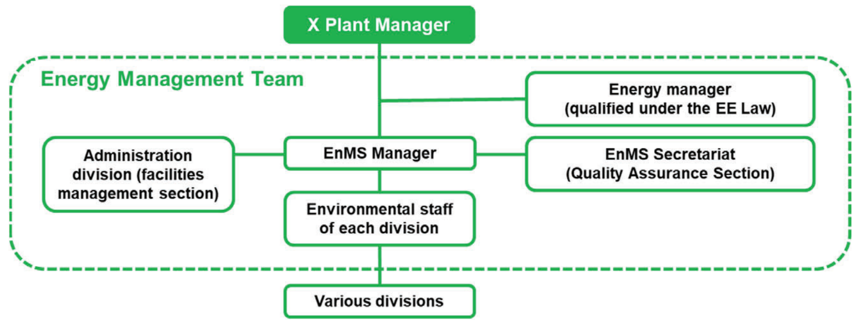
Items	Technology transfer/sharing contents in Sep.2022
Building code	▪ Introduced the Japanese building code situation in Japan (residence) and a simple evaluation method. 【EE standards】 Envelope performance (U value, η value) Primary energy consumption





Activity and Achievement (EE): Visits in Sep.2022

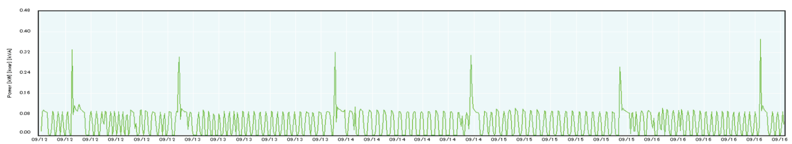
Items	Technology transfer/sharing contents in Sep.2022
Energy Management (EnMS)／Energy Audit	▪ EnMS methods based on ISO 50001 were shared. ▪ Good practices of acquiring the ISO certificate was introduced. (the figure below is an example of the EnMS team of a Japanese company). • Energy audit methods based on ISO 50002 were shared. • Good practices of energy audits were introduced.



Activity and Achievement (EE): Visits in Sep.2022

Items	Technology transfer/sharing contents in Sep.2022
Power consumption measurement/analysis using a data logger	▪ Explained how to use data logger, accessories (for current/voltage measurement), and software, including demonstrations. ▪ Proposed it is essential to use actual power consumption data for each device when formulating EE&C policies. ▪ Delivered data loggers and its software to Barbados (MEB).

Measured Power Consumption Data of Refrigerator in MEB Office (Sep.12 – 16, 2022)



Activity and Achievement (EE): #1 Workshop

1. Dates and venue

Nov.24 (2days), Meeting Room in Dover Beach Club Hotel, Barbados

2. Participants

Participated relevant entities(Barbados)		
	Name of entity	# of participants (5 persons in total)
BL&P	Barbados Light and Power Company Limited	1 persons (on site)
BNSI	Barbados National Standards Institution	2 persons (on site)
UWI	University of West Indies	2 persons (on site)

Activity and Achievement (EE): #1 Workshop

3. Workshop program

Time	Contents	Speaker	Session Time (min.)
9:30	Reception Start	-	-
10:00	Opening Remarks	Barbados Light & Power	10
10:10	<Presentation> Energy Management & Energy Audit (International Standers and introduction of successful practices)	JET	50
11:00	Q&A	-	15
11:15	Break Time	-	15
11:30	<Presentation> Energy Efficiency Roadmap with country energy balance and efficient technologies	JET	45
12:15	Q&A	All	15
12:30	Lunch Time	-	60
13:30	<Presentation> EV and Storage Battery Market Trends	JET	60
14:30	Q&A	All	15
14:45	Closing	-	-

Activity and Achievement (EE): #2 Workshop

1. Dates and venue

Jan.23-24(2 Days),COURTYARD BRIDGETOWN, BARBADOS

2. Participants

Participated relevant entities(Barbados)		
	Name of entity	# of participants (10 persons in total)
MEB	Ministry of Energy and Business	3 persons (on site)
BNSI	Barbados National Standards Institution	4 persons (on site)
BREA	Barbados Renewable Energy Association	1 persons (on site)
CCREEE	Caribbean Centre for Renewable Energy and Energy Efficiency	2 persons (on site)

Activity and Achievement (EE): #2 Workshop

3. Workshop program (Day 1: Jan.23 (Mon))

Time	Contents	Speaker	Session Time (min.)
9:30	Reception Start	-	-
10:00	Opening Remarks	MEB	10
10:10	<Presentation> Energy balance, energy efficiency and conservation roadmap (Residential & commercial sector integration) Including break time and Q&A session <Presentation (additional)> Energy Efficiency Policy in Japan	JET	110
12:00	Lunch Time	-	60
13:00	<Presentation> Energy Efficiency Building Code (Including Okinawa Situation and EE&C Evaluation Study * Including break time and Q&A session	JET	120
15:00	Closing	-	-

Activity and Achievement (EE): #2 Workshop

3. Workshop program (Day 2: Jan.24 (Tue))

Time	Contents	Speaker	Session Time (min.)
9:30	Reception Start	-	-
10:00	Recap of First Day	JET	10
10:10	<Presentation> Report on Energy Audits Results <Presentation (additional)> Energy Audit Best Practice at Aquarium & Amusement Park in Japan	JET	80
11:30	Break Time	-	15
11:45	<Demonstration> Data Logger Software	JET	15
12:00	Lunch Time	-	60
13:00	<Presentation> Lecture on Organizational Collaboration	JET	60
14:00	Break Time	-	15
14:15	<Free Discussion Time>	All	20
14:35	Closing Remarks	MEB	10
14:45	Photo Session	All	15
15:00	Closing	-	-

Activity and Achievement (EE): Workshop Summary

1. Summary of Workshops Contents

	Contents of Workshops	WS, etc.
I	Energy Management & Energy Audit (International Standards and introduction of successful practices)	#1WS
II-a	EE Roadmap with Country Energy Balance and efficient technologies (residential sector)	#1WS
II-b	EE&C Roadmap with Country Energy Balance and efficient technologies (Res & Com sector integration)	#2WS
III-a	Introduction of EE Building Code in Japan	Conducted in Sep visit
III-b	EE Building Code (Including Okinawa & Hawaii Situation and EE&C Evaluation Study)	#2WS
IV	Report on Energy Audits Results incl. Walk Through Survey	#2WS
V	Demonstration: Data Logger & Software	To MEB: conducted in Sep visit To BNSI: conducted in Nov visit
VI	EE policy in Japan	#2WS

Activity and Achievement (EE): Workshop Summary

2. Comments from Participants

Comments collected after #2 EE Workshop Day-1

- ✓ The industry increase when compared to the overall energy use is quite small. The commercial decrease can be attributed to decrease in economic activity in that sector.
- ✓ It takes about 3 joules of fossil fuel produces only 1 joule of electricity.
- ✓ There are examples of inefficient LED installations in Barbados that needs to suit the Street lighting application.
- ✓ Passive Cooling is something we as Barbadians should look into, primarily insulation of roofs.
- ✓ Large eaves can't work in Barbados as we are in the Hurricane Belt, so we can use paints etc.
- ✓ There is still a need to ensure the EE measures are done correctly in Barbados, despite the lack of resources.

Activity and Achievement (EE): Workshop Summary

2. Comments from Participants

Comments collected after #2 EE Workshop Day-2
✓ For companies renting buildings, there is no incentives to invest in energy savings as this doesn' t benefit the landlord. If there is a mechanism where the tenant and landlord both benefit.
✓ EE building certifications can be used to incentivize EE measures including LED.
✓ There are about 4 buildings that are focused on EE in Barbados and use this as a selling point for their tenanted buildings.
✓ The office of the MEB can have a reduction in lighting requirements as the light levels are about 900 Lux.
✓ The temperature variation is the highest from late night till midday. If we utilize the variations in temperature during the night and weather variations, we can boost energy efficiency in cooling in Barbados. (night parge)
✓ The avoidance of being dazzled by several possibilities is one key measure BNSI takes to progress the national standards.

Activity and Achievement (EE): Workshop Summary

2. Comments from Participants

Topics you would like us to cover at next training (after #2 EE workshop)
✓ Need to introduce an EE Standard for houses in Barbados.
✓ The CREEBC is very complex, and Japanese approach is simple and easy to use.
✓ Battery storage integration into utility grid. Standards for safety and performance.
✓ Infrastructure for Electric Vehicles

Activity and Achievement (EE): Data Loggers

- Demonstration was conducted and data loggers were handed over to Barbados
  - MEB: 1 data logger
  - BNSI: 1 data logger

Demonstration @ Pantry in MEB Building

Confirmation of PDM (Project Design Matrix)

Overall Goals & Achievement

Description	Verifiable Indicator	Achievement
Overall Goal Energy security is ensured through introduction of renewable energy	**1.** Energy self-dependency Target Value:**100% (100%RE by 2030)** **2.** Imported amount of fossil fuel Target Value: **To 0% by 2030**	**1.** - **2.** -

Project Purpose & Achievement (1)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**1.** Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant Target Value: - **PV 10 MW (BLPC) + 25 MW (Other) + Wind 10 MW**	**1.** -

Project Purpose & Achievement (2)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**2.** Number of public buildings with EE program including BEMS Target Value: **TBC**	**2.** -

Project Purpose & Achievement (3)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**3.** Number of trained staffs for introduction of RE Target Value: **6 personnel (MEB:3, BLPC:3) and others**	**3.** In total, number of participants (accumulated total) was **36 personnel (MEB and BLPC)** MEB: **around 3 personnel** BLPC: **2-4 personnel** - Remote training in Dec 2020 was 4 personnel (MEB: 4) - 1st Seminar in Jul 2022 was 4 personnel (MEB: 2, BLPC: 2) - 2nd Seminar in Oct 2022 was 33 personnel (MEB: 12, BLPC: 3) - 3rd Seminar in Dec 2022 was 19 personnel (MEB: 4, BLPC: 4) - Final (4th) Seminar in Jan 2023 was 13 personnel (MEB: 3, BLPC: 2)

Project Purpose & Achievement (4)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	4. Number of trained staffs for promotion of EE Target Value: **7 personnel**	4. In total, number of participants (accumulated total) was **35 personnel** **Average:** **35/4 = 8.5 personnel/time** - Demonstration on EE roadmap program etc. in Feb 2020 was 15 personnel - Remote training in Dec 2020 was 4 personnel - 1st Workshop in Nov 2022 was 5 personnel - Final (2nd) Workshop in Jan 2023 was 11 personnel

Output 1 & Achievement

Description	Verifiable Indicator	Achievement
Outputs Output 1 (to be achieved in Phase 1) The basic information is confirmed for the capacity building for the introduction of RE	**1-1.** Assessment of number and qualification of staffs responsible for RE **1-2.** Human resource development plan for the introduction of RE **1-3.** Number of training courses for the introduction of RE **1-4.** Total capacity of RE	**1-1.** Confirmed **1-2.** Confirmed **1-3.** Confirmed **1-4.** Confirmed **＊Achievement of Output 1 was already confirmed when 1st JCC which was held in Nov 2019**

Output 2 & Achievement

Description	Verifiable Indicator	Achievement
Outputs Output 2(to be achieved in Phase 1) The basic information is confirmed for the capacity building for the promotion of EE	**2-1.** Assessment of number and qualification of staffs responsible for EE **2-2.** Human resource development plan for the introduction of EE **2-3.** Number of training courses for the promotion of EE **2-4.** Number of facilities conducted energy audit	**2-1.** Confirmed **2-2.** Confirmed **2-3.** Confirmed **2-4.** Confirmed **＊Achievement of Output 2 was already confirmed when 1st JCC which was held in Nov 2019**

Output 3 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-1.** Number of trained staffs Target Value: **6 personnel (MEB, BLPC)** **3-2.** Textbooks/ manuals Target Value: **3 programs** (2 domestic trainings and 1 training in Japan)	**3-1.** In total, number of participants (accumulated total) was **36 personnel** **MEB: 3 personnel/time** **BLPC: 2 – 4 personnel/time** **3-2.** In total, **6 (7) materials** were prepared. - 1 manual for simulation software of system analysis. - 1 training material for remote training in Dec 2020. - 4 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan (Available next month)

Output 3 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-3.** Number of participants of workshops to disseminate introduction of RE to the relevant organizations Target Value: - **Kick-off workshop: 10 personnel** - **Final workshop: 10 - 15 personnel**	**3-3.** - Kick-off workshop in Nov 2019 was **9 personnel** - Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 4 personnel - 1st Seminar in Jul 2022 was 4 personnel - 2nd Seminar in Oct 2022 was 33 personnel - 3rd Seminar in Dec 2022 was 19 personnel - Final (4th) Seminar in Jan 2023 was **13 personnel**

Output 3 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**3-4.** In total, **6 times** - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Jul 2022 - 2nd Seminar was conducted in Oct 2022 - 3rd Seminar was conducted in Dec 2022 - Final (4th) Seminar was conducted in Jan 2023

Output 4 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-1.** Number of trained staffs Target Value: **6 personnel** **4-2.** Textbooks/ manuals Target Value: **3 programs** (2 domestic trainings and 1 training in Japan)	**4-1.** In total, number of participants (accumulated total) was **35 personnel** **Average: 8.5 personnel/time** **4-2.** In total, **3 (4) materials** were prepared. - 1 training material for remote training in Dec 2020. - 2 training materials about 'Energy Efficiency Workshop' for domestic training in Nov 2022 and Jan 2023. - 1 training material for training in Japan in Apr 2023. (Available next month)

Output 4 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-3.** Number of participants of workshops to disseminate promotion of EE to the relevant organizations Target Value: - **Kick-off workshop: 10 personnel** - **Final workshop: 10 - 15 personnel**	**4-3.** - Kick-off workshop in Nov 2019 was **9 personnel** - Demonstration on EE roadmap program and power consumption measurement was conducted in Feb 2020 was 15 personnel - Remote training in Dec 2020. Number of participants was 4 personnel - 1st Workshop in Nov 2022 was 5 personnel - Final (2nd) Workshop in Jan 2023 was **11 personnel**

Output 4 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**4-4.** In total, **5 times** - Kick-off workshop was conducted in Nov 2019 - Demonstration on EE roadmap program and power consumption measurement in Mar 2020 - Remote training about 'impact of COVID-19 on EE' in Dec 2020 - 1st workshop was conducted in Nov 2022 - Final (2nd) workshop was conducted in Jan 2023

Output 5 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-1.** Number of trained staffs Target Value: **6 personnel** (MEB, BLPC) **5-2.** Textbooks/ manuals Target Value: **2 programs** (1 domestic trainings and 1 training in Japan)	**5-1.** In total, number of participants (accumulated total) was **36 personnel** **MEB: 3 personnel/time** **BLPC: 2 – 4 personnel/time** **5-2.** In total, **4 (5) materials** were prepared. - 1 training material for remote training in Dec 2020. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan (Available next month)

Output 5 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-3.** Number of participants of workshops to disseminate promotion of power network resiliency to the relevant organizations Target Value: - **Kick-off workshop: 10 personnel** - **Final workshop: 10 – 15 personnel**	**5-3.** - Kick-off workshop in Nov 2019 was **9 personnel** - Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 4 personnel - 1st Seminar in Jul 2022 was 4 personnel - 2nd Seminar in Oct 2022 was 33 personnel - 3rd Seminar in Dec 2022 was 19 personnel - Final (4th) Seminar in Jan 2023 was **13 personnel**

Output 5 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**5-4.** In total, **6 times** - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Jul 2022 - 2nd Seminar was conducted in Oct 2022 - 3rd Seminar was conducted in Dec 2022 - Final (4th) Seminar was conducted in Jan 2023

Discussion

Closing Remarks

Thank you.

Minutes of Meeting
of
Joint Coordination Committee #3
of
Technical Cooperation to Promote Energy Efficiency in Caribbean Countries
among
MPI, JICA, and JICA Expert Team

March 21, 2023

Ministry of Public Infrastructure, Post, Urban Development, and Transport (MPI)

Bertill Browne

Dr. Bertille Browne, Director of Energy unit

19/4/23

Japan International Cooperation Agency, St. Lucia Office

Mr. Ichiro MIMURA, Chief Representative

JICA Expert Team (JET)

Mr. Tomoyasu FUKUCHI, Team Leader

Date and Time:

March 21, 2023, 9:30am (in St. Kitts and Nevis), 10:30pm (in Japan)

Location:

Online (Virtual Meeting by Zoom)

Participants:

1) Ministry of Public Infrastructure, Energy, and Utilities (MPI)

- Dr. Bertille Browne, Director of the Energy Unit
- Mr. Denasio Frank, Energy Officer, Energy Unit

2) Nevis Island Administration (NIA)

- Ms. Michelle Walters, Energy Commissioner

3) St. Kitts Electricity Company (SKELEC)

- Mr. Jonathan Kelly, Engineering Manager

4) Nevis Electricity Company (NEVLEC)

- Mr. Ian Ward, Chief Engineer

5) Nevis Water Department (NWD)

- Mr. Clychawn Wilson, Water Technician

6) Japan International Cooperation Agency (JICA), Tokyo

- Mr. Kentaro KUNIKATA, Special Advisor, Team 2, Energy and Mining Group

6) Japan International Cooperation Agency (JICA), St. Lucia Office

- Mr. Ichiro MIMURA, Chief Representative
- Ms. Hitomi URUSHIHATA, Programme Formulation Advisor
- Dr. Ayodele HIPPOLYTE, Project Officer
- Ms. Elvinette Wilson

7) Caribbean Community (CARICOM), Guyana

- Mr. Tatsuya MORITA, CARICOM Advisor (Dispatched from JICA)

8) JICA Expert Team (JET)

- Mr. Tomoyasu FUKUCHI, Team Leader/Power System
- Mr. Yasuhiro SAKAMOTO, Energy Efficiency
- Ms. Yuka NAKAGAWA, Renewable Energy
- Dr. Hisao TAOKA, Electrical Grid Expert
- Ms. Anna MIYAURA, Human Resource Development
- Mr. Tomoaki TSUJI, Grid Stabilization/Coordinator
- Mr. I-Ronn Audain, Technical Assistant

Discussions:

<Looking Back Over all the Project>

- JET explained that the project is a technical cooperation project by JICA and that the project was originally from March 2019 to March 2022 however due to the COVID-19 pandemic it was extended to June 2023.
- JET explained that the purpose of the project is to enhance the human and institutional capacity of St. Kitts and Nevis in the areas of Renewable Energy (RE) and the promotion of Energy Efficiency (EE). At the first phase of the project, which went from March to September of 2019, JET confirmed the baseline of the country by gathering the information to be able to develop a plan for the capacity building of the participants for the introduction of the RE and the promotion of the EE. The second phase, from October 2019 to June 2023 concentrated on developing the human and institutional capacity by workshop and seminars.
- Activities of Phase 1 for EE
  - Baseline survey was conducted.
  - A recommendation was made by JET that it was necessary to collect the end user energy consumption data by equipment as it would help to shape future (EE) policies.
  - JET decided to provide two data loggers and the necessary software, one for each island. This was to facilitate the collection of the power consumption data.
- Activities of Phase 1 for RE
  - Baseline survey was conducted, and sector challenges were identified as RE plans, standards, and tools of grid analysis. This information was used to determine the capacity building plan, which include: (i) Modeling of existing power line network, (ii) Provision of grid simulation software and training and grid analysis with 35 MW PV and 6 MW wind, (iii) Recommendation for grid code revision, and (iv) introduction of network asset management.
  - NEVLEC requested a hydrogen/ammonia utilization study with geothermal, which was to be included in seminar agenda.

- JET explained that activities in St. Kitts and Nevis till March 2020, after which local activities were suspended until November 2020 of the same year when an online webinar was conducted. In November 2021 a second JCC was conducted to determine the way forward for 2022.

<Achievement of Phase 2 "Technical Transfer">

- The capacity building activities were conducted through seminars and workshops based on the baseline survey in the areas of RE and EE. The activities of JET in Caribbean region were resumed in Jul 2022, however, due to travel restriction of JET, officers of St, Kitts and Nevis were requested to attend workshops and seminars in Barbados. JET expressed appreciation for their several times travel management to attend. Three seminars on Large RE and Grid Stability and two workshops on EE were conducted by combination of face to face and online method from Oct2022 to Jan 2023.

- JET reported about the equipment provision that (i) the power flow analysis software "Microgrid Designer" were handed over to St. Kits and Nevis, (ii) the asset management system with SKELEC data were installed in a PC of SKELEC for demonstration purpose, and (iii) power consumption data collection device (logger, software) was handed over to each island.

- Activities of Phase 2 for RE,

  - JET presented about (i) the result of grid modeling and analysis and recommendation for St. Kitts and Nevis with current plan and future interconnection with geothermal development in Nevis, (ii) demonstration of asset management, and (iii) hydrogen/ammonia study with geothermal power.
  - JET made some recommendations for grid stability:

  1. There is a need for a spinning reserve to compensate variable RE (VRE) fluctuation.
  2. There should be reactive power compensation
  3. For grid stability, the Short Circuit Ratio (SCR) (= AC power in grid / Power from inverter based resource (PV and wind)) should be kept more than 3.0
  4. In case SCR will be less than 3.0, Grid Forming Inverter (GFM) should be applied.
  5. If the VRE will be installed more than 1 MW, a BESS should be installed

- JET summarized recommendations for future RE and grid plans for St. Kitts and Nevis.

- Activities of Phase 2 for EE,
  - Major contents presented from JET are as follows.
  1. Energy Management & Energy Audit (International Standards and introduction of successful practices).
  2. EE&C Roadmap with Country Energy Balance and efficient technologies (residential & commercial sector integration).
  3. EE Building Code including Okinawa & Hawaii Situation and EE&C Evaluation Study.
  4. Report on Energy Audits Results including Walk Through Survey.
  5. Demonstration: Data Logger and its Software.
  6. EE policy in Japan.

<Confirmation of Project Design Matrix (PDM)>

- JET explained the goals of the projects and discussed the achievements in terms of the number of personnel trained in RE and EE, the number of training sessions and the number of training manuals. In each area all the goals were surpassed.

- Mr. Browne of MPI agreed that the goals of the project as explained by JET was correct.

  * Note:

  After the JCC, JICA and JET requested MPI to provide further information on the achievements described in the material but not discussed in detail during the JCC.

<Training in Japan>

- JET explained the detailed schedule training in Japan to be held in April 2023. It was informed that the duration of the training is 14 days, but they would be out of St. Kitts and Nevis for 17 days. Participants were given a preliminary tip such as how to deal with issues such as jet lag, clothing, SIM card, etc.

- Participants were also informed about the immigration entry procedures for entering Japan.

List of Attachment:

Attachment-1 Presentation Material for 3rd JCC

Attachmetn-2 Presentation Material for Training in Japan

End of the MoM

Joint Coordinating Committee (JCC) #3 for Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

March 21, 2023
JET (JICA Expert Team)
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Contents and Timetable

5 min.	Opening Remark from JICA
5 min.	Introduction of Participants
5 min.	Project Outline and Recap of Project
30 min.	Detail of Activities in Phase 2
30 min.	Confirmation of PDM (Project Design Matrix)
10 min.	Discussion
5 min.	Closing Remark from MPI

Opening Remarks from JICA

Today's Participants

Today's Participants (1/4)

St. Kitts and Nevis

- Ministry of Public Infrastructure, Post, Urban Development, and Transport (MPI)
- Nevis Island Administration (NIA)
- SKELEC
- NEVLEC
- Nevis Water Department (NWD)

JICA

- JICA HQ
- JICA Office (JICA Saint Lucia Office)

JET

- Japanese Experts
- Local Expert

Today's Participants (2/4)

St. Kitts and Nevis

Organization	Name and Title
MPI	Mr. Daryll Lloyd, Permanent Secretary Dr. Bertille Browne, Director of the Energy unit Mr. Denasio Frank, Energy Officer
NIA	Ms Michelle Walters, Energy Commissioner
SKELEC	Mr. Clement J Williams, General Manager Mr. Jonathan Kelly, Engineering Manager
NEVLEC	Mr. Albert Gordon, General Manager Mr. Ian Ward, Chief Engineer
NWD	Mr. Clychawn Wilson, Water Technician

Today's Participants (3/4)

JICA

Organization	Name
HQ, Tokyo	Mr. Kentaro KUNIKATA, Special Advisor, Team 2, Energy and Mining Group, Infrastructure Management Department
Saint Lucia Office	Mr. Ichiro MIMURA, Chief Representative Ms. Hitomi URUSHIHATA, Programme Formulation Advisor Dr. Ayodele HIPPOLYTE, Project Officer

CARICOM

Organization	Name
HQ	Mr. Tatsuya MORITA, CARICOM Advisor (Dispatched from JICA)

Today's Participants (4/4)

JET

Name	Position
Mr. Tomoyasu FUKUCHI	Team Leader/Power System
Mr. Masaaki EBINA	Sub Team Leader/Power System
Mr. Yasuhiro SAKAMOTO	Energy Efficiency
Ms. Yuka NAKAGAWA	Renewable Energy
Dr. Hisao TAOKA	Electrical Grid Expert
Ms. Anna MIYAURA	Human Resource Development
Mr. Tomoaki TSUJI	Grid Stabilization/Coordinator
Mr. I-Ronn AUDIN	Technical Assistant

Project Outline and Recap of Project

Project Outline

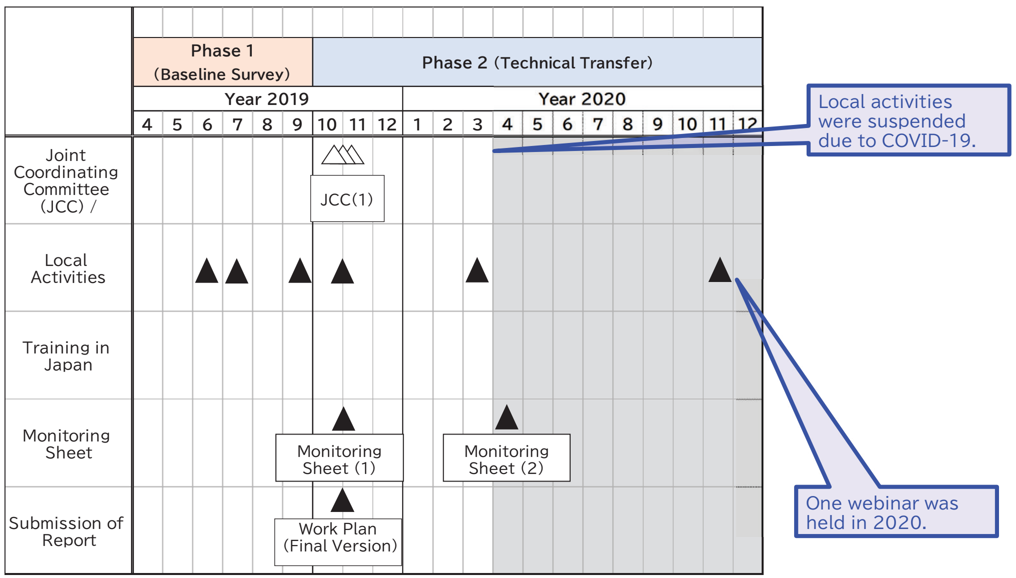
This project is a technical cooperation project by Japan International Cooperation Agency (JICA), which is a governmental agency of Japan.

Duration
- Originally 3 Years from March 2019 to March 2022.
- >>> Extended until Jun 2023.

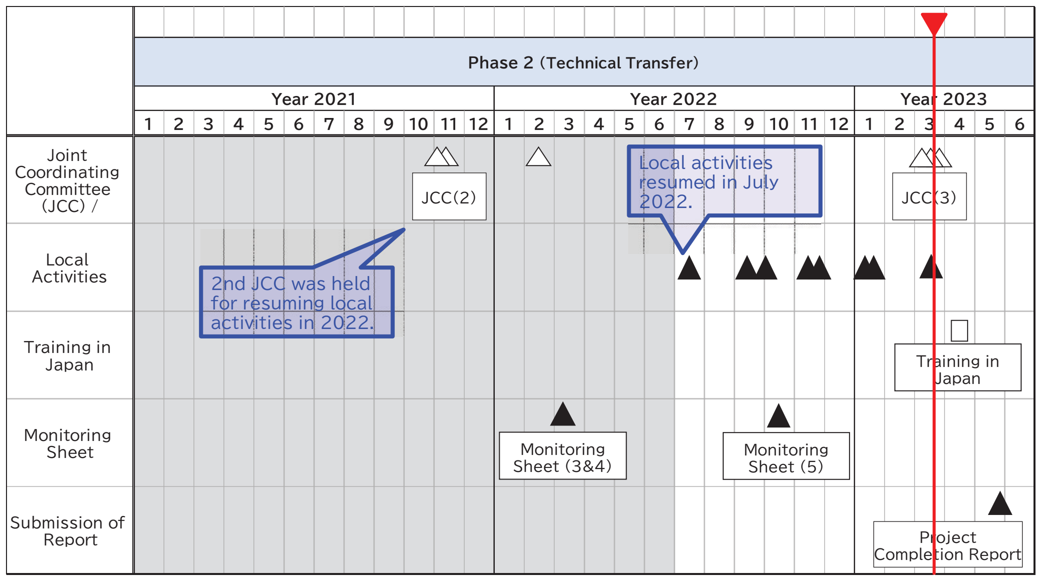
Purpose
- Human and institutional capacities are enhanced for the introduction of Renewable Energy (RE) and the promotion of Energy Efficiency (EE).

Output
- The basic information is confirmed for the capacity building for the introduction of RE and for the promotion of EE. (Phase 1: from Mar to Sep 2019)
- The human and institutional capacities are enhanced for the introduction of RE and the promotion of EE. (Phase 2: from Oct 2019 to Jun 2023)

Recap of Project (1/5)



Recap of Project (2/5)



Recap of Project (3/5)

Phase1 Baseline Survey (EE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

- In EE, in addition to JET's original activities plan, the importance and necessity to collect energy consumption data by end-use/equipment basis has been shared and confirmed with the counterparts toward the formulation of future EE policies.
- Power consumption data collection device (logger, software) are to be provided through this project.

Recap of Project (4/5)

Phase1 Baseline Survey (RE)

- Baseline survey was conducted in 2019 as Phase 1 of this project.

RE Installation:
- 100% RE by 2020 target
- 0.7+0.5 MW PV (St. Kitts)
- 2MW wind operated at 1.1 MW (Nevis)
- Bellevue 5.4MW wind, Leclanche 35MW PV to be installed
- Nevis Geothermal plan (10-30 MW + potential

Grid Stability:
- 34MWh BESS planned for 35MW PV
- Output suppression of wind is conducted in NEVLEC

Needs for:
1) Modeling for existing transmission and distribution network
2) Provision of grid simulation software and training and grid analysis with 35 MW PV
3) Proposal for grid code revision
4) Introduction of network asset management
5) Additional request of hydrogen utilization study (from NEVLEC, 2021)

Recap of Project (5/5)

Phase 2 Technical Transfer

- JET conducted capacity building related to RE and EE based on baseline survey.
- Seminar or Workshop were held online or face to face in Barbados
  - 3 RE and Grid Stability Seminars
  - 2 EE Workshops
- The following equipment was also provided from JET
  - RE: Grid Analysis Software
    Asset management Software (St. Kitts only)
  - EE: Data Loggers
- The only remaining activity is the training in Japan, April 2023.

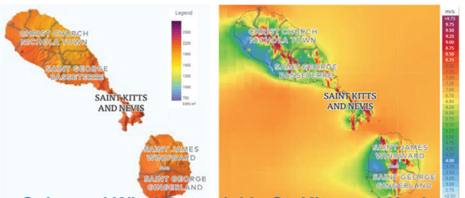
Detail of Activities in Phase 2

Activity and Achievement (RE)

Baseline Study, RE Potential and RE Projects

Challenges: 1% RE in 2019 → 100% RE in 2030

- RE Target: **100% electricity by RE by 2030**, Nationally Determined Contribution (NDC, Oct 2020)
- Sector challenges are: (i) the need for RE plans, (ii) human resource development, (iii) standards, (iv) research, and (v) tools incl. grid analysis
  - Large VRE will be installed in St. Kitts → concern for grid stability
- Solar potential 5.2 to 6.0 kWh/m^2/day, mountain and southern peninsula has high wind potential >8m/s
- Geothermal potential at Mt. Liamuiga in St. Kitts and Nevis Peak , >200 MW geothermal potential in Nevis
- Interconnection plan → grid analysis is necessary
- One thermal station in one island → Resilience is concerned.



Solar and Wind Potential in St. Kitts and Nevis

RE Projects in St. Kitts and Nevis

Location	Project and Location	Type	Capacity	Year
St.Kitts	SCASPA	PV	0.7	2013
St.Kitts	SKELEC	PV	0.5	2015
Nevis	Windwatt	Wind	2.2	2011
St.Kitts	Leclanche	PV	35	2024?
St.Kitts	Bellevue	Wind	5.7	planned
Nevis	N3 Geothermal -Ph2	Geo	30	2025
Nevis	N3 Geothermal -Ph3	Geo	15	proposed
Nevis	N1 Geothermal -Ph4	Geo	15-30	proposed
Nevis	Off-shore wind -Ph4	Wind	50	proposed

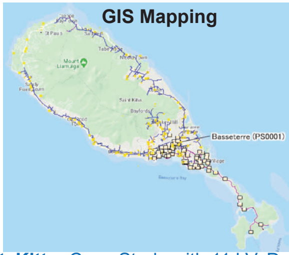
Concept for Geothermal and Grid Development in Nevis

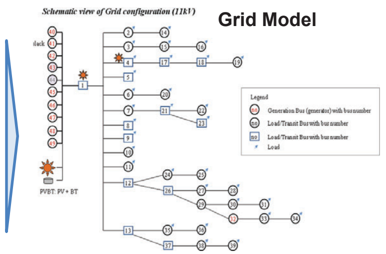
Phase	Nevis Geothermal and Grid Interconnection Plan (provisional)
Phase-1	Power Grid Reinforcement from 11kV to 66kV
Phase-2	Expand 66kV, 30 MW Geothermal at N3, Connect into St. Kitts Power System
Phase-3	Hydrogen Based Project at Long Point, Install 15 MW Geothermal at N3
Phase-4	66KV from Long Point to Camp, Offshore Wind at 50 MW, 4hr BESS, Additional Geothermal from 15MW to 30MW at N1, Expansion of Hydrogen Based Project

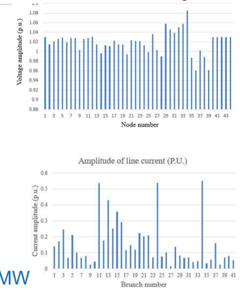
Activity and Achievement (RE)

Grid Modeling for St. Kitts and Nevis

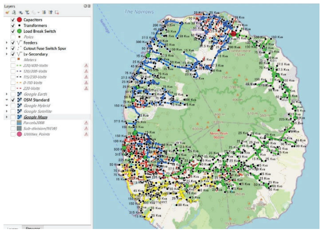
Exercise for grid analysis was conducted with "Microgrid Designer"

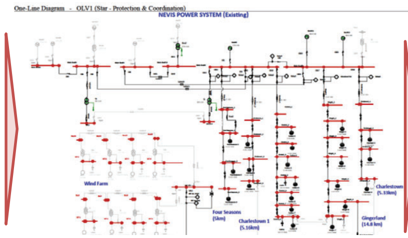


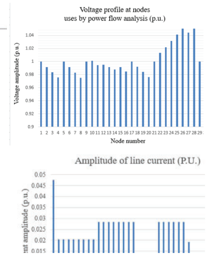




St. Kitts: Case Study with 11 kV, Demand 25MW, Thermal, PV 1.2MW + PV 35MW, Wind 7 MW
→ No problem, but reactive power compensation is recommended for future.







Nevis: Case Study with 11 kV, Demand 10 MW, Thermal, Wind 2 MW
→ No problem, but reactive power compensation is recommended for future.

Activity and Achievement (RE)

Grid Modeling for Interconnection of both Islands

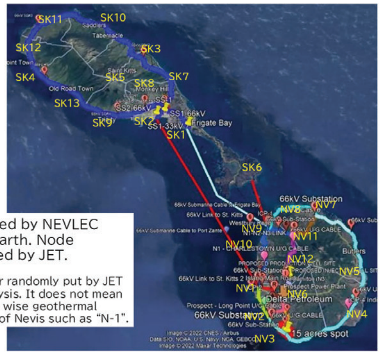
Interconnection is considered to be necessary to achieve 100% RE unless geothermal or further VRE is developed in St. Kitts.

- Nevis will have 100% RE once 10MW geothermal is commenced.
- St. Kitts 35 MW PV + 6 MW Wind will suffice 30-40 % of overall demand. Thermal power is still necessary

→ Grid Analysis was conducted for interconnection.

St. Kitts & Nevis Future Grid

Data is assumed from Google Earth KML file provided from NEVLEC. Both network of St. Kitts and Nevis are connected by 66kV transmission line.



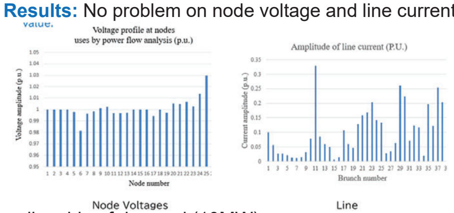
Source: Prepared by NEVLEC using Google Earth. Node Number is added by JET.

"N" is node number randomly put by JET for Nevis grid analysis. It does not mean the name of phase wise geothermal development plan of Nevis such as "N-1".

Assumptions:

- Demand: 25 MW in St. Kitts, 10 MW in Nevis
- 1.2 MW PV, 35 MW PV, 5.7 MW wind, 6 MW charging/discharging BESS in St. Kitts
- 2.2 MW+50MW wind,30 MW geothermal with assumption that 20 MW hydrogen plant

Results: No problem on node voltage and line current value.



Recommendations:

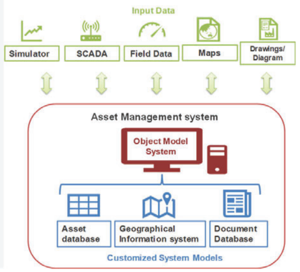
- Maximum interconnection capacity is generally limited to be smaller side of demand (10MW)
- Reactive power compensation is necessary to increase interconnection capacity
- In case full interconnection for St.Kitts (25MW) at all time with stable interconnection, it is recommended to (i) apply DC line to maintain stability, or (ii) use one of 66 kV loop line for exclusive supply to St. Kitts from one geothermal
- Further detailed F/S is recommended with transient stability analysis with local detailed data for optimum operation.

Activity and Achievement (RE)

Demonstration of Asset Management System

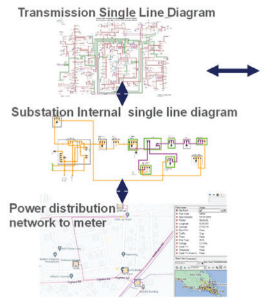
- To Optimize planning
- To Minimize time for recovery from failure with system integration

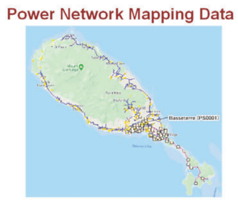
- ✓ GIS: Spec. for each facility & equipment on the map
- ✓ CAD: analyze each spec. with comprehensive & panoramic view
- ✓ SCADA: Real time monitoring on the map
- ✓ ERP: liked immediately with updated facility data into ERP
- ✓ Others (Simulator, etc.)



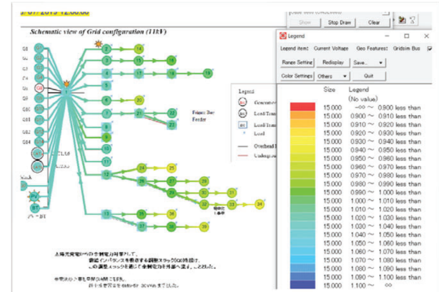
Network asset management system for St. Kitts was demonstrated, as one of the measures of enhancement of resilience

- It has elements of power system equipment for generation, transmission, substation, distribution, meters, switches, etc.
- Power flow analysis result was visualized to find where power cut is likely to occur with future plan
- It can speed up finding and restoration after a failure or disaster when combined with SCADA





- Visualization of precise location
- Base for fast fault recovery
- Asset management of small VREs
- Database for EE verification



Activity and Achievement (RE)

Study for Geothermal Hydrogen/Ammonia

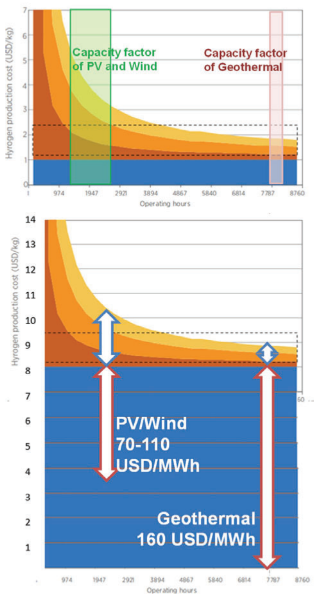
Cost of hydrogen electrolysis is dominated by generation costs than plant factor
- cost of hydrogen production from PV and wind: 7-11 USc/kWh → **7 USD/kg.**
- In case of geothermal generation cost is 16 USc/kW → **9 USD/kg**.
- Ammonia has advantage in transportation, but conversion cost is high.
  - At USD/MJ base, NH3 is 1.4-1.6 times than H2 due to conversion cost

- Electrolyser system cost (USD 770/kW) + fixed costs
- Electrolyser system cost (USD 500/kW) + fixed costs
- Electrolyser system cost (USD 200/kW) + fixed costs
- Electricity price (20 USD/MWh)
- Blue hydrogen cost range

RE Type	Capacity factor	Hour/yr	Electrolyser cost w/o electricity USD/kg*
PV	13-25%	1140-2190	2.8-4.5
Wind	20-30%	1752-2752	2.3-3.3
Geothermal	90-95%	7784-8322	0.8-0.9

*Electrolyser system cost (770USD/kW)

Source: IRENA Green Hydrogen Cost Reduction
Note: Efficiency at nominal capacity is 65% (with an LHV of 51.2 kWh/kg H2), the discount rate 8% and the stack lifetime 80,000 hours



Cost of Hydrogen, LOHC, NH3 tanker

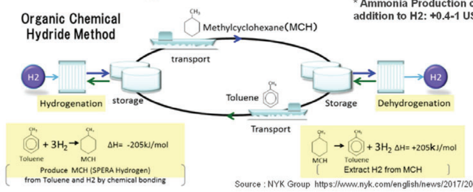
Geothermal capacity	10 MW
Operation hr	8000 hr/year
Power Production	80,000 MWh/year
Hydrogen efficiency	48.95 MWh/ton
Hydrogen production	1,634 ton/year
LOHC carriage	62 kgH2/t_LOHC
LOHC tanker	15,000 ton/year
H2 by LOHC tanker	930 tonH2/year
nos of tanker	2 tankers/yr

NH3/ LOHC Career cost (USD/kg)

Hydrogen market	km	LHOC/tanker	H2	NH3
Barbados	500	2	2.35	2
Jamaica	1,500	2.05	2.4	2.1
Miami	2,100	2.1	2.5	2.2
New York	3,900	2.2	2.6	2.25
Tokyo	18000	2.5	3.2	2.45

Source : Prepared by JET IEA Global Hydrogen Review

* Ammonia Production cost in addition to H2: +0.4-1 USD/kg



Source : NYK Group https://www.nyk.com/english/news/2017/20170727_01.html

Activity and Achievement (RE)

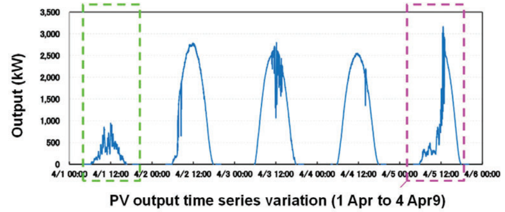
Weather Prediction System

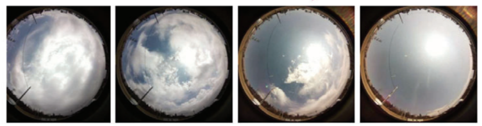
Weather prediction system provides forecast PV/wind output
- Satellite is used for more than 1hour ahead prediction
- The system enables preparation of optimized spinning reserve and contribute stability
- Jamaica JPS applies AWE system

In case of Solcast API
- Analysis on live and forecast data
- The live and forecast data products deliver PV power, irradiance, and weather data globally, with spatial resolution of 2km and data updates every 5 to 15 min

For short time advance prediction, whole-sky camera system will do.
- Weather prediction for 5-30 minutes advance by detection of cloud movement with Whole-Sky Camera
- AI reads image and predict short-term irradiation (ex. SolarMi by Skyperfect JSAT)

Type	Data source	+1 hours ahead error(%)	+3 hours ahead error(%)	+24 hours ahead error(%)
Tropical/Subtropical, Humid (7 sites)	Solcast	(2.4% to 3.8%)	(3.2% to 5.6%)	(4.5% to 7.0%)
	Smart Persistence	(3.0% to 5.3%)	(3.7% to 6.9%)	(3.8% to 8.6%)
	GFS	(4.6% to 8.5%)		





Activity and Achievement (RE)

Recommendations for Grid with 100%RE

Need of Spinning Reserve:
- stand-by thermal generation source should be kept to absorb output fluctuation of VRE

Reactive Power Compensation:
- Reactive power is necessary to establish and maintain the electromagnetic field in the grid and keep voltage. VRE can lead to voltage fluctuations and instability. Reactive power compensation should be installed.

Provision of Sufficient Synchronous generator (thermal or geothermal) and Inertia:
- In case VRE generates more than 1/3 of the grid capacity, insufficient synchronous generator and inertia will be a problem.

SCR (short circuit ratio):
- SCR = AC in grid / IBR power, Keep SCR>3.0

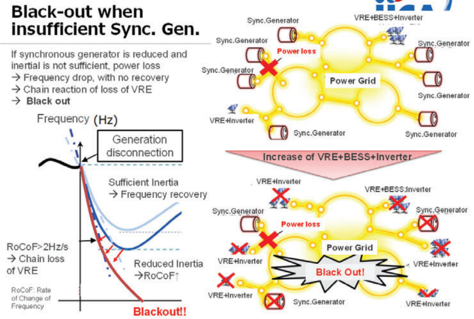
IEEE Std 1204-1997(R2003) IBR: Inverter based resource (PV & wind)

BESS: VRE more than 1 MW should mandate to install BESS, more than 80% of VRE, 4hrs

Application of Grid Forming Inverter (GFM):
- To keep SCR >3.0 with VRE, apply GFM with BESS and PV and wind as soon as it can be procured in the market

Black-out when insufficient Sync. Gen.

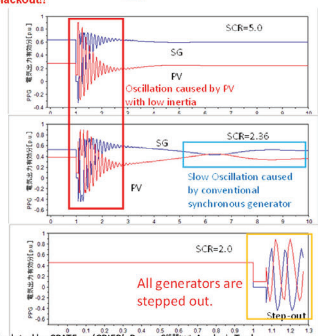
If synchronous generator is reduced and inertial is not sufficient, power loss
→ Frequency drop, with no recovery
→ Chain reaction of loss of VRE
→ Black out



Difference of SCR value

Red: PV (Low Inertia)
Blue: Synchronous Generator (SG) (High Inertia)

70 msec 3 line ground fault by lightning at 1 of 2 circuit transmission line close to SG.



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Activity and Achievement (RE)

Recommendation for Future RE and Grid Plan

Item	Description
Interconnection	- St. Kitts and Nevis is recommended to be interconnected by AC or DC 66kV line to achieve stable 100% RE also for resilience. F/S is needed.
Hydrogen/Ammonia	- Hydrogen/Ammonia with geothermal need to be considered with geothermal cost reduction.
Investment to secure inertia and spinning reserve for grid	- Maintaining sufficient synchronous generator for spinning reserve - Introduction of Grid Forming Inverter (GFM) for VRE source - Weather projection system for optimum spinning reserve plan
Investment for voltage and reactive power	- Mandatory application of Inverter with reactive power compensation for and energy storage for Wind/Solar IPP

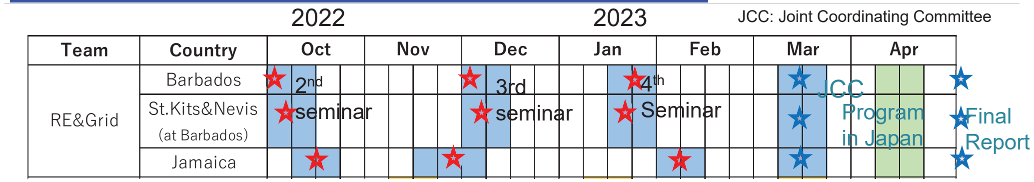
Activity and Achievement (RE)

Recommendation for Future RE and Grid Plan

Item	Description
Sharing responsibility of grid stability among utility, IPP, consumers	- Utility: maintaining transmission and distribution line frequency and voltage stability, ancillary service - IPP of VRE: installation of reactive power compensation and energy storage - Consumer: demand response, ToU setting& EV charging, peak shifting
Option for storage (especially with inertia)	- In addition to BESS, consideration of V2G, hydrogen, (pumped storage), Compressed Air Energy Storage (CAES) and Gravity Storage based on cost analysis and future development
Data management	- Database management, update plans based on implementation status
Recycle/disposal	- Consideration for disposal and recycling of battery and PV panel
"Best-Mix" Energy	- Multiple alternative for RE and storage, not a single source (Solar/CSP/Wind/Biomass, BESS/Thermal/new storage, etc.)

Activity and Achievement (RE)

Schedule and Key Events



Title	Date	Objective	Contents
1st Seminar	27 Jul 2022	To confirm present situation and needs for seminar	• RE target and challenges, revise of activity, general issues of grid with large RE penetration • Microgrid Concept for resilience
2nd Seminar	3-5 Oct 2022	To share basic technical knowledge for grid analysis with large RE	Overview of Power system, per unit method, modeling, load flow analysis, introduction of method, software and tools
3rd Seminar	6-8 Dec 2022	To conduct and exercise grid modeling and analysis	Grid modeling, Microgrid, example, Load flow analysis and stability analysis, evaluation
4th Seminar	18-19 Jan 2023	Review with feedbacks and exercise of grid analysis with scenario cases	Detailed system and countermeasures, protection, Exercise of tools for grid analysis with various RE scenarios
Final JCC	Mar 2023	To confirm outcome of project and way forward	Review of TC activity output, policy recommendation, Program in Japan

Activity and Achievement (RE)

Seminars on Grid Stability and Large RE (1)

Seminar	Agenda of 1st Seminar	Participants
1st Seminar 3, 4, & 5 Oct 2022	<Day-1 on-line only> **Basics of Power System Engineering for Grid Stability** 1. What is Power System?, Three-phase AC, Single line network description 2. Per Unit Method 3. Modeling of Power System Equipment: Transmission Line Transformer, Generator & Load 4. Active Power & Frequency: Frequency control, Area requirement 5. Reactive Power & Voltage: P-V Curve, Reactive power resource 6. Practice of Modeling of Grid	Day-1: 61 nos in total (joint with Barbados 2nd Seminar) MPI:3, SKEKEC:10, NEVLEC:3 NIA:1 Other :44
	<Day2 online/off-line hybrid > **Basics and Exercise for Load Flow Analysis** 1. Overview of Load Flow Analysis: Purpose, Methods, Modeling of grid 2. Newton-Raphson Method: Theory, Characteristics 3. DC Flow Method: Theory, Simple method to solve load flow manually 4. Exercise of DC Flow Method 5. Practice on Microgrid/VPP Designer 6. Load Flow Analysis & Evaluation of sample Grid	Day-2: 44 nos (joint with Barbados 2nd seminar) MPI:3, SKEKEC:10, NEVLEC:3 NIA:1, Other :27
	<Day-3 on-line/off-line hybrid> **Analysis of Grid Stability and LFC/ELD Overview of Stability: Definition, Methods, Swing equation** 1. Stability Model: Simplified grid model, Equivalent circuit of synchronous generator 2. Equal Area Criterion: Theory, Simple method to solve stability manually 3. Available Transmission Capacity & Spinning Reserve 4. Exercise of Equal Area Criterion 5. Practice on Microgrid/VPP Designer and LFC/ELD 6. Discussion for Interconnection, RE and Grid Stabilization in St. Kitts&Nevis	Day-3: 17 nos MPI:3, SKEKEC:10, NEVLEC:3 NIA:1

Activity and Achievement (RE)

Seminars on Grid Stability and Large RE (2)

Seminar	Agenda of 2nd Seminar	Participants
2nd Seminar 6 Dec (full day)	<Day-1 on-line >: **Preparation for Exercise and Grid Modeling** 1. Opening Remarks. 2. Project Outline, Feedback of 2nd seminar, Microgrid, Why Grid Stability is necessary 3. Grid Modeling 4. Basics of Power System Engineering, 5. Load Flow Analysis and its Evaluation 6. Transient Stability Analysis and Evaluation of Stability. 7. Discussion	Day1: 45 nos (Joint with Barbados) MPI:3, SKEKEC:12, NEVLEC:6
8, Dec 2022 (Half day	<Day-2 on-line> **Exercise for Grid Analysis** 1. Introduction and Schedule 2. Evaluation of Load Flow Analysis by Microgrid Designer, and Transient Stability Analysis 3. Example of LFC and ELD in Microgrid Designer 4. Hydrogen and Ammonia concept with Nevis Geothermal 5. Draft Program of Training in Japan 6. Consideration of Large VRE into Grid, Discussion	Day-2: 21nos MPI:3, SKEKEC:12, NEVLEC:6,

Activity and Achievement (RE)

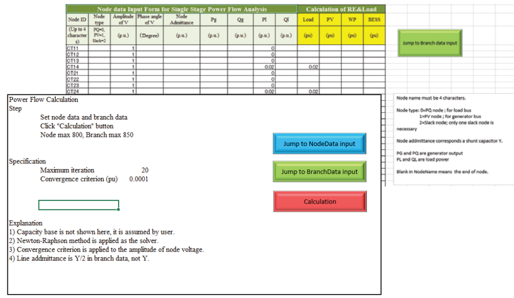
Seminars on Grid Stability and Large RE (3)

Seminar	Agenda of 3rd Seminar	Participants
3rd Seminar 17-18, Jan 2023 (All full day)	<Day-1 on-line only> **Review of grid analysis with scenario cases** 1. Introduction for the Seminar, Review, and feedback 2. RE and Microgrid Planning, 3. Grid Forming Inverter and its Safety - Current Status, Blackout with GFM & Black Start using BESS 1. Battery & Hydrogen as an Electricity Storage, cost comparison 2. Special Protection System including Load Shedding, PV/WT Trip 3. Inter-connection, Simulation Cases for future grid of St. Kitts &Nevis 4. Harmonics and filtering. 5. Measurement Function of Inverter, Grid Code 6. Sample of Other Countries Situations of Grid and RE 7. Demonstration of Asset Management System 8. Presentation from SKELEC and NEVLEC about current status and challenges	Day-2: 14 nos MPI:2, NIA:2, SKEKEC:4, NEVLEC:4, NWD: 2
	<Day-2 on-line/off-line hybrid > **Grid analysis with scenario cases** 1. Introduction of Microgrid Designer and Transient Analysis - Role of Tools for Power System Analysis, - Load Flow Analysis - Transient Stability Analysis for Operation and Control 2. Investment of MW and MWh of Energy Storage for VRE 3. Exercise on simple grid example and Microgrid - Load Flow Analysis, - Transient Stability Analysis 4. Exercise on Future Grid: Design, Operation Planning - Load Flow Analysis, - Transient Stability Analysis 5. Analysis Result and Countermeasure of Grid Stability 6, Discussion, policy recommendation, and Way Forward 7. Conclusion and Closing Remarks	Day-2: 14 nos MPI:2, NIA:2, SKEKEC:4, NEVLEC:4, NWD: 2

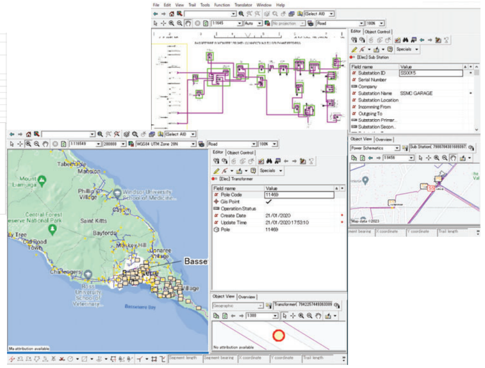
Activity and Achievement (RE)

Provision of Software

- Software for grid analysis "Microgrid Designer" were handed over and training was conducted.
  - *Replacement to new folder to be provided is requested to cope with error.*
- Demonstration of asset management "Smallworld" were provided to SKELEC with software installation.
  - *License is up to Mar 2023, to be extended half year.*



Grid Modeling tool "Microgrid Designer "



Asset Management tool "Smallworld "

Activity and Achievement (EE): #1 Workshop

Year 2022

1. Dates and venue

Nov.14-15 (2days),COURTYARD BRIDGETOWN, BARBADOS

2. Participants

Participated relevant entities(St. Kitts & Nevis)		
Name of entity		# of participants (16 persons in total)
MPI	Ministry of Public Infrastructure	3 persons (online)
NIA	Nevis Island Administration	2 persons (online)
SKELEC	St. Kitts Electricity Company	2 persons (on site)/ 4 persons (online)
NEVLEC	Nevis Electricity Company	2 persons (on site)/ 2persons (online)
NWD	Nevis Water Department	1 person (on site)

Activity and Achievement (EE): #1 Workshop

3. Workshop program (Day 1: Nov.14 (Mon))

Time	Contents	Speaker	Session Time (min.)
9:30	Reception Start	-	-
10:00	Self-introduction of participants	All	15
10:15	<Presentation> Energy Management & Energy Audit (International Standards and introduction of successful practices)	JET	50
11:05	Q&A	All	20
11:25	Break Time	-	15
11:40	<Demonstration> Data Logger and its Software	JET	15
11:55	Q&A	All	15
12:10	Lunch Time	-	60
13:10	<Presentation> EV and Storage Battery Market Trends	JET	60
14:10	Q&A	All	20
14:30	Closing	-	-

Activity and Achievement (EE): #1 Workshop

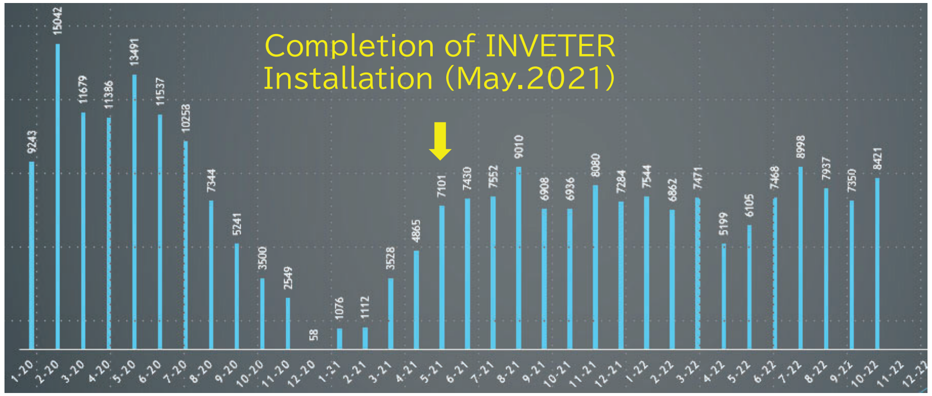
3. Workshop program (Day 2: Nov.15 (Tue))

Time	Contents	Speaker	Session Time (min.)
10:00	<Presentation> Successful implementation in EE improvements at pumping stations	NWD	25
10:25	Q&A	All	15
10:40	Break Time	-	10
10:50	<Presentation> EE Roadmap with country energy balance and efficient technologies (residential sector)	JET	50
11:40	Q&A	All	15
11:55	<Key note speech> EE in St. Kitts and Nevis	MPI	20
12:15	Lunch time	-	60
13:15	<Presentation> Introduction of Energy Efficiency Building Code in Japan	JET	40
13:55	Q&A	All	15
14:10	<Discussion time> *Energy Auditors/Managers system, ESCO business opportunities?*	All	30
14:40	Photo Session - Closing (15:00)	All	20

Activity and Achievement (EE): #1 Workshop

- **Approximately 30% energy savings has been observed** with inverter introduction to 8 water pumps out of 17 pumps (by NWD)

Power Consumption Trend at PADLOCK #1 Pumping Station



Source:: NWD material

Activity and Achievement (EE): #2 Workshop

1. Dates and venue

Jan.16-17 (2days), COURTYARD BRIDGETOWN, BARBADOS

2. Participants

Participated relevant entities(St. Kitts & Nevis)		
Name of entity		# of participants (24 persons in total)
MPI	Ministry of Public Infrastructure	2 persons (on site)
NIA	Nevis Island Administration	2 persons (on site)/ 1 person (online)
SKELEC	St. Kitts Electricity Company	4 persons (on site)/ 6 persons (online)
NEVLEC	Nevis Electricity Company	4 persons (on site)/ 3 persons (online)
NWD	Nevis Water Department	2 persons (on site)

Activity and Achievement (EE): #2 Workshop

3. Workshop program (Day 1: Jan.16 (Mon))

Time	Contents	Speaker	Session Time (min.)
9:30	Reception Start	-	-
10:00	Opening Remarks	MPI	10
10:10	<Presentation> Part-1 Energy balance, EE&C roadmap (residential & commercial sector integration) Break Time <Presentation> Part-2 Energy balance, EE&C roadmap (residential & commercial sector integration) <Presentation (additional)> Energy Efficiency Policy in Japan Q&A	JET	110
12:00	Lunch Time	-	
13:00	<Presentation> Part-1 EE Building Code (Including Okinawa Situation and EE&C Evaluation Study) Break Time <Presentation> Part-2 EE Building Code (Including Okinawa Situation and EE&C Evaluation Study) Q&A	JET	120
15:00	Closing	-	-

Activity and Achievement (EE): #2 Workshop

3. Workshop program (Day 2: Jan.17 (Tue))

Time	Contents	Speaker	Session Time (min.)
9:30	Reception Start	-	-
10:00	Recap of First Day	JET	10
10:10	<Presentation> Report on Energy Audits Results including Walk Through Survey <Presentation (additional)> Energy Audit Best Practice at Aquarium & Amusement Park in Japan Q&A	JET	80
11:30	Break Time	-	15
11:45	<Demonstration> Data Logger Software	JET	15
12:00	Lunch time	-	60
13:00	<Presentation> Lecture on Organizational Collaboration Q&A	JET	60
14:00	Break Time	-	15
14:15	<Free discussion time: Request and needs during Japan training>	All	20
14:35	Closing Remarks	NIA	10
14:45	Photo Session	All	15
15:00	Closing	-	

Activity and Achievement (EE): Workshop Summary

1. Summary of Workshops Contents

	Contents of Workshops	WS
I.	Energy Management & Energy Audit (International Standards and introduction of successful practices)	#1WS
II-a.	EE Roadmap with Country Energy Balance and efficient technologies (residential sector)	#1WS
II-b.	EE&C Roadmap with Country Energy Balance and efficient technologies (residential & commercial sector integration)	#2WS
III-a.	Introduction of EE Building Code in Japan	#1WS
III-b.	EE Building Code (Including Okinawa & Hawaii Situation and EE&C Evaluation Study)	#2WS
IV.	Report on Energy Audits Results including Walk Through Survey	#2WS
V.	Demonstration: Data Logger Software	#1,2WS

Activity and Achievement (EE): Workshop Summary

2. Comments from Participants

Comments collected after #1 EE Workshop
✓ Great sessions, very informative.
✓ Very informative. I have gain knowledge that I thought was not necessary. This has now broaden my scope.

Comments collected after #2 EE Workshop
✓ the overall training was very informative and education.
✓ There isn't much more to be touched on, I think the facilitators did an excellent job in disseminating the information on hand.
✓ Great Training I look forward to the next one.
✓ Great Presentation. JICA should visit St. Kitts & Nevis.
✓ Very good presentation.
✓ Very informative presentations. Presenters were engaging and offered practical examples.

Topics you would like us to cover at next training (after #2 EE workshop)
Leadership in EE and Management of Resources to support EE

Activity and Achievement (EE): Data Loggers

- **Demonstration was conducted and data loggers were handed over to St. Kitts and Nevis**
  - St. Kitts: 1 data logger
  - Nevis: 1 data logger

Source: https://nia.gov.kn/nevis-government-grateful-for-electrical-equipment-donated-by-japanese-agency/

Confirmation of PDM (Project Design Matrix)

Overall Goals & Achievement

Description	Verifiable Indicator	Achievement
Overall Goal Energy security is ensured through introduction of renewable energy	1. Energy self-dependency Target Value: **100% RE in Power Generation by 2030** 2. Imported amount of fossil fuel Target Value: **2% of total fuel import**	1. Approximately 2 percent 2. Unchanged

Project Purpose & Achievement (1)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant Target Value: - **PV 35MW by 2020** - **Wind 5MW** - **BESS 44.2MWh (St. Kitts)** - **Geothermal power 9MWh (Nevis)**	1. EC$ 25,000 budgeted for RE training in 2023 * 1 EC $ = about 50 JPY 25,000 * 50 =1,250,000 JPY

Project Purpose & Achievement (2)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	2. Number of public buildings with EE program including BEMS Target Value: **Proposal by JET will be prepared for the BEMS introduction**	2. EC$ 30,000 budgeted for EE promotion in 2023 * 1 EC $ = about 50 JPY 30,000 * 50 =1,500,000 JPY

Project Purpose & Achievement (3)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	**3.** Number of trained staffs for introduction of RE Target Value:**10 personnel**	**3.** In total, number of participants (accumulated total) was **62 personnel** **Average:** **62/4 = 15.5 personnel/time** - Remote training in Dec 2020 was 18 personnel - 1st Seminar in Oct 2022 was 11 personnel - 2nd Seminar in Dec 2022 was 19 personnel - Final (3rd) Seminar in Jan 2023 was 14 personnel

Project Purpose & Achievement (4)

Description	Verifiable Indicator	Achievement
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	4. Number of trained staffs for promotion of EE Target Value: **10 personnel**	4. In total, number of participants (accumulated total) was **58 personnel** **Average:** **58/4 = 14.5 personnel/time** - Demonstration on EE roadmap program etc. in Feb 2020 was 10 personnel - Remote training in Dec 2020 was 18 personnel - 1st Workshop in Nov 2022 was 16 personnel - Final (2nd) Workshop in Jan 2023 was 14 personnel

Output 1 & Achievement

Description	Verifiable Indicator	Achievement
Outputs Output 1 (to be achieved in Phase 1) The basic information is confirmed for the capacity building for the introduction of RE	**1-1.** Assessment of number and qualification of staffs responsible for RE **1-2.** Human resource development plan for the introduction of RE **1-3.** Number of training courses for the introduction of RE **1-4.** Total capacity of RE	**1-1. Confirmed** **1-2. Confirmed** **1-3. Confirmed** **1-4. Confirmed** *** Achievement of Output 1 was already confirmed when 1st JCC which was held in Nov 2019**

Output 2 & Achievement

Description	Verifiable Indicator	Achievement
Outputs Output 2(to be achieved in Phase 1) The basic information is confirmed for the capacity building for the promotion of EE	**2-1.** Assessment of number and qualification of staffs responsible for EE **2-2.** Human resource development plan for the introduction of EE **2-3.** Number of training courses for the promotion of EE **2-4.** Number of facilities conducted energy audit	**2-1. Confirmed** **2-2. Confirmed** **2-3. Confirmed** **2-4. Confirmed** *** Achievement of Output 2 was already confirmed when 1st JCC which was held in Nov 2019**

Output 3 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-1.** Number of trained staffs Target Value: **10 personnel** **3-2.** Textbooks/ manuals Target Value: **3 programs** (2 domestic trainings and 1 training in Japan)	**3-1.** In total, number of participants (accumulated total) was **62 personnel** **Average: 15.5 personnel/time** **3-2.** In total, **5 (6) materials** were prepared. - 1 manual for simulation software of system analysis. - 1 training material for remote training in Dec 2020. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan (Available next month)

Output 3 & Achievement (2)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-3.** Number of participants of workshops to disseminate introduction of RE to the relevant organizations Target Value: - **Kick-off workshop: 9 personnel** - **Final workshop: 10 personnel**	**3-3.** - Kick-off workshop in Nov 2019 was **9 personnel** - Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 18 personnel - 1st Seminar in Oct 2022 was 11 personnel - 2nd Seminar in Dec 2022 was 19 personnel - Final (3rd) Seminar in Jan 2023 was **14 personnel**

Output 3 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	**3-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**3-4.** In total, **5 times** - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Dec 2022 - Final (3rd) Seminar was conducted in Jan 2023

Output 4 & Achievement (1)

Description	Verifiable Indicator	Achievement
Outputs Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	**4-1.** Number of trained staffs Target Value: **10 personnel** **4-2.** Textbooks/ manuals Target Value: **3 programs** (2 domestic trainings and 1 training in Japan)	**4-1.** In total, number of participants (accumulated total) was **58 personnel** **Average: 14.5 personnel/time** **4-2.** In total, **3 (4) materials** were prepared. - 1 training material for remote training in Dec 2020. - 2 training materials about 'Energy Efficiency Workshop' for domestic training in Nov 2022 and Jan 2023. - 1 training material for training in Japan in Apr 2023. (Available next month)

Output 4 & Achievement (2)

Description	Verifiable Indicator	Achievement
<u>Outputs</u> <u>Output 4 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of EE	**4-3.** Number of participants of workshops to disseminate promotion of EE to the relevant organizations Target Value: - **Kick-off workshop: 9 personnel** - **Final workshop: 10 personnel**	**4-3.** - Kick-off workshop in Nov 2019 was **9 personnel** - Demonstration on EE roadmap program and power consumption measurement was conducted in Feb 2020 was 10 personnel - Remote training in Dec 2020. Number of participants was 18 personnel - 1st Workshop in Nov 2022 was 16 personnel - Final (2nd) Workshop in Jan 2023 was **14 personnel**

Output 4 & Achievement (3)

Description	Verifiable Indicator	Achievement
<u>Outputs</u> <u>Output 4 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of EE	**4-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**4-4.** In total, **4 times** - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on EE' in Dec 2020 - 1st workshop was conducted in Nov 2022 - Final (2nd) workshop was conducted in Jan 2023

Output 5 & Achievement (1)

Description	Verifiable Indicator	Achievement
<u>Outputs</u> <u>Output 5 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-1.** Number of trained staffs Target Value: **10 personnel** **5-2.** Textbooks/ manuals Target Value: **2 programs** (1 domestic trainings and 1 training in Japan)	**5-1.** In total, number of participants (accumulated total) was **62 personnel** **Average: 15.5 personnel/time** **5-2.** In total, **4 (5) materials** were prepared. - 1 training material for remote training in Dec 2020. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan (Available next month)

Output 5 & Achievement (2)

Description	Verifiable Indicator	Achievement
<u>Outputs</u> <u>Output 5 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-3.** Number of participants of workshops to disseminate promotion of power network resiliency to the relevant organizations Target Value: - **Kick-off workshop: 9 personnel** - **Final workshop: 10 personnel**	**5-3.** - Kick-off workshop in Nov 2019 was **9 personnel** - Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 18 personnel - 1st Seminar in Oct 2022 was 11 personnel - 2nd Seminar in Dec 2022 was 19 personnel - Final (3rd) Seminar in Jan 2023 was **14 personnel**

Output 5 & Achievement (3)

Description	Verifiable Indicator	Achievement
Outputs Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	**5-4.** Number of workshops Target Value: **2 times** (Kick-off workshop and Final workshop)	**5-4.** In total, **5 times** - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Dec 2022 - Final (3rd) Seminar was conducted in Jan 2023

Discussion

Closing Remarks from MPI

Thank you.

PM Form 3-1 Monitoring Sheet Summary

TO CR of JICA JAMAICA OFFICE

Project Monitoring Sheet
(Jamaica)

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries
Version of the Sheet: Ver.6（Term: October 2022 – May 2023）

Name: Mrs. Olive Wilson Cross
Title: Director Programme Management
Name: Mr. Tomoyasu Fukuchi
Title: Team Leader
Submission Date: 24th May 2023

I. Summary
1 Progress
1.1. Progress of Inputs
1.1.1. Inputs from the Japan Side
(1) Dispatch of Japanese Experts

- ✓ JICA expert team (JET) postponed its field activities due to continuous travel restrictions caused by COVID-19 from March 2020 by June 2022. Under the circumstance, JET was continuing remote activities in Japan and related research as well as preparation of trainings were conducted. JET has resumed the field activities since July 2022.
- ✓ Actual assignments of JET in this project for three target countries (Jamaica, St. Kitts & Nevis, and Barbados) are shown below.

Assignments of JET in the project (three countries)

No	Technical Area	Total MM (Apr 2019–Apr 2023)		
		Field	Field	Field
1	Chief advisor/ Power System/Diesel/Gas-turbine Power Plant (2)	0.97	0.97	0.97
2	Subchief Advisor/Power system (2)	2.30	2.30	2.30
3	Renewable Energy	4.37	4.37	4.37
4	Energy Efficiency	4.93	4.93	4.93
5	Grid Stabilization	3.26	3.26	3.26
6	Diesel/Gas-turbine Power Plant/Coordinator	1.53	1.53	1.53
7	Human Resources Development/Monitoring	2.57	2.57	2.57
8	Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	4.33	4.33	4.33
	Total	**24.26**	**24.26**	**24.26**

(2) Assignment of Local Staff

- ✓ Local staff was continuously assigned to support JET.

Assignment of Local Staff

No	Name of Local Staff
1.	Mr. Kevin Douglas

(3) Equipment

- ✓ One power logger was provided to BSJ in November 2022.
- ✓ One power logger was provided to MSET in March 2023.

1.1.2. Inputs from Jamaica Side

(1) Assignment of Counterparts

- ✓ Mrs. Olive Wilson Cross, Director Programme Management was assigned.
- ✓ Project implementation structure of C/P was formed.

1.2. Progress of Activities

- ✓ JET conducted coordination of business trip schedule as well as whole project schedule during the monitoring period.
- ✓ JET (RE team) conducted the 6th field visit in Jamaica and Barbados in October 2022. JET

(RE team) conducted the 7th field visit in Jamaica, St. Kitts & Nevis (online), and Barbados in November and December 2022. JET (RE team) conducted the 8th field visit in St. Kitts & Nevis (online) and Barbados in January and February 2023.

- ✓ JET (EE team) conducted the 7th field visit in Jamaica, St. Kitts & Nevis (in Barbados and online), and Barbados in November 2022. JET (EE team) conducted the 8th field visit in St. Kitts and Nevis (online) and Barbados in January and February 2023.
- ✓ JET (RE team and EE team) conducted reporting meeting of the 7th field visit and pre-departure briefings of the 8th field visit in December 2022.
- ✓ JET prepared the 5th and 6th contract change during the monitoring period.
- ✓ JET discussed on the details of the potential program including potential sites for training in Japan.
- ✓ JET submitted Draft Final Report to JICA in February 2023.
- ✓ JET conducted the 3rd JCC with C/Ps in March 2023. (Jamaica: 30th March via online, St. Kitts & Nevis: 21st March via online, and Barbados: 27th March both face to face and via online).
- ✓ JET conducted the 9th field visit in Barbados (RE team) and Jamaica (EE team) in March and April 2023.
- ✓ JET coordinated with C/Ps and JICA regarding invitation for training in Japan. Training in Japan was conducted in April 2023.
- ✓ JET submitted monitoring sheets in October 2022 and May 2023.
- ✓ JET has prepared the Final Report both in English and Japanese for submission in Jun 2023.

1.3. Achievement of Output

(1) Achievement of Outputs

Technical transfer in phase 2 has been implemented for Output 3, Output 4 and Output 5. The status of Achievement of Output is shown below.

Achievement of each Output on PDM (October 2019 – May 2023)

Output	Indicator	Target Value	Achievement
Overall Goal: Energy security is ensured through introduction of RE	1.Energy self-dependency	50% (50%RE by 2030)	As of March 2023, RE generation accounts for 12.4% of total generation.
	2. Imported amount of fossil fuel	To 80% (20% by RE in energy base)	As of March 2023, imported amount of fossil fuel is 87.6% in energy base.
Project Purpose: Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant	To be set according to IRP	PV Total = 57MW; Wind Total = 101MW; Battery Total (plus Fly Wheel) = 24.5MW; Hydro Power Total = 28.6MW
	2. Number of public buildings with EE program including BEMS	EE program in total for 44 facilities in next 4 years	Number of public buildings which are implemented or introduced EE program is approximately 60 since 2015.
	3. Number of trained staffs for introduction of RE	Domestic trainings: 20-30 personnel Training in Japan: 1-4 personnel	In total, number of participants (accumulated total) was 125 personnel
	4. Number of trained staffs for promotion of EE	Domestic trainings: 20-30 personnel Training in Japan: 1-4 personnel	In total, number of participants (accumulated total) was 21 personnel

Output 3: (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	3-1. Number of trained staffs	MSET/PCJ: 6 personnel	In total, number of participants (accumulated total) was 125 personnel
	3.2. Textbooks/ manuals	For 3 programs (2 domestic trainings and 1 training in Japan)	In total, 4 materials were prepared.
	3-3. Number of participants of workshops to disseminate introduction of RE to the relevant organizations	Kick-off workshop: 15 personnel Final workshop: 20-30 personnel	In total, number of participants (accumulated total) was 123 personnel
	3-4. Number of workshops	2 times (Kick-off workshop and Final workshop)	In total, 4 times.
Output 4: (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	4-1. Number of trained staffs	MSET/PCJ: 4 personnel	In total, number of participants (accumulated total) was 21 personnel
	4-2. Textbooks/ manuals	For 3 programs (For 2 domestic trainings and 1 training in Japan)	In total, 3 materials were prepared.
	4-3. Number of participants of workshops to disseminate promotion of EE to the relevant organizations	Kick-off workshop: 15 personnel Final workshop: 20-30 personnel	In total, number of participants (accumulated total) was 19 personnel
	4.4. Number of workshops	2 times (Kickoff workshop and Final workshop)	In total, 3 times.

Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	5-1. Number of trained staffs	MSET/PCJ: 6 personnel	In total, number of participants (accumulated total) was 125 personnel.
	5-2. Textbooks/ manuals	For 2 programs (For 1 domestic training and 1 training in Japan)	In total, 4 materials were prepared.
	5-3. Number of participants of workshops to disseminate promotion of Power Network Resilience to the relevant organizations	Kick-off workshop: 15 personnel Final workshop: 20-30 personnel	In total, number of participants (accumulated total) was 123 personnel.
	5-4. Number of workshops	2 times (Kick-off workshop and Final workshop)	In total, 4 times.

(2) Evaluation of Trainings

JET was conducted following trainings and monitoring activities using following questions.

Q.1. Was JICA experts' explanation clear and easy to understand?
Q.2. Were training materials well organized and easy to understand?
Q.3. Was the content of lecture enough to understand?
Q.4. Were JICA experts maximize participants' opportunities?
Q.5. Were training aids and facilities are satisfied?
Q.6. If you have any topics that you would like us to cover next training, please write down.
Q.7. Do you have any other comments?

Overview of each training is shown below.

List of Trainings (October 2022 – March 2023)

Time	Target country	Contents	No. of Participants	Score (*/5)
Jul 2022	Barbados	1st RE grid stability seminar	4	-
Oct 2022	Barbados, St. Kitts & Nevis	2nd RE grid stability seminar for Barbados 1st RE grid stability seminar for St. Kitts & Nevis	44	3.3
Oct 2022	**Jamaica**	**1st RE grid stability seminar**	**31**	**4.3**
Nov 2022	St. Kitts & Nevis	1st EE workshop	12	3.8
Nov 2022	Barbados	1st EE workshop	5	3.7
Dec 2022	**Jamaica**	**2nd RE grid stability seminar**	**45**	**3.9**
Dec 2022	Barbados	3rd RE grid stability seminar	19	3.8
Dec 2022	St. Kitts & Nevis	2nd RE grid stability seminar	19	3.8
Jan 2022	St. & Nevis	2nd EE workshop	11	4.4
Jan 2022	Barbados	2nd EE workshop	11	3.9
Jan 2022	St. Kitts & Nevis	3rd RE grid stability seminar	14	3.8
Jan 2022	Barbados	4th RE grid stability seminar	13	4.1
Feb 2022	**Jamaica**	**1st EE workshop**	**3**	**4.5**
Mar 2022	**Jamaica**	**2nd EE workshop**	**8**	**3.9**

(3) Training in Japan

✓ Training in Japan was conducted in April 2023. 9 participants had lectures, site visits and reporting session. Participants learnt RE and EE efforts in Japan. Details was shown in the report prepared by JET.

1.4. Achievement of the Project Purpose

✓ As mentioned above.

1.5. Changes of Risks and Actions for Mitigation

✓ Travel restrictions caused by COVID-19

✓ Meteorological influence (hurricane etc.)

1.6. Progress of Actions undertaken by JICA

- ✓ JICA coordinated with C/Ps and JET regarding invitation for training in Japan.

1.7. Progress of Actions undertaken by C/P

- ✓ C/P timely provided information of travel restrictions caused by COVID-19 in the country to JET.

1.8. Progress of Environmental and Social Considerations (if applicable)

- ✓ N/A

1.9. Progress of Considerations on Gender/Peace Building/Poverty Reduction (if applicable)

- ✓ N/A

1.10. Other remarkable/considerable issues related/affect to the project (such as other JICA's projects, activities of counterparts, other donors, private sectors, NGOs etc.)

- ✓ N/A

2. Delay of Work Schedule and/or Problems (if any)

2.1. Detail

- ✓ Field activities have been postponed due to COVID-19 since March 2020 to June 2022.

2.2. Cause

- ✓ Due to JICA's recommendation due to COVID-19 mentioned in 1.6.

2.3. Action to be taken

- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021 and April 2022. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

2.4. Roles of Responsible Persons/Organization (JICA, C/P)

- ✓ N/A

3. Modification of the Project Implementation Plan

3.1. PO

- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

3.2. Other modifications on detailed implementation plan

(Remarks: The amendment of R/D and PDM (title of the project, duration, project site(s), target group(s), implementation structure, overall goal, project purpose, outputs, activities, and input) should be authorized by JICA HDQs. If the project team deems it necessary to modify any part of R/D and PDM, the team may propose the draft.)

- ✓ N/A

4. Current Activities of Gov. of Jamaica to Secure Project Sustainability after its Completion

- ✓ N/A

II. Project Monitoring Sheet I & II

as Attached

Project Monitoring Sheet I (Revision of Project Design Matrix)

Project Title: Technical Cooperation to Promote Energy Efficiency in the Caribbean Countries
Implementing Agency: MSET (Ministry of Science, Energy and Technology)
Target Group: Senior engineer, Engineer, Senior technical officer, Technical officer
Period of Project: 4 Years, Phase 1: 6 months, Phase 2: 42 months
Project Site: Jamaica

Version : 6
Date: 24th May 2023

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions	Achievement	Remarks
Overall Goal Energy security is ensured through introduction of renewable energy (hereinafter referred to as "RE") and promotion of energy efficiency (hereinafter referred to as "EE")	1. Energy self-dependency ***Target Value**:50% (50%RE by 2030)* 2. Imported fossil fuel reduction ***Target Value**: To 80% (20% by RE in energy base)*	Data from annual report	The current relevant policies on promotions of RE and EE are sustained after the Project.	1. As of March 2023, RE generation accounts for 12.4% of total generation. 2. As of March 2023, imported amount of fossil fuel is 87.6% in energy base.	
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant ***Target Value**: To be set according to IRP* 2. Number of public buildings with EE program including BEMS: Building Energy Management System ***Target Value:** EE program in total for 44 facilities in next 4 years)* 3. Number of trained staffs for introduction of RE ***Target Value:** Domestic trainings: 20-30 personnel, Training in Japan: 1-4 personnel* 4. Number of trained staffs for promotion of EE ***Target Value:** Domestic trainings: 20-30 personnel, Training in Japan: 1-4 personnel*	Project Report	C/P agency continues commitment to the Project by continuing budget allocation as well as assignment of personnel for the post- Project activities.	1. PV Total = 57MW; Wind Total = 101MW; Battery Total (plus Fly Wheel) = 24.5MW; Hydro Power Total = 28.6MW 2. Number of public buildings which are implemented or introduced EE program is approximately 60 since 2015. 3. In total, number of participants (accumulated total) was 117 personnel - 1st Seminar in Oct 2022 was 31 personnel - 2nd Seminar in Nov 2022 was 45 personnel - Final (3rd) Seminar in Feb 2023 was 39 personnel - 2 officers participated in the training in Japan. 4. In total, number of participants (accumulated total) was 21 personnel - Demonstration on EE roadmap program etc. in Feb 2020 was 8 personnel - 1st Workshop in Feb 2023 was 3 personnel - Final (2nd) Workshop in Mar 2023 was 8 Personnel - 2 officers participated in the training in Japan.	
Outputs Output 1 (to be achieved in Phase 1) The basic information is confirmed for the capacity building for the introduction of RE	1-1. Assessment of number and qualification of staffs responsible for RE 1-2. Human resource development plan for the introduction of RE 1-3. Number of training courses for the introduction of RE 1-4. Total capacity of RE	Project Report		1-1. Confirmed 1-2. Confirmed 1-3. Confirmed 1-4. Confirmed	There was an organizational reform of MSET and PCJ. Information of the organizational reform will be updated by JET.
Output 2(to be achieved in Phase 1) The basic information is confirmed for the capacity building for the promotion of EE	2-1. Assessment of number and qualification of staffs responsible for EE 2-2. Human resource development plan for the introduction of EE 2-3. Number of training courses for the promotion of EE 2-4. Number of facilities conducted energy audit	Project Report		2-1. Confirmed 2-2. Confirmed 2-3. Confirmed 2-4. Confirmed	There was an organizational reform of MSET and PCJ. Information of the organizational reform will be updated by JET.
Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	3-1. Number of trained staffs ***Target Value:** MSET/PCJ: 6 personnel* 3-2. Textbooks/ manuals ***Target Value:** For 3 programs (2 domestic trainings and 1 training in Japan)* 3-3. Number of participants of workshops to disseminate introduction of RE to the relevant organizations ***Target Value:** Kick-off workshop: 15 personnel, Final workshop: 20-30 personnel* 3-4. Number of workshops ***Target Value:** 2 times (Kick-off workshop and Final workshop)*	Project Report		3-1. In total, number of participants (accumulated total) was 125 personnel 3-2. In total, 4 materials were prepared. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Nov 2022 and Feb 2023. - 1 training material for training in Japan 3-3. In total, number of participants (accumulated total) was 123 personnel - Kick-off workshop in Nov 2019 was 8 personnel - 1st Seminar in Oct 2022 was 31 personnel - 2nd Seminar in Nov 2022 was 45 personnel - Final (3rd) Seminar in Feb 2023 was 39 personnel	

				3-4. In total, 4 times - Kick-off workshop was conducted in Nov 2019 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Nov 2022 - Final (3rd) Seminar was conducted in Feb 2023	
<u>Output 4 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of EE	4-1. Number of trained staffs ***Target Value:*** *MSET/PCJ: 4 personnel* 4-2. Textbooks/ manuals ***Target Value:*** *For 3 programs (2 domestic trainings and 1 training in Japan)* 4-3. Number of participants of workshops to disseminate promotion of EE to the relevant organizations ***Target Value:*** *Kick-off workshop: 15 personnel, Final workshop: 20-30 personnel* 4-4. Number of workshops ***Target Value:*** *2 times (Kick-off workshop and Final workshop)*	Project Report		4-1. In total, number of participants (accumulated total) was 21 personnel 4-2. In total, 3 materials were prepared. - 2 training materials about 'Energy Efficiency Workshop' for domestic training in Feb and Mar 2023. - 1 training material for training in Japan in Apr 2023. 4-3. In total, number of participants (accumulated total) was 19 personnel - Kick-off workshop in Nov 2019 was 8 personnel - 1st Workshop in Feb 2023 was 3 personnel - Final (2nd) Workshop in Mar 2023 was 8 personnel 4-4. In total, 3 times - Kick-off workshop was conducted in Nov 2019 - 1st workshop was conducted in Feb 2023 - Final (2nd) workshop was conducted in mar 2023	
<u>Output 5 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of Power Network Resiliency	5-1. Number of trained staffs ***Target Value:*** *MSET/PCJ: 6 personnel* 5-2. Textbooks/ manuals ***Target Value:*** *For 2 programs (For 1 domestic training and 1 training in Japan)* 5-3. Number of participants of workshops to disseminate promotion of Power Network Resilience to the relevant organizations ***Target Value:*** *Kick-off workshop: 15 personnel, Final workshop: 20-30 personnel* 5-4. Number of workshops ***Target Value:*** *2 times (Kick-off workshop and Final workshop)*	Project Report		5-1. In total, number of participants (accumulated total) was 125 personnel (Domestic training 123 personnel + Training in Japan 2 personnel) 5-2. In total, 4 materials were prepared. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan 5-3. In total, number of participants (accumulated total) was 123 personnel - Kick-off workshop in Nov 2019 was 8 personnel - 1st Seminar in Oct 2022 was 31 personnel - 2nd Seminar in Nov 2022 was 45 personnel - Final (3rd) Seminar in Feb 2023 was 39 personnel 5-4. In total, 4 times - Kick-off workshop was conducted in Nov 2019 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Nov 2022 - Final (3rd) Seminar was conducted in Feb 2023	

<u>Activities</u>	**<u>Inputs</u>**		Important Assumptions
<u>Activities for achieving Output 1</u> 1-1. To verify the fundamental indicators for the power supply side, e.g. access to electricity (electrification rate), cost (composition of power sources, electricity tariff), low carbon (CO_2 emission coefficient) and power system reliability (SAIDI/SAIFI), etc. 1-2. To verify the existing situations in introduction of the technologies of grid stabilization and relevant policies/ national plans pertaining to RE 1-3. To verify human and institutional capacities for the introduction of RE	**(Japanese side)** 1. Dispatch of the Japanese experts in respect of following: - Chief advisor/ Power System/Diesel/Gas-turbine Power Plant (2) - Subchief Advisor/Power system (2) - Renewable Energy - Energy Efficiency - Grid Stabilization - Diesel/Gas-turbine Power Plant/Coordinator - Human Resources Development/Monitoring - Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2) 2. Training in Japan -Micro Grid system including Grid Stabilization	**(Jamaica side)** 1. Assignment of C/Ps -Project Director (P/D) -Project Manager (P/M) - Other C/Ps 2. Facilities and equipment for the Project office To allocate office space with furniture for experts during their stay in Jamaica (desks, chairs, meeting tables, copy machines, etc) 3. Recurrent costs -C/Ps' wages and allowances -In-land transportation and allowances	Most of the trained C/Ps continues commitment to the Project activities Preconditions Contents of the current relevant policies on promotion of RE and EE are not largely changed.
<u>Activities for achieving Output 2</u> 2-1. To verify the fundamental indicators on promotion of EE for the electricity demand side, e.g. electric power consumption unit requirement, final energy consumption, etc. 2-2. To verify the existing conditions in promotion of EE, relevant policies/ national plans 2-3. To verify the existing conditions of transmission and distribution system losses 2-4. To verify human and institutional capacities for the promotion of EE			Issues and countermeasures

<u>Activities for achieving Output 3</u> 3-1. To consider and propose additional policy/ legal system for achieving RE goals 3-2. To introduce micro-grid concept in one of the agreed areas and develop computer modelling based on existing grid data. Identify issues in introducing micro-grid concept in the area. 3-3. To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '3-1 through to 3-2' 3-4. To review the training plan though monitoring of the training conducted in Activity '3-3' 3-5. To provide advice on realization of the RE projects in Jamaica 3-6. To provide recommendations on design of the policy/ legal system proposed in Activity '3-1' 3-7. To share the project output among other recipient countries <u>Activities for achieving Output 4</u> 4-1. To consider and propose the EE goals through cost-benefit analysis on introduction of the facilities contributing to EE 4-2. To consider and propose the EE facilities necessary for achieving the EE goals 4-3. To consider and propose necessary technologies for achieving EE goals, including building energy management system (BEMS), etc. 4-4. To consider and propose the necessary policy/ legal system for achieving EE goals such as introduction of energy service company (ESCO) and energy management service, etc. 4-5. To prepare the necessary training plan for doing the above Activities '4-1' through '4-4' 4-6. To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '4-5' 4-7. To review the training plan though monitoring of the training conducted in Activity '4-6' 4-8. To provide advice on realization of the EE projects 4-9. To provide recommendation on design of the policy/ legal system proposed in Activity '4-4' 4-10. To share the project output among other recipient countries <u>Activities for achieving Output 5</u> 5-1. To demonstrate the way to enhance resiliency of power infrastructure using Power Network Asset Management System. *	Technology in small island (e.g. Okinawa, Tokyo and other cities) -Policies and technologies for promotion of EE (Energy load labelling, policies, regulations and incentives) (Tokyo and Other cities) -Site visit in Japan 3. Training/Workshop in each recipient country -Training/Workshop for project counterparts in each recipient country 4. Equipment -Power loggers		

Appendix 6-2-1-3 Monitoring Sheet II, Revision of Plan of Operation (Jamaica)

Project Monitoring Sheet II (Revision of Plan of Operation)

Version 6
Date 24 May 2023

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries (Jamaica)

Monitoring (Up to May 2023)

Inputs	Year / Month (2019: 4–12; 2020: 1–12; 2021: 1–12; 2022: 1–12; 2023: 1–6)	Remarks	Issue	Solution
Expert				
1. Chief Advisor/Power System (1) /Diesel/Gas-turbine Power Plant (2)	Plan / Actual	Blue highlights were inputs from Japan.		
2. Subchief Advisor/Power System (2)	Plan / Actual			
3. Renewable Energy	Plan / Actual			
4. Energy Efficiency	Plan / Actual			
5. Grid Stabilization	Plan / Actual			
6. Diesel/Gas-turbine Power Plant/Coordinator	Plan / Actual			
7. Human Resources Development/Monitoring	Plan / Actual			
8. Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	Plan / Actual			
Equipment				
Power loggers	Plan / Actual	Handed over in September and November 2022.		
Training in Japan				
Training in Japan	Plan / Actual	Training in Japan was conducted in April 2023.		
In-country Training				
Trainings in country (RE)	Plan / Actual	4 in-country trainings were conducted.		
Trainings in country (EE)	Plan / Actual	2 in-country trainings were condcuted.		

Activities / Sub-Activities	Year (2019–2023)	Responsible Organization: JET	Responsible Organization: C/P	Achievements	Issue & Countermeasures
Output 1: The basic information is confirmed for the capacity building for the introduction of RE					
1.1 To verify the fundamental of indicators for the power supply side, e.g. access to electricity (electrification rate), cost (composition of power sources, electricity tariff), low carbon (CO2 emission coeffient) and power system realibility (SAIDI/SAIFI), etc.	Plan / Actual	○	○		
1.2 To verify the existing situations in introduction of the technologies of grid stabilization and relevant policies/ national plans pertaining to RE	Plan / Actual	○			
1.3 To verify human and institutional capacities for the introduction of RE	Plan / Actual	○			
Output 2: The basic information is confirmed for the capacity building for the promotion of EE					
2.1 To verify the fundamental indicators on promotion of EE for the electricity demand side, e.g. electric power consumption unit requirement, final energy consumption, etc.	Plan / Actual	○	○		
2.2 To verify the existing conditions in promotion of EE, relevant policies/national plans	Plan / Actual	○	○		
2.3 To verify the existing conditions of transmission and distribution system losses	Plan / Actual	○			
2.4 To verify human and institutional capacities for the promotion of EE	Plan / Actual	○	○		
Output 3: The human and institution capacity are enhanced for the introduction of RE					
3.1 To consider and propose additional policy/ legal system for achieving RE goals	Plan / Actual	○	○		
3.2 To introduce micro-grid concept in one of the agreed areas and develop computer modelling based on existing grid data. Identify issues in introducing micro-grid concept in the area.	Plan / Actual	○	○		
3.3 To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '3.1 through to 3.2'	Plan / Actual	○	○	A total of 3 RE and grid stabilization seminars were held. A total of 116 people (accumulated total) participated.	
3.4 To review the training plan though monitoring of the training conducted in Activity '3.3'	Plan / Actual	○	○		
3.5 To provide advice on realization of the RE projects in Jamaica	Plan / Actual	○			
3.6 To provide recommendations on design of the policy/ legal system proposed in Activity '3.1'	Plan / Actual	○			
3.7 To share the project output among other recipient countries	Plan / Actual	○	○		

Project Monitoring Sheet II（Revision of Plan of Operation）

Version 6

Date 24 May 2023

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries (Jamaica)

Monitoring (Up to May 2023)

Inputs		2019	2020	2021	2022	2023	Remarks		Issue	Solution
Output 4: The human and institution capacity are enhanced for the promotion of EE										-
4.1 To consider and propose the EE goals through cost-benefit analysis on introduction of the facilities contributing to EE	Plan						○	○	-	-
	Actual									
4.2 To consider and propose the EE facilities necessary for achieving the EE goals	Plan						○	○	-	-
	Actual									
4.3 To consider and propose necessary technologies for achieving EE goals, including building energy management system (BEMS), etc.	Plan						○	○	-	-
	Actual									
4.4 To consider and propose the necessary policy/ legal system for achieving EE goals such as introduction of energy service company (ESCO) and energy management service, etc.	Plan						○	○	-	-
	Actual									
4.5 To prepare the necessary training plan for doing the above Activities '4.1' through '4.4'	Plan						○	○		-
	Actual									
4.6 To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '4.5'	Plan						○	○	A total of 2 energy efficiency workshop was held. A total of 20 people (accumulated total) participated.	-
	Actual									
4.7 To review the training plan though monitoring of the training conducted in Activity '4.6'	Plan						○	○		
	Actual									
4.8 To provide advice on realization of the EE projects	Plan						○			
	Actual									
4.9 To provide recommendation on design of the policy/ legal system proposed in Activity '4.4'	Plan						○			
	Actual									
4.10 To share the project output among other recipient countries	Plan						○	○		
	Actual									
Output 5: The human and institution capacity are enhanced for the promotion of Power Network Resiliency										
5.1 To demonstrate the way to enhance resiliency of power infrastructure using Power Network Asset Management System.	Plan						○	○	A total of 3 RE and grid stabilization seminars were held. A total of 116 people (accumulated total) participated.	-
	Actual									
Duration / Phasing	Plan	Phase 1	Phase 2							
	Actual									

Monitoring Plan		2019	2020	2021	2022	2023	Remarks	Issue	Solution
Monitoring									
Joint Coordinating Committee	Plan								
	Actual								
Set-up the Detailed Plan of Operation	Plan								
	Actual								
Submission of Monitoring Sheet	Plan								
	Actual								
Reports/Documents									
Project Completion Report	Plan						Project completion report will be submitted in June 2023.		
	Actual								
Public Relations									
Public Relation Activities	Plan								
	Actual								

■ :Activity by JICA Expert Team

PM Form 3-1 Monitoring Sheet Summary

TO CR of JICA SAINT LUCIA OFFICE

Project Monitoring Sheet
(Barbados)

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries
Version of the Sheet: Ver.6（Term: October 2022 – May 2023）

Name: Mr. Andrew Gittens
Title: Project Director
Name: Mr. Tomoyasu Fukuchi
Title: Team Leader
Submission Date: 24th May 2023

I. Summary
1 Progress
1.1. Progress of Inputs
1.1.1. Inputs from the Japanese Side
(1) Dispatch of Japanese Experts

- ✓ JICA expert team (JET) postponed its field activities due to continuous travel restrictions caused by COVID-19 from March 2020 by June 2022. Under the circumstance, JET was continuing remote activities in Japan and related research as well as preparation of trainings were conducted. JET has resumed the field activities since July 2022.
- ✓ Actual assignments of JET in this project for three target countries (Jamaica, St. Kitts & Nevis, and Barbados) are shown below.

Assignments of JET in the project (three countries)

No	Technical Area	Total MM (Apr 2019–Apr 2023)		
		Field	Home	Total
1	Chief advisor/ Power System/Diesel/Gas-turbine Power Plant (2)	0.97	6.20	7.17
2	Subchief Advisor/Power system (2)	2.30	4.75	7.05
3	Renewable Energy	4.37	6.75	11.12
4	Energy Efficiency	4.93	5.65	10.58
5	Grid Stabilization	3.26	3.70	6.96
6	Diesel/Gas-turbine Power Plant/Coordinator	1.53	0.37	1.90
7	Human Resources Development/Monitoring	2.57	3.70	6.27
8	Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	4.33	6.25	10.58
	Total	**24.26**	**37.37**	**61.63**

(2) Assignment of Local Staff

- ✓ Local staff was continuously assigned to support JET.

Assignment of Local Staff

No	Name of Local Staff
1.	Mr. Alex Harewood

(3) Equipment

- ✓ Two power loggers were provided. One power logger was provided to MEB in September 2022, the other one was provided to BNSI in November 2022.
- ✓ Grid Analysis Software was provided to MEB in January 2023.

1.1.2. Inputs from Barbados Side

(1) Assignment of Counterparts

- ✓ Project Director, Ms. Francine Blackman replaced to Mr. Andrew Gittens.
- ✓ Project Manager, Mr. Horace Archer was continuously assigned.
- ✓ Project implementation structure of C/P was continuously formed.
  (Note: Although the Energy Division was under the Division of Energy and Telecommunications (DET), the Prime Minister's Office in 2019, it was transferred to Ministry of Energy and Water Resources (MEWR) in 2020, furthermore it was transferred again to Ministry of Small Business and Entrepreneurship (MESBE) in 2020, the division is currently under the Ministry of Energy

and Business (MEB) due to government restructuring in 2022.)

1.2. Progress of Activities

- ✓ JET conducted coordination of business trip schedule as well as whole project schedule during the monitoring period.
- ✓ JET (RE team) conducted the 6th field visit in Jamaica and Barbados in October 2022. JET (RE team) conducted the 7th field visit in Jamaica, St. Kitts & Nevis (online), and Barbados in November and December 2022. JET (RE team) conducted the 8th field visit in St. Kitts & Nevis (online) and Barbados in January and February 2023.
- ✓ JET (EE team) conducted the 7th field visit in Jamaica, St. Kitts & Nevis (in Barbados and online), and Barbados in November 2022. JET (EE team) conducted the 8th field visit in St. Kitts and Nevis (online) and Barbados in January and February 2023.
- ✓ JET (RE team and EE team) conducted reporting meeting of the 7th field visit and pre-departure briefings of the 8th field visit in December 2022.
- ✓ JET prepared the 5th and 6th contract change during the monitoring period.
- ✓ JET discussed on the details of the potential program including potential sites for training in Japan.
- ✓ JET submitted Draft Final Report to JICA in February 2023.
- ✓ JET conducted the 3rd JCC with C/Ps in March 2023. (Jamaica: 30th March via online, St. Kitts & Nevis: 21st March via online, and Barbados: 27th March both face to face and via online).
- ✓ JET conducted the 9th field visit in Barbados (RE team) and Jamaica (EE team) in March and April 2023.
- ✓ JET coordinated with C/Ps and JICA regarding invitation for training in Japan. Training in Japan was conducted in April 2023.
- ✓ JET submitted monitoring sheets in October 2022 and May 2023.
- ✓ JET has prepared the Final Report both in English and Japanese for submission in Jun 2023.

1.3. Achievement of Output

(1) Achievement of Outputs

Technical transfer in phase 2 was implemented in Output 3, Output 4 and Output 5. The status of Achievement of each Output is shown below.

Achievement of each Output on PDM (October 2019 – May 2023)

Output	Indicator	Target Value	Achievement
Overall Goal: Energy security is ensured through introduction of RE and promotion of EE	1.Energy self-dependency	100% (100%RE by 2030)	Renewable energy now makes up 3% of Barbados overall energy mix (12% of electricity production).
	2. Imported amount of fossil fuel	To 0% by 2030	The importation of fossil fuel has decreased by 14.7% since the 2010 baseline. Through the use of renewable energy and improvements in energy efficiency in the energy sector there has been a steady decrease of about 1.2% per year.
Project Purpose: Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant	PV 10 MW (BL&P) + 25 MW (Other)+ 10 MW Wind	As of January 1, 2023, there was 10 MW Utility owned PV, 73.5 MW of Distributed PV, 1MW of wind energy and 5MW (21MWh) utility battery energy storage connected to the grid.

	2. Number of public buildings with EE program including BEMS	2 Government facilities	An optimized building energy management systems (BEMS) was deployed in 2 Government facilities. The goal being to provide a comprehensive understanding of the energy consumption of their physical plant and provide for the optimal control of energy supply and demand. The goal is to reduce the energy consumption in these buildings by as much at 50%. It features: 265 kW PV, 400 kWh LiFePo4 battery storage, Lighting control equipment, Smart metering equipment, Power conditioning equipment. Other EE interventions such as retrofit of more efficient air conditioning and lighting is planned to be rolled out throughout Government with a target of reducing energy consumption by 40% against the 2030 business as usual case.
	3. Number of trained staffs for introduction of RE	6 personnel MEB:3 BL&P:3 others	In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12).

			Average (Local only): MEB: around 3 personnel BLPC: 2-4 personnel
	4. Number of trained staffs for promotion of EE	7 personnel	In total, number of participants (accumulated total) was 38 personnel.
Output 3: (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	3-1. Number of trained staffs	6 personnel (MEB, BL&P)	In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12). Average (Local only): MEB: around 3 personnel BLPC: 2-4 personnel
	3-2. Textbooks/ manuals	For 3 programs (2 domestic trainings and 1 training in Japan)	In total, 7 materials were prepared.
	3-3. Number of participants of workshops to disseminate introduction of RE to the relevant organizations	Kick-off workshop: 10 personnel Final workshop: 10-15 personnel	In total, number of participants (accumulated total) was 82 personnel.
	3-4. Number of workshops for CARICOM region	2 times (Kickoff workshop and Final workshop)	In total, 6 times.
Output 4: (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	4-1. Number of trained staffs	6 personnel	In total, number of participants (accumulated total) was 38 personnel.
	4-2. Textbooks/ manuals	3 programs (2 domestic trainings and 1 training in Japan)	In total, 4 materials were prepared.

	4-3. Number of participants of workshops to disseminate promotion of EE to the relevant organizations	Kick-off workshop: 10 personnel Final workshop: 10-15 personnel	In total, number of participants (accumulated total) was 44 personnel.
	4-4. Number of workshops of CARICOM region	2 times (Kick-off workshop and Final workshop)	In total, 5 times.
Output 5: (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of power network resiliency	5-1. Number of trained staffs	6 personnel (MEB, BL&P)	In total, number of participants (accumulated total) was 39 personnel
	5-2. Textbooks/ manuals	2 programs (For 1 local training and 1 training in Japan)	In total, 5 materials were prepared.
	5-3. Number of participants of workshops to disseminate promotion of Resilience to the relevant organizations	Kick-off workshop: 10 personnel Final workshop: 10-15 personnel	In total, number of participants (accumulated total) was 82 personnel.
	5-4. Number of workshops	2 times (Kick-off workshop and Final workshop)	In total, 6 times.

(2) Evaluation of Trainings

JET was conducted following trainings and monitoring activities using following questions.

Q.1. Was JICA experts' explanation clear and easy to understand?
Q.2. Were training materials well organized and easy to understand?
Q.3. Was the content of lecture enough to understand?
Q.4. Were JICA experts maximize participants' opportunities?
Q.5. Were training aids and facilities are satisfied?
Q.6. If you have any topics that you would like us to cover next training, please write down.
Q.7. Do you have any other comments?

Overview of each training is shown below.

List of Trainings (October 2022 – March 2023)

Time	Target country	Contents	No. of Participants	Score (*/5)
Jul 2022	**Barbados**	**1st RE grid stability seminar**	**4**	**-**
Oct 2022	**Barbados, St. Kitts & Nevis**	**2nd RE grid stability seminar for Barbados** **1st RE grid stability seminar for St. Kitts & Nevis**	**44**	**3.3**
Oct 2022	Jamaica	1st RE grid stability seminar	31	4.3
Nov 2022	St. Kitts & Nevis	1st EE workshop	12	3.8
Nov 2022	**Barbados**	**1st EE workshop**	**5**	**3.7**
Dec 2022	Jamaica	2nd RE grid stability seminar	45	3.9
Dec 2022	**Barbados**	**3rd RE grid stability seminar**	**19**	**3.8**
Dec 2022	St. Kitts & Nevis	2nd RE grid stability seminar	19	3.8
Jan 2022	St. Kitts & Nevis	2nd EE workshop	11	4.4
Jan 2022	**Barbados**	**2nd EE workshop**	**11**	**3.9**
Jan 2022	St. Kitts & Nevis	3rd RE rid stability seminar	14	3.8
Jan 2022	**Barbados**	**4th RE grid stability seminar**	**13**	**4.1**
Feb 2022	Jamaica	1st EE workshop	3	4.5
Mar 2022	Jamaica	2nd EE workshop	8	3.9

(3) Training in Japan

- ✓ Training in Japan was conducted in April 2023. 9 participants had lectures, site visits and reporting session. Participants learnt RE and EE efforts in Japan. Details was shown in the report prepared by JET.

1.4. Achievement of the Project Purpose

- ✓ As mentioned above.

1.5. Changes of Risks and Actions for Mitigation

- ✓ Travel restrictions caused by COVID-19
- ✓ Meteorological influence (hurricane etc.)

1.6. Progress of Actions undertaken by JICA

- ✓ JICA coordinated with C/Ps and JET regarding invitation for training in Japan.

1.7. Progress of Actions undertaken by C/P

- ✓ C/P timely provided information of travel restrictions caused by COVID-19 in the country to JET.

1.8. Progress of Environmental and Social Considerations (if applicable)

- ✓ N/A

1.9. Progress of Considerations on Gender/Peace Building/Poverty Reduction (if applicable)

- ✓ N/A

1.10. Other remarkable/considerable issues related/affect to the project (such as other JICA's projects, activities of counterparts, other donors, private sectors, NGOs etc.)

- ✓ N/A
- ✓

2. Delay of Work Schedule and/or Problems (if any)

2.1. Detail

- ✓ Field activities have been postponed due to COVID-19 since March 2020 to June 2022.

2.2. Cause

- ✓ Due to JICA's recommendation due to COVID-19 mentioned in 1.6.

2.3. Action to be taken

- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021 and April 2022. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

2.4. Roles of Responsible Persons/Organization (JICA, C/P)

- ✓ N/A

3. Modification of the Project Implementation Plan

3.1. PO

- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

3.2. Other modifications on detailed implementation plan

(Remarks: The amendment of R/D and PDM (title of the project, duration, project site(s), target group(s), implementation structure, overall goal, project purpose, outputs, activities, and input) should be authorized by JICA HDQs. If the project team deems it necessary to modify any part of R/D and PDM, the team may propose the draft.)

- ✓ There was an organizational reform of the Ministry of Energy and Water Resources (MEWR). MEWR was reformed to Ministry of Energy, Small Business and Entrepreneurship (MESBE). MESBE was also reformed to Ministry of Energy and Business (MEB).
- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

4. Current Activities of Gov. of Barbados to Secure Project Sustainability after its Completion

- ✓ N/A

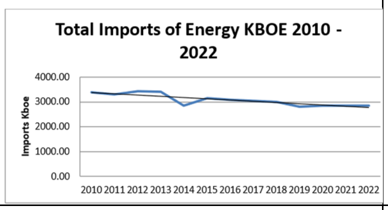
II. Project Monitoring Sheet I & II

as Attached

Project Monitoring Sheet I (Revision of Project Design Matrix)

Project Title: Technical Cooperation to Promote Energy Efficiency in the Caribbean Countries
Implementing Agency: MEB (Ministry of Energy and Business of Barbados), BLPC (Barbados Light and Power Co., Ltd.)
Target Group: Senior engineer, Engineer, Senior technical officer, Technical officer
Period of Project: 4 Years, Phase 1: 6 months, Phase 2: 42 months
Project Site: Barbados

Version : 6
Date: 24th May 2023

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions	Achievement	Remarks
Overall Goal Energy security is ensured through introduction of renewable energy (hereinafter referred to as "RE") and promotion of energy efficiency (hereinafter referred to as "EE")	1. Energy self-dependency ***Target Value**:100% (100%RE by 2030)* 2. Imported amount of fossil fuel ***Target Value**: To 0% by 2030*	Data from MEB Energy chapter (annual report)	The current relevant policies on promotions of RE and EE are sustained after the Project.	1. Renewable energy now makes up 3% of Barbados overall energy mix (12% of electricity production). 2. The importation of fossil fuel has decreased by 14.7% since the 2010 baseline. Using renewable energy and improvements in energy efficiency in the energy sector there has been a steady decrease of about 1.2% per year. See graph below. 	
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant ***Target Value**: PV 10 MW (BLPC) + 25 MW (Other)+ Wind 10 MW* 2. Number of public buildings with EE program including BEMS ***Target Value**: 2 Government facilities.* 3. Number of trained staffs for introduction of RE ***Target Value**: 6 personnel (MESBE:3, BLPC:3) and others* 4. Number of trained staffs for promotion of EE ***Target Value**: 7 personnel*	Project Report	C/P agency continues commitment to the Project by continuing budget allocation as well as assignment of personnel for the post-Project activities.	1. As of January 1, 2023 there was 10 MW Utility owned PV,73.5 MW of Distributed PV, 1MW of wind energy and 5MW (40MWh) utility battery energy storage connected to the grid. 2. An optimized building energy management systems (BEMS) was deployed in 2 Government facilities. The goal being to provide a comprehensive understanding of the energy consumption of their physical plant and provide for the optimal control of energy supply and demand. The goal is to reduce the energy consumption in these buildings by as much at 50%. It features: 265 kW PV, 400 kWh LiFePo4 battery storage, Lighting control equipment, Smart metering equipment, Power conditioning equipment. Other EE interventions such as retrofit of more efficient air conditioning and lighting is planned to be rolled out throughout Government with a target of reducing energy consumption by 40% against the 2030 business as usual case. 3. In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12) Average (Local only): MEB: around 3 personnel BLPC: 2-4 personnel - Remote training in Dec 2020 was 4 personnel (MEB: 4) - 1st Seminar in Jul 2022 was 4 personnel (MEB: 2, BLPC: 2) - 2nd Seminar in Oct 2022 was 33 personnel (MEB: 12, BLPC: 3) - 3rd Seminar in Dec 2022 was 19 personnel (MEB: 4, BLPC: 4) - Final (4th) Seminar in Jan 2023 was 13 personnel (MEB: 3, BLPC: 2) - Training in Japan in Apr 2023 was 3 personnel (MEB: 2, BLPC:1) 4. In total, number of participants (accumulated total) was 38 personnel - Demonstration on EE roadmap program etc. in Feb 2020 was 15 personnel - Remote training in Dec 2020 was 4 personnel - 1st Workshop in Nov 2022 was 5 personnel - Final (2nd) Workshop in Jan 2023 was 11 personnel - Training in Japan in Apr 2023 was 3 personnel	

Output Output 1 (to be achieved in Phase 1) The basic information is confirmed for the capacity building for the introduction of RE	1-1. Assessment of number and qualification of staffs responsible for RE 1-2. Human resource development plan for the introduction of RE 1-3. Number of training courses for the introduction of RE 1-4. Total capacity of RE	Project Report		1-1. Confirmed 1-2. Confirmed 1-3. Confirmed 1-4. Confirmed	MEWR changed to MESBE. After that, MESBE was reformed and changed to MEB
Output 2(to be achieved in Phase 1) The basic information is confirmed for the capacity building for the promotion of EE	2-1. Assessment of number and qualification of staffs responsible for EE 2-2. Human resource development plan for the introduction of EE 2-3. Number of training courses for the promotion of EE 2-4. Number of facilities conducted energy audit	Project Report		2-1. Confirmed 2-2. Confirmed 2-3. Confirmed 2-4. Confirmed	MEWR changed to MESBE. After that, MESBE was reformed and changed to MEB
Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	3-1. Number of trained staffs ***Target Value****: 6 personnel (MEB, BLPC)* 3-2. Textbooks/ manuals ***Target Value****: For 3 programs (2 domestic trainings and 1 training in Japan)* 3-3. Number of participants of workshops to disseminate introduction of RE to the relevant organizations ***Target Value****: Kick-off workshop: 10 personnel, Final workshop: 10-15 personnel* 3-4. Number of workshops for CARICOM region ***Target Value****: 2 times (Kick-off workshop and Final workshop)*	Project Report		3-1. In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12). Average (Local only): MEB: around 3 personnel BLPC: 2-4 personnel 3-2. In total, 7 materials were prepared. - 1 manual for simulation software of system analysis. - 1 training material for remote training in Dec 2020. - 4 training materials about ‘Seminar on Grid stability and RE’ for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan 3-3. In total, number of participants (accumulated total) was 82 personnel - Kick-off workshop in Nov 2019 was 9 personnel - Remote training about ‘impact of COVID-19 on RE’ in Dec 2020 was 4 personnel - 1st Seminar in Jul 2022 was 4 personnel - 2nd Seminar in Oct 2022 was 33 personnel - 3rd Seminar in Dec 2022 was 19 personnel - Final (4th) Seminar in Jan 2023 was 13 personnel 3-4. In total, 6 times - Kick-off workshop was conducted in Nov 2019 - Remote training about ‘impact of COVID-19 on RE’ in Dec 2020 - 1st Seminar was conducted in Jul 2022 - 2nd Seminar was conducted in Oct 2022 - 3rd Seminar was conducted in Dec 2022 - Final (4th) Seminar was conducted in Jan 2023	
Output 4 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	4-1. Number of trained staffs ***Target Value****: 6 personnel* 4-2. Textbooks/ manuals ***Target Value****: For 3 programs (2 domestic trainings and 1 training in Japan)* 4-3. Number of participants of workshops to disseminate promotion of EE to the relevant organizations ***Target Value****: Kick-off workshop: 10 personnel, Final workshop: 10-15 personnel* 4-4. Number of workshops for CARICOM region ***Target Value****: 2 times (Kick-off workshop and Final workshop)*	Project Report		4-1. In total, number of participants (accumulated total) was 38 personnel 4-2. In total, 4 materials were prepared. - 1 training material for remote training in Dec 2020. - 2 training materials about ‘Energy Efficiency Workshop’ for domestic training in Nov 2022 and Jan 2023. - 1 training material for training in Japan in Apr 2023. 4-3. In total, number of participants (accumulated total) was 44 personnel - Kick-off workshop in Nov 2019 was 9 personnel - Demonstration on EE roadmap program and power consumption measurement was conducted in Feb 2020 was 15 personnel	

				- Remote training in Dec 2020. Number of participants was 4 personnel - 1st Workshop in Nov 2022 was 5 personnel - Final (2nd) Workshop in Jan 2023 was 11 personnel 4-4. In total, 5 times. - Kick-off workshop was conducted in Nov 2019 - Demonstration on EE roadmap program and power consumption measurement in Mar 2020 - Remote training about 'impact of COVID-19 on EE' in Dec 2020 - 1st workshop was conducted in Nov 2022 - Final (2nd) workshop was conducted in Jan 2023	
Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of power network resiliency	5-1. Number of trained staffs ***Target Value**: 6 personnel (MESBE, BLPC)* 5-2. Textbooks/ manuals ***Target Value**: For 2 programs (1 domestic training and 1 training in Japan)* 5-3. Number of participants of workshops to disseminate promotion of Resilience to the relevant organizations ***Target Value**: Kick-off workshop: 10 personnel, Final workshop: 10-15 personnel* 5-4. Number of workshops ***Target Value**: 2 times (Kick-off workshop and Final workshop)*	Project Report		5-1. In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12). Average (Local only): MEB: around 3 personnel BLPC: 2-4 personnel 5-2. In total, 5 materials were prepared. - 1 training material for remote training in Dec 2020. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan 5-3. In total, number of participants (accumulated total) was 82 personnel - Kick-off workshop in Nov 2019 was 9 personnel - Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 4 personnel - 1st Seminar in Jul 2022 was 4 personnel - 2nd Seminar in Oct 2022 was 33 personnel - 3rd Seminar in Dec 2022 was 19 personnel - Final (4th) Seminar in Jan 2023 was 13 personnel 5-4. In total, 6 times - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Jul 2022 - 2nd Seminar was conducted in Oct 2022 - 3rd Seminar was conducted in Dec 2022 - Final (4th) Seminar was conducted in Jan 2023	

Activities	**Inputs**		Important Assumptions
Activities for achieving Output 1 1-1. To verify human and institutional capacities for the introduction of RE Activities for achieving Output 2 2-1. To verify the fundamental indicators on promotion of EE for the electricity demand side, e.g. electric power consumption unit requirement, final energy consumption, etc. 2-2. To verify the existing conditions in promotion of EE, relevant policies/ national plans 2-3. To carry out a review of the current maintenance practices for thermal power plants and these practices to international best practices. 2-4. To verify human and institutional capacities for the promotion of EE Activities for achieving Output 3 3-1. To develop microgrid concept in view of maximizing VRE introduction.	**(Japanese side)** 1. Dispatch of the Japanese experts in respect of following: - Chief advisor/ Power System/Diesel/Gas-turbine Power Plant (2) - Subchief Advisor/Power system (2) - Renewable Energy - Energy Efficiency - Grid Stabilization - Diesel/Gas-turbine Power Plant/Coordinator - Human Resources Development/Monitoring - Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2) 2. Training in Japan -Micro Grid system including Grid Stabilization Technology in small island (e.g. Okinawa, Tokyo and other cities) -Policies and technologies for promotion of EE (Energy load labelling, policies, regulations and incentives) (Tokyo and other cities) -Site visit in Japan	**(Barbados side)** 1. Assignment of C/Ps -Project Director (P/D) -Project Manager (P/M) - Other C/P 2. Facilities and equipment for the Project office -To allocate office space with furniture for experts during their stay in Barbados (desks, chairs, meeting tables, copy machine, etc) 3. Recurrent costs Project Director, Project Manager and Project Administrator's salaries will be met by DET	Most of the trained C/Ps continues commitment to the Project activities. Preconditions Contents of the current relevant policies on promotion of RE and EE are not largely changed. Issues and countermeasures

3-2. To model microgrid concept in the agreed area carry out case studies using own computer simulator as part of capacity building. 3-3. To consider the use of electric transportation in Barbados and its effects (positive and negative) on the grid and economy. 3-4. Review of the effectiveness of the existing Government policies on RE and propose changes to the existing policies to promote the uptake of electric vehicles. 3-5. To prepare the necessary training plan for doing the above Activities '3-1' through '3-4' 3-6. To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '3-5' 3-7. To review the training plan though monitoring of the training conducted in Activity '3-6' 3-8. To provide advice on realization of the RE projects 3-9. To provide recommendations on design of the policy/ legal system proposed in Activity '3-4' 3-10. To share the project output with other recipient countries	3. Training/Workshop in each recipient country -Training for project counterparts in each recipient country 4. Equipment - Power loggers		
<u>Activities for achieving Output 4</u> 4-1. To consider and propose the EE goals through cost-benefit analysis on introduction of the facilities contributing to EE, e.g. Green Wall, Green roofs, thermal insulations, LED lighting etc. 4-2. To consider and propose the EE facilities necessary for achieving the EE goals 4-3. To consider and propose necessary technologies for achieving EE goals, including building energy management system (BEMS) for public sector, etc. 4-4. To carry out a review of the current methods of operation and load dispatch and compare to international best practices for thermal power plants 4-5. To consider and propose measures to improve the maintenance system for thermal power plants, including measures to do periodic maintenance and overhaul and procurement of spare parts 4-6. To consider and propose the necessary policy and/or regulatory frameworks for achieving EE initiatives such as introduction of energy service company (ESCO) and energy management service and items mentioned in '4-1'. 4-7. To prepare the necessary training plan for doing the above Activities '4-1' through '4-6' 4-8. To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '4-7' 4-9. To review the training plan though monitoring of the training conducted in Activity '4-8' 4-10. To provide advice on realization of the EE projects 4-11. To provide recommendation on design of the policy/ legal system proposed in Activity '4-6' 4-12. To share the project output with other recipient countries			
<u>Activities for achieving Output 5</u> 5-1. To demonstrate the way to enhance resiliency of the power infrastructure using network asset management system.			

Appendix 6-2-2-3 Monitoring Sheet II, Revision of Plan of Operation (Barbados)

Project Monitoring Sheet II （Revision of Plan of Operation）

Version 6

Date 24 May 2023

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries (Barbados)

Inputs	Year: 2019 / 2020 / 2021 / 2022 / 2023	Remarks	Monitoring (Up to May 2023): Issue	Monitoring (Up to May 2023): Solution
Expert				
1. Chief Advisor/Power System (1) /Diesel/Gas-turbine Power Plant (2)	Plan	Blue highlights were inputs from Japan.		
	Actual			
2. Subchief Advisor/Power System (2)	Plan			
	Actual			
3. Renewable Energy	Plan			
	Actual			
4. Energy Efficiency	Plan			
	Actual			
5. Grid Stabilization	Plan			
	Actual			
6. Diesel/Gas-turbine Power Plant/Coordinator	Plan			
	Actual			
7. Human Resources Development/Monitoring	Plan			
	Actual			
8. Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	Plan			
	Actual			
Equipment				
Power loggers	Plan	Handed over in September 2022 and November 2022		
	Actual			
Grid Analysis Software	Plan	Handed over in January 2023		
	Actual			
Training in Japan				
Training in Japan	Plan	Training in Japan was conducted in April 2023.		
	Actual			
In-country Training				
Trainings in country (RE)	Plan	4 in-country trainings were conducted.		
	Actual			
Trainings in country (EE)	Plan	2 in-country trainings were condcuted.		
	Actual			

Activities / Sub-Activities	Year: 2019 / 2020 / 2021 / 2022 / 2023	Responsible Organization: JET	Responsible Organization: C/P	Achievements	Issue & Countermeasures
Output 1:The basic information is confirmed for the capacity building for the introduction of RE					
1.1 To verify human and institutional capacities for the introduction of RE	Plan / Actual	○	○		DET was reformed to MEWR, MEWR was reformed to MESBE and MESBE was reformed to MEB.
Output 2: The basic information is confirmed for the capacity building for the promotion of EE					
2.1 To verify the fundamental indicators on promotion of EE for the electricity demand side, e.g. electric power consumption unit requirement, final energy consumption, etc.	Plan / Actual	○	○		
2.2 To verify the existing conditions in promotion of EE, relevant policies/national plans	Plan / Actual	○	○		
2.3 To carry out a review of the current maintenance practices for thermal power plants and these practices to international best practices	Plan / Actual	○			
2.4 To verify human and institutional capacities for the promotion of EE	Plan / Actual	○	○		DET was reformed to MEWR, MEWR was reformed to MESBE and MESBE was reformed to MEB.
Output 3: The human and institution capacity are enhanced for the introduction of RE					
3.1 To develop microgrid concept in view of maximizing VRE introduction.	Plan / Actual	○	○		
3.2 To model microgrid concept in the agreed area carry out case studies using own computer simulator as part of capacity building.	Plan / Actual	○	○		
3.3 To consider the use of electric transportation in Barbados and its effects (positive and negative) on the grid and economy	Plan / Actual	○	○		
3.4 Review of the effectiveness of the existing Government policies on RE and purpose changes to the existing policies to promote the uptake of electric vehicles	Plan / Actual	○	○		
3.5 To prepare the necessary training plan for doing the above Activities '3.1' through '3.4'	Plan / Actual	○	○	A total of 4 RE and grid stabilization seminars were held.	-
3.6 To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/manuals using the training plan prepared in Activity '3.5'	Plan / Actual	○	○	A total of 39 people (accumulated total) participated.	
3.7 To review the training plan through monitoring of the training conducted in Activity '3.6'	Plan / Actual	○	○		
3.8 To provide advice on realization of the RE projects	Plan / Actual	○			
3.9 To provide recommendations on design of the policy/legal system proposed in Activity '3.4'	Plan / Actual	○			
3.10 To share the project output with other recipient countries	Plan / Actual	○	○		

Project Monitoring Sheet II （Revision of Plan of Operation）

Version 6

Date 24 May 2023

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries (Barbados)

Inputs	Year / Month	2019	2020	2021	2022	2023	Remarks		Issue (Monitoring (Up to May 2023))	Solution (Monitoring (Up to May 2023))
Output 4: The human and institution capacity are enhanced for the promotion of EE										
4.1 To consider and propose the EE goals through cost-benefit analysis on introduction of the facilities contributing to EE, e.g. Green Wall, Green roofs, thermal inslations, LED lighting etc.	Plan / Actual						○	○		-
4.2 To consider and propose the EE facilities necessary for achieving the EE goals	Plan / Actual						○	○		-
4.3 To consider and propose necessary technologies for achieving EE goals, including building energy management system (BEMS) for public sector, etc.	Plan / Actual						○	○		-
4.4 To carry out a review of the current methods of operation and load dispatch and compare to international best practices for thermal power plants	Plan / Actual						○	○	-	-
4.5 To consider and propose measures to improve the maintenance system for thermal power plants, including measures to do periodic maintenance and overhaul and procurement of spare parts	Plan / Actual						○	○	-	-
4.6 To consider and propose the necessary policy and/or regulatory frameworks for achieving EE initiatives such as introduction of energy service company (ESCO) and energy management service and items mentioned in '4.1'	Plan / Actual						○	○	-	-
4.7 To prepare the necessary training plan for doing the above Activities '4.1' through '4.6'	Plan / Actual						○	○	A total of 2 energy efficiency workshops were held. A total of 38 people (accumulated total) participated.	-
4.8 To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/manuals using the training plan prepared in Activity '4.7'	Plan / Actual						○	○		
4.9 To review the training plan though monitoring of the training conducted in Activity '4.8'	Plan / Actual						○	○		
4.10 To provide advice on realization of the EE projects	Plan / Actual						○			
4.11 To provide recommendation on design of the policy/ legal system proposed in Activity '4.6'	Plan / Actual						○			
4.12 To share the project output with other recipient countries	Plan / Actual						○	○		
Output 5: The human and institution capacity are enhanced for the promotion of power network Resiliency										
5.1 To demonstrate the way to enhance resiliency of the power infrastructure using network asset management system.	Plan / Actual						○	○	A total of 4 RE and grid stabilization seminars were held. A total of 39 people (accumulated total) participated.	-

Duration / Phasing	Plan / Actual	Phase 1	Phase 2	Remarks	Issue	Solution

Monitoring Plan	Year	2019	2020	2021	2022	2023	Remarks	Issue	Solution
Monitoring									
Joint Coordinating Committee	Plan / Actual								
Set-up the Detailed Plan of Operation	Plan / Actual								
Submission of Monitoring Sheet	Plan / Actual								
Reports/Documents									
Project Completion Report	Plan / Actual						Project completion report will be submitted in June 2023.		
Public Relations									
Public Relation Activities	Plan / Actual								

■ :Activity by JICA Expert Team

PM Form 3-1 Monitoring Sheet Summary

TO CR of JICA SAINT LUCIA OFFICE

Project Monitoring Sheet
(St. Kitts & Nevis)

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries
Version of the Sheet: Ver.6（Term: October 2022 – May 2023）

Name: Mr. Bertille Browne
Title: Project Manager
Name: Mr. Tomoyasu Fukuchi
Title: Team Leader
Submission Date: 24th May 2023

I. Summary
1 Progress
1.1. Progress of Inputs
1.1.1. Inputs from Japan Side
(1) Dispatch of Japanese Experts

- ✓ JICA expert team (JET) postponed its field activities due to continuous travel restrictions caused by COVID-19 from March 2020 by June 2022. Under the circumstance, JET was continuing remote activities in Japan and related research as well as preparation of trainings were conducted. JET has resumed the field activities since July 2022.
- ✓ Actual assignments of JET in this project for three target countries (Jamaica, St. Kitts & Nevis, and Barbados) are shown below.

Assignments of JET in the project (three countries)

No	Technical Area	Total MM (Apr 2019–Apr 2023)		
		Field	Field	Field
1	Chief advisor/ Power System/Diesel/Gas-turbine Power Plant (2)	0.97	0.97	0.97
2	Subchief Advisor/Power system (2)	2.30	2.30	2.30
3	Renewable Energy	4.37	4.37	4.37
4	Energy Efficiency	4.93	4.93	4.93
5	Grid Stabilization	3.26	3.26	3.26
6	Diesel/Gas-turbine Power Plant/Coordinator	1.53	1.53	1.53
7	Human Resources Development/Monitoring	2.57	2.57	2.57
8	Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	4.33	4.33	4.33
	Total	**24.26**	**24.26**	**24.26**

(2) Assignment of Local Staff

- ✓ Local staff was continuously assigned to support JET.

Assignment of Local Staff

No	Name of Local Staff
1.	Mr. I-Ronn Audain

(3) Equipment

- ✓ Two power loggers were provided. One power logger was provided to MPI, the other one was provided to NIA in January 2023.
- ✓ Grid analysis software was provided to MPI and NIA both in January 2023.
- ✓ Asset management software was provided to MPI in January 2023.

1.1.2. Inputs from St. Kitts & Nevis Side

(1) Assignment of Counterparts

- ✓ Project Manager, Mr. Bertill Browne was continuously assigned.
- ✓ Project implementation structure of C/P was continuously formed.

1.2. Progress of Activities

- ✓ JET conducted coordination of business trip schedule as well as whole project schedule during the monitoring period.
- ✓ JET (RE team) conducted the 6th field visit in Jamaica and Barbados in October 2022. JET (RE team) conducted the 7th field visit in Jamaica, St. Kitts & Nevis (online), and Barbados in November and December 2022. JET (RE team) conducted the 8th field visit in St. Kitts & Nevis (online) and Barbados in January and February 2023.
- ✓ JET (EE team) conducted the 7th field visit in Jamaica, St. Kitts & Nevis (in Barbados and online), and Barbados in November 2022. JET (EE team) conducted the 8th field visit in St. Kitts and Nevis (online) and Barbados in January and February 2023.
- ✓ JET (RE team and EE team) conducted reporting meeting of the 7th field visit and pre-departure briefings of the 8th field visit in December 2022.
- ✓ JET prepared the 5th and 6th contract change during the monitoring period.
- ✓ JET discussed on the details of the potential program including potential sites for training in Japan.
- ✓ JET submitted Draft Final Report to JICA in February 2023.
- ✓ JET conducted the 3rd JCC with C/Ps in March 2023. (Jamaica: 30th March via online, St. Kitts & Nevis: 21st March via online, and Barbados: 27th March both face to face and via online).
- ✓ JET conducted the 9th field visit in Barbados (RE team) and Jamaica (EE team) in March and April 2023.
- ✓ JET coordinated with C/Ps and JICA regarding invitation for training in Japan. Training in Japan was conducted in April 2023.
- ✓ JET submitted monitoring sheets in October 2022 and May 2023.
- ✓ JET has prepared the Final Report both in English and Japanese for submission in Jun 2023.

1.3. Achievement of Output

(1) Achievement of Outputs

Technical transfer in phase 2 was implemented for Output 3, Output 4 and Output 5. The status of Achievement of each Output is shown below.

Achievement of each Output on PDM (October 2019 –May 2023)

Output	Indicator	Target Value	Achievement
Overall Goal: Energy security is ensured through introduction of renewable energy	1.Energy self-dependency	100% (100% RE in Power Generation by 2030)	Approximately 2 percent
	2. Imported amount of fossil fuel	2% of total fuel import	Unchanged
Project Purpose: Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant	PV 35MW by 2020, Wind 5MW, BESS 44.2MWh (St. Kitts), Geothermal power 9MWh (Nevis)	None.
	2. Number of public buildings with EE program including BEMS	Proposal by JET will be prepared for the BEMS introduction	One. The Alexandra Hospital was upgraded to be more energy efficient.
	3. Number of trained staffs for introduction of RE	10 personnel	In total, number of participants (accumulated total) was 66 personnel
	4. Number of trained staffs for promotion of EE	10 personnel	In total, number of participants (accumulated total) was 62 personnel

Output 3: (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	3-1. Number of trained staffs	10 personnel	In total, number of participants (accumulated total) was 66 personnel.
	3-2. Textbooks/ manuals	3 programs (2 domestic trainings and 1 training in Japan)	In total, 6 materials were prepared.
	3-3. Number of participants of workshops to disseminate introduction of RE to the relevant organizations	Kick-off workshop: 9 personnel Final workshop: 10 personnel	In total, number of participants (accumulated total) was 71 personnel.
	3-4. Number of workshops	2 times (Kick-off workshop and Final workshop)	In total, 5 times
Output 4: (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of EE	4-1. Number of trained staffs	10 personnel	In total, number of participants (accumulated total) was 62 personnel
	4-2. Textbooks/ manuals	3 programs (2 domestic trainings and 1 training in Japan)	In total, 4 materials were prepared.
	4-3. Number of participants of workshops to disseminate promotion of EE to the relevant organizations	Kick-off workshop: 9 personnel Final workshop: 10 personnel	In total, number of participants (accumulated total) was 67 personnel
	4-4. Number of workshops	2 times (Kick-off workshop and Final workshop)	In total, 4 times

Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of Power Network Resiliency	5-1. Number of trained staffs	10 personnel	In total, number of participants (accumulated total) was 66 personnel
	5-2. Textbooks/ manuals	2 programs (For 1 local training and 1 training in Japan)	In total, 5 materials were prepared.
	5-3. Number of participants of workshops to disseminate promotion of power network resiliency to the relevant organizations	Kick-off workshop: 9 personnel Final workshop: 10 personnel	In total, number of participants (accumulated total) was 71 personnel
	5-4. Number of workshops	2 times (Kick-off workshop and Final workshop)	In total, 5 times

(2) Evaluation of Trainings

JET was conducted following trainings and monitoring activities using following questions.

Q.1. Was JICA experts' explanation clear and easy to understand?
Q.2. Were training materials well organized and easy to understand?
Q.3. Was the content of lecture enough to understand?
Q.4. Were JICA experts maximize participants' opportunities?
Q.5. Were training aids and facilities are satisfied?
Q.6. If you have any topics that you would like us to cover next training, please write down.
Q.7. Do you have any other comments?

Overview of each training is shown below.

List of Trainings (October 2022 – March 2023)

Time	Target country	Contents	No. of Participants	Score (*/5)
Jul 2022	Barbados	1st RE grid stability seminar	4	-
Oct 2022	**Barbados, St. Kitts & Nevis**	**2nd RE grid stability seminar for Barbados 1st RE grid stability seminar for St. Kitts & Nevis**	**44**	**3.3**
Oct 2022	Jamaica	1st RE grid stability seminar	31	4.3
Nov 2022	**St. Kitts & Nevis**	**1st EE workshop**	**12**	**3.8**
Nov 2022	Barbados	1st EE workshop	5	3.7
Dec 2022	Jamaica	2nd RE grid stability seminar	45	3.9
Dec 2022	Barbados	3rd RE grid stability seminar	19	3.8
Dec 2022	**St. Kitts & Nevis**	**2nd RE grid stability seminar**	**19**	**3.8**
Jan 2022	**St. Kitts & Nevis**	**2nd EE workshop**	**11**	**4.4**
Jan 2022	Barbados	2nd EE workshop	11	3.9
Jan 2022	**St. Kitts & Nevis**	**3rd RE grid stability seminar**	**14**	**3.8**
Jan 2022	Barbados	4th RE grid stability seminar	13	4.1
Feb 2022	Jamaica	1st EE workshop	3	4.5
Mar 2022	Jamaica	2nd EE workshop	8	3.9

(3) Training in Japan

✓ Training in Japan was conducted in April 2023. 9 participants had lectures, site visits and reporting session. Participants learnt RE and EE efforts in Japan. Details was shown in the report prepared by JET.

1.4. Achievement of the Project Purpose

✓ As mentioned above.

1.5. Changes of Risks and Actions for Mitigation
- ✓ Travel restrictions caused by COVID-19
- ✓ Meteorological influence (hurricane etc.)

1.6. Progress of Actions undertaken by JICA
- ✓ JICA coordinated with C/Ps and JET regarding invitation for training in Japan.

1.7. Progress of Actions undertaken by C/P
- ✓ C/P timely provided information of travel restrictions caused by COVID-19 in the country to JET.

1.8. Progress of Environmental and Social Considerations (if applicable)
- ✓ N/A

1.9. Progress of Considerations on Gender/Peace Building/Poverty Reduction (if applicable)
- ✓ N/A

1.10. Other remarkable/considerable issues related/affect to the project (such as other JICA's projects, activities of counterparts, other donors, private sectors, NGOs etc.)
- ✓ N/A

2. Delay of Work Schedule and/or Problems (if any)
2.1. Detail
- ✓ Field activities have been postponed due to COVID-19 since March 2020 to January 2023 in St. Kitts and Nevis. Workshops for St. Kitts and Nevis were conducted in Barbados.

2.2. Cause
- ✓ Due to government restriction on entry under COVID-19 in St. Kitts and Nevis.

2.3. Action to be taken
- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021 and April 2022. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

2.4. Roles of Responsible Persons/Organization (JICA, C/P)

- ✓ N/A

3. Modification of the Project Implementation Plan

3.1. PO

- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

3.2. Other modifications on detailed implementation plan

(Remarks: The amendment of R/D and PDM (title of the project, duration, project site(s), target group(s), implementation structure, overall goal, project purpose, outputs, activities, and input) should be authorized by JICA HDQs. If the project team deems it necessary to modify any part of R/D and PDM, the team may propose the draft.)

- ✓ Project schedule was reviewed in anticipation of resuming field assignments from April 2021. End of project has been extended for 1 year and 3 months by June 2023 from March 2022.

4. Current Activities of Gov. of St. Kitts & Nevis to Secure Project Sustainability after its Completion

- ✓ N/A

II. Project Monitoring Sheet I & II

as Attached

Project Monitoring Sheet I (Revision of Project Design Matrix)

Project Title: Technical Cooperation to Promote Energy Efficiency in the Caribbean Countries
Implementing Agency: MPI (Ministry of Public Infrastructure, Post, Urban Development and Transport), NIA (Nevis Island Administration), SKELEC (St. Kitts Electricity Company Ltd.), NEVLEC (Nevis Electricity Company Ltd.)
Target Group: Senior engineer, Engineer, Senior technical officer, Technical officer
Period of Project: 4 years, Phase1: 6 months, Phase2: 42 months
Project Site: Saint Christopher and Nevis

Version : 6
Date: 24th May 2023

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Important Assumptions	Achievement	Remarks
Overall Goal Energy security is ensured through introduction of renewable energy (hereinafter referred to as "RE") and promotion of energy efficiency (hereinafter referred to as "EE")	1. Energy self-dependency ***Target Value**: 100% RE in Power Generation by 2030* 2. Imported amount of fossil fuel ***Target Value**: 2% of total fuel import*	Data from MPI annual report	The current relevant policies on promotions of RE and EE are sustained after the Project.	1. Approximately 2 percent 2. Unchanged	
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	1. Number of RE facilities such as PV power station, wind generating facility, battery application, high-efficiency thermal power plant ***Target Value:** PV 35MW by 2020, Wind 5MW, BESS 44.2MWh (St. Kitts), Geothermal power 9MWh (Nevis)* 2. Number of public buildings with EE program including BEMS ***Target Value:** Proposal by JET will be prepared for the BEMS introduction* 3. Number of trained staffs for introduction of RE ***Target Value:**10 personnel* 4. Number of trained staffs for promotion of EE ***Target Value:** 10 personnel*	Project Report	C/P agency continues commitment to the Project by continuing budget allocation as well as assignment of personnel for the post- Project activities.	1. 10MW geothermal is in procurement process. 2. One. The Alexandra Hospital was upgraded to be more energy efficient. 3. In total, number of participants (accumulated total) was 66 personnel - Remote training in Dec 2020 was 18 personnel - 1st Seminar in Oct 2022 was 11 personnel - 2nd Seminar in Dec 2022 was 19 personnel - Final (3rd) Seminar in Jan 2023 was 14 personnel - Training in Japan in Apr 2023 was 4 personnel 4. In total, number of participants (accumulated total) was 62 personnel - Demonstration on EE roadmap program etc. in Feb 2020 was 10 personnel - Remote training in Dec 2020 was 18 personnel - 1st Workshop in Nov 2022 was 16 personnel - Final (2nd) Workshop in Jan 2023 was 14 personnel - Training in Japan in Apr 2023 was 4 personnel	
Outputs Output 1 (to be achieved in Phase 1) The basic information is confirmed for the capacity building for the introduction of RE	1-1. Assessment of number and qualification of staffs responsible for RE 1-2. Human resource development plan for the introduction of RE 1-3. Number of training courses for the introduction of RE 1-4. Total capacity of RE	Project Report		1-1. Confirmed 1-2. Confirmed 1-3. Confirmed 1-4. Confirmed	
Output 2(to be achieved in Phase 1) The basic information is confirmed for the capacity building for the promotion of EE	2-1. Assessment of number and qualification of staffs responsible for EE 2-2. Human resource development plan for the introduction of EE 2-3. Number of training courses for the promotion of EE 2-4. Number of facilities conducted energy audit	Project Report		2-1. Confirmed 2-2. Confirmed 2-3. Confirmed 2-4. Confirmed	
Output 3 (to be achieved in Phase 2) The human and institution capacity are enhanced for the introduction of RE	3-1. Number of trained staffs ***Target Value:** 10 personnel* 3-2. Textbooks/ manuals ***Target Value:** 3 programs (2 domestic trainings and 1 training in Japan)* 3-3. Number of participants of workshops to disseminate introduction of RE to the relevant organizations ***Target Value:** Kick-off workshop: 9 personnel,*	Project Report		3-1. In total, number of participants (accumulated total) was 66 personnel. 3-2. In total, 6 materials were prepared. - 1 manual for simulation software of system analysis. - 1 training material for remote training in Dec 2020. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan 3-3. In total, number of participants (accumulated total) was 71 personnel. - Kick-off workshop in Nov 2019 was 9 personnel	

	Final workshop: 10 personnel 3-4. Number of workshops ***Target Value:*** *2 times (Kick-off workshop and Final workshop)*			- Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 18 personnel - 1st Seminar in Oct 2022 was 11 personnel - 2nd Seminar in Dec 2022 was 19 personnel - Final (3rd) Seminar in Jan 2023 was 14 personnel 3-4. In total, 5 times - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Dec 2022 - Final (3rd) Seminar was conducted in Jan 2023	
<u>Output 4 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of EE	4-1. Number of trained staffs ***Target Value:*** *10 personnel* 4-2. Textbooks/ manuals ***Target Value:*** *3 programs (2 domestic trainings and 1 training in Japan)* 4-3. Number of participants of workshops to disseminate promotion of EE to the relevant organizations ***Target Value:*** *Kick-off workshop: 9 personnel, Final workshop: 10 personnel* 4-4. Number of workshops ***Target Value:*** *2 times (Kick-off workshop and Final workshop)*	Project Report		4-1. In total, number of participants (accumulated total) was 62 personnel 4-2. In total, 4 materials were prepared. - 1 training material for remote training in Dec 2020. - 2 training materials about 'Energy Efficiency Workshop' for domestic training in Nov 2022 and Jan 2023. - 1 training material for training in Japan in Apr 2023. 4-3. In total, number of participants (accumulated total) was 67 personnel - Kick-off workshop in Nov 2019 was 9 personnel - Demonstration on EE roadmap program and power consumption measurement were conducted in Feb 2020 was 10 personnel - Remote training in Dec 2020. Number of participants was 18 personnel - 1st Workshop in Nov 2022 was 16 personnel - Final (2nd) Workshop in Jan 2023 was 14 personnel 4-4. In total, 4 times - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on EE' in Dec 2020 - 1st workshop was conducted in Nov 2022 - Final (2nd) workshop was conducted in Jan 2023	
<u>Output 5 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of Power Network Resiliency	5-1. Number of trained staffs ***Target Value:*** *10 personnel* 5-2. Textbooks/ manuals ***Target Value:*** *2 programs (1 domestic trainings and 1 training in Japan)* 5.3. Number of participants of workshops to disseminate promotion of power network resiliency to the relevant organizations ***Target Value:*** *Kick-off workshop: 9 personnel, Final workshop: 10 personnel* 5-4. Number of workshops ***Target Value:*** *2 times (Kick-off workshop and Final workshop)*	Project Report		5-1. In total, number of participants (accumulated total) was 66 personnel 5-2. In total, 5 materials were prepared. - 1 training material for remote training in Dec 2020. - 3 training materials about 'Seminar on Grid stability and RE' for domestic training in Oct, Dec 2022 and Jan 2023. - 1 training material for training in Japan 5-3. In total, number of participants (accumulated total) was 71 personnel - Kick-off workshop in Nov 2019 was 9 personnel - Remote training about 'impact of COVID-19 on RE' in Dec 2020 was 18 personnel - 1st Seminar in Oct 2022 was 11 personnel - 2nd Seminar in Dec 2022 was 19 personnel - Final (3rd) Seminar in Jan 2023 was 14 personnel 5-4. In total, 5 times - Kick-off workshop was conducted in Nov 2019 - Remote training about 'impact of COVID-19 on RE' in Dec 2020 - 1st Seminar was conducted in Oct 2022 - 2nd Seminar was conducted in Dec 2022 - Final (3rd) Seminar was conducted in Jan 2023	

Activities	Inputs		Important Assumption
	(Japanese side)	**(Saint Christopher and Nevis side)**	
<u>Activities for achieving Output 1</u> 1-1. To verify the fundamental indicators for the power supply side, e.g. access to electricity (electrification rate), cost (composition of power sources, electricity tariff), low carbon (CO_2 emission coefficient) and power system reliability (SAIDI/SAIFI), etc. 1-2. To verify the existing situations in introduction of the technologies of grid stabilization and relevant policies/ national plans pertaining to RE 1-3. To verify human and institutional capacities for the introduction of RE <u>Activities for achieving Output 2</u> 2-1. To verify the fundamental indicators on promotion of EE for the electricity demand side, e.g. electric power consumption unit requirement, final energy consumption, etc. 2-2. To verify the existing conditions in promotion of EE, relevant policies/ national plans 2-3. To verify the existing conditions to carry out maintenance work for thermal power plants 2-4. To verify the existing conditions of transmission and distribution system losses 2-5. To verify human and institutional capacities for the promotion of EE <u>Activities for achieving Output 3</u> 0-1. To conduct the potential survey of RE (PV, Wind, Biomass etc.) 0-2. To introduce computer modelling for grid analysis and examine issues associated with a large penetration of VRE in St. Kitts. 0-3. To consider and propose the necessary technologies for achieving the RE goals, including battery applications for grid stabilization, for improvement of load following capability and load operation of thermal power plants 0-4. To consider and propose additional policy/ legal system for achieving RE goals 0-5. To prepare the necessary training plan for doing the above Activities '3-1' through '3-4' 0-6. To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '3-6' 0-7. To review the training plan though monitoring of the training conducted in Activity '3-6' 0-8. To provide advice on realization of the RE projects 3-9. To provide recommendations on design of the policy/ legal system proposed in Activity '3-4' 3-10. To share the project output among other CARICOM member states <u>Activities for achieving Output 4</u> 0-1. To consider and propose the EE goals through cost-benefit analysis on introduction of the facilities contributing to EE 0-2. To consider and propose the EE facilities necessary for achieving the EE goals 0-3. To consider and propose necessary technologies for achieving EE goals, including building energy management system (BEMS), etc. 0-4. To consider and propose the necessary measures for efficient operation of thermal power plants, including introduction of economic load dispatching control (EDC), etc. 0-5. To consider and propose measures to improve the maintenance system for thermal power plants, including measures to do periodic maintenance and overhaul and procurement of spare parts 0-6. To consider and propose the necessary policy/ legal system for achieving EE goals such as introduction of energy service company (ESCO) and energy management service, etc. 0-7. To prepare the necessary training plan for doing the above Activities '4-1' through '4-6' 0-8. To conduct training including on the job training (OJT), training in Japan, training for preparation of textbooks/ manuals using the training plan prepared in Activity '4-7' 0-9. To review the training plan though monitoring of the training conducted in Activity '4-8' 4-10. To provide advice on realization of the EE projects 4-11. To provide recommendation on design of the policy/ legal system proposed in Activity '4-6' 4-12. To share the project output among other CARICOM member states <u>Activities for achieving Output 5</u> 5-1. To demonstrate the way to enhance resiliency by use of power network asset management system.	1. Dispatch of the Japanese experts in respect of following: - Chief advisor/ Power System/Diesel/Gas-turbine Power Plant (2) - Subchief Advisor/Power system (2) - Renewable Energy - Energy Efficiency - Grid Stabilization - Diesel/Gas-turbine Power Plant/Coordinator - Human Resources Development/Monitoring - Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2) 2. Training in Japan -Micro Grid system including Grid Stabilization Technology in small island (e.g. Okinawa, Tokyo and other cities) -Policies and technologies for promotion of EE (Energy load labelling, policies, regulations and incentives) (Tokyo and other cities) -Site visit in Japan 3. Training/Workshop in each recipient country -Training for project counterparts in each recipient country (costs for holding workshops in Barbados including accommodation, flight, allowance, transportation, and venue fees) 4. Equipment - Software of grid analysis - Power loggers - Software of asset management (Small world)	1. Assignment of C/Ps -Project Director (P/D) -Project Manager (P/M) - Other C/P 2. Facilities and equipment -Project office 3. Recurrent costs -C/Ps' wages and allowances	Most of the trained C/Ps continues commitment to the Project activities. **Preconditions** Contents of the current relevant policies on promotion of RE and EE are not largely changed. Issues and countermeasures

Appendix 6-2-3-3 Monitoring Sheet II, Revision of Plan of Operation (St. Kitts and Nevis)

Project Monitoring Sheet II（Revision of Plan of Operation）

Version 6
Date 24 May 2023

Project Title: The Project to Promote Energy Efficiency in Caribbean Countries (St.Kitts & Nevis)

Monitoring (Up to May 2023)

Inputs	Year	2019	2020	2021	2022	2023	Remarks	Issue	Solution
	Month	4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6			
Expert									
1. Chief Advisor/Power System (1) /Diesel/Gas-turbine Power Plant (2)	Plan / Actual						Blue highlights were inputs from Japan.		
2. Subchief Advisor/Power System (2)	Plan / Actual								
3. Renewable Energy	Plan / Actual								
4. Energy Efficiency	Plan / Actual								
5. Grid Stabilization	Plan / Actual								
6. Diesel/Gas-turbine Power Plant/Coordinator	Plan / Actual								
7. Human Resources Development/Monitoring	Plan / Actual								
8. Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	Plan / Actual								
Equipment									
Software of grid analysis	Plan / Actual						This software was handed over in January		
Power loggers	Plan / Actual						Handed over in January 2023		
Software of asset management	Plan / Actual						This software was handed over in January 2023		
Training in Japan									
Training in Japan	Plan / Actual						Training in Japan was conducted in April 2023.		
In-country Training									
Trainings in country (RE)	Plan / Actual						3 in-country trainings were conducted.		
Trainings in country (EE)	Plan / Actual						2 in-country trainings were condcuted.		

Activities / Sub-Activities	Year	2019	2020	2021	2022	2023	Responsible Organization JET	C/P	Achievements	Issue & Countermeasures
Output 1:The basic information is confirmed for the capacity building for the introduction of RE										
1.1 To verify the fundamental indicators for the power supply side, e.g. access to electricity	Plan / Actual						○	○		
1.2 To verify the existing situations in introduction of the technologies of grid stabilization and	Plan / Actual						○			
1.3 To verify human and institutional capacities for the introduction of RE	Plan / Actual						○			
Output 2：The basic information is confirmed for the capacity building for the promotion of EE										
2.1 To verify the fundamental indicators on promotion of EE for the electricity demand side,	Plan / Actual						○	○		
2.2 To verify the existing conditions in promotion of EE, relevant policies/national plans	Plan / Actual						○	○		
2.3 To verify the existing conditions to carry out maintenance work for thermal power plants	Plan / Actual						○			
2.4 To verify the existing conditions of transmission and distribution system losses	Plan / Actual						○			
2.5 To verify human and institutional capacities for the promotion of EE	Plan / Actual						○	○		
Output 3: The human and institution capacity are enhanced for the introduction of RE										
3.1 To conduct the potential survey of RE (PV, Wind, Biomass etc.)	Plan / Actual						○	○	-	-
3.2 To introduce computer modelling for grid analysis and examine issues associated with a	Plan / Actual						○	○	-	-
3.3 To consider and propose the necessary technologies for achieving the RE goals,	Plan / Actual						○	○	-	-
3.4 To consider and propose additional policy/ legal system for achieving RE goals	Plan / Actual						○	○		
3.5 To prepare the necessary training plan for doing the above Activities '3.1' through '3.4'	Plan / Actual						○	○	A total of 3 RE and grid stabilization seminars were held. A total of 65 people (accumulated total) participated.	-
3.6 To conduct training including on the job training (OJT), training in Japan, training for	Plan / Actual						○	○		
3.7. To review the training plan though monitoring of the training conducted in Activity '3.6'	Plan / Actual						○	○		
3.8 To provide advice on realization of the RE projects	Plan / Actual						○			
3.9 To provide recommendations on design of the policy/ legal system proposed in Activity '3.4'	Plan / Actual						○			
3.10 To share the project output among other CARICOM member states	Plan / Actual						○	○		

Project Monitoring Sheet II（Revision of Plan of Operation）

Version 6

Date 24 May 2023

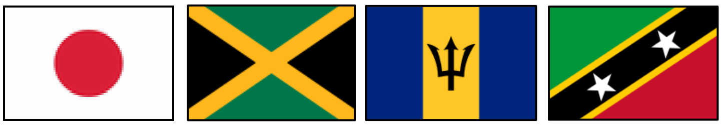
Project Title: The Project to Promote Energy Efficiency in Caribbean Countries (St.Kitts & Nevis)

Monitoring (Up to May 2023)

Inputs		Year: 2019 – 2020 – 2021 – 2022 – 2023	Remarks		Issue	Solution
Output 4: The human and institution capacity are enhanced for the promotion of EE						
4.1 To consider and propose the EE goals through cost-benefit analysis on introduction of	Plan / Actual		○	○		
4.2 To consider and propose the EE facilities necessary for achieving the EE goals	Plan / Actual		○	○	-	-
4.3 To consider and propose necessary technologies for achieving EE goals, including	Plan / Actual		○	○	-	-
4.4 To consider and propose the necessary measures for efficient operation of thermal power	Plan / Actual		○	○	-	-
4.5 To consider and propose measures to improve the maintenance system for thermal	Plan / Actual		○	○	-	-
4.6 To consider and propose the necessary policy/ legal system for achieving EE goals such	Plan / Actual		○	○	-	-
4.7 To prepare the necessary training plan for doing the above Activities '4.1' through '4.6'	Plan / Actual		○	○	A total of 2 energy efficiency workshops were held. A total of 61 people (accumulated total) participated.	-
4.8 To conduct training including on the job training (OJT), training in Japan, training for	Plan / Actual		○	○		
4.9 To review the training plan though monitoring of the training conducted in Activity '4.8'	Plan / Actual		○	○		
4.10 To provide advice on realization of the EE projects	Plan / Actual		○			
4.11 To provide recommendation on design of the policy/ legal system proposed in Activity '4.6'	Plan / Actual		○			
4.12 To share the project output among other CARICOM member states	Plan / Actual		○	○		
Output 5: The human and institution capacity are enhanced for the promotion of Power Network Resiliency						
5.1 To demonstrate the way to enhance resiliency by use of power network asset management system.	Plan / Actual		○	○	A total of 3 RE and grid stabilization seminars were held. A total of 65 people (accumulated total) participated.	-
					-	-
Duration / Phasing	Plan / Actual	Phase 1 / Phase 2				

Monitoring Plan		Year: 2019 – 2020 – 2021 – 2022 – 2023	Remarks	Issue	Solution
Monitoring					
Joint Coordinating Committee	Plan / Actual				
Set-up the Detailed Plan of Operation	Plan / Actual				-
Submission of Monitoring Sheet	Plan / Actual				
Reports/Documents					
Project Completion Report	Plan / Actual		Project completion report will be submitted in June 2023.		
Public Relations					
Public Relation Activities	Plan / Actual			-	-

█ :Activity by JICA Expert Team



Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Project Outline and Result of Activities

Photographs:
Wind Firm in Jamaica / EE Testing Laboratory in Jamaica
Solar PV System in St. Kristopher Nevis / Coverley Village in Barbados
EVs and Quick Charging Spot with Solar PV in Barbados

May 2023

JICA (Japan International Cooperation Agency)

Nippon Koei Co., Ltd. / PADECO Co., Ltd.

Outline of the Project

Challenges

◇ **Challenges for Caribbean countries:**

- Heavy dependence on imported fossil fuel
  >> Need of energy saving and large RE penetration with grid stability
- High Hurricane risk
  >> Necessity for Enhancement of resilience

Project Purpose

◇ **To enhance human and institutional capacities for**

- The introduction of RE (Renewable Energy)
- The promotion of EE (Energy Efficiency)

Expected Outputs

1. The basic information is confirmed for the capacity development for the introduction of RE and the promotion of EE
2. The human and institution capacity are enhanced for the introduction of RE and the promotion of EE

Project Period and Target Area

◇ **From April 2019 to June 2023 (for about Four Years)**

Phase I: Baseline Survey (for Half Years, Apr ~ Oct 2019)

Phase II: Technology Transfer (for about Three and Half Years, Nov 2019 ~ Jun 2023)

◇ **Jamaica, Barbados, and St. Kitts and Nevis (Three Countries)**

Counterparts / Relevant Organizations

◇ **Jamaica**

- MSET (Ministry of Science, Energy and Technology)

◇ **Barbados**

- MEB (Ministry of Energy and Business)
- BL&P (Barbados Light and Power Co., Ltd.)

◇ **St. Kitts and Nevis**

- MPI (Ministry of Public Infrastructure, Post, Urban Development and Transport)
- NIA (Nevis Island Administration)
- SKELEC (St. Kitts Electricity Company Ltd.)
- NEVLEC (Nevis Electricity Company Ltd.)

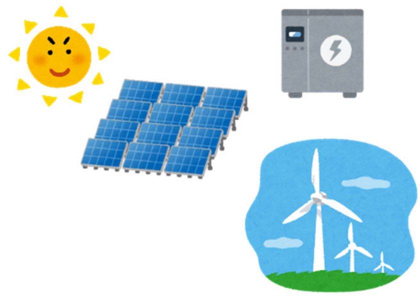
Contact regarding this Project

JICA Expert Team (JET) *for the Project (E-mail:* [redacted]*)*
Jamaica: MSET
Barbados: MEB
St. Kitts & Nevis: MPI *(St. Kitts) and* ***NIA*** *(Nevis)*
JICA Offices *(in St. Lucia and Jamaica)*

Activities of the Project

Renewable Energy (RE)

[Phase 1]



- Baseline Survey of RE
- Identification of RE potential, RE project status, and future RE projects
- Study of issues on grid stability with large RE penetration
- Preparation of Sample Model (Asset Data of St. Kitts) (Feb-March 2020)
- Data Collection for Demonstration Modeling

[Phase 2]

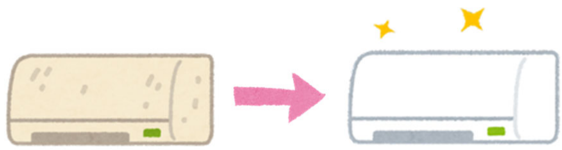
- Microgrid concept
- Grid modeling and recommendation for grid stabilization and energy storage
- Capacity Building for Power System Analysis based on Sicario for large RE penetration
- Demonstration for asset management of power network
- Introduction for future development

Energy Efficiency (EE)

[Phase 1]

- Baseline Survey of EE
- Identification of EE Policies Status
- Identification of Minimum Energy Performance Standard & Labelling Status for Home Appliances
- Economic Feasibility Study of Room Air Conditioners
- Needs Assessment for EE Technologies

[Phase 2]



- Preparation of EE Roadmap
- Energy Audit (Walk-through Survey)
- Demonstration of Data logger, and Handover
- Capacity Building for EE
- Recommendations for the promotion of EE

Activities of the Project

Common / Others

[2019]

- Kick-off Meeting
- 1st JCC (Joint Coordinating Committee)

[2020]

- * Inactive due to COVID-19

[2021]

- 2nd JCC

[2022]

- Local Training (RE) 2 ~ 4 times
- Local Training (EE) 2 times

[2023]

- 3rd JCC
- Training in Japan (RE and EE) 2 weeks

Photographs of the Project (Phase 1: Baseline Survey)

Discussion and Demonstration

JET (JICA Expert Team) works with the counterparts for technical transfer on EE and RE.

Geothermal Potential Site in Navis Island

Geothermal is one of the renewable energies, which can produce electricity with stable output.

CariMET Conference

JET introduced this project to the participants at the CariMET Meeting.

First JCC in Jamaica

JET held the first JCC in Jamaica and report the result of baseline survey.

First JCC in Barbados

JET held the first JCC in Barbados and report the result of baseline survey.

First JCC in St. Kitts and Nevis

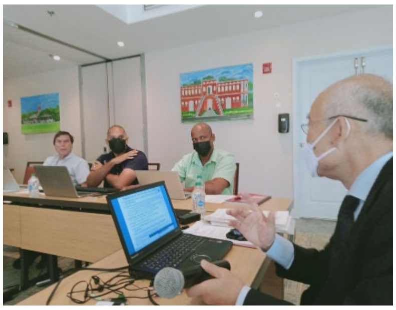
JET held the first JCC in St. Kitts and Nevis and report the result of baseline survey.

Photographs of the Project (Phase 2: Technical Transfer)

Renewable Energy (RE)

Holding of RE Seminars

JET conducted seminars with the counterparts for technology transfer on RE. and grid stability.



Discussion for Policy Recommendation

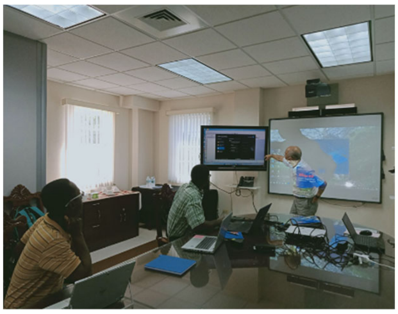
JET had a discussion with the participants about policy recommendation during RE Seminar.

Handover of Software

JET handed over the power flow analysis software to counterparts of Barbados and St. Kitts & Nevis

Site visit (BESS) in Barbados

JET conducted the site visit of the power station which has battery energy storage system (BESS).



Lectures related to RE

JET provided lectures including microgrid, asset management, and grid stability with large RE.

Training in Japan "Geothermal"

JET held lectures and site visits at Japan. This picture shows lecture of geothermal.

Training in Japan "New Inverter"

The latest inverters were lectured on their performance for output fluctuations of VRE.

Training in Japan "Offshore Wind"

The participants of training visited the offshore wind farm already in operation.

Training in Japan "Microgrid"

Participants visited the microgrid consisting of PV and storage batteries in a remote island in Japan.

Photographs of the Project (Phase 2: Technical Transfer)

Energy Efficiency (EE)

Holding of EE Workshops

JET conducted workshops with the counterparts for technology transfer on EE.

Discussions for Recommendation

JET had a discussion with the counterparts about recommendations related EE.

Survey of EV Charging Station

JET conducted the survey of EV charging station in Barbados.

Demonstration of Data Logger

JET conducted the demonstration of data logger to counterparts.

Handover of Data Logger

JET handed over data loggers to Jamaica, Barbados, and St. Kitts & Nevis.

Training in Japan "EE Technology"

JET held lectures and site visits at Japan. This picture shows lecture of EE Technologies.

Training in Japan "Latest AC"

The latest air-conditioning technology was lectured on their performance and efficiency at showroom.

Training in Japan "EE Management"

The participants were lectured about demand side management from Japanese electric power company.

Training in Japan "ZEB"

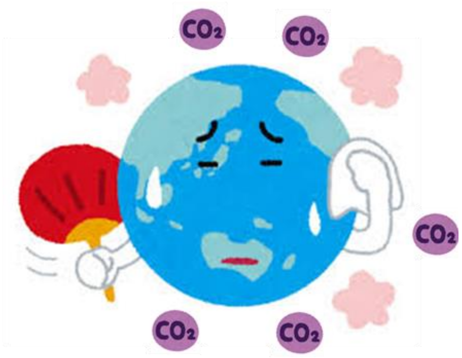
Participants visited the Zero Emission Building and were lectured of their technologies.

Tips for Saving Energy at Home

What is happening in the world?

- Carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases trap heat from the sun, which helps keep the earth at a temperature suitable for us to live.
- However, since the industrial revolution, the amount of greenhouse gases has increased rapidly. This has led to more heat being retained than ever before, causing the earth's temperature to rise.
- This is **"global warming"**.

The average global temperature has already risen by about 1°C since 1880-1899



CO_2 is also emitted when energy is used.
So, let's use energy wisely and efficiently!

Impacts of Climate Change

Prolonged periods of high temperatures alter climate patterns and disrupt the normal balance of nature. This exposes humans and all other life forms on earth to many risks.

- **Rising Temperatures**

There are more extreme hot days and heat waves. Higher temperatures increase heat-related illnesses and makes outdoor work more strenuous.

- **Increased Storm Damage**

Warmer temperatures cause more water to evaporate, resulting in more intense rainfall and flooding, and more destructive storms.

- **Increased Drought**

Water scarcity is exacerbated, increasing the risk of drought. Deserts are expanding, and many people face the threat of not having enough water.

- **Ocean Warming and Sea Level Rise**

Melting ice sheets raises sea levels, threatening coastal areas and island communities.

- **Food Shortage**

Climate change negatively impacts food systems, causing an increase to hunger and undernourishment.

- **Loss of Species**

Climate change threatens the survival of many different species. The world is losing species at a rate 1,000 times faster than in any other period in history.

- **Increased Health Risks**

Impacts on health due to climate change include air pollution, disease, extreme weather, hunger and malnutrition.

- **Poverty and Forced Migration**

Many refugees are from countries that are least prepared to adapt to the impacts of climate change.

Energy consumption at home

There are so many appliances at home.... Which ones use a lot of energy?

Refrigerators, lights, and air conditioners use lots of energy in a home.
Good question!

Thank you! So...if we can reduce our energy use with those appliances, we can save energy efficiently!

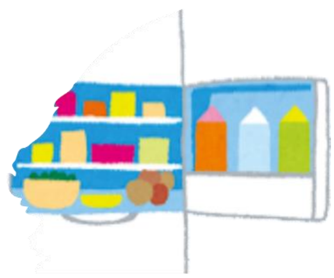
Electricity use in homes makes up about 30% of total energy consumption, so reducing energy use at home is very important!

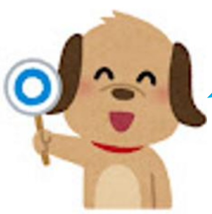
Tip 1: Good Refrigerator Use

Because it is never turned off, refrigerators are one of the largest energy consumers in a home.

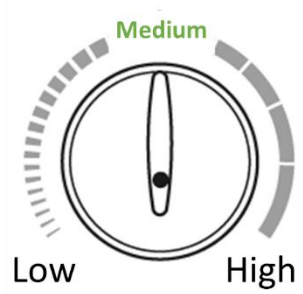
- Do not overstuff the refrigerator.
- Open the refrigerator for short periods only.
- Open the refrigerator only when you need to.
- Set the refrigerator temperature to "medium".
- Place the refrigerator an appropriate distance from the wall.

Let’s stop overstuffing and don’t keep the door open too long.

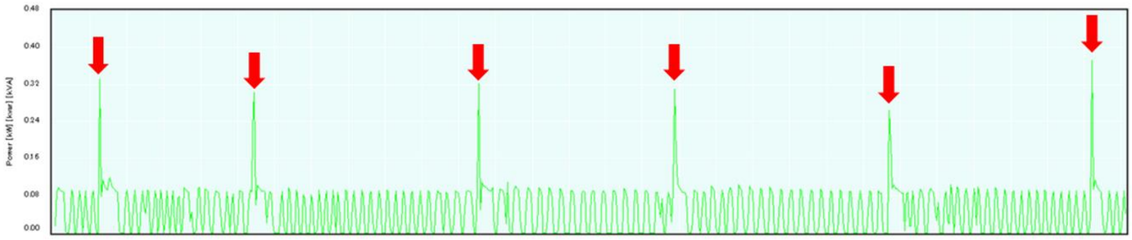




Let’s set the temperature at “medium”



This graph shows a refrigerator's energy consumption over several days. You can see that consumption goes up around lunch time when everyone opens the fridge.



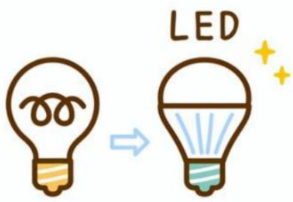
Many appliances have become more energy-efficient in the last 10 years. The refrigerator consumes about 39-46% less energy than models from a decade ago. Replacing your fridge can cut electricity use significantly.

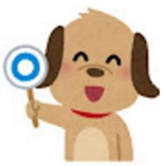
Right, refrigerators have gotten better and better with inverter technology and improved insulation.

Tip 2: Good Lighting Use

Next, let’s focus on lighting.
We turn lights on at home every night, so this is a large proportion of our total electricity use.

- Replacing incandescent or fluorescent bulbs with LED light bulbs is the biggest energy saver!
- Clean lighting covers regularly.
- Turn lights off when not in use.





LED ceiling lights save 50% energy compared to fluorescent ceiling lights.

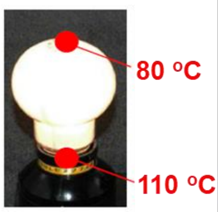
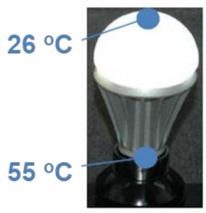
Fluorescent lamps typically need replacing after 6,000 hours, while LED lamps last over 40,000 hours

LED light bulbs vary by product in how it spreads the light, so choose a bulb that best suits the lighting fixture and the space.

About 260°	About 180°	About 140°
Illuminated area Entire space	Illuminated area Wide area	Illuminated area Downward
Recommended places Living room	Recommended places Dining room Entrance	Recommended places Corridor Toilet

LEDs come in a variety of colors, including light bulb, warm white, daylight white, and daylight, so use them according to the scene.

LEDs emit less heat, so it also reduces the load on the air conditioner.

Incandescent Lamp (810 lm, 54W)	LED lamp (810 lm, 9W)
30 minutes after lighting	
	

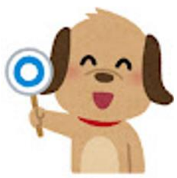
Tip 3: Good Air Conditioner Use

Air conditioners are one of the largest energy consumers not only in a home but in many places as it is used throughout the year.

- Clean the filter once or twice a year.
- Use an electric fan along with your air conditioner.
- Cool air descends, so the cold air should be directed horizontally or upwards.
- Do not place objects around the outdoor unit.
- Do not turn on and off repeatedly.

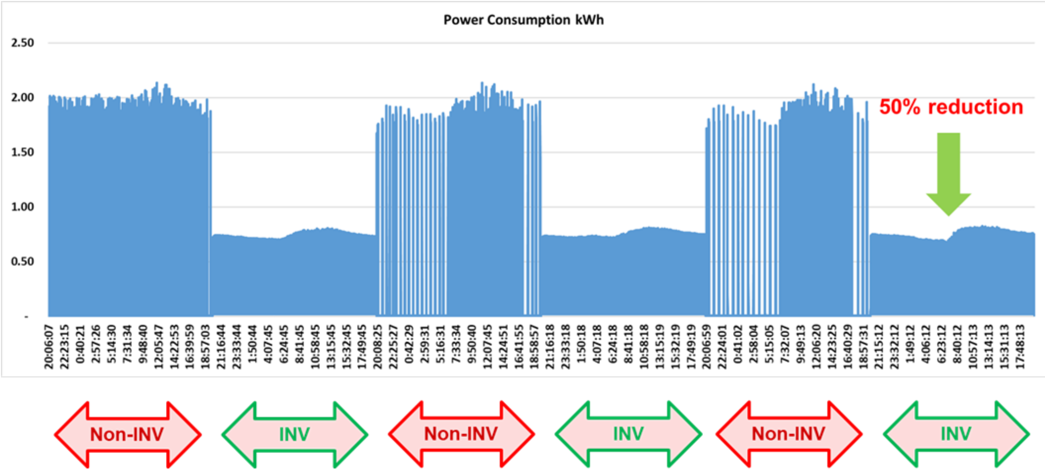
Let's clean the filter.
Clogging reduces the amount of air drawn in and reduces the cooling power.

A fan will help circulate cool air.

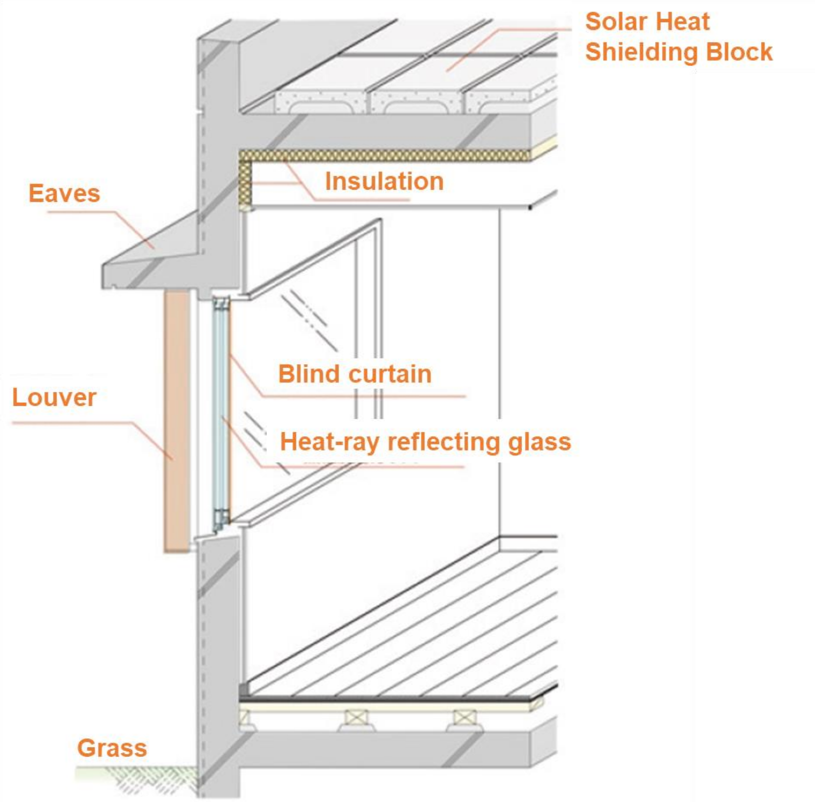


Raising the temperature setting of AC by 1°C saves about 10% energy.

The following graph shows power consumption of an INVERTER AC and Non-INVERTER AC over several days. It shows that an INVERTER AC consumes about half the amount of power, so it saves energy and is better for the family budget.



It is also very important to reduce the amount of solar heat that enters the house.



MicroGrid Designer

User and Technical Reference Manual

Nippon Koei Co., Ltd

Energy and Environment Technology Research Institute

December 23, 2022

CONTENTS

Terminologies and Abbreviations

Terms and Abbreviations	Description
AGC	automatic generation control
AR	area requirement
CSPH	constant speed pumped-storage hydro
VSPH	variable speed pumped-storage hydro
EDC	economic dispatch control
EETRI	Energy & Environment Technology Research Institute
ELD	economic load dispatch
IEEE	The Institute of Electrical and Electronics Engineers
LFC	load frequency control
MICROGRID DESIGNER	Power System Analysis and Simulation Tool produced by EETRI
PV	Photovoltaics
TBC	Tie line-Bias Control

1. ABOUT THE MICROGRID DESIGNER

Power System Analysis and Simulation Tool " *The MicroGrid Designer*" is comprised of a comprehensive suite of software for investigations and studies for electric power grids, transmission/distribution networks and generation performance in both steady-state (single stage) and dynamic (multi stage) conditions.

*The **MicroGrid Designer*** has the following functions (modules) available in the current version.

- **Single Stage Economic Load Dispatch Module**

  The determination of the optimal output of a number of electricity generation facilities to meet the system load at the lowest possible cost subject to transmission and operational constraints

- **Multi Stage Economic Load Dispatch and LFC Module**

  Chronological determination of the output of a number of electricity generation facilities to meet time varying system loads at the lowest possible cost and load frequency control commands to maintain the system frequency within the permissible range.

- **Single Stage Power Flow Analysis Module**

  Steady-state analysis tool whose target is to determine the voltages, currents, and active and reactive power flows in a system under a given load conditions and planning ahead for various hypothetical situations.

- **Multi Stage Power Flow Analysis Module**

  Chronological power flow analysis for time varying loads to determine the transitions of voltages, currents, and active and reactive power flows in a system over time horizon.

By referring the rest of this manual, users and power grid designers will become familiar with following:

- How to use the interface of the ***MicroGrid Designer***
- How to treat and manage model data, input data and output data files in the ***MicroGrid Designer***
- How to perform fundamental studies of power grid operation, control and planning by the ***MicroGrid Designer***

The MicroGrid Designer can be used extensively by microgrid designers and electrical power system engineers for power flow and transmission loss analysis, economic load dispatching and cost analysis, evaluation of renewable energy source and overload/voltage/frequency diagnosis of distribution and transmission networks.

The manual serves to guide users in the process of entering data into the ***MicroGrid Designer*** and to show users how *The* ***MicroGrid Designer*** processes these data.

The ***MicroGrid Designer*** provides compact but high performance for the power flow profiles and economic power system operation states, such as active power, reactive power, voltage, phase angle, frequency and is applicable not only to conventional power systems but to various kinds of new and advanced grids such as micro grids, smart city and smart grids

- Conventional electric power system
- Distribution networks with sustainable energy generation
- Micro grid
- Autonomous reginal grid
- Smart and eco city
- Smart grid (including Smart house, Smart building, Smart industrial park, Smart parking etc.)
- Smart community

- Grids in islands and remote areas
- Future grid planning for non-electrified areas

2. MODULE STRUCTURE AND PROCEDURES OF USE OF ***THE MICROGRID DESIGNER***

2.1. HOW TO INPUT AND OUTPUT

Input and output for modules can be done by the following steps.

- Import of t*he **MicroGrid Designer*** input files;
- Import of EXCEL data file;
- EXCEL export all the results by tables and graphs

2.2. PROCEDURES OF EXECUTIONS OF *THE* ***MICROGRID DESIGNER***

The ***MicroGrid Designer*** software code is written in C++.

For all modules, user is to conduct the following program steps.

- Input of data required by modules
- Excursion of calculations by utilizing modules;
- Output and reporting of results from modules by tables and figures.

2.3. SEQUENTIAL USE OF MODULES OF ECONOMIC LOAD DISPATCH AND POWER FLOW ANALYSIS

Each module can be used independently but users can use modules sequentially by applying the obtained data in the previous calculations of single stage economic load dispatching, multi stage economic load dispatching, single stage power flow analysis and multi stage power flow analysis
as shown in the following figure.

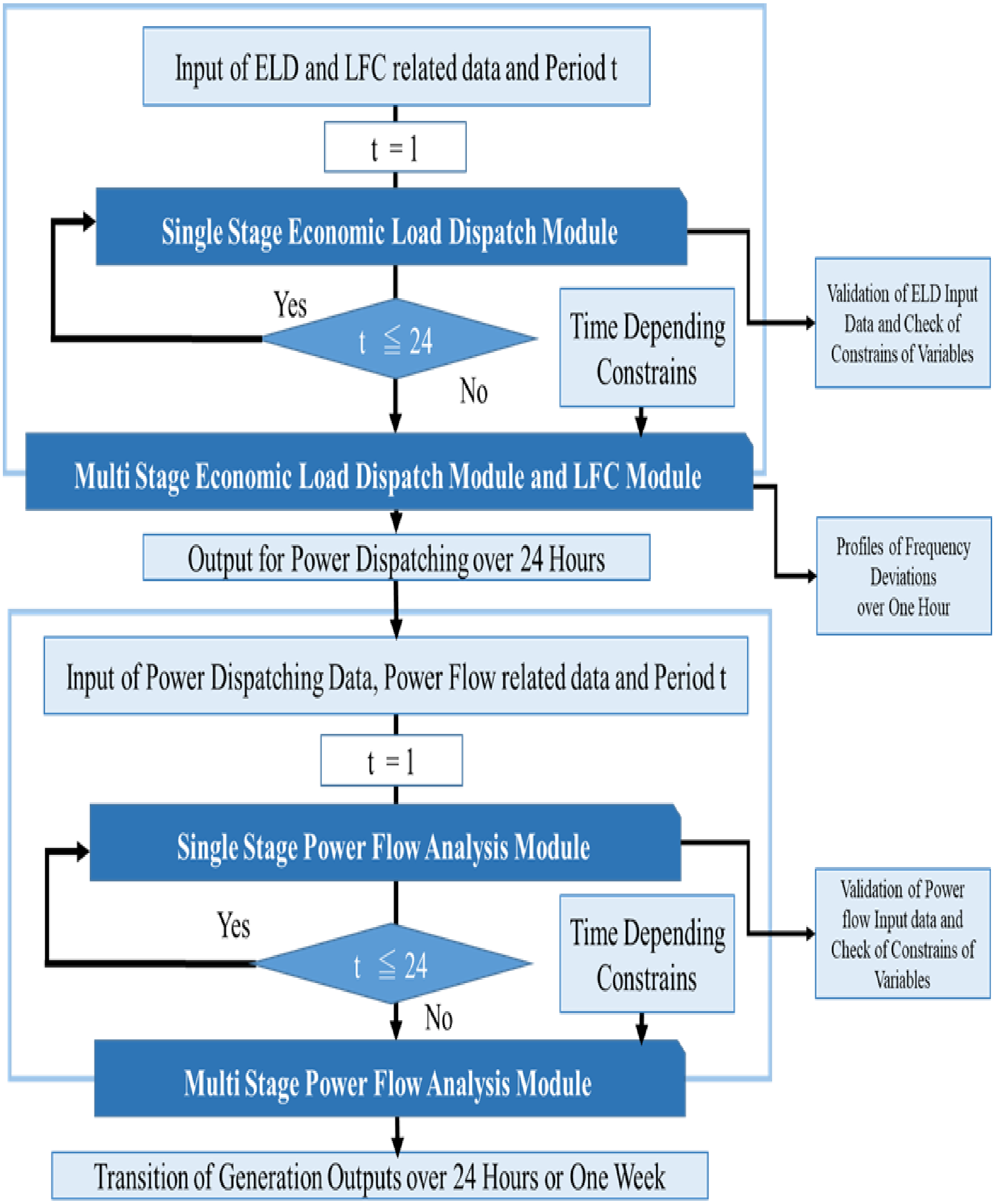


Figure 2.1 Sequential use of modules of economic load dispatch and load plow analysis

(In the chart, the number of stages is specified as 24 hours and the number can be selected by users)

3. FORMULATION AND SOLUTION OF ECONOMIC LOAD DISPATCH

In this chapter, for better understanding about the input and output form of the Economic Load Dispatch and Load Frequency Control by ***the MicroGrid Designer,*** fundamental formulations and solutions of economic load dispatch, load dispatching control and load frequency control are described briefly for microgrid designers, power system engineers and users.

3.1. FORMULATION AND SOLUTION OF ECONOMIC LOAD DISPTACH

The Economic Load Dispatch (ELD) (this is a part of Economic Dispatching Control (EDC) that consists of load forecasting and generation control) can be defined as the process of allocating generation level to the generating generations, so that the system load is supplied entirely and most economically. For an interconnected system, it is necessary to minimize the expenses.

The economic load dispatch is used to define the production level of each generator, so that the total cost of generation and transmission is minimized for a prescribed schedule of load. The objective of economic load dispatch is to minimize the overall cost of generation. The method of economic load dispatch for generating generations at different loads must have total fuel cost at the minimum point.

In a typical power system, multiple generators are operated to provide enough total output to satisfy a given total consumer demand. Each of these generating stations can, and usually does, have unique cost-per-hour characteristic for its output operating range.

A station has incremental operating cost for fuel and maintenance; and fixed costs associated with the station itself that can be quite considerable in the case of a nuclear power plant, for example things get even more complicated when utilities try to account for transmission line losses, and the seasonal changes associated with hydroelectric plants.

There are many conventional methods that are used to solve economic load dispatch problem such as Lagrange multiplier methods, lambda iteration method and Newton- Raphson method. In the conventional methods, it is difficult to solve the optimal economic problem if the load changed. It needs to compute the economic load dispatch each time which uses a long time in each of computation loops.

It is a computational process where the total required generation is distribution among the generation generations in operation, by minimizing the selected cost criterion, and subjects it to load and operational constraints as well.

Economic Load Dispatch (ELD) is an optimization problem and may be solved by known methods of numerical optimization. ELD is the short-term determination of the optimal output of a number of electricity generators to meet the system demand, at the lowest possible fuel cost, while serving power to the public in a robust and reliable manner. Performing an ELD more frequently (e.g., 5 or 15 minutes rather than each hour) affects the level of costs.

3.2. THE PROCESSING OF THE ECONOMIC LOAD DISPATCH AND ECONOMIC DISPATCHING CONTROL

The processing of the Economic Load Dispatch (ELD) and Economic Dispatching Control (EDC) is shown in the following figure.

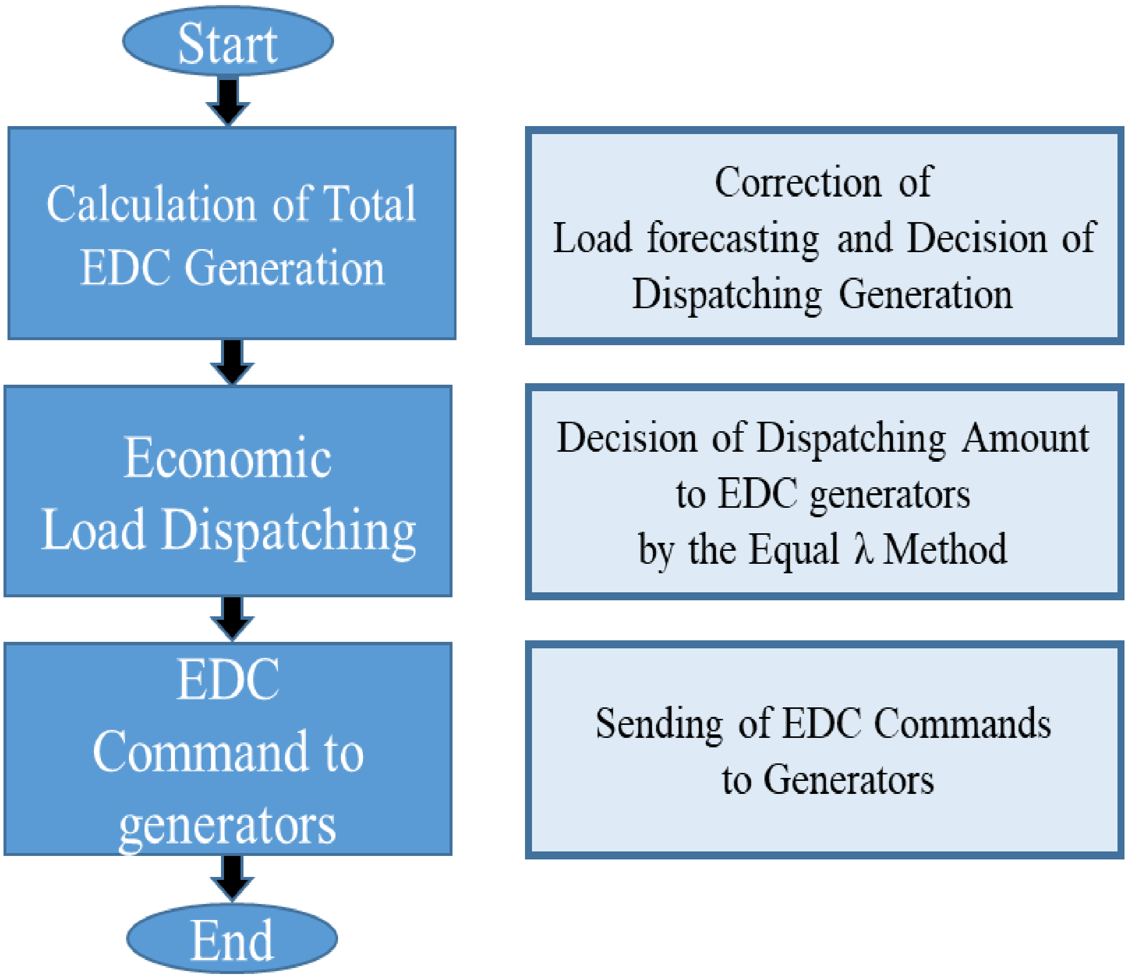


Figure 3.1 Processing of EDC computation module

3.3. FORMULATION OF THE ELD AS A CONSTRAINED OPTIMIZATION PROBLEM WITH AN OBJECTIVE FUNCTION

The primary concern of an ELD problem is the minimization of its objective function. The total cost generated that meets the demand and satisfies all other constraints associated is selected as the objective function. In general, the ELD problem can be formulated mathematically as a constrained optimization problem with an objective function of the form, as illustrated in the following equation/

For multiple generators,

$$f(P) = \sum_{i=1}^{n} f_i(P_i)$$

Where *f is* the total generation cost. N is the total number of generating generations. f (Pi) is the power generation cost function of the i-th unit. This is the Classical Smooth Fuel Cost Functions and generally, the fuel cost of a thermal generation unit is considered as a second order polynomial function (Neglecting valve-point effects) and this is called classical and smooth cost function as below.

$$f(P) = aP^2 + bP + c$$

Where *P* is the power of the generating unit; *a, b, c* are the fuel cost coefficients of the generating unit.

Reference

1) Attia A. El-Fergany, Member, IACSIT, "Solution of Economic Load Dispatch Problem with Smooth and Non-Smooth Fuel Cost Functions Including Line Losses Using Genetic Algorithm", International Journal of Computer and Electrical Engineering, Vol. 3, No. 5, October 2011)

3.4. GENERATOR START UP PRIORITY DETERMINATION (MAXIMUM LOAD POINT UNIT PRICE)

For developing a simple and practical method which used to introduce starting and stopping priority of generators, this program provides the concept of the maximum power generation unit price of the generator as below.

<u>Generator maximum power generation unit price:</u>

Definition: It is the maximum power generation unit price at the maximum power generation P

$P_{i.max}$ of the generator i, and represents the maximum cost characteristic of the generator. The formula is defined as follows.

$$\mu_{i,\max} = \frac{\text{Fuel consumption at maximum load of generator i}}{\text{Maximum load of generator i}}$$

See "Dynamic ELD calculation tool manual" for detailed calculation procedure.

The table below is an example of generator start up priority determination results calculated based on above methodology. It shows the load band range and the combination of generators which shouold be started within that range

Table 3.1 Generator start up priority determination results

Generator priority input combination table																	
Gene Mix ID	Output lower limit	Output upper limit (a)	Generator Turn/Off State (Tuen - 1, Off - 0)														
	(kW)	(kW)	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12	No.13	No.14	No.15
1	1226	6130	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	6130	9630	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
3	9630	13520	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0
4	13520	17410	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0
5	17410	21300	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0
6	21300	25190	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0
7	25190	29080	1	0	1	0	1	1	1	1	1	0	0	0	0	0	0
8	25190	29080	1	0	1	0	1	1	1	1	1	0	0	0	0	0	0
9	29080	30720	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0
10	30720	32360	1	0	1	0	1	1	1	1	1	1	1	0	0	0	0
11	32360	34000	1	0	1	0	1	1	1	1	1	1	1	1	0	0	0
12	34000	35640	1	0	1	0	1	1	1	1	1	1	1	1	1	0	0
13	35640	37280	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0
14	37280	38920	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
15	38920	42790	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1

3.5. Calculation of Environmental Emissions

This tool uses the "emission factor related to fuel consumption" as the calculation standard. To calculate the CO_2 emissions by multiplying the carbon coefficient (tC / GJ) by the fuel consumption (GJ) according to the output of the generator. The calculation formula is as follows,

CO_2 emissions = fuel consumption (GJ) ・ carbon coefficient (tC / GJ) (tC)

The carbon coefficient should be obtained from some reliable reference materials, for example, reports from international organizations or governments

3.6. Decision of EDC command by using load forcast ing

As shown in the figure below, by using 5-minutes ahead load forcast valu, the load is dispatched to generators used for ELD.

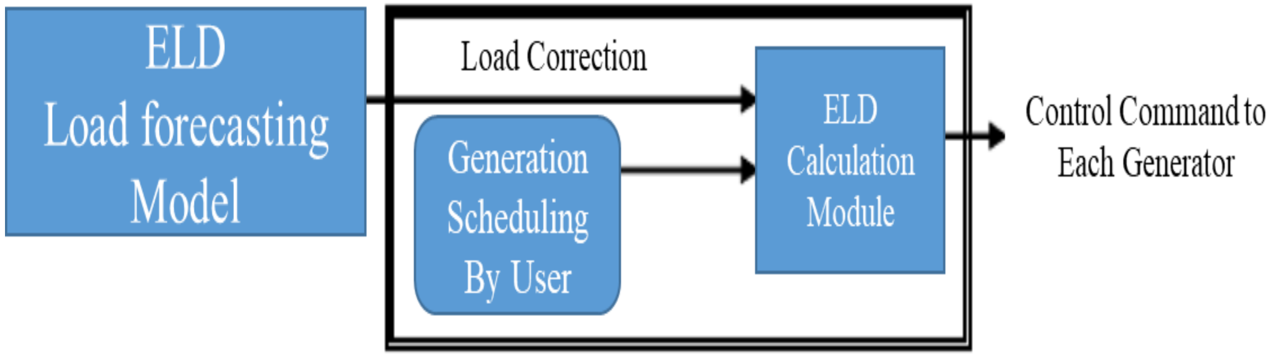


Figure 3.2 Block diagram of ELD standerd model

This duspatching must be satisfied with the following load and generation balance equetion.

$$P_L = L_C - (P_S + P_C + P_0)$$

$$\sum_{i=1}^{n} P_i = P_L$$

Where

Pl: Generation for ELD

Lc: 5-minutes ahead forecasted load

Ps: Sum of generation for scheduled operation

Pc: Sum of generation for base loads

P0: Scheduled tie line power flow

3.7. ECONOMIC DISPATCHING CONTROL BY THE EQUAL LAMBDA METHOD

As an optimization method in actual operation, usually" Equal λ method" is used and the formulation and solution of the method are described as follows.

The objective function for ELD is expressed as below.

$$
\begin{aligned}
f(P) &= \sum_{i=1}^{n} f_i(P_i) \\
&= \sum_{i=1}^{n} (a_i P_i^2 + b_i P_i + c_i)
\end{aligned}
$$

Where

F (P): Objective function of ELD (Fuel consumption at the targeted period)

fi (Pi): Fuel consumption function for i-th generator

Pi: Output of i-th generator

n: Number of generators

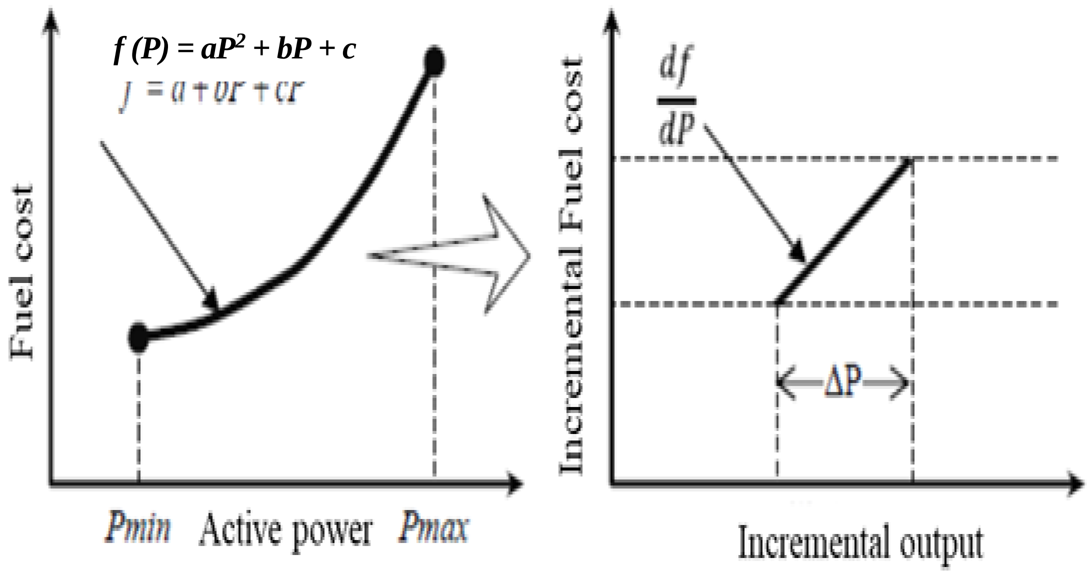


Figure3.3 Fuel consumption function and incremental output

This type of optimization problems which has the nonlinear optimization function and linear constraint equations is solved by using Lagrange Multiplier Method as the following equations.

The Lagrange function is described as below.

$$L(P,\lambda) = \sum_{i=1}^{n} f_i(P_i) - \lambda\left(\sum_{i=1}^{n} P_i - P_L\right)$$

The necessary condition of the optimal solution is given as the following five equations

$$\frac{\partial L}{\partial P_i} = \frac{df_i(P_i)}{dP_i} - \lambda = 0$$

$$\frac{\partial L}{\partial \lambda_i} = \sum_{i=1}^{n} P_i - P_L = 0$$

$$\frac{dF_i(P_i)}{dP_i} = 2a_i P_i + b_i = \lambda$$

$$P_i = \frac{\lambda - b_i}{2a_i}$$

$$\sum_{i=1}^{n} P_i = P_L$$

These equations mean that the optimal solution is obtained when λ for all generators is equal and this is called as Low of Equal Incremental Fuel Cost.

By substituting equations into λ equation, the following relation is obtained.

$$\lambda \sum_{i=1}^{n} \frac{1}{2a_i} - \sum_{i=1}^{n} \frac{b_i}{2a_i} = P_L$$

As shown in this equation, λ is proportional to the amount of Pl. When loads increase,

λ also increases.

For two generates as in the figure below, when λ1 = 2.5, generator outputs, $P_{1\lambda 1}$ and $P_{2\lambda 1}$ are decided as in the figure and when loads increased and λ2 = 2.6, generator outputs, $P_{1\lambda 2}$ and $P_{2\lambda 2}$ are also decided in the same way.

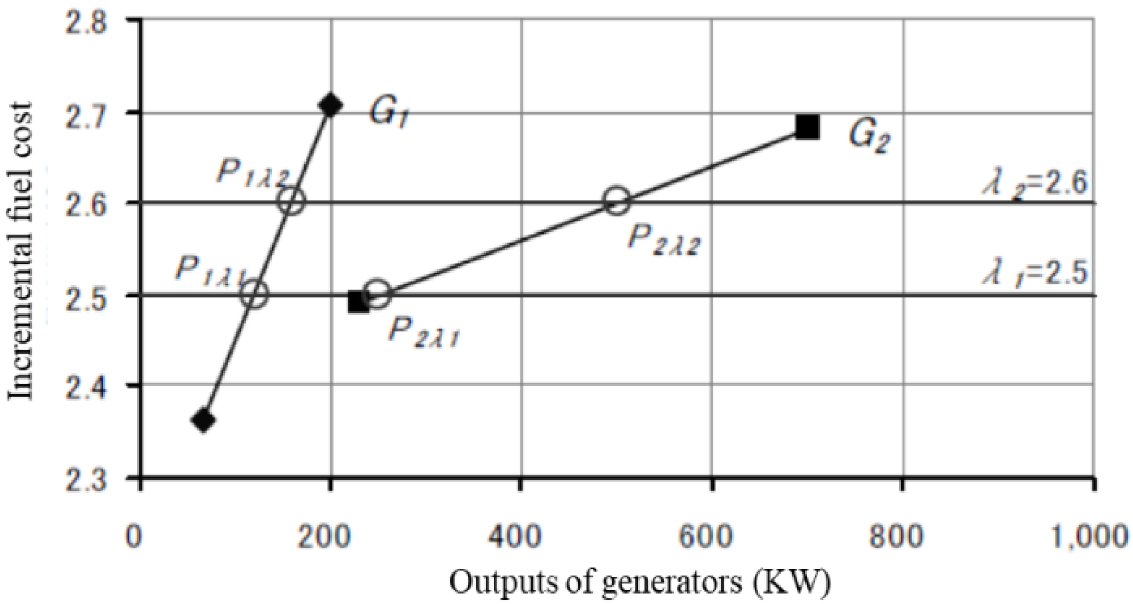


Figure 3.4 Relation of output of generators and Lagrange Multiplier

3.8. SCHEDULED OUTPUT AND CONTROL MODE USED FOR EDC COMPUTATIONS

For reference for engineers and users, Fuel Characteristic Coefficients of four kinds of generators are shown in the table below. Coefficients *a, b, c* are specific to generators, and values in the table are typical examples.

Table 3.1 Fuel Characteristic Coefficients of four kinds of generators

Type of generator	Rated output (KW)	Fuel coefficient a	Fuel coefficient b	Fuel coefficient c
Oil thermal generator	250	0.00105	4.6	316
	500	0.00005	5.0	200
	700	0.00038	5.0	260
LNG thermal Generator	200	0.00250	2.2	66
	700	0.00040	2.4	117
Coal thermal Generator	200	0.00020	2.0	40
	700	0.00016	1.3	182
	1000	0.00070	0.4	550
Gas turbine combined cycle	100	0.00073	0.9	104
	250	0.00166	1.4	120

The Scheduled output and control mode used for EDC computations are described as below.

Table 3.2 Scheduled output and control mode used for EDC computations

Items		Functions
Generators used for EDC	Control mode	Decision of output of EDC generators according to EDC commands or scheduled values
	Scheduled output value (Generation plans)	Scheduled outputs of EDC generators at the stage of the generation planning
Generators not used for EDC	Scheduled output value for base load generators	Scheduled outputs of generators not used for EDC
	Scheduled values for tie line power flow etc.	Scheduled values for power transfer by using tie lines between areas

For treating the upper limit P max and lower limit P min (Table3.3), the calculation of deciding λ is conducted firstly and when the output of some generators violates the limits, the output of those generator is fixed at the limit and the calculation of λ is conducted again as shown in the flow chart (Figure 3.5).

Table 3.3 Treatment of output constrains in EDC standard module

Items	Decision of limitations
Upper limits of generator outputs	Select the smaller value from • Upper limit of scheduled generation output • Current EDC command + output change speed ×5 minutes
Lower limits of generator outputs	Select the larger value from • Lower limit of scheduled generation output • Current EDC command + output change speed ×5 minutes

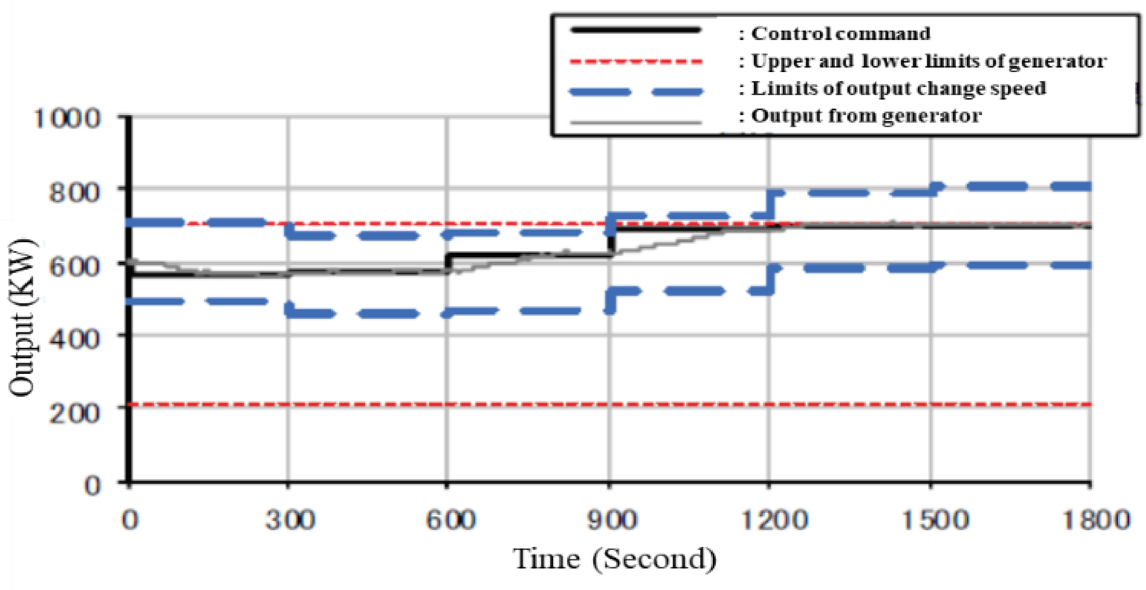


Figure 3.5 Output constraints of generators

3.9. Flow chart of Economic dispatching control considering output constraints of generator

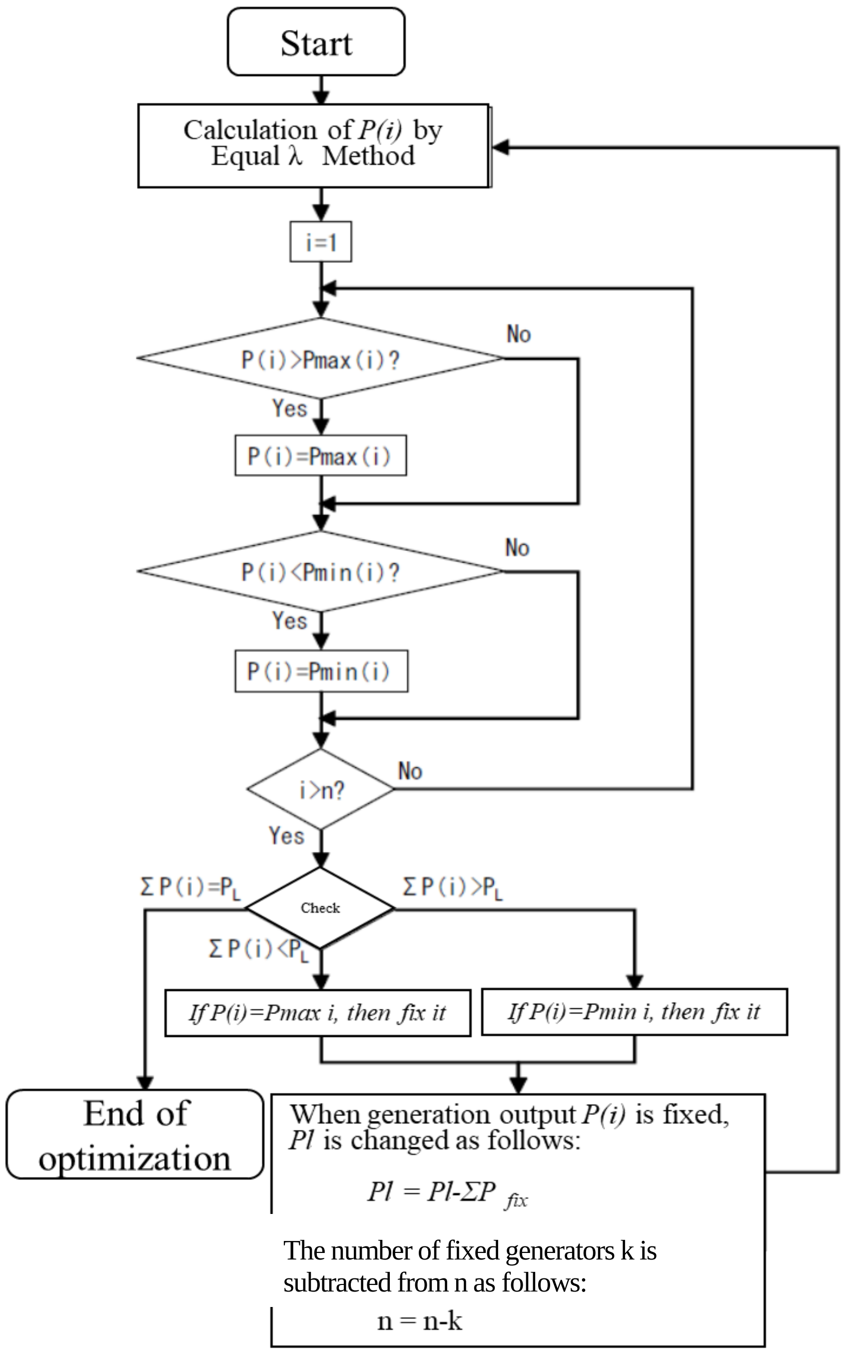


Figure 3.6 Economic dispatching control considering output constraints of generator

Reference

1) Standard analysis models for Economic Dispatching Control and Load Frequency Control,

The Institute of Electrical Engineers of Japan, IEEJ Technical Repot 1386(IEEJ-GH 1386)

3.10. INPUT AND OUTPUT DATA FORMS AND APPLICATION OF ELD TO 15-GENERATOR SYSTEM

Input and output data forms including a time series information required for simulations are shown in the following sections..

To make users and grid engineers understand how to input and output of this module easily, the economic load dispatch method mentioned in the previous sections is applied to a 31-generator system to verify the performances of ELD/EDC modules developed in this project.

(1) The Per-Unit System for input and output of this module

As well as KW , the Per-Unit System (p.u.) that is a specific expression of numerical values is used to input and output data in the economic load dispatch as follows.

The Per-Unit System (p.u. in short) is widely used in the power system analysis to express the values of voltages, currents, powers, and impedances to make the calculation convergence faster and to minimize the required calculation time.

.

For a given quantity, the per- unit value is the value related to a base quantity: per-unit value = quantity in some unit / base quantity

Generally, the following two base quantities are given as:

- Vbase: The base voltage quantity
- Sbase: The base power quantity
- All other base quantities are derived from these two base quantities, using the natural laws of

electrical circuits.

- Typical base quantities in IEEE test systems are as follows.

Vbase : 1～132 kV,

Sbase : 100 MVA

So, the voltage Amplitude 1.0 in p.u. actually means the Vbase value. If the power generation and the load data (P, Q) are given in units MW and MVAr respectively, the conversion of these values into Per-Unit System is simply done by dividing them by Sbase 100.

Based upon the Per-Unit System described above, it is necessary to input the Vbase and Sbase values in the Interface of power flow. The other Input data as to the load and generation values in units [MW] or [MVAr] will be automatically converted into the (p.u.) by using the Sbase, and then those values in Output data by the power flow will be automatically inverted into the original units by using the Sbase.

(2) Demand data （A time series of demand (kW) data of the targeted system）

The stage of simulation, the amount of loads from the initial time to the final time of simulations, load amounts at each stage, the base load that is the constant demand throughout simulation and outputs of renewable energy generation, such as PV generation, wind generation, biomass generation, and small-sale hydro generation are always required as long as the demand is larger than such RE generation to run any Singe and Multi Stage Economic Load Dispatch Module.

The data required are shown in the below Table 3.4

Column 1: The stage of simulation, the amount of loads from the initial time to the final time of simulations [Hour]

Column 2: Amount of the total load at each stage of simulation [kW]

Column 3: The base load that is the constant demand throughout simulation [kW]

Column 4: Amount of outputs of renewable energy generation (PV generation, wind generation, biomass generation, and small-sale hydro generation) [kW]

In case of using the Single Stage Economic Load Dispatch, a total demand at one stage is specified in Table3.4.

In case of using the Multi Economic Load Dispatch, a series of total demands at stages are specified in Table3.4, such as 24 stages (hours).

(3) Input data form for generator characteristics

The characteristics of generators including the rated capacity, coefficients of the fuel cost function and upper and lower limits of outputs are always required to run any Singe and Multi Stage Economic Load Dispatch.

The data required are shown in the below Table 3.5.

Column 1: Generator ID (Up to 5 characters)

Column 2: Rated output of the generator [kW]

Column 3: Coefficient a of the Fuel Cost Function

Column 4: Coefficient b of the Fuel Cost Function

Column 5: Coefficient c of the Fuel Cost Function

Column 6: CO_2 emission coefficient (tC / GJ) (tC / GJ)

Column 7: Upper limit of the generators [p.u.]

Column 8: Lower limit of the generators [p.u.]

Column 9: Upper limit of the generators [%]

Column 10: Lower limit of the generators [%]

(4) Output data form for generations decided by applying the economic load dispatching module

After execution of the Economic Load Dispatch Module, outputs of simulation results are shown as is in Table3.6. These are time series of outputs of generators used for the Economic Load Dispatch over multi stages (over 24 hours).

(5) Application of the economic load dispatch method to a 31-generator system

As an example, the economic load dispatch method mentioned in the previous sections is applied to a 31-generator system.

Table3.4 shows time series of outputs of total demands (kW) of the targeted system

The ELD test system has the radial structure as in Figure3.7 and is composed of:

- Diesel generators (Up to 10 units in this version)
- LNG thermal generator (Up to 10 units)
- Constant speed pumped-storage hydro generators (Up to 5 units)
- Variable speed pumped-storage hydro generators (Up to 5 units)

Coal-fired power generation is not included in this test system since usually microgrids and smart grids do not equip the coal generation plants. If necessary we can add the IGCC and sustainable energy generation such as PV generation, Wind generation and Biomass generation to the test system.

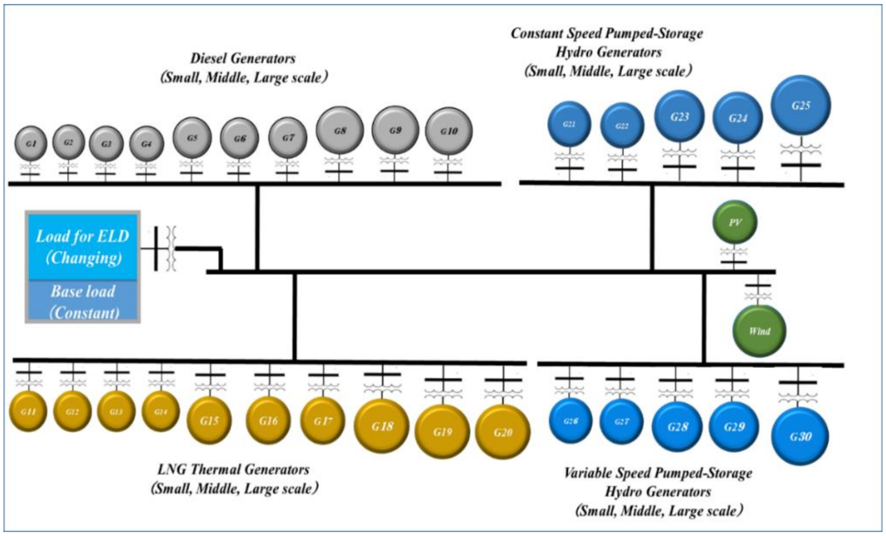


Figure 3.7 Structurer and components of ELD test system

Table 3.4 Input data form of A time series demand (kW) of the targeted system for Load Dispatch

Comments	Load data Input Each Hours	
	Hour ID	Load
	(Up to 4 characters)	(kW)
	1	21500
	2	20900
	3	20100
	4	20300
	5	21300
	6	20700
	7	21300
	8	23100
	9	27200
	10	27500
	11	28100
	12	27600
	13	28300
	14	28600
	15	27800
	16	27800
	17	25600
	18	23800
	19	24800
	20	25400
	21	24300
	22	22000
	23	22500
	24	21300

Input data of total demands (with out base loads) at satages are dipicted by using Excel functions as Figure3.8. Table3.5 shows the input data form for generator characteristics. After execution of the Economic Load Dispatch, outputs of simulation results are shown as is in Table3.6. Finally, transition of outputs of 30 generators over 24 stages (hours) are dipicted by using Excel functions as shown in Figure3.9.

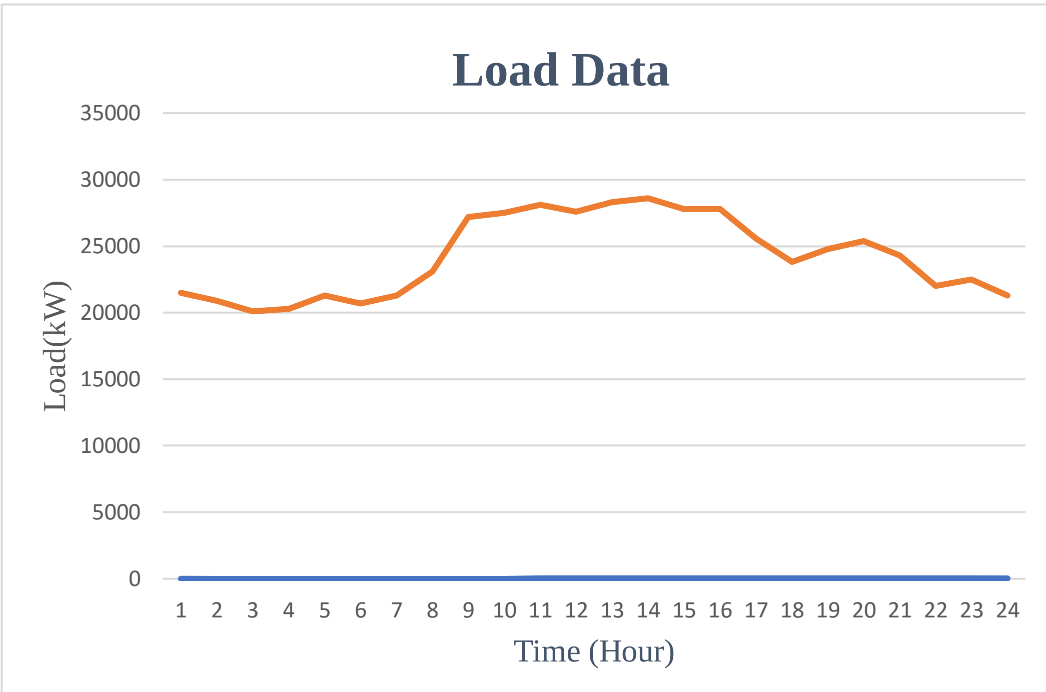


Figure 3.8 Change of demand over 24 hours (Example)

Table 3.5 Input data form for generator characteristics

Generator data Input Form for Dynamic ELD									
Generator ID	Rated Output	FuelCost (a)	FuelCost (b)	FuelCost (c)	CO2 emission (tC / GJ)	Upper Limit	Lower Limit	Gen_Up Rate	Gen_Down Rate
(Up to 4 characters)	(kW)					(p.u.)	(p.u.)	%	%
1	6130	0.000020	0.020900	18.254000	0.002580	1	0.2	100	100
2	3870	0.000005	0.034400	25.372000	0.002580	1	0.2	100	100
3	3890	0.000004	0.025900	54.378000	0.002580	1	0.2	100	100
4	3600	0.000001	0.050300	12.250000	0.002580	1	0.2	100	100
5	3500	0.000020	0.046900	133.520000	0.002580	1	0.2	100	100
6	3890	0.000001	0.044000	23.768000	0.002580	1	0.2	100	100
7	3890	0.000001	0.044300	23.650000	0.002580	1	0.2	100	100
8	3890	0.000001	0.044100	22.126000	0.002580	1	0.2	100	100
9	3890	0.000001	0.044133	23.181333	0.002580	1	0.2	100	100
10	1640	0.000003	0.044900	12.044000	0.002580	1	0.2	100	100
11	1640	0.000003	0.044900	12.044000	0.002580	1	0.2	100	100
12	1640	0.000003	0.044900	12.044000	0.002580	1	0.2	100	100
13	1640	0.000003	0.044900	12.044000	0.002580	1	0.2	100	100
14	1640	0.000003	0.044900	12.044000	0.002580	1	0.2	100	100
15	1640	0.000003	0.044900	12.044000	0.002580	1	0.2	100	100

Table 3.6 Output data form for 15 generations decided by the economic load dispatching

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	Supply	Demand
T1	3,295	0	0	0	2,645	3,890	3,890	3,890	3,890	0	0	0	0	0	0	21,500	21,500
T2	5,730	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	20,900	20,900
T3	4,930	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	20,100	20,100
T4	5,130	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	20,300	20,300
T5	6,130	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	21,300	21,300
T6	5,530	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	20,700	20,700
T7	6,130	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	21,300	21,300
T8	4,095	0	0	0	3,445	3,890	3,890	3,890	3,890	0	0	0	0	0	0	23,100	23,100
T9	4,250	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	27,200	27,200
T10	4,550	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	27,500	27,500
T11	5,150	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	28,100	28,100
T12	4,650	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	27,600	27,600
T13	5,350	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	28,300	28,300
T14	5,650	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	28,600	28,600
T15	4,850	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	27,800	27,800
T16	4,850	0	3,890	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	27,800	27,800
T17	3,400	0	3,890	0	2,750	3,890	3,890	3,890	3,890	0	0	0	0	0	0	25,600	25,600
T18	4,740	0	0	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	23,800	23,800
T19	5,740	0	0	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	24,800	24,800
T20	3,300	0	3,890	0	2,650	3,890	3,890	3,890	3,890	0	0	0	0	0	0	25,400	25,400
T21	5,240	0	0	0	3,500	3,890	3,890	3,890	3,890	0	0	0	0	0	0	24,300	24,300
T22	3,545	0	0	0	2,895	3,890	3,890	3,890	3,890	0	0	0	0	0	0	22,000	22,000
T23	3,795	0	0	0	3,145	3,890	3,890	3,890	3,890	0	0	0	0	0	0	22,500	22,500
T24	6,130	0	0	0	3,500	3,890	0	3,890	3,890	0	0	0	0	0	0	21,300	21,300

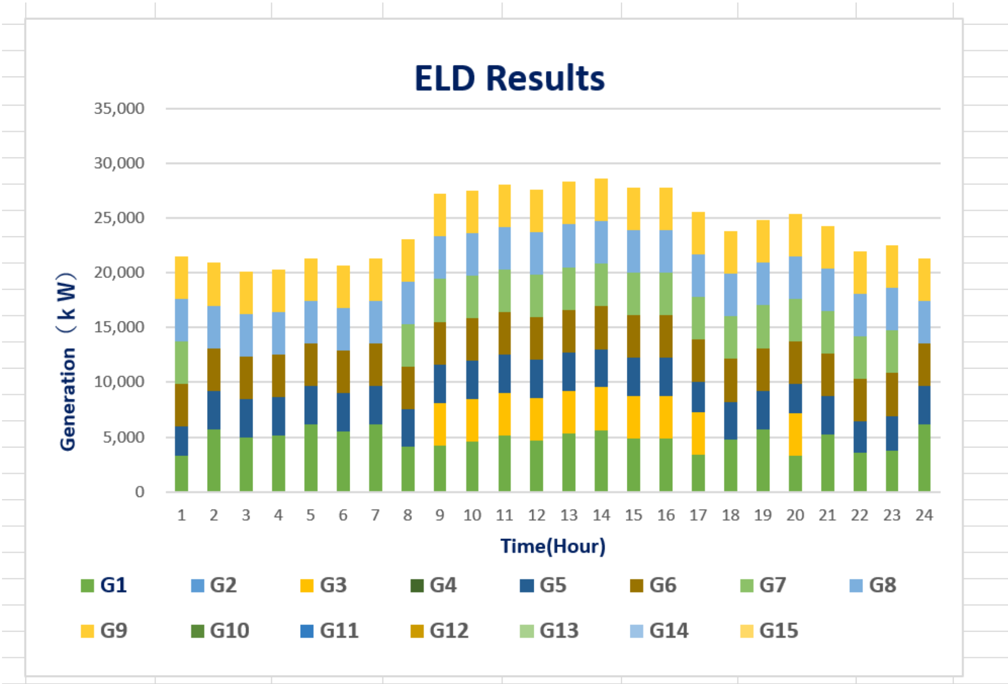


Figure 3.9 Outputs of 30 generators decided by the economic load dispatching

3.11. Interface of the Multi Stage Economic Load Dispatch for Data Input, Calculation and Result Output

In the ***MicroGrid Designer***, an interface of the multi stage economic load dispatch for data input, calculation and results output is utilized as Figuer3.10 and 3.11 follows and essential results are depicted as plots and graphs. For calculating the Single Stage Economic Load Dispatch usually applied to the peak load or the base load、the number of stages is specified as “1” and one period that you want to calculate is also specified such as “ 12,13 ” (12:00-13:00, the peak time) and ELD results at Stage 12 and 13 are available.

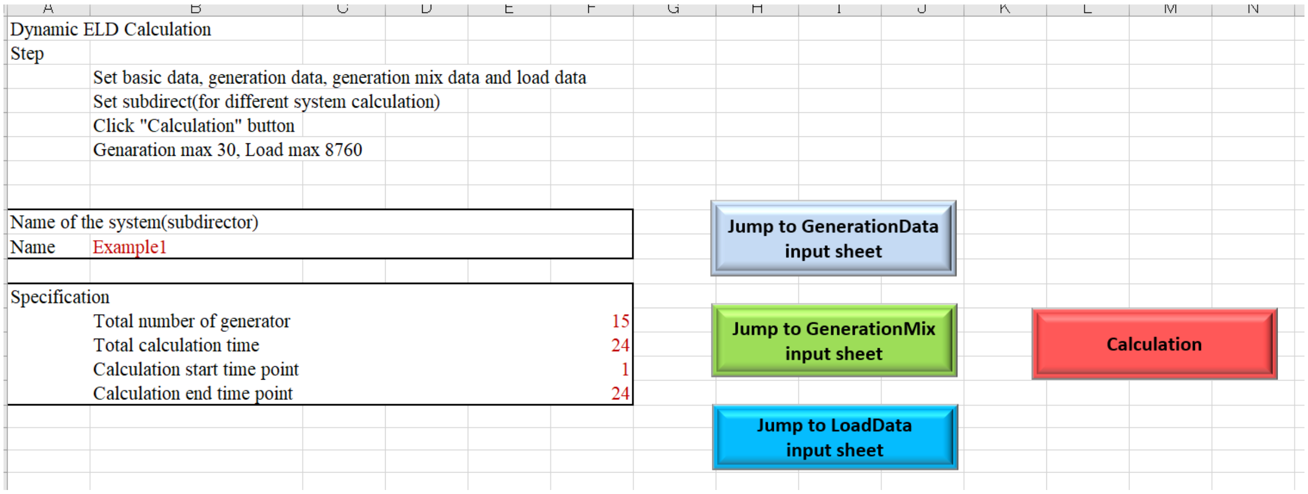


Figure 3.10 Interface of the economic load dispatching for data input, calculation and results output

The following diagram summarizes the screen transition diagram for ELD calculation.

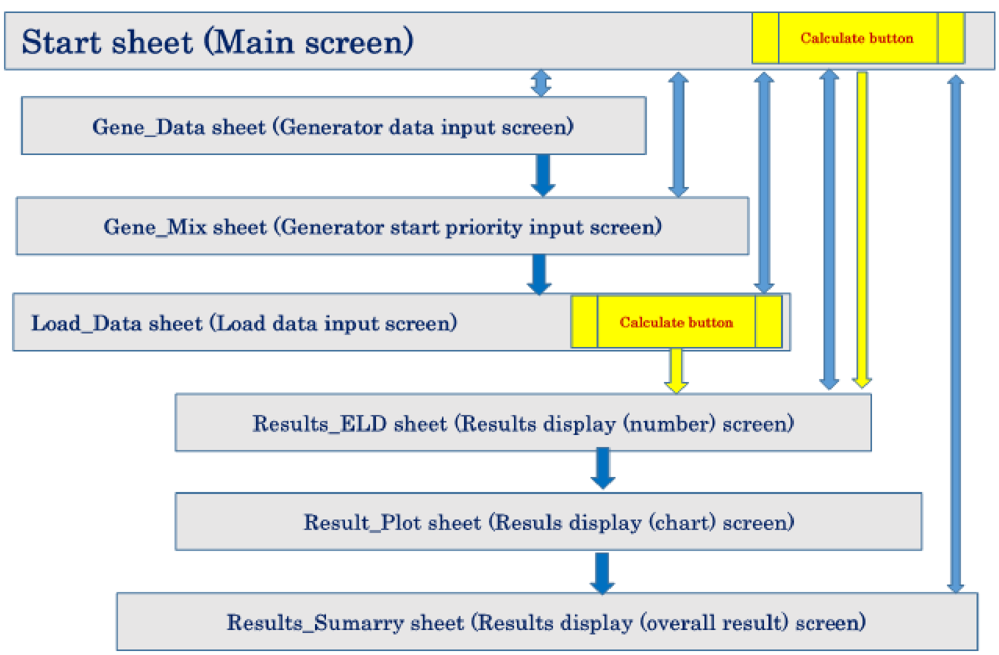


Figure 3.11 Procedure of calculations by utilizing the interface of ELD

(Screen transition diagram- based in the EXCEL tool)

See "Dynamic ELD calculation tool manual" for detailed information in ELD Interface.

4. INPUT AND OUTPUT FORM FOR SINGLE AND MULTI POWER FLOW ANALYSIS

In this section, a solution method of power flow, the per unit system specifically used in power flow analysis, interface of **the *Microgrid Designer,*** input and output data form for simulations and designs of micro grids, several input and output data for standard power networks such as the IEEE 30-node network, and application of power flow analysis to the IEEE 30-node network and microgrid with typical structure and components are described for users and grid engineers.

4.1. SOLUTION METHOD OF POWER FLOW ANALYSIS

To solve the Power flow equations in the form of the simultaneous nonlinear equations with many variables, some numerically iterative methods will be generally adopted such as the Newton-Raphson method for Transmission/Distribution grid and the Backward/Forward method for Distribution grid.

As for the Power flow analysis here, the Newton-Raphson method is adopted. Also, an improved Newton -Raphson method can be applicable for the large-scale power grids. It features in the points that the solution scheme is fully based on the complex polar form, the complex Nodal Admittance matrix is represented as a sparse matrix, and also a sparse solution method is introduced in the Newton-Raphson method. Convergence property of the solution method

The Newton-Raphson method adopted in power flow analysis utilizes an iterative procedure, which firstly giving the initial values of the complex voltage variables, repeats the up- dating the values of the variables by the predefined rule until the power balances will be satisfied at all nodes. This procedure will converge normally at less than 5 times. How- ever, you may happen to encounter the divergences if the initial values of variables are not good enough, or if the grid state is ill-conditioned under the circumstances such that the voltage Amplitudes in some nodes are near to the limit.

For a given power network, with known complex power loads and some set of specifications or restrictions on power generations and voltages, any unknown node voltage, unspecified generation and the complex power flow in the network components are solved by the power flow calculation.

They are calculated according to the following procedures.

- Determine element values for passive network components;
- Determine locations and values of all complex power loads;
- Determine generation specifications and constraints;
- Develop a mathematical model describing power flow in the network;
- Solve for the voltage profile of the network;
- Solve for the power flows and losses in the network;
- Check for constraint violations.

4.2. PER-UNIT SYSTEM IN POWER FLOW ANALYSIS

The Input and Output data in the power flow is based on the Per-Unit System (p.u.). It is described as follows: Per-Unit System. The Per-Unit System (p.u. in short) is specifically used in the power system analysis to express the values of voltages, currents, powers, and impedances.

For a given quantity, the per unit value is the value related to a base quantity: per-unit value = quantity in some unit / base quantity. Generally, the following two base quantities are given as:

- Vbase: The base voltage quantity
- Sbase: The base power quantity
- All other base quantities are derived from these two base quantities, using the natural laws of electrical circuits.
- Typical base quantities in IEEE test systems are as follows.

  Vbase : 1～132 kV

  Sbase : 100 MVA

So, the voltage Amplitude 1.0 in p.u. actually means the Vbase value. If the power generation and the load data (Active power P, Reactive power Q) are given in units MW and MVAr respectively, the conversion of these values into Per-Unit System is simply done by dividing them by Sbase 100.

Based upon the Per-Unit System described above, it is necessary to input the Vbase and Sbase values in the Interface of power flow. The other Input data as to the load and generation values in units [MW] or [MVAr] will be automatically converted into the (p.u.) by using the Sbase, and then those values in Output data by the power flow will be automatically inverted into the original units by using the Sbase. However, since the Vbase is only for a reference usage, it is necessary to input the (p.u.) values directly for input items such as voltage Amplitude, impedance, or capacitor's admittance for nodes and branches.

For all power flow analysis, node and branch properties are fundamental data to input.

Hence by entering the data in these tables first the user limits the data required to only those relevant to the study. The various tables will be discussed in detail in the following sections.

4.3. NETWORK REPRESENTATION IN POWER FLOW ANALYSIS

In *The **MicroGrid Designer***, Pi Pad Circuit type is by default the circuit type being used to formulate the power flow system. The input data described below is based on this type of circuit.

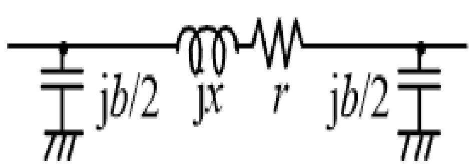


Figure 4.1 π-shaped equivalent circuit

The resistance of the entire transmission line is *r*, the inductance component (reactance component) at commercial frequency is *x*, and the admittance component is *b*. j is the imaginary unit. Transformers can also be expressed with this model. Next consider the state that this model is connected to the node. In addition to the branch, the node may be connected with a phase-adjustment capacitor or a phase-matching reactor

The resistance of the entire transmission line is r, the inductance component (reactance component) at commercial frequency is x, and the admittance component is b. j is the imaginary unit. Transformers can also be expressed with this model.

4.4. INPUT AND OUTPUT FORM OF THE POWER FLOW ANALYSIS MODULE

(1) Input Data to the power flow analysis

The Input data of the power flow is usually classified into the following 4 types.

(a) Per Unit System

Vbase [kV] and Sbase [MVAr] are the input items.

(b) Basic data

The number of nodes in the grid is an input item.

(c) Node data

(d) Branch data

The node related information are required to input as follows.

- Node name
- Node ID
- Node type
- Specified value of voltage Amplitude V (generally is specified around 1.0 p.u.)
- Specified value of voltage phase angel θ (generally is specified around 0.0 degree)
- Node admittance Y/2
- Generator active power for scheduled operation Pg
- Generator reactive power for scheduled operation Qg
- Active power required by load Pl
- Reactive power required by load Ql

Regarding the branch related information, the followings are required to input for each branch in the target grid.

- Branch name (If necessary. Specify names by characters)
- Branch number
- Sending branch
- Receiving branch
- Number of circuits
- Resistance of branch R
- Reactance of branch X
- Admittance of branch Y/2
- Tap ratio of transformer

(2) Output Data from the power flow analysis

The outputs by the power flow are basically the complex voltage solutions for all nodes. Also, they include the complex generation solutions for the generation nodes, the complex power loss in the whole grid and so on, which will be computed from the voltage solutions.

In particular, the complex generation solution for the slack node has an important meaning such that it definitely indicates the adjustment in the power balance of the whole grid. The generation of the slack node is the sum of generation of other nodes except for the slack node and total power loss in the grid. Consequently, the generation value for the slack node may be negative if the total loads in the grid is smaller than the sum of generation of other nodes in an isolated grid.

When the active power generation of the slack node is negative in an isolated grid, it implies no practical power flow solution exists. However, the slack node is an interconnection point to the other grid, the signed generation value of the slack node implies the in/out power transfer quantity between the other grid. In this case we can judge that a practical Power flow solution has been obtained.

The complex voltage solution for each node will be output usually in the polar form with the voltage Amplitude [p.u.] and its phase angle [degree].

The voltage Amplitude in nodes is one of the indicators of the voltage stability in the grids. There is a standard for voltage Amplitudes in the normal grids that the 5% deviance from 1.0 p.u. can be allowed.

In the case that some voltage Amplitudes much exceed the allowable range [0.95, 1.05] p.u., the engineers should change the grid attributes especially near the nodes with high deviance.

4.5. APPLICATION OF POWER FLOW ANALYSIS TO A MICROGRID WITH STANDARD STRUCTURES

In this section, the power flow analysis is applied to a Micro Grid with standard structure and components. This Micro Grid is consisted of 10 nodes and 9 distribution lines. A gas turbine is installed at node G1, PV generation at node G2, diesel generators at nodes G3 and G4 and a small hydro generator (Constant output) at node G5. Nodes L1, ～L5 are load nodes that supply electricity to demands.

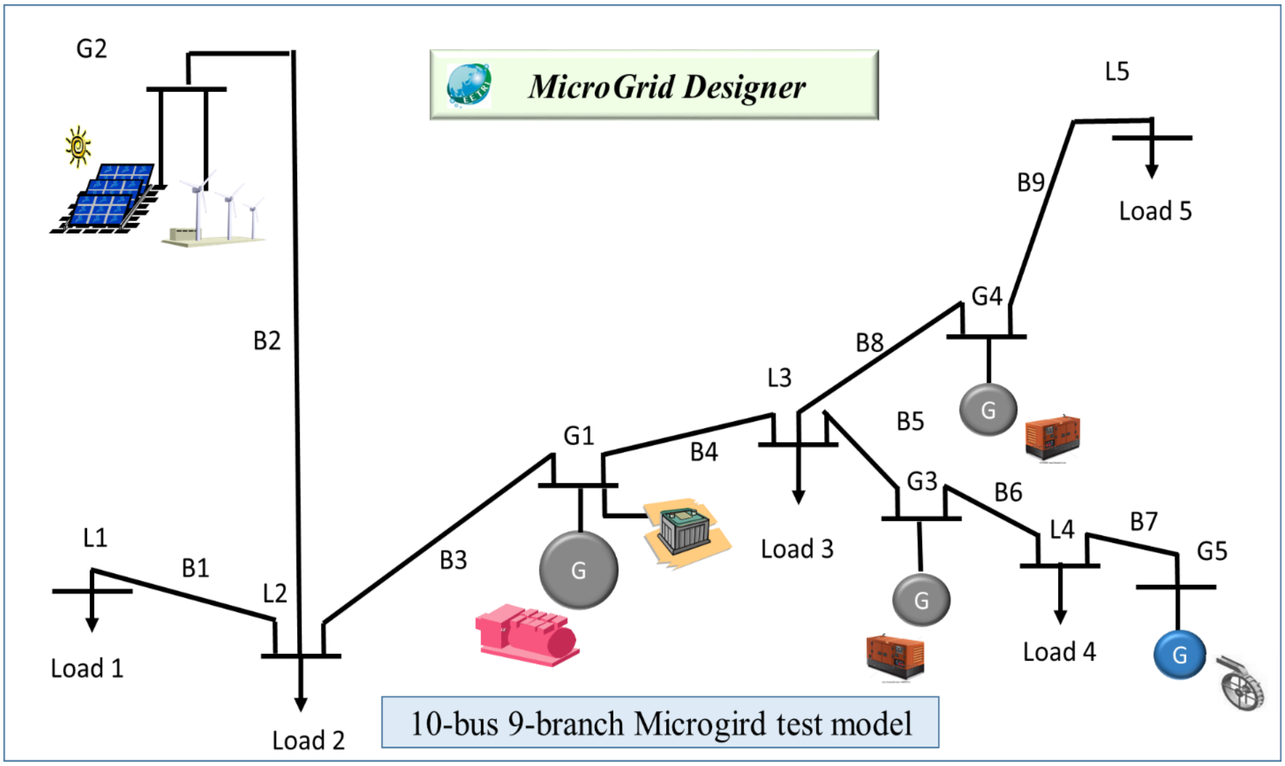


Figure 4.2 Micro Grid with standard structure and components.

The Input forms of node information for the power flow analysis will be described below.

Column 1: Node name or comment (If necessary. Specify by characters)

Column 2 Node ID (Up to 4 characters)

Column 3 Node type (PQ node=0, PV node=1, Slack node=2)

For Multi Power Flow Analysis、The first letter of Node ID must be "G" for generator, "P" for PV, "W" for wind power, "B" for battery, and "L" for load.

Column 4 Specified value of voltage Amplitude V (p.u.)

Column 5 Specified value of voltage phase angel θ (Degree)

Column 6 Node admittance Y/2 (p.u.)

Column 7 Generator active power for scheduled operation Pg (p.u.)

Column 8 Generator reactive power for scheduled operation Qg (p.u.)

Column 9 Active power required by load Pl (p.u.)

Column 10 Reactive power required by load Ql (p.u.)

Grid designers and users are required to fill in data correctly into each column of the input form.

Table 4.2 Input data form for node information

Input Data Form for Node Information									
Commnet	Node ID	Type	Specify V	Specified θe	Node addmittance	PG	QG	PL	QL
Characters	Up to 4 characters	PQ,PV,Slack	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)
Diesel	G1	2	1	0					
PV	PV1	0	1	0					
Diesel	G3	1	1	0					
Diesel	G4	1	1	0					
WaterP	WP1	0	1	0					
	L1	0	1	0					
	L2	0	1	0					
	L3	0	1	0					
	L4	0	1	0					
	L5	0	1	0					

The Input forms of branch information for the power flow analysis will be described below.

Column 1 Branch name (If necessary. Specify names by characters)

Column 2 Branch number (Up to 5 integer)

Column 3 Sending branch (Up to 4 characters)

Column 4 Receiving branch (Up to 4 characters)

Column 5 Number of circuits (Default value is 1)

Column 6 Resistance of branch R (p.u.)

Column 7 Reactance of branch X (p.u.)

Column 8 Admittance of branch Y/2 (p.u.)

Column 9 Tap ratio of transformer (Default value is 1.0)

Grid designers and users are required to fill in data correctly into each column of the input form.

Table 4.3 Input data form for branch information

Input data form for bramche information								
Branch name	Buanch No,	Sending B.	Receiving B.	No of circuits	ResistanceR	Reactance X	Admitance Y/2	Tap ratio
If necessary	5 integer	4 characters	4 characters	default=1	(pu)	(pu)	(pu)	default=1.0
	1	L1	L2		0.058	0.08	0.00010	
PV line	200	PV1	L2		0.290	0.40	0.00050	
	3	L2	G1		0.029	0.04	0.00005	
	4	G1	L3		0.029	0.04	0.00005	
	5	L3	G3		0.029	0.04	0.00005	
	6	G3	L4		0.029	0.04	0.00005	
Hydro line	7	L4	WP1		0.029	0.04	0.00005	
	8	L3	G4		0.029	0.04	0.00005	
	9	G4	L5		0.029	0.04	0.00005	

In order to execute the power flow computations, time series of generation outputs and load data at load nodes (PL,QL) are required for one hour for the single stage power flow analysis and over 24 hours for the multi stage power flow analysis as Table 4.4 and 4.5.

Table4.4 Input form of time series generation outputs for the multi stage power flow analysis

Genarator node	P and Q of Slack node are zero, they are determined from power flow calculation.														
Node Nam	G1			G3			G4								
Stage	V(pu)	PG(p.u.)	QG(p.u.)	V(p.u.)	PG(p.u.)	PQ(p.u.)	V(p.u.)	PG(p.u.)	PQ(p.u.)	V(p.u.)	PG(p.u.)	PQ(p.u.)	V(p.u.)	PG(p..u.)	PQ(p.u.)
1	1	0	0	1	0.150		1	0.17							
2	1	0	0	1	0.150		1	0.17							
3	1	0	0	1	0.150		1	0.17							
4	1	0	0	1	0.180		1	0.2							
5	1	0	0	1	0.180		1	0.2							
6	1	0	0	1	0.200		1	0.22							
7	1	0	0	1	0.190		1	0.21							
8	1	0	0	1	0.220		1	0.24							
9	1	0	0	1	0.210		1	0.23							
10	1	0	0	1	0.210		1	0.23							
11	1	0	0	1	0.250		1	0.27							
12	1	0	0	1	0.250		1	0.27							
13	1	0	0	1	0.250		1	0.27							
14	1	0	0	1	0.260		1	0.28							
15	1	0	0	1	0.280		1	0.3							
16	1	0	0	1	0.280		1	0.3							
17	1	0	0	1	0.190		1	0.21							
18	1	0	0	1	0.200		1	0.22							
19	1	0	0	1	0.220		1	0.24							
20	1	0	0	1	0.170		1	0.19							
21	1	0	0	1	0.165		1	0.185							
22	1	0	0	1	0.160		1	0.18							
23	1	0	0	1	0.155		1	0.175							
24	1	0	0	1	0.150		1	0.17							

Table 4.5 Input form of time series loads for the multi stage power flow analysis

Node nam	L1		L2		L3		L4		L5	
Statge	PL(p.u.)	QL(p.u.)	PL(p.u.)	QL(p.u.)	PL(p.u.)	QL(p.u.)	PL(p.u.)	QL(p.u.)	PL(p.u.)	QL(p.u.)
1	0.0800	0.0131	0.0100	0.0033	0.0300	0.0098	0.1500	0.0492	0.2000	0.0616
2	0.0800	0.0131	0.0100	0.0033	0.0300	0.0098	0.1500	0.0492	0.2000	0.0616
3	0.0800	0.0131	0.0100	0.0033	0.0300	0.0098	0.1500	0.0492	0.2000	0.0616
4	0.0800	0.0131	0.0100	0.0033	0.0300	0.0098	0.1500	0.0492	0.3000	0.0924
5	0.0900	0.0148	0.0100	0.0033	0.0400	0.0131	0.1500	0.0492	0.3000	0.0924
6	0.1200	0.0197	0.0100	0.0033	0.0415	0.0136	0.2000	0.0656	0.3000	0.0924
7	0.1500	0.0246	0.0100	0.0033	0.0430	0.0141	0.2000	0.0656	0.3000	0.0924
8	0.1700	0.0279	0.0100	0.0033	0.0440	0.0144	0.2000	0.0656	0.4000	0.1232
9	0.1800	0.0295	0.0100	0.0033	0.0450	0.0148	0.2000	0.0656	0.4000	0.1232
10	0.1900	0.0312	0.0100	0.0033	0.0460	0.0151	0.2000	0.0656	0.4000	0.1232
11	0.2000	0.0328	0.0100	0.0033	0.0470	0.0154	0.2000	0.0656	0.5000	0.1540
12	0.2000	0.0328	0.0100	0.0033	0.0480	0.0157	0.2000	0.0656	0.5000	0.1540
13	0.2000	0.0328	0.0100	0.0033	0.0500	0.0164	0.2000	0.0656	0.5000	0.1540
14	0.2200	0.0361	0.0100	0.0033	0.0500	0.0164	0.2000	0.0656	0.5000	0.1540
15	0.2100	0.0344	0.0100	0.0033	0.0500	0.0164	0.2000	0.0656	0.5000	0.1540
16	0.2000	0.0328	0.0100	0.0033	0.0500	0.0164	0.2000	0.0656	0.5000	0.1540
17	0.1900	0.0312	0.0100	0.0033	0.0480	0.0157	0.2000	0.0656	0.3000	0.0924
18	0.1700	0.0279	0.0100	0.0033	0.0470	0.0154	0.2000	0.0656	0.3000	0.0924
19	0.1500	0.0246	0.0100	0.0033	0.0450	0.0148	0.1500	0.0492	0.3000	0.0924
20	0.1300	0.0213	0.0100	0.0033	0.0440	0.0144	0.1500	0.0492	0.2000	0.0616
21	0.1200	0.0197	0.0100	0.0033	0.0430	0.0141	0.1500	0.0492	0.2000	0.0616
22	0.1000	0.0164	0.0100	0.0033	0.0400	0.0131	0.1500	0.0492	0.2000	0.0616
23	0.0900	0.0148	0.0100	0.0033	0.0360	0.0118	0.1500	0.0492	0.2000	0.0616
24	0.0800	0.0131	0.0100	0.0033	0.0300	0.0098	0.1500	0.0492	0.2000	0.0616

After specifying the time series load data, load changes at nodes over 24 hours can be plotted as Figure4.3

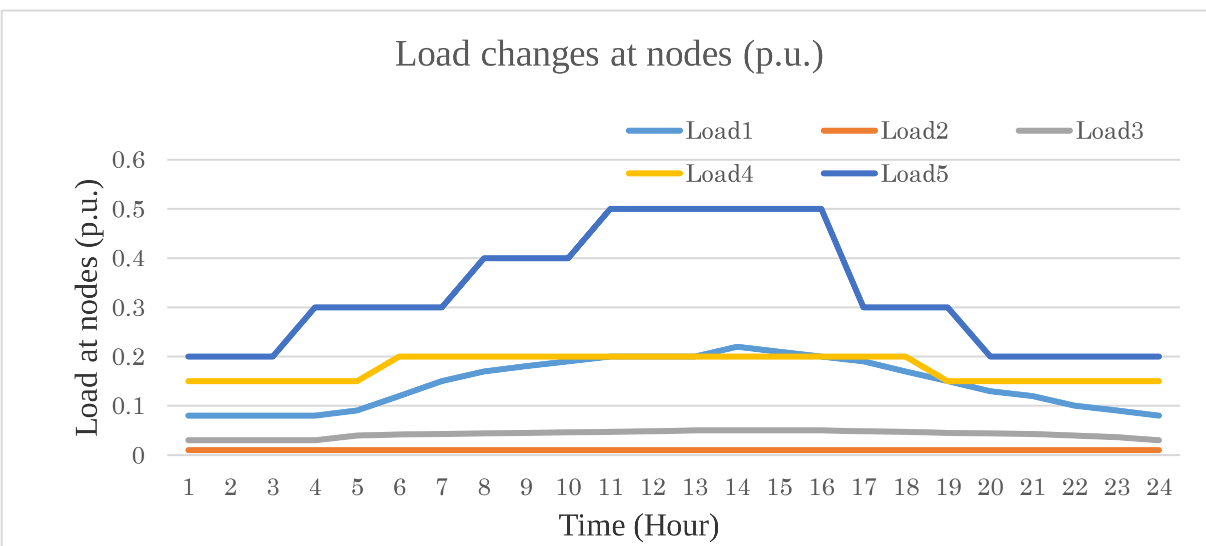


Figure 4.3 Load changes at nodes over 24 hours

After the convergence of power flow calculations, the output of node voltage information obtained by the power flow analysis will be produced like Table4.6 and changes of loads are depicted as Figure4.4.

Table 4.6 Voltage profiles at nodes over 24 hours by the multi stage power flow analysis

Voltage (pu)	Type of nodes									
Stage	G1	PV1	G3	G4	WP1	L1	L2	L3	L4	L5
1	1	0.99671	1	1	0.99655	0.99093	0.99669	0.99958	0.9951	0.99165
2	1	0.99671	1	1	0.99655	0.99093	0.99669	0.99958	0.9951	0.99165
3	1	0.99671	1	1	0.99655	0.99093	0.99669	0.99958	0.9951	0.99165
4	1	0.99671	1	1	0.99655	0.99093	0.99669	0.99957	0.9951	0.9874
5	1	0.99634	1	1	0.99655	0.98984	0.99632	0.99943	0.9951	0.9874
6	1	0.99842	1	1	0.99442	0.98682	0.9955	0.99941	0.99296	0.9874
7	1	1.00968	1	1	0.99442	0.98461	0.9955	0.99938	0.99296	0.9874
8	1	1.02363	1	1	0.99442	0.98367	0.99604	0.99935	0.99296	0.98311
9	1	1.03443	1	1	0.99442	0.98352	0.99662	0.99933	0.99296	0.98311
10	1	1.03678	1	1	0.99442	0.98262	0.99647	0.99932	0.99296	0.98311
11	1	1.0444	1	1	0.99442	0.98217	0.99675	0.99928	0.99296	0.97877
12	1	1.047	1	1	0.99442	0.98238	0.99697	0.99926	0.99296	0.97877
13	1	1.04958	1	1	0.99442	0.9826	0.99718	0.99923	0.99296	0.97877
14	1	1.04885	1	1	0.99442	0.98033	0.99641	0.99924	0.99296	0.97877
15	1	1.04403	1	1	0.99442	0.98103	0.99637	0.99925	0.99296	0.97877
16	1	1.0391	1	1	0.99442	0.98172	0.99631	0.99925	0.99296	0.97877
17	1	1.03406	1	1	0.99442	0.98239	0.99624	0.99931	0.99296	0.9874
18	1	1.02363	1	1	0.99442	0.98367	0.99604	0.99933	0.99296	0.9874
19	1	0.9941	1	1	0.99655	0.98317	0.99408	0.99936	0.9951	0.9874
20	1	0.99486	1	1	0.99655	0.98541	0.99484	0.99938	0.9951	0.99165
21	1	0.99523	1	1	0.99655	0.98652	0.99521	0.99939	0.9951	0.99165
22	1	0.99597	1	1	0.99655	0.98874	0.99595	0.99944	0.9951	0.99165
23	1	0.99634	1	1	0.99655	0.98984	0.99632	0.99949	0.9951	0.99165
24	1	0.99671	1	1	0.99655	0.99093	0.99669	0.99958	0.9951	0.99165

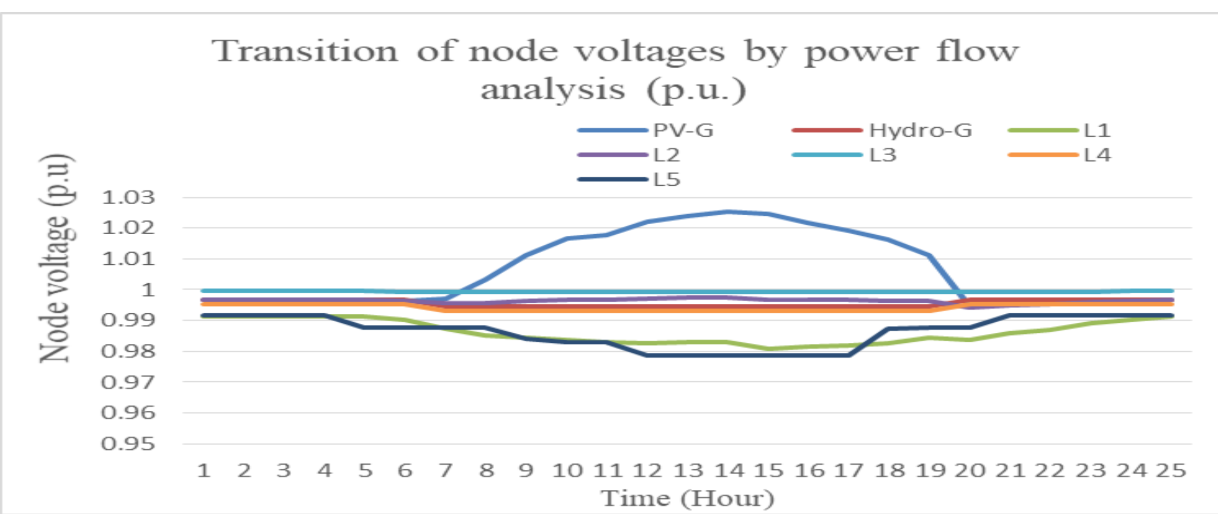


Figure 4.4 Transition of voltage at nodes over 24 hours by the multi stage power flow analysis

Table 4.7 Transition of output of generators over 24 hours by the multi stage power flow analysis

Node pow	G1		PV1		G3		G4		WP1	
Stage	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)
1	0.10252	0.01909	0	0	0.15	0.02449	0.17	0.09668	0.05	0
2	0.10252	0.01909	0	0	0.15	0.02449	0.17	0.09668	0.05	0
3	0.10252	0.01909	0	0	0.15	0.02449	0.17	0.09668	0.05	0
4	0.14488	−0.01126	0	0	0.18	0.00316	0.2	0.18241	0.05	0
5	0.16509	−0.01311	0	0	0.18	0.00668	0.2	0.18596	0.05	0
6	0.19731	−0.01537	0.01	0	0.2	0.04599	0.22	0.17171	0.05	0
7	0.21014	−0.02387	0.05	0	0.19	0.0538	0.21	0.17965	0.05	0
8	0.22722	−0.04856	0.1	0	0.22	0.03304	0.24	0.26788	0.05	0
9	0.22127	−0.05797	0.14	0	0.21	0.04072	0.23	0.27579	0.05	0
10	0.22329	−0.05532	0.15	0	0.21	0.04108	0.23	0.27615	0.05	0
11	0.23192	−0.06725	0.18	0	0.25	0.01334	0.27	0.35912	0.05	0
12	0.22386	−0.06635	0.19	0	0.25	0.0137	0.27	0.35948	0.05	0
13	0.21686	−0.06574	0.2	0	0.25	0.01441	0.27	0.36021	0.05	0
14	0.21702	−0.0473	0.2	0	0.26	0.00709	0.28	0.35257	0.05	0
15	0.1841	−0.02322	0.18	0	0.28	−0.00746	0.3	0.33738	0.05	0
16	0.19211	−0.02761	0.16	0	0.28	−0.00746	0.3	0.33738	0.05	0
17	0.17044	−0.01193	0.14	0	0.19	0.05557	0.21	0.18143	0.05	0
18	0.16628	−0.00447	0.1	0	0.2	0.04793	0.22	0.17366	0.05	0
19	0.15134	0.05467	0	0	0.22	−0.02028	0.24	0.15834	0.05	0
20	0.12759	0.05244	0	0	0.17	0.01502	0.19	0.08707	0.05	0
21	0.12632	0.04359	0	0	0.165	0.01825	0.185	0.09034	0.05	0
22	0.11288	0.0336	0	0	0.16	0.02079	0.18	0.09292	0.05	0
23	0.10869	0.02596	0	0	0.155	0.02299	0.175	0.09515	0.05	0
24	0.10252	0.01909	0	0	0.15	0.02449	0.17	0.09668	0.05	0

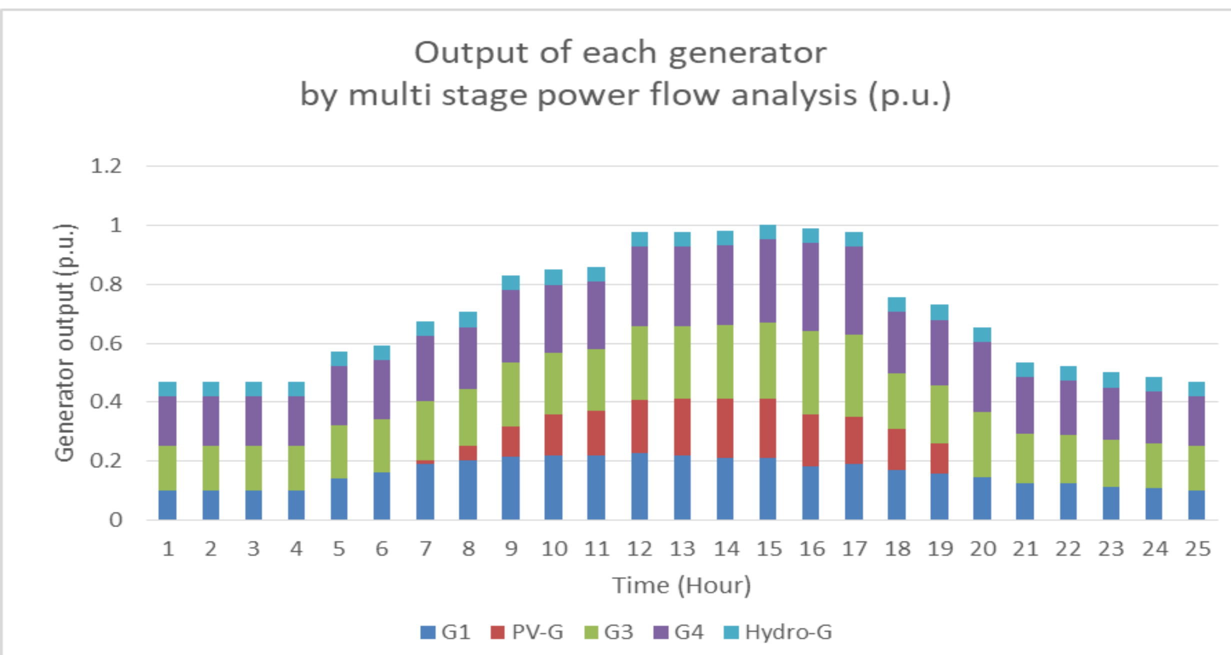


Figure 4.5 Transition of generator outputs over 24 hours by the multi stage power flow analysis

Table 4.8 Transition of branch power flows over 24 hours by the multi stage power flow analysis

Lone flow	1		2		3		4		5		6		7		8		9	
Stage	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)
1	-0.08	-0.01312	0	0	-0.09039	-0.01682	0.01188	0.00195	-0.04947	0.02538	0.10044	0.04976	-0.04993	0.00008	0.03135	-0.03325	0.20129	0.06336
2	-0.08	-0.01312	0	0	-0.09039	-0.01682	0.01188	0.00195	-0.04947	0.02538	0.10044	0.04976	-0.04993	0.00008	0.03135	-0.03325	0.20129	0.06336
3	-0.08	-0.01312	0	0	-0.09039	-0.01682	0.01188	0.00195	-0.04947	0.02538	0.10044	0.04976	-0.04993	0.00008	0.03135	-0.03325	0.20129	0.06336
4	-0.08	-0.01312	0	0	-0.09039	-0.01682	0.05424	-0.0284	-0.07932	0.04693	0.10044	0.04976	-0.04993	0.00008	0.10345	-0.08529	0.30293	0.09642
5	-0.09	-0.01476	0	0	-0.10049	-0.0186	0.06429	-0.03211	-0.07933	0.0434	0.10044	0.04976	-0.04993	0.00008	0.10347	-0.08881	0.30293	0.09642
6	-0.12	-0.01968	0.01	0	-0.12091	-0.0241	0.07595	-0.04006	-0.04905	0.02085	0.15086	0.06675	-0.04993	0.00008	0.08329	-0.0748	0.30293	0.09642
7	-0.15	-0.0246	0.05	0	-0.11209	-0.03065	0.09766	-0.05504	-0.03909	0.013	0.15086	0.06675	-0.04993	0.00008	0.09338	-0.08262	0.30293	0.09642
8	-0.17	-0.02788	0.10001	0	-0.08454	-0.0373	0.14243	-0.08618	-0.06897	0.03393	0.15086	0.06675	-0.04993	0.00008	0.16659	-0.13562	0.40525	0.13043
9	-0.18	-0.02952	0.14	0	-0.05731	-0.04276	0.16382	-0.10092	-0.05902	0.02617	0.15086	0.06675	-0.04993	0.00008	0.17676	-0.14331	0.40526	0.13043
10	-0.19	-0.03116	0.15	0	-0.0583	-0.04576	0.16483	-0.10128	-0.05902	0.02582	0.15086	0.06675	-0.04993	0.00008	0.17676	-0.14367	0.40526	0.13043
11	-0.2	-0.0328	0.18	0	-0.04108	-0.05124	0.19071	-0.11865	-0.09877	0.0539	0.15086	0.06675	-0.04993	0.00008	0.24102	-0.18996	0.50829	0.16541
12	-0.2	-0.0328	0.19	0	-0.03202	-0.05253	0.19173	-0.11902	-0.09877	0.05354	0.15086	0.06675	-0.04993	0.00008	0.24102	-0.19031	0.50829	0.16541
13	-0.2	-0.0328	0.2	0	-0.023	-0.05388	0.19376	-0.11975	-0.09877	0.05282	0.15086	0.06675	-0.04993	0.00008	0.24103	-0.19103	0.50829	0.16541
14	-0.22	-0.03608	0.2	0	-0.04355	-0.05792	0.17332	-0.10541	-0.10869	0.06026	0.15086	0.06675	-0.04993	0.00008	0.23081	-0.18369	0.50829	0.16541
15	-0.21	-0.03444	0.18	0	-0.05135	-0.05325	0.13259	-0.07667	-0.12849	0.07508	0.15086	0.06675	-0.04993	0.00008	0.2104	-0.16907	0.50829	0.16541
16	-0.2	-0.0328	0.16	0	-0.05935	-0.04885	0.13259	-0.07667	-0.12849	0.07508	0.15086	0.06675	-0.04993	0.00008	0.2104	-0.16907	0.50829	0.16541
17	-0.19	-0.03116	0.14	0	-0.06754	-0.04472	0.1027	-0.05689	-0.03909	0.01123	0.15086	0.06675	-0.04993	0.00008	0.09339	-0.08439	0.30293	0.09642
18	-0.17	-0.02788	0.10001	0	-0.08454	-0.0373	0.08149	-0.0421	-0.04906	0.01891	0.15086	0.06675	-0.04993	0.00008	0.0833	-0.07674	0.30293	0.09642
19	-0.15	-0.0246	0	0	-0.16139	-0.02967	-0.01083	0.02393	-0.11901	0.07079	0.10044	0.04976	-0.04993	0.00008	0.06316	-0.06163	0.30293	0.09642
20	-0.13	-0.02132	0	0	-0.14104	-0.02591	-0.01405	0.02571	-0.06939	0.03497	0.10044	0.04976	-0.04993	0.00008	0.01131	-0.0237	0.20129	0.06336
21	-0.12	-0.01968	0	0	-0.13088	-0.02406	-0.00508	0.01883	-0.06441	0.0317	0.10044	0.04976	-0.04993	0.00008	0.01632	-0.02696	0.20129	0.06336
22	-0.1	-0.0164	0	0	-0.11061	-0.0204	0.0019	0.01271	-0.05944	0.02912	0.10044	0.04976	-0.04993	0.00008	0.02133	-0.02952	0.20129	0.06336
23	-0.09	-0.01476	0	0	-0.10049	-0.0186	0.00789	0.00696	-0.05446	0.0269	0.10044	0.04976	-0.04993	0.00008	0.02634	-0.03174	0.20129	0.06336
24	-0.08	-0.01312	0	0	-0.09039	-0.01682	0.01188	0.00195	-0.04947	0.02538	0.10044	0.04976	-0.04993	0.00008	0.03135	-0.03325	0.20129	0.06336

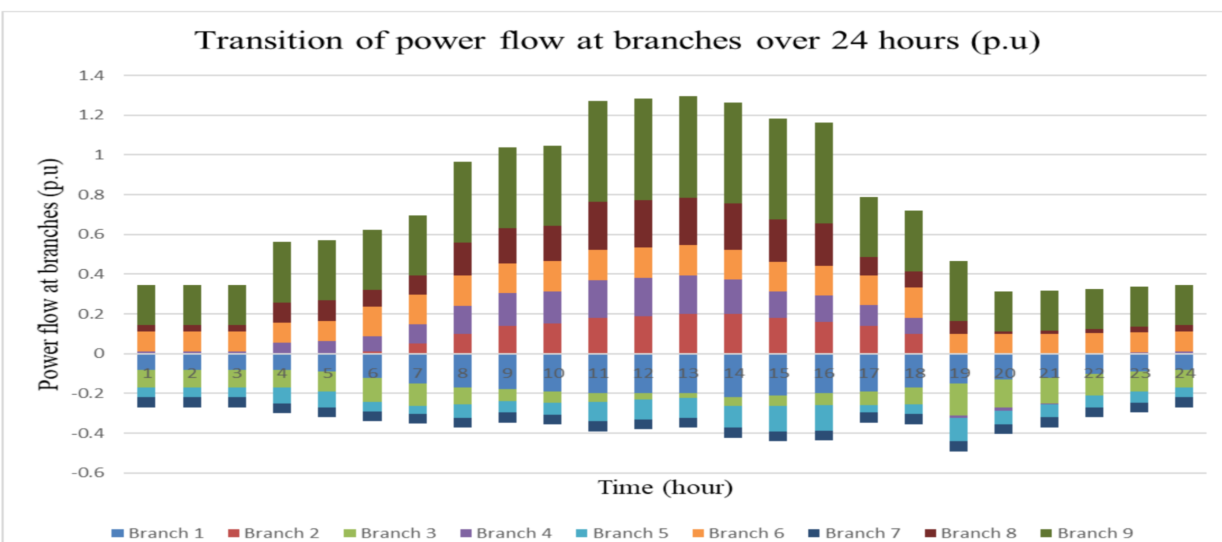


Figure 4.6 Transition of power flow at branches over 24 hours by the multi stage power flow analysis

4.6. EVALUATIONS OF POWER LOSS IN THE GRID OPERATION

The Outputs by the power flow are basically the complex voltage solutions for all nodes. Also, they include the complex generation solutions for the generation nodes, the complex power loss in the whole grid and so on, which will be computed from the voltage solutions.

In particular, the complex generation solution for the slack node has an important meaning such that it definitely indicates the adjustment in the power balance of the whole grid. That is, the equation holds that the generation of the slack the sum generations of nodes other than the slack = total loads in the grid and total power loss in the grid. Consequently, the generation value for the slack node may be negative if the total loads in the grid falls below the sum generations of nodes other than the slack.

When the active power generation of the slack node is negative, if the slack node is really of a generator, it implies that there exist no practical power flow solutions in the grid. However, if the slack node is an interconnection point to the other grid, the signed generation value of the slack node implies the in/out power transfer quantity between the other grid. In this case we can judge that a practical power flow solution has been obtained.

The complex voltage solution for each node will be output usually in the polar form with the voltage Amplitude [p.u.] and its phase angle [degree]. The active power loss rate may be about 3～5% in the standard grids.

The voltage Amplitude in nodes is one of the indicators of the voltage stability in the grids. There is a standard for voltage Amplitudes in the normal grids that the 5% deviance from 1.0 p.u. can be allowed. In the case that some voltage Amplitudes much exceed the allowable range [0.95, 1.05] p.u., the engineers should change the grid attributes especially near the nodes with high deviance.

In this module, single stage power flow analysis and mufti stage power flow analysis can be conducted simultaneously, such as:

- When the single stage power flow analysis module is used, amplitude and phase angel of voltage at each node and power flows at each branch are obtained only for one hour (stage).

- When the multi stage power flow analysis module is used, amplitude and phase angel of voltage at each node and power flows at each branch are obtained over 24 hours (stages)
- If necessary, the multi stage power flow analysis module can be applied the calculation of power flows for a week, a month and a year, when weekly, monthly and yearly data are available.

4.7. Interface of multi Stage Power Flow Analysis for Data Input, Calculation and Result Output

In the *MicroGrid Designer*, an interface of the multi stage power flow analysis for data input, calculation and results output is utilized as follows and essential results are depicted as plots and graphs.

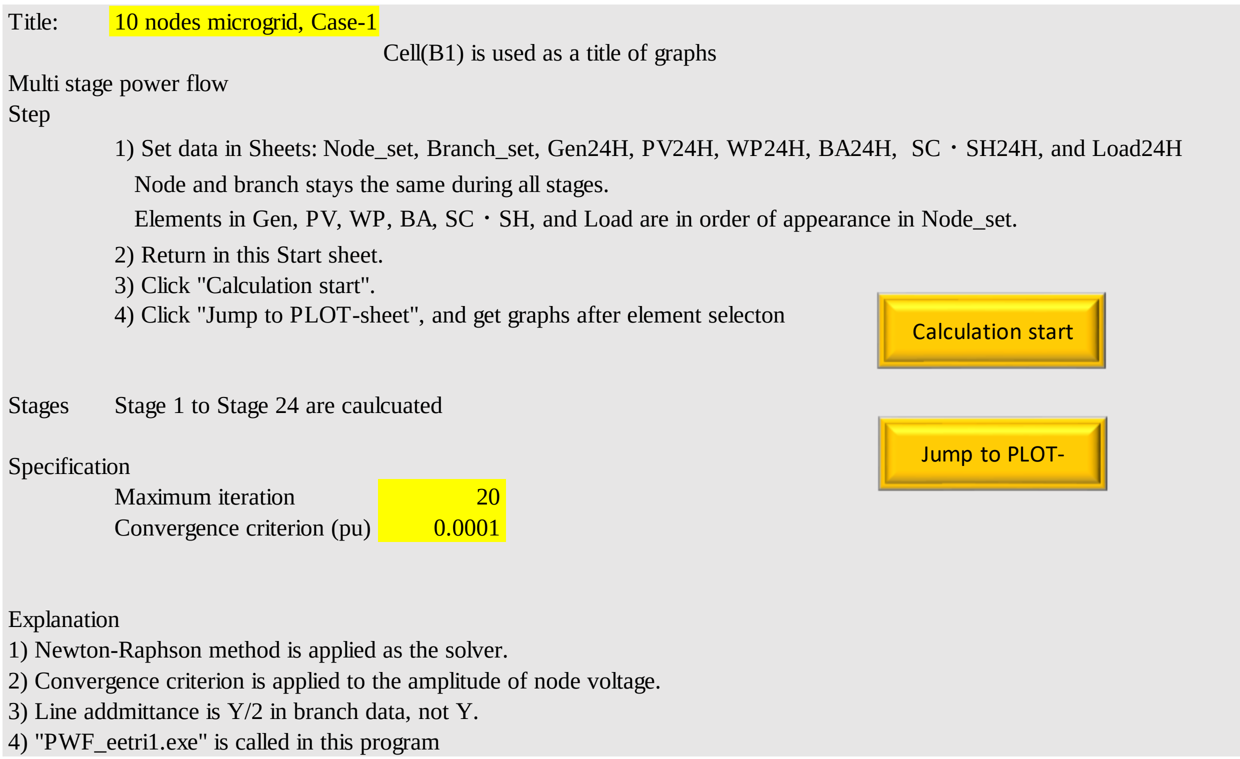


Figure 4.7 Interface of the Multistage Power Flow Analysis for data input, calculation and results output

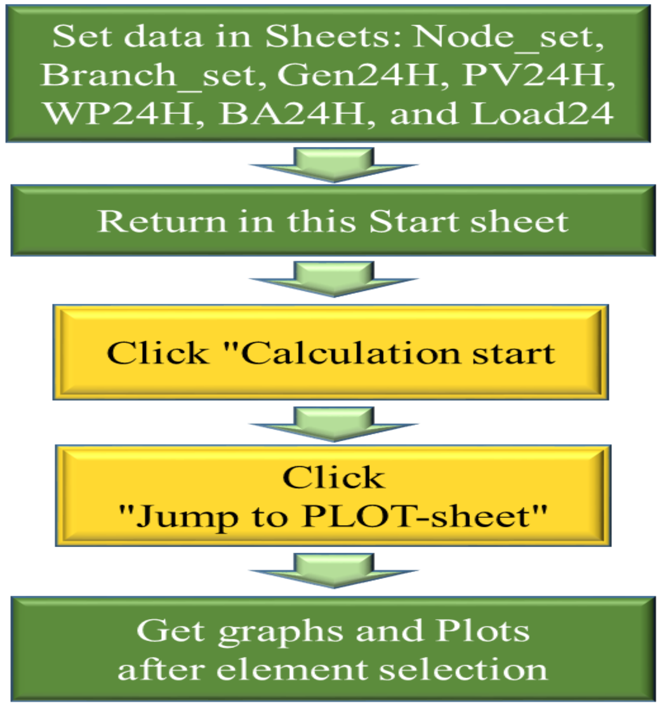


Figure 4.8 Procedure of calculations by utilizing the interface of the Multi Stage Power Flow Analysis

5. APPLICATION OF POWER FLOW ANALYSIS TO THE IEEE 30 NODE POWER SYSTEM

In the application of this power flow analysis module, single line diagram of power system and micro grid, such as, the IEEE 30 node Power System is useful to understand the structure of the grid as shown in the following. This standard power system is recommended to be used for calculations and simulations by micro grid designers and users for studies. The node data and transmission line data are also required on Base Capacity of the power system 100 MVA as in Table 5.1 and Table 5.2 respectively.

5.1. Single line diagram of the IEEE 30 node Power SYSTEM

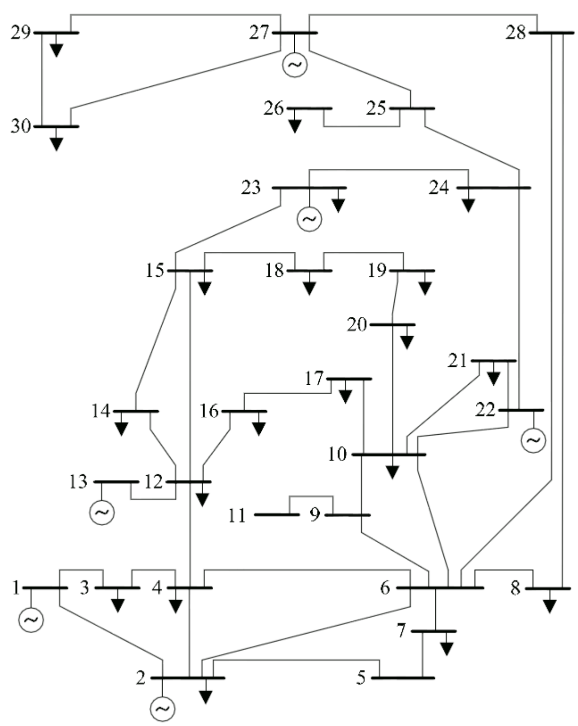


Figure 5.1 Single line diagram of the IEEE 30 node Power System (Example)

Reference:

1) IEEE 30 Node System, http://www.fglongatt.org/Test_Systems/IEEE_30node.html,

Node data for the IEEE 30 node Power System is shown as Table 5.1

Table 5.1 Input form of node data for the IEEE 30 node Power System

Node data Input Form for Single Stage Power Flow Analysis								
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql
(Up to 4 characters)	PQ=0、PV=1、,Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)
1	2	1.06	0	0			0	0
2	1	1	0	0	0.8		0.217	0.127
3	0	1	0	0			0.024	0.012
4	0	1	0	0			0.076	0.016
5	1	1	0	0	0.5		0.942	0.19
6	0	1	0	0			0	0
7	0	1	0	0			0.228	0.109
8	1	1	0	0	0.2		0.3	0.3
9	0	1	0	0			0	0
10	0	1	0	0			0.058	0.02
11	1	1	0	0	0.2		0	0
12	0	1	0	0			0.112	0.075
13	1	1	0	0	0.2		0	0
14	0	1	0	0			0.062	0.016
15	0	1	0	0			0.082	0.025
16	0	1	0	0			0.035	0.018
17	0	1	0	0			0.09	0.058
18	0	1	0	0			0.032	0.009
19	0	1	0	0			0.095	0.034
20	0	1	0	0			0.022	0.007
21	0	1	0	0			0.175	0.112
22	0	1	0	0			0	0
23	0	1	0	0			0.032	0.016
24	0	1	0	0			0.087	0.067
25	0	1	0	0			0	0
26	0	1	0	0			0.035	0.023
27	0	1	0	0			0	0
28	0	1	0	0			0	0
29	0	1	0	0			0.024	0.009
30	0	1	0	0			0.106	0.019

Table 5.2 Branch data for the IEEE 30 node Power System

Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 digit)	(Up to 4 characters)	(Up to 4 characters)	default = 1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	1	2		0.0192	0.0575	0.0264	0
2	1	3		0.0452	0.1652	0.0204	0
3	2	4		0.057	0.1737	0.0184	0
4	3	4		0.0132	0.0379	0.0042	0
5	2	5		0.0472	0.1983	0.0209	0
6	2	6		0.0581	0.1763	0.0187	0
7	4	6		0.0119	0.0414	0.0045	0
8	5	7		0.046	0.116	0.0102	0
9	6	7		0.0267	0.082	0.0085	0
10	6	8		0.012	0.042	0.0045	0
11	6	9		0	0.208	0	0
12	6	10		0	0.556	0	0
13	9	11		0	0.208	0	0
14	9	10		0	0.11	0	0
15	4	12		0	0.256	0	0
16	12	13		0	0.14	0	0
17	12	14		0.1231	0.2559	0	0
18	12	15		0.0662	0.1304	0	0
19	12	16		0.0945	0.1987	0	0
20	14	15		0.221	0.1997	0	0
21	16	17		0.0524	0.1923	0	0
22	15	18		0.1073	0.2185	0	0
23	18	19		0.0639	0.1292	0	0
24	19	20		0.034	0.068	0	0

25	10	20		0.0936	0.209	0	0
26	10	17		0.0324	0.0845	0	0
27	10	21		0.0348	0.0749	0	0
28	10	22		0.0727	0.1499	0	0
29	21	22		0.0116	0.0236	0	0
30	15	23		0.1	0.202	0	0
31	22	24		0.115	0.179	0	0
32	23	24		0.132	0.27	0	0
33	24	25		0.1885	0.3292	0	0
34	25	26		0.2544	0.38	0	0
35	25	27		0.1093	0.2087	0	0
36	28	27		0	0.396	0	0
37	27	29		0.2198	0.4153	0	0
38	27	30		0.3202	0.6027	0	0
39	29	30		0.2399	0.4533	0	0
40	8	28		0.0636	0.2	0	0
41	6	28		0.0169	0.0599	0	0

5.2. OBTAINED RESULTS FOR NODES BY SINGLE STAGE POWER FLOW ANALYSIS

Table 5.3 Output Form of Obtained Results for Nodes by Single Stage Power Flow Analysis

Output Form of Obtained Results for Nodes by Single Stage Power Flow Analysis										
Node ID	Node type	Specified voltage	Obtained value		Specified P&Q	Obtained P&Q			Injection current	
(Up to 4 characters)	PQ=0、PV=1、,Slack =2	V (p.u.)	V (p.u.)	(Degree)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	I (p.u.)	Angel (Degree)
1	2	1.06	1.06	0	0	0	1.00941	1.07891	1.39385	-46.91
2	1	1	1	-0.83	0.583	-0.127	0.583	-1.16657	1.30414	62.61
3	0	1	1.00962	-3.34	-0.024	-0.012	-0.024	-0.012	0.02658	150.1
4	0	1	0.99718	-4.06	-0.076	-0.016	-0.076	-0.016	0.07789	164.05
5	1	1	1	-6.27	-0.442	-0.19	-0.442	0.2059	0.48761	-161.29
6	0	1	0.99217	-4.92	0	0	0	0	0	-156.8
7	0	1	0.98726	-6.02	-0.228	-0.109	-0.228	-0.109	0.25598	148.43
8	1	1	1	-5.37	-0.1	-0.3	-0.1	0.27424	0.2919	-115.41
9	0	1	0.97597	-6.46	0	0	0	0	0	-169.16
10	0	1	0.95606	-8.66	-0.058	-0.02	-0.058	-0.02	0.06417	152.32

11	1	1	1	-4.02	0.2	0	0.2	0.1198	0.23313	-34.94
12	0	1	0.9764	-7.86	-0.112	-0.075	-0.112	-0.075	0.13805	138.34
13	1	1	1	-6.21	0.2	0	0.2	0.17146	0.26343	-46.82
14	0	1	0.95919	-8.91	-0.062	-0.016	-0.062	-0.016	0.06676	156.62
15	0	1	0.95312	-9	-0.082	-0.025	-0.082	-0.025	0.08994	154.04
16	0	1	0.95944	-8.49	-0.035	-0.018	-0.035	-0.018	0.04102	144.3
17	0	1	0.95164	-8.87	-0.09	-0.058	-0.09	-0.058	0.11251	138.33
18	0	1	0.94085	-9.71	-0.032	-0.009	-0.032	-0.009	0.03533	154.59
19	0	1	0.93702	-9.9	-0.095	-0.034	-0.095	-0.034	0.10768	150.41
20	0	1	0.94092	-9.66	-0.022	-0.007	-0.022	-0.007	0.02454	152.69
21	0	1	0.94249	-9.2	-0.175	-0.112	-0.175	-0.112	0.22045	138.18
22	0	1	0.94308	-9.19	0	0	0	0	0	-128.39
23	0	1	0.93939	-9.47	-0.032	-0.016	-0.032	-0.016	0.03809	143.97
24	0	1	0.93028	-9.69	-0.087	-0.067	-0.087	-0.067	0.11804	132.71
25	0	1	0.93789	-9.84	0	0	0	0	0	-123.62
26	0	1	0.91865	-10.33	-0.035	-0.023	-0.035	-0.023	0.04559	136.36
27	0	1	0.95212	-9.61	0	0	0	0	0	-137.21
28	0	1	0.98724	-5.42	0	0	0	0	0	-171.26
29	0	1	0.93061	-11.03	-0.024	-0.009	-0.024	-0.009	0.02754	148.41
30	0	1	0.91818	-12.06	-0.106	-0.019	-0.106	-0.019	0.11728	157.78

5.3. Obtained Voltage profile and active and Reactive Power at nodes

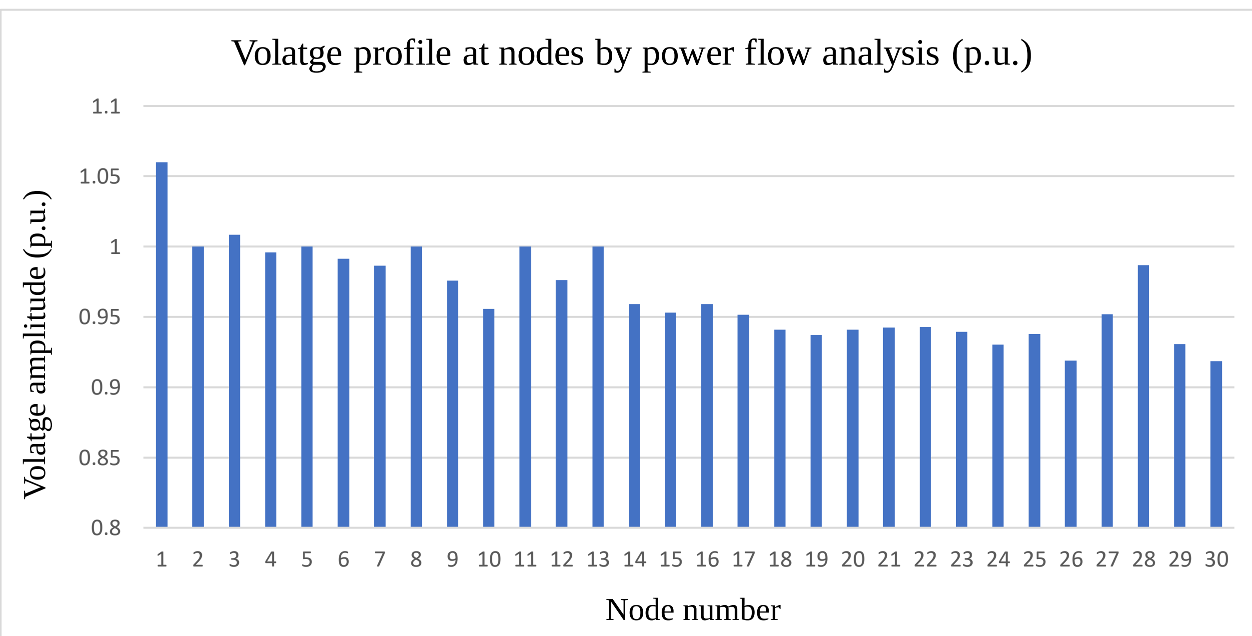


Figure 5.2 Voltage profile at nodes obtained by power flow analysis

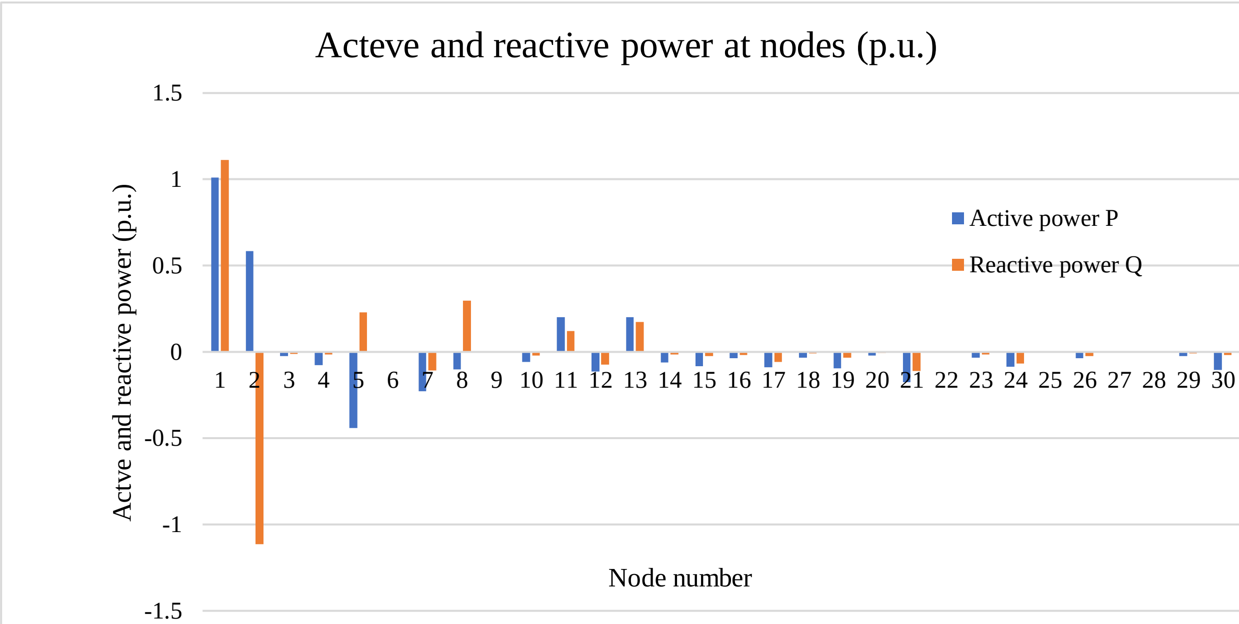


Figure 5.3 Active and reactive power at nodes obtained by power flow analysis

5.4. Obtained Results for Branches by Single Stage Power Flow Analysis

Table 5.4 Output Form of Obtained Results for Branches by Single Stage Power Flow Analysis

Output Form of Obtained Results for Branches by Single Stage Power Flow Analysis								
Branch ID	Connected nodes		Power flow from node-M		Power flow from node-N		Line current	
(Number)	M	N	P (p.u.)	Q(p.u.)	P(p.u.)	Q(p.u.)	I (p.u.)	Phase angle (Degree)
1	1	2	0.57355	0.88685	-0.55358	-0.88309	0.99637	-57.11
2	1	3	0.43585	0.19206	-0.42635	-0.20105	0.44933	-23.78
3	2	4	0.29931	-0.09129	-0.2939	0.07107	0.31292	16.13
4	3	4	0.40235	0.18905	-0.39977	-0.1901	0.44032	-28.5
5	2	5	0.45754	-0.10709	-0.44731	0.10828	0.4699	12.34
6	2	6	0.37973	-0.0851	-0.3711	0.07419	0.38915	11.8
7	4	6	0.36588	0.01373	-0.36427	-0.01704	0.36717	-6.21
8	5	7	0.00531	0.09762	-0.00477	-0.11641	0.09777	-93.16
9	6	7	0.2246	-0.01985	-0.22323	0.00741	0.22726	0.13
10	6	8	0.12269	-0.22366	-0.12192	0.21742	0.25711	56.33
11	6	9	0.12487	0.07897	-0.12487	-0.07436	0.14891	-37.23

12	6	10	0.11105	0.06806	-0.11105	-0.05848	0.13127	-36.43
13	9	11	-0.2	-0.10849	0.2	0.1198	0.23313	145.06
14	9	10	0.32487	0.18285	-0.32487	-0.1668	0.38197	-35.83
15	4	12	0.25179	0.0893	-0.25179	-0.07093	0.26791	-23.59
16	12	13	-0.2	-0.16174	0.2	0.17146	0.26343	133.18
17	12	14	0.08064	0.0275	-0.0797	-0.02555	0.08726	-26.68
18	12	15	0.18428	0.08216	-0.18145	-0.07659	0.20665	-31.88
19	12	16	0.07487	0.04801	-0.07409	-0.04636	0.09109	-40.52
20	14	15	0.0177	0.00955	-0.01761	-0.00946	0.02097	-37.26
21	16	17	0.03909	0.02836	-0.03895	-0.02787	0.05033	-44.45
22	15	18	0.06206	0.02336	-0.06154	-0.0223	0.06957	-29.63
23	18	19	0.02954	0.0133	-0.02946	-0.01315	0.03443	-33.95
24	19	20	-0.06554	-0.02085	0.06572	0.02122	0.0734	152.45
25	10	20	0.08862	0.03022	-0.08772	-0.02822	0.09793	-27.49
26	10	17	0.05117	0.03046	-0.05105	-0.03013	0.06229	-39.42
27	10	21	0.16035	0.09926	-0.159	-0.09635	0.19725	-40.41
28	10	22	0.07777	0.04534	-0.07713	-0.04401	0.09416	-38.89
29	21	22	-0.016	-0.01565	0.01601	0.01567	0.02375	126.43
30	15	23	0.055	0.0377	-0.05451	-0.03671	0.06996	-43.42
31	22	24	0.06112	0.02834	-0.06053	-0.02743	0.07144	-34.06
32	23	24	0.02251	0.02071	-0.02237	-0.02042	0.03256	-52.08
33	24	25	-0.00409	-0.01915	0.00418	0.0193	0.02105	92.37
34	25	26	0.03553	0.02379	-0.035	-0.023	0.04559	-43.64
35	25	27	-0.03971	-0.04309	0.04013	0.0439	0.06247	122.82
36	28	27	0.17342	0.09391	-0.17342	-0.07811	0.19977	-33.85
37	27	29	0.06211	0.01709	-0.0611	-0.01519	0.06765	-24.99
38	27	30	0.07118	0.01712	-0.06929	-0.01355	0.0769	-23.13
39	29	30	0.0371	0.00619	-0.03671	-0.00545	0.04042	-20.5
40	8	28	0.02192	0.05682	-0.02169	-0.05607	0.0609	-74.27
41	6	28	0.15216	0.03934	-0.15174	-0.03784	0.1584	-19.42

5.5. OBTAINED ACTIVE /REACTIVE POWER FLOW ON BRANCHES BY POWER FLOW ANALYSIS

Obtained results of active and reactive power flow, amplitude and phase angel of line current at branches are depicted as graphs or plots by using Excel function as shown in Figure5.4 ～5.6.

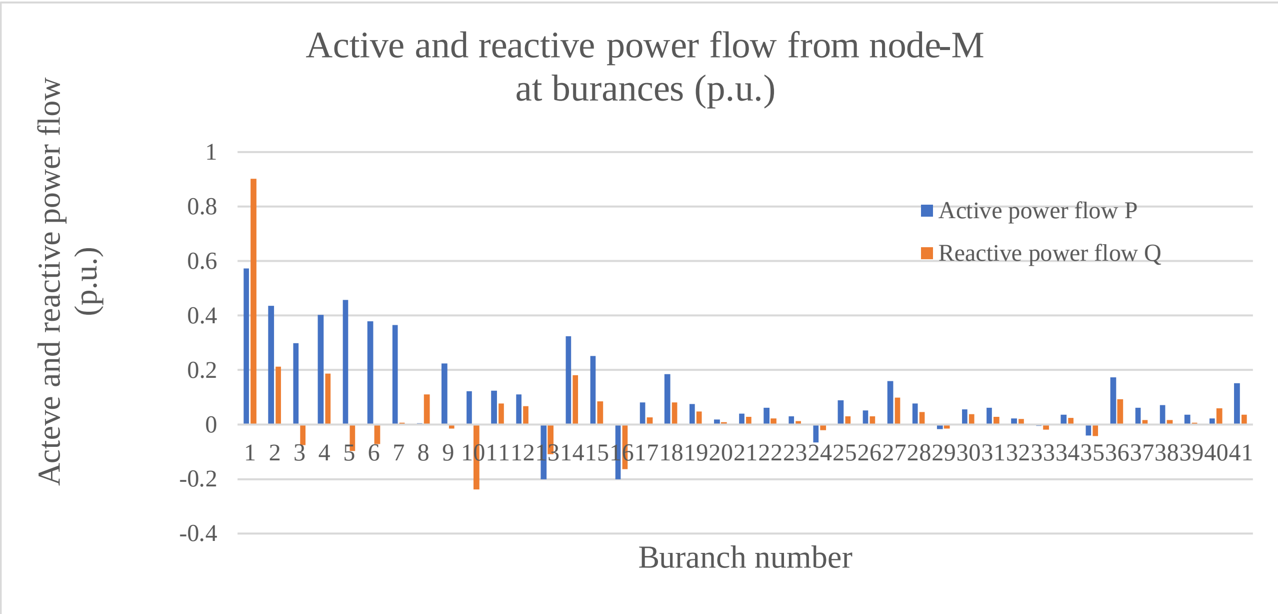


Figure 5.4 Active and reactive power flow at branches obtained by power flow analysis

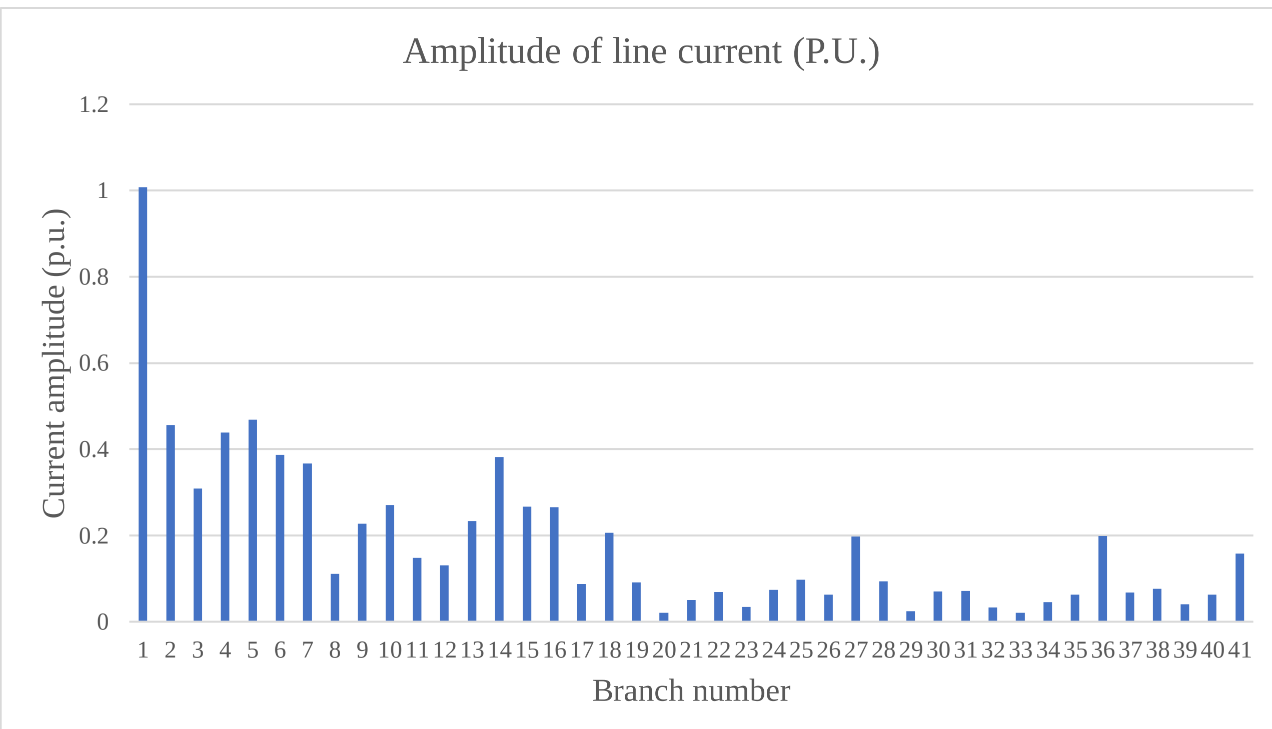


Figure 5.5 Amplitude of line current obtained by power flow analysis

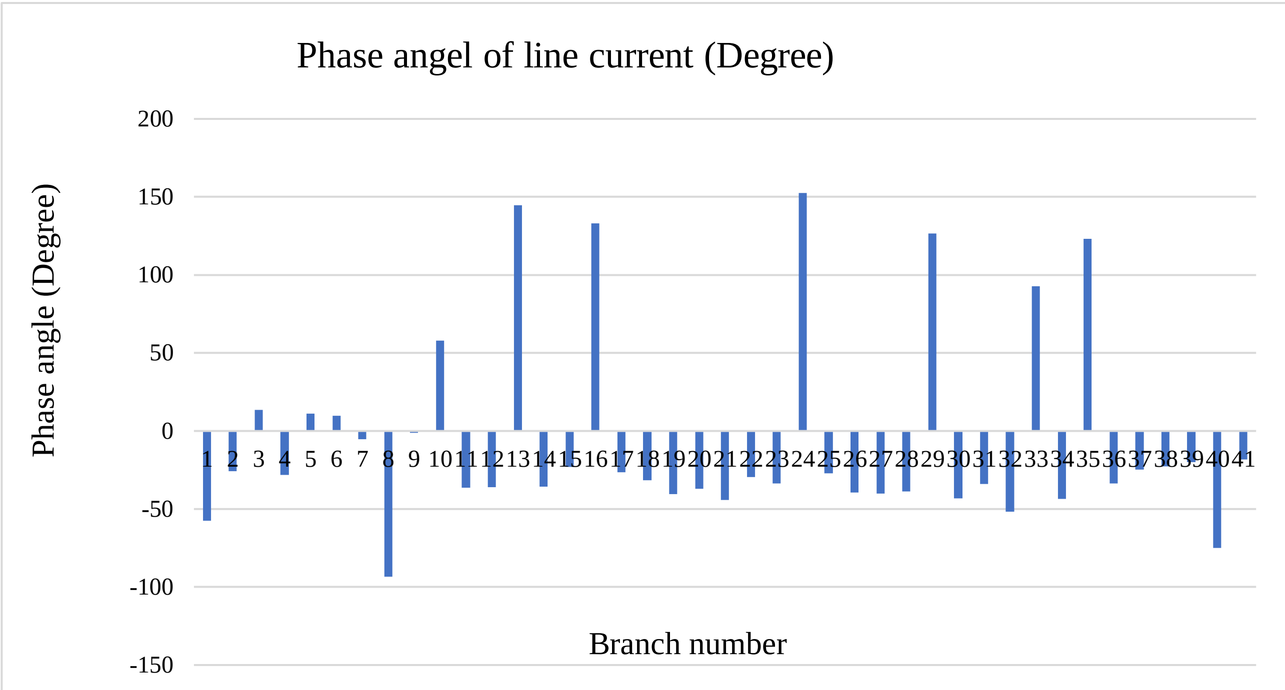


Figure 5.6 Phase angel of line current at branches obtained by power flow analysis

5.6. Interface of Single Stage Power Flow Analysis for Data input, Calculation and Result output

In **the *MicroGrig Sim***, an interface of the single stage power flow analysis for data input, calculation and results output is utilized as follows and essential results are depicted as plots and graphs.

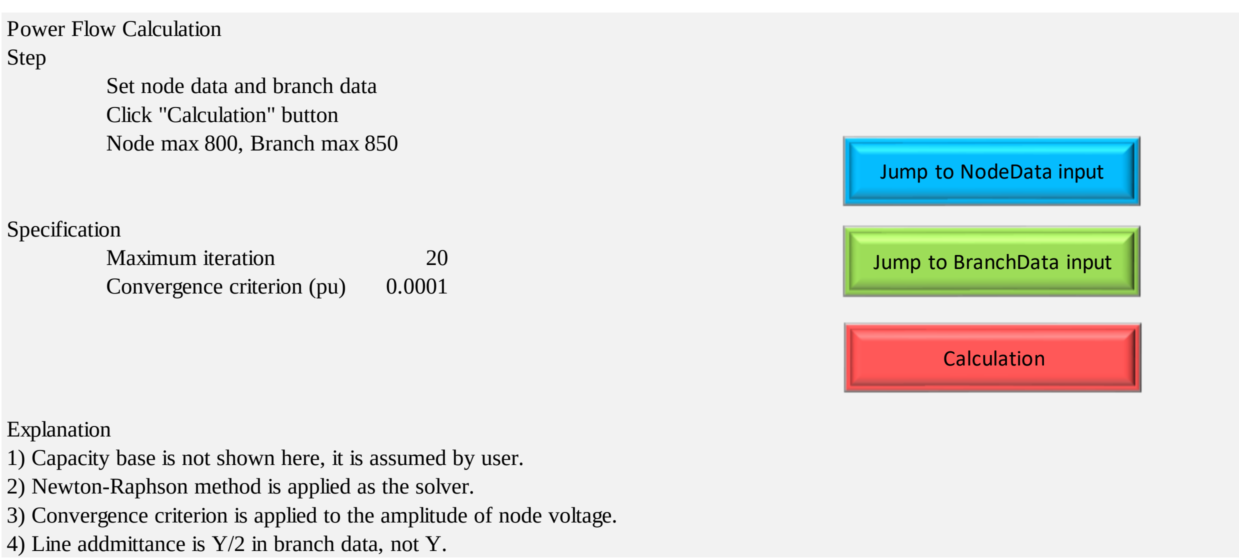


Figure 5.7 Interface of the single stage power flow analysis for data input, calculation and results output

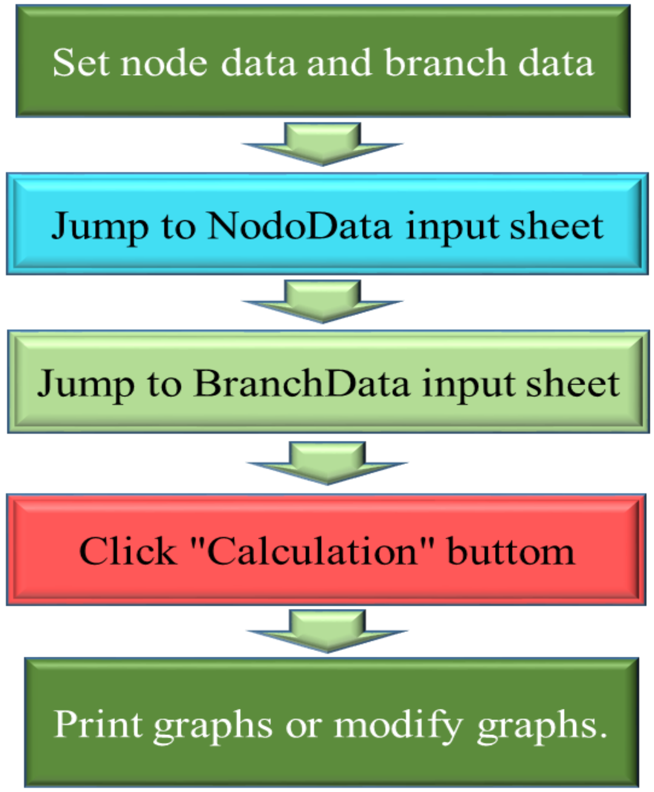


Figure 5.8 Procedure of Calculations by utilizing the interface of Power Flow Analysis

5.7. EXTENSION OF POWER FLOW ANALYSIS TO LONG TERM POWER FLOW ANALYSIS

For the power flow analysis with time-dependent input data, the power flow is solved retentively with multi sage equations describing system with multi stage behaviors, leading to the Multi Stage Power Flow Analysis as mentioned in the previous chapter.

In the Multi Stage Power Flow Analysis, Single Stage Power Flow is carried out repetitively for time varying loads to determine the transitions of voltages, line currents, and active and reactive power flows in the system over time horizon.

By using The Multi Stage Power Flow Analysis, the following solutions can be available.

- One-hour power system profile can be calculated by solving the single stage power flow analysis

- One day total power system profile can be calculated by the sum of 24 sets of hourly data for one day;
- One month and one-year power system profile and the power loss evaluation can be calculated based on the multi stage power flow analysis;

The power flow analysis for 24 hours already has been shown in Chapter 6.

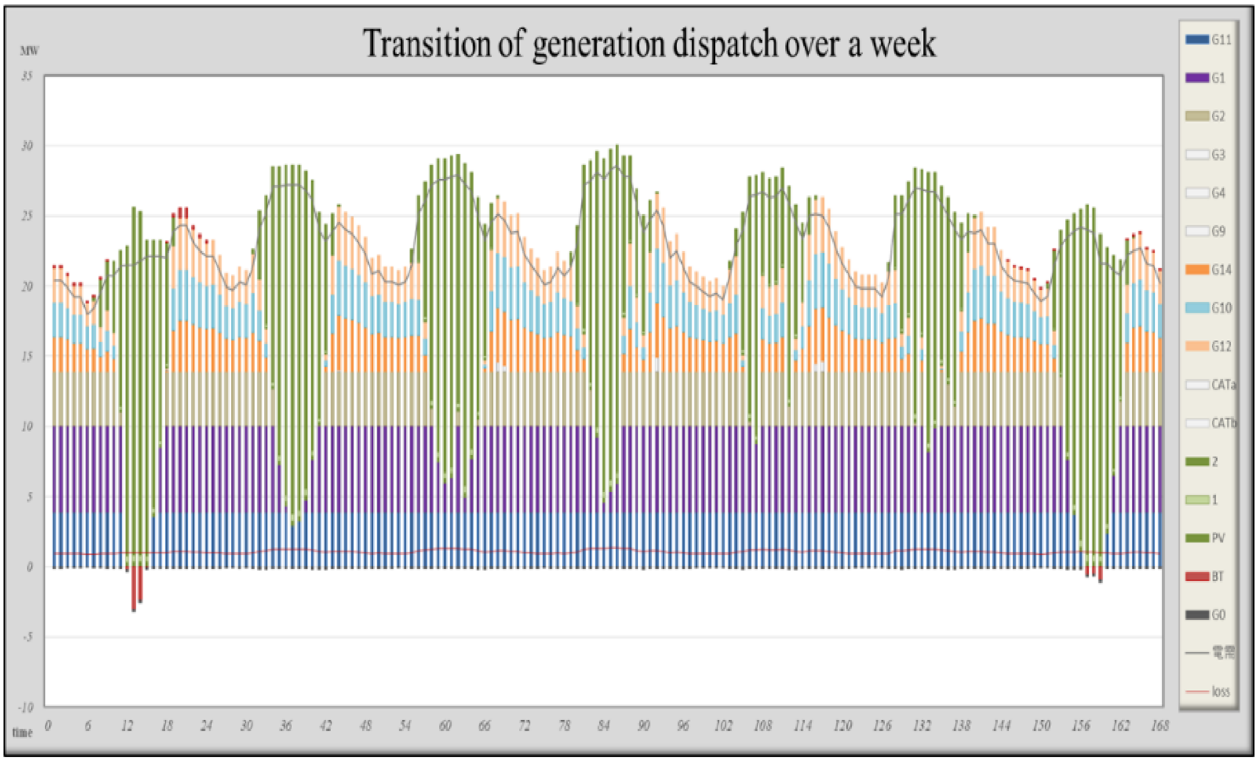


Figure 5.9 Image of transition of Generation dispatch by the extended power flow analysis

6. APPENDIX-A FORMULATIONS AND SOLUTION OF POWER FLOW ANALYSIS

6.1. COMPONENTS OF POWER SYSTEM

An electric power system is composed of generators, transformers, transmission lines and loads. A simple power system is illustrated in the Figure below.

In the process of power system analysis, the static components, such as transformers, transmission lines, shunt capacitors and reactors, are represented by their equivalent consisting of R, L,C elements. Therefore, the network formed by these static components can be considered as a linear network and represented by the corresponding admittance matrix or impedance matrix.

In load flow calculation, the generators and loads are treated as nonlinear components.

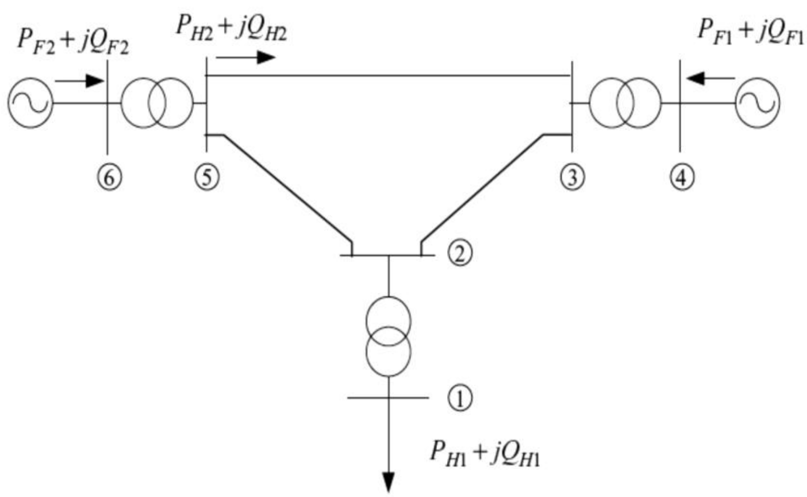


Figure 6.1 Components of Power system

The first step in developing the mathematical model describing the power flow in the network is the formulation of the node admittance matrix.

The generators and loads cannot be embodied in the linear network, see the Figure.

In load flow calculation, the generators and loads are treated as nonlinear components.

The connecting nodes with zero injected power also represent boundary conditions on the network

The key step in developing the mathematical model describing the power flow in the network is the formulation of the node admittance matrix, which is an n×n matrix (where n is the number of nodes) constructed from the admittances of the equivalent circuit elements of the segments making up the power system. Most system segments are represented by a combination of shunt elements (connected between a node and the reference node) and series elements (connected between two system nodes). Formulation of the node admittance matrix follows two simple rules:

The admittance of elements connected between node k and reference is added to the (k, k) entry of the admittance matrix.

The admittance of elements connected between nodes j and k is added to the (j, j) and (k, k) entries of the admittance matrix. The negative of the admittance is added to the (j, k) and (k, j) entries of the admittance matrix.

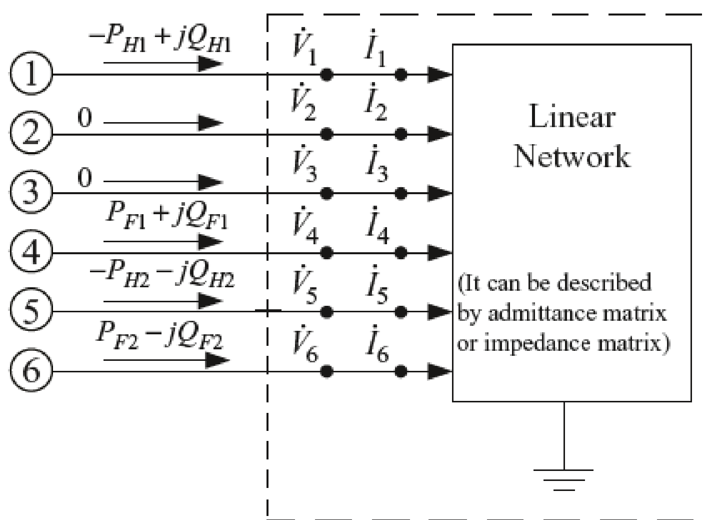


Figure 6.2 linear network of power system

6.2. POWER FLOW EQUATION

The relationship between node current and voltage in the linear network can be described by the following node equation:

$$\begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \\ \vdots \\ \bar{I}_n \end{bmatrix} = \begin{bmatrix} \bar{Y}_{11} & \bar{Y}_{12} & \cdots & \bar{Y}_{1n} \\ \bar{Y}_{21} & \bar{Y}_{22} & \cdots & \bar{Y}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \bar{Y}_{n1} & \bar{Y}_{n2} & \cdots & \bar{Y}_{nn} \end{bmatrix} \begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \\ \vdots \\ \bar{V}_n \end{bmatrix}$$

Or

$$\dot{I}_i = \sum_{j=1}^{n} Y_{ij}\dot{V}_j \quad (i = 1, 2, \ldots, n)$$

where Ii and Vj are the injected current at node i and voltage at node j, respectively, *Yij* is an element of the admittance matrix, n is the total number of nodes in the system.

To solve the load flow equation, the relation of node power with current should be used

$$\dot{I}_i = \frac{P_i - jQ_i}{\hat{V}_i} \quad (i = 1, 2, \ldots, n)$$

where Pi, Qi are the injected active and reactive power at node i, respectively.

If node i is a load node, then Pi and Qi should take negative values.

In the above equation, $\dot{V}_i$ is the conjugate of the voltage vector at node i. Substituting this relation, we have,

$$\frac{P_i - jQ_i}{\hat{V}_i} = \sum_{j=1}^{n} Y_{ij}\dot{V}_j \quad (i = 1, 2, \ldots, n)$$

Or

$$\frac{P_i + jQ_i}{\dot{V}_i} = \sum_{j=1}^{n} \hat{Y}_{ij}\hat{V}_j \quad (i = 1, 2, \ldots, n)$$

There are n nonlinear complex equations. They are the principal equations in load flow calculation. Based on different methods to solve these equations, various load flow algorithms can be formed.

In the power system load flow problem, the variables are nodal complex voltages and complex powers: V, δ, P, Q.

If there are n nodes in a power system, then the total number of variables is 4 n. There are n complex equations or 2n real equations defined in principal by PF equation, thus only 2n variables can be solved from these equations, while the other 2n variables should be specified as original data.

Usually, two variables at each node are assumed known, while the other two variables are treated as state variables to be resolved. According to the original data, the nodes in power systems can be classified into three types.

As described above, power system load flow calculations can be roughly considered as the problem of solving the node voltage phasor for each node when the injecting complex power is specified. If the complex power can be represented by equations of complex voltages, then a nonlinear equation solving method, such as the Newton–Raphson method, can be used to solve the node voltage phasors.

The complex node voltage has two representation forms, the polar form and the rectangular form. Accordingly, the node power equations also have two forms and the node power equations can be expressed as;

$$P_i + jQ_i = \dot{V}_i \sum_{j \in i} \hat{Y}_{ij}\hat{V}_j \quad (i = 1, 2, \ldots, n)$$

Where j € i means the node j should be directly connected with node i, including j . i. and the admittance matrix is a sparse matrix and the terms in S are correspondingly few.

If the voltage vector is expressed by the polar form,

$$\dot{V}_i = V_i e^{j\theta_i}$$

Where *Vi* , *yi* are the Amplitude and phase angle of voltage at node i.

The elements of admittance matrix can be expressed as

$$Y_{ij} = G_{ij} + jB_{ij}$$

Hence nodal powers can be rewritten as

$$P_i + jQ_i = V_i e^{j\theta_i} \sum_{j \in i} (G_{ij} - jB_{ij}) V_j e^{-j\theta_j} \quad (i = 1, 2, \ldots, n)$$

Combining the exponential items of above equation and using the exponential relationship

$$P_i + jQ_i = V_i \sum_{j \in i} V_j (G_{ij} - jB_{ij})(\cos\theta_{ij} + j\sin\theta_{ij}) \quad (i = 1, 2, \ldots, n)$$

Where yij -jΘ , yi yj is the voltage phase angle difference between node i and j.

Dividing above equations into real and imaginary parts,

$$\left.\begin{aligned} P_i &= V_i \sum_{j \in i} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i &= V_i \sum_{j \in i} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{aligned}\right\} \quad (i = 1, 2, \cdots, n)$$

This is the polar form of the nodal power equations. It is not only very important in the Newton–Raphson calculation process, but also essential to establish the fast decoupled method.

When the voltage vector is expressed in rectangular form,

$$\dot{V}_i = e_i + jf_i \qquad e_i = V_i \cos\theta_i \quad f_i = V_i \sin\theta_i$$

We can obtain the following from;

$$\left.\begin{aligned} P_i &= e_i \sum_{j\in i} (G_{ij}e_j - B_{ij}f_j) + f_i \sum_{j\in i} (G_{ij}f_j + B_{ij}e_j) \\ Q_i &= f_i \sum_{j\in i} (G_{ij}e_j - B_{ij}f_j) - e_i \sum_{j\in i} (G_{ij}f_j + B_{ij}e_j) \end{aligned}\right\} \quad (i = 1, 2, \ldots, n)$$

Let

$$\left.\begin{aligned} \sum_{j\in i} (G_{ij}e_j - B_{ij}f_j) &= a_i \\ \sum_{j\in i} (G_{ij}f_j + B_{ij}e_j) &= b_i \end{aligned}\right\}$$

$$\left.\begin{aligned} P_i &= e_i a_i + f_i b_i \\ Q_i &= f_i a_i - e_i b_i \end{aligned}\right\} \quad (i = 1, 2, \ldots, n)$$

Obviously, a_i and bi are the real and imaginary parts of injected current at node I and this is the rectangular form of the nodal power equations. Both equations are the simultaneous nonlinear equations of node voltage phasors. They are usually expressed as the following forms as mathematical models of the load flow problem.

$$\left.\begin{aligned} \Delta P_i &= P_{\mathrm{is}} - V_i \sum_{j\in i} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \\ \Delta Q_i &= Q_{\mathrm{is}} - V_i \sum_{j\in i} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \end{aligned}\right\} \quad (i = 1, 2, \ldots, n)$$

where P_{is}, Q_{is} are the specified active and reactive powers at node i.

6.3. Classification of Nodes into Three Types

In the power system load flow problem, the variables are nodal complex voltages and complex powers: V, δ, P, Q.

If there are n nodes in a power system, then the total number of variables is 4 n.

There are n complex equations or 2n real equations defined in principal by PF equation, thus only 2n variables can be solved from these equations, while the other 2n variables should be specified as original data.

Usually, two variables at each node are assumed known, while the other two variables are treated as state variables to be resolved. According to the original data, the nodes in power systems can be classified into three types

Bus type		Data inputs	Unknown variables
SL		V, δ	P, Q
PQ		P, Q	V, δ
PV		P, V	δ, Q
Coupled	P	P, K	V, δ, Q
	PVQ	P, V, Q	δ

Figure 6.1 Classification of Nodes into Three Types

PQ Nodes:

For PQ nodes, the active and reactive power (P;Q) are specified as known parameters, and the complex voltage (V; y) is to be resolved.

Usually, substation nodes are taken as PQ nodes where the load powers are given constants.

When output P and Q are fixed in some power plants, these nodes can also be taken as PQ node. Most nodes in power systems belong to the PQ type in load flow calculation.

PV Nodes:

For PV nodes, active power P and voltage Amplitude V are specified as known variables, while reactive power Q and voltage angle y are to be resolved.

Usually, PV nodes should have some controllable reactive power resources and can thus maintain node voltage Amplitude at a desirable value.

Generally speaking, the nodes of power plants can be taken as PV nodes, because voltages at these nodes can be controlled with reactive power capacity of their generators and some substations can also be considered as PV nodes when they have enough reactive power compensation devices to control the voltage.

Slack Node:

In load flow studies, there should be one and only one slack node specified in the power system, which is specified by a voltage, constant in Amplitude and phase angle, and therefore, V and y are given as known variables at the slack node, while the active power P and reactive power Q are the variables to be solved.

The effective generator at this node supplies the losses to the network. This is necessary because the Amplitude of losses will not be known until the calculation of currents is complete, and this cannot be achieved unless one node has no power constraint and can feed the required losses into the system.

6.4. Load Flow Solution by Newton–Raphson Method

The Newton–Raphson method is an efficient algorithm to solve nonlinear equations. Based on the power flow simultaneous equations, the load flow problem can be roughly summarized as: for specified *Pis, Qis* (i=1; 2; . . . ; n), find voltage vector *Vi, δi* or *ei,* fi (1; 2; . . . ; n), such that the Amplitudes of the power errors *ΔPi, ΔQi,*

(i = 1; 2; . . . ; n) in equations are less then an acceptable tolerance.

It transforms the procedure of solving nonlinear equations into the procedure of repeatedly solving linear equations and this sequential linearization process is the core of the Newton–Raphson method and we now introduce the Newton–Raphson method by the following nonlinear equation.

$$f(x) = 0$$

$$x = x^{(0)} - \Delta x^{(0)}$$

Let x(0) be the initial guess value of the above equation solution and assume the real solution x is close to x(0),

$$f(x^{(0)} - \Delta x^{(0)}) = 0$$

Where Δx(0) is a modification value of x(0) and the following equation holds.

When Δx(0) is known, the solution x can be calculated by expanding this function in a Taylor series expansion about point x(0) yields:

$$f(x^{(0)} - \Delta x^{(0)}) = f(x^{(0)}) - f'(x^{(0)})\Delta x^{(0)} + f''(x^{(0)})\frac{(\Delta x^{(0)})^2}{2!} - \cdots + (-1)^n f^{(n)}(x^{(0)})\frac{(\Delta x^{(0)})^n}{n!} + \cdots = 0$$

Then, f'1 (x(0) ,. . ., f ' n(x(0)) are the different order partial derivatives of f (x) at x(0).

If the initial guess is sufficiently close to the actual solution, the higher order terms of the Taylor series expansion could be neglected and equation becomes,

$$f(x^{(0)}) - f'(x^{(0)})\Delta x^{(0)} = 0$$

This is a linear equation in *Δx(0)* and can be easily solved and using *Δx(0)* to modify x（0）, we can get x（1）:

$$x^{(1)} = x^{(0)} - \Delta x^{(0)}$$

$x^{(1)}$ may be more close to the actual solution. Then using x（1） as the new guess value, we solve the following equation similar to the above equation,

$$f(x^{(1)}) - f'(x^{(1)})\Delta x^{(1)} = 0$$

Thus $x(2)$ is obtained:

$$x^{(2)} = x^{(1)} - \Delta x^{(1)}$$

Repeating this procedure, we establish the correction equation in the t-th iteration:

$$f(x^{(t)}) - f'(x^{(t)})\Delta x^{(t)} = 0$$

The left hand of the equation can be considered as the error produced by approximate solution x(t).

When f (x(t)) becomes zero, the equation is satisfied, so *x(t)* is the solution of the equation. *f'(x(t))* is the first-order partial derivative of function f (x) at point x(t). It is also the slope of the curve at point *x(t)*, as shown in the Figure.

The correction value *Δx(t)* *i*s determined by the intersection of the tangent line at x(t)with the abscissa.

Where.

$$f(x^{(t)}) = f'(x^{(t)})\Delta x^{(t)}$$

$$\tan \alpha^{(t)} = f'(x^{(t)})$$

We can comprehend the iterative process more intuitively from the following Figure.

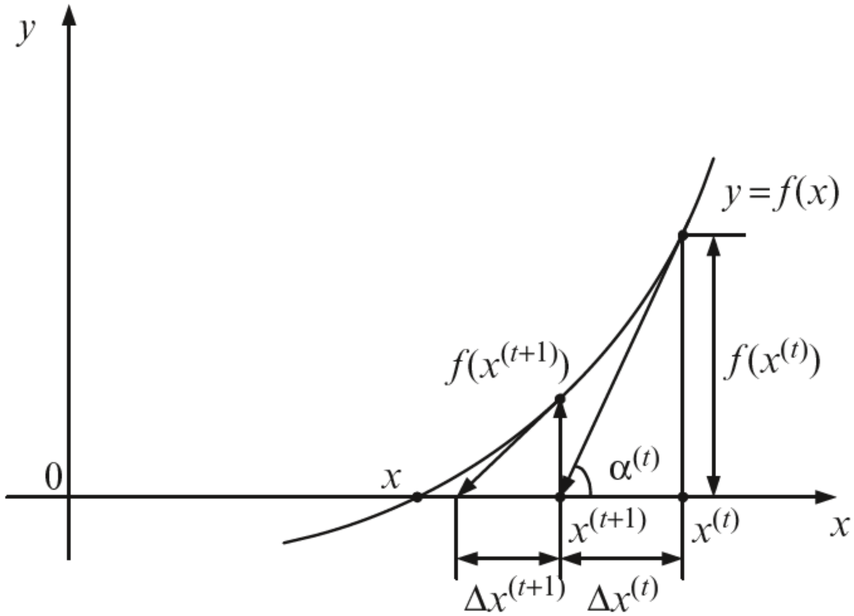


Figure 6.3 Iterative Solution by the Newton–Raphson Method

6.5. EXTENSION OF THE NEWTON METHOD TO SIMULTANEOUS NONLINEAR EQUATIONS

Now we will extend the Newton method to simultaneous nonlinear equations.

Assume the nonlinear equations with variables *x1, x2 . . . xn* as shown the equation left. Specify the initial guess values of all variables *xn(1)* be the correction values to satisfy the next equations, will approach the actual solution more closely.

The updated values are used as the new guess to solve the correction equation and to further correct the variables. In this way the iterative process of the Newton–Raphson method is formed.

Generally, the correction equation in the t-th iteration can be written as the right equation.

$$\left.\begin{aligned} x_1^{(1)} &= x_1^{(0)} - \Delta x_1^{(0)} \\ x_2^{(1)} &= x_2^{(0)} - \Delta x_2^{(0)} \\ \vdots \quad & \quad \vdots \quad\quad \vdots \\ x_n^{(1)} &= x_n^{(0)} - \Delta x_n^{(0)} \end{aligned}\right\}$$

$$\left.\begin{aligned} & f_1(x_1^{(0)} - \Delta x_1^{(0)}, x_2^{(0)} - \Delta x_2^{(0)}, \ldots, x_n^{(0)} - \Delta x_n^{(0)}) = 0 \\ & f_2(x_1^{(0)} - \Delta x_1^{(0)}, x_2^{(0)} - \Delta x_2^{(0)}, \ldots, x_n^{(0)} - \Delta x_n^{(0)}) = 0 \\ & \vdots \\ & f_n(x_1^{(0)} - \Delta x_1^{(0)}, x_2^{(0)} - \Delta x_2^{(0)}, \ldots, x_n^{(0)} - \Delta x_n^{(0)}) = 0 \end{aligned}\right\}$$

Expanding the above n equations via the multivariate Taylor series and neglecting the higher order terms, we have the following equations

$$\left.\begin{aligned} & f_1(x_1^{(0)}, x_2^{(0)}, \ldots, x_n^{(0)}) - \left[\frac{\partial f_1}{\partial x_1}\Big|_0 \Delta x_1^{(0)} + \frac{\partial f_1}{\partial x_2}\Big|_0 \Delta x_2^{(0)} +, \ldots, + \frac{\partial f_1}{\partial x_n}\Big|_0 \Delta x_n^{(0)}\right] = 0 \\ & f_2(x_1^{(0)}, x_2^{(0)}, \ldots, x_n^{(0)}) - \left[\frac{\partial f_2}{\partial x_1}\Big|_0 \Delta x_1^{(0)} + \frac{\partial f_2}{\partial x_2}\Big|_0 \Delta x_2^{(0)} +, \ldots, + \frac{\partial f_2}{\partial x_n}\Big|_0 \Delta x_n^{(0)}\right] = 0 \\ & \vdots \\ & f_n(x_1^{(0)}, x_2^{(0)}, \ldots, x_n^{(0)}) - \left[\frac{\partial f_n}{\partial x_1}\Big|_0 \Delta x_1^{(0)} + \frac{\partial f_n}{\partial x_2}\Big|_0 \Delta x_2^{(0)} +, \ldots, + \frac{\partial f_n}{\partial x_n}\Big|_0 \Delta x_n^{(0)}\right] = 0 \end{aligned}\right\}$$

The above equation in matrix form is shown as follows.

$$\begin{bmatrix} f_1(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \\ f_2(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \\ \vdots \quad \vdots \quad \vdots \\ f_n(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1}\big|_t \frac{\partial f_1}{\partial x_2}\big|_t \cdots \frac{\partial f_1}{\partial x_n}\big|_t \\ \frac{\partial f_2}{\partial x_1}\big|_t \frac{\partial f_2}{\partial x_2}\big|_t \cdots \frac{\partial f_2}{\partial x_n}\big|_t \\ \vdots \quad \vdots \quad \vdots \\ \frac{\partial f_n}{\partial x_1}\big|_t \frac{\partial f_n}{\partial x_2}\big|_t \cdots \frac{\partial f_n}{\partial x_n}\big|_t \end{bmatrix} \begin{bmatrix} \Delta x_1^{(t)} \\ \Delta x_2^{(t)} \\ \vdots \\ \Delta x_n^{(t)} \end{bmatrix}$$

This is a set of simultaneous linear equations in the variables Δx usually called the correction equations of the Newton–Raphson method.

After solving Δx ; we can get,

$$\left.\begin{array}{l} x_1^{(1)} = x_1^{(0)} - \Delta x_1^{(0)} \\ x_2^{(1)} = x_2^{(0)} - \Delta x_2^{(0)} \\ \quad\vdots \qquad \vdots \qquad \vdots \\ x_n^{(1)} = x_n^{(0)} - \Delta x_n^{(0)} \end{array}\right\}$$

x_n (1) will approach the actual solution more closely and the updated values are used as the new guess to solve the above correction equation and to further correct the variables.

In this way the iterative process of the Newton–Raphson method is formed.

Generally, the correction equation in the t-th iteration can be written as,

$$\begin{bmatrix} f_1(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \\ f_2(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \\ \vdots \quad \vdots \quad \vdots \\ f_n(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1}\big|_t & \frac{\partial f_1}{\partial x_2}\big|_t & \cdots & \frac{\partial f_1}{\partial x_n}\big|_t \\ \frac{\partial f_2}{\partial x_1}\big|_t & \frac{\partial f_2}{\partial x_2}\big|_t & \cdots & \frac{\partial f_2}{\partial x_n}\big|_t \\ \vdots & \vdots & & \vdots \\ \frac{\partial f_n}{\partial x_1}\big|_t & \frac{\partial f_n}{\partial x_2}\big|_t & \cdots & \frac{\partial f_n}{\partial x_n}\big|_t \end{bmatrix} \begin{bmatrix} \Delta x_1^{(t)} \\ \Delta x_2^{(t)} \\ \vdots \\ \Delta x_n^{(t)} \end{bmatrix}$$

The above equations are expressed in matrix form.

$$\mathbf{F}(\mathbf{X}^{(t)}) = \mathbf{J}^{(t)} \Delta \mathbf{X}^{(t)}$$

Where,

$$\mathbf{F}(\mathbf{X}^{(t)}) = \begin{bmatrix} f_1(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \\ f_2(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \\ \vdots \\ f_n(x_1^{(t)}, x_2^{(t)}, \ldots, x_n^{(t)}) \end{bmatrix} \quad \mathbf{J}^{(t)} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1}|_t \frac{\partial f_1}{\partial x_2}|_t \cdots \frac{\partial f_1}{\partial x_n}|_t \\ \frac{\partial f_2}{\partial x_1}|_t \frac{\partial f_2}{\partial x_2}|_t \cdots \frac{\partial f_2}{\partial x_n}|_t \\ \vdots \\ \frac{\partial f_n}{\partial x_1}|_t \frac{\partial f_n}{\partial x_2}|_t \cdots \frac{\partial f_n}{\partial x_n}|_t \end{bmatrix} \quad \Delta\mathbf{X}^{(t)} = \begin{bmatrix} \Delta x_1^{(t)} \\ \Delta x_2^{(t)} \\ \vdots \\ \Delta x_n^{(t)} \end{bmatrix}$$

The correction value vector in the t-th iteration and convergence can be evaluated by the norm of the correction value by the norm of the function.

$$\mathbf{X}^{(t+1)} = \mathbf{X}^{(t)} - \Delta\mathbf{X}^{(t)}$$

$$\left\|\mathbf{F}(\mathbf{X}^{(t)})\right\| < \varepsilon_2$$

$$\left\|\Delta\mathbf{X}^{(t)}\right\| < \varepsilon_1$$

The development of these methods is mainly led by the basic requirements of load flow calculation, which can be summed up as:

1. The convergence properties
2. The computing efficiency and memory requirements
3. The convenience and flexibility of the implementation

Mathematically, the load flow problem is a problem of solving a system of nonlinear algebraic equations.

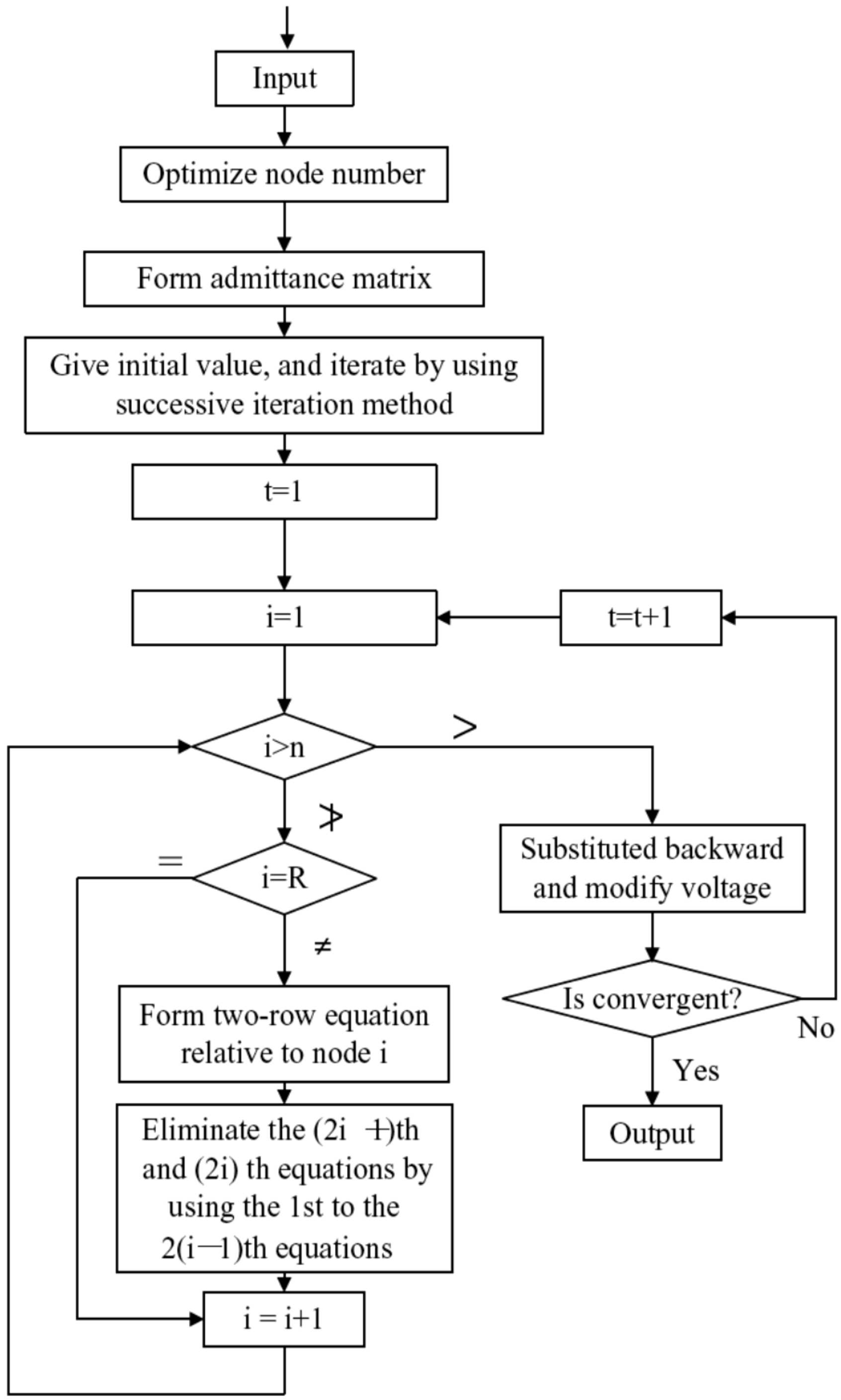
Its solution usually cannot avoid some iteration process.

Thus, reliable convergence becomes the prime criterion for a load flow calculation method.

With the scale of power system continually expanding, the dimension of load flow equations now becomes very high (several thousands to tens of thousands).

For the equations with such high dimensions, we cannot ensure that any mathematical method can converge to a correct solution.

This situation requires the researchers and scholars in the power system analysis field to seek more reliable methods



Figure

6.4 General procedures of the power flow analysis

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7. APPENDIX-B TERMINOLOGIES FOR THE *MICROGRID DESIGNER*

7.1. POWER SYSTEM NETWORK MODEL

Power flow calculation refers to the calculation of the complex voltage of each node of a network. Because the branch current was originally used for calculation purposes, it is called power flow calculation, or voltage calculation.

Some Amplitude of injection power and complex voltage are specified as calculation conditions, which provides the same number of equations as unknowns. Since power flow calculation conforms to AC theory, it can be considered that the voltage and current have the patterns of the sine waves. In particular, a steady state or a quasi-steady state can be assumed if change in various variables is slow. In addition, it is assumed that the effective power and terminal voltage are determined at the generator end and the effective reactive power at the load end, respectively. This gives the steady-state characteristics of the generator and the load. Therefore, the steady-state power flow calculation can be used to obtain the complex voltage.

First, find the relationship between the current (injection current) injected from the outside of the network to the node and the node voltage. Specifically, it corresponds to a generator or a load device. In the time domain we are considering, the transmission line can be simulated with the so-called π-shaped equivalent circuit in the figure below.

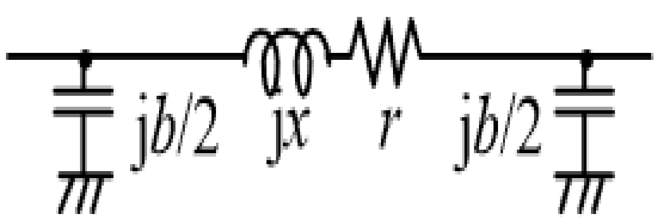

Figure7.1 π-shaped equivalent circuit

The resistance of the entire transmission line is r, the inductance component (reactance component) at commercial frequency is x, and the admittance component is b. j is the imaginary unit. Transformers can also be expressed with this model. Next consider the state that this model is connected to the node. In addition to the branch, the node may be connected with a phase-adjustment capacitor or a phase-matching reactor. Let b_{ci} be such a admittance component connected to node i as shown in the figure below.

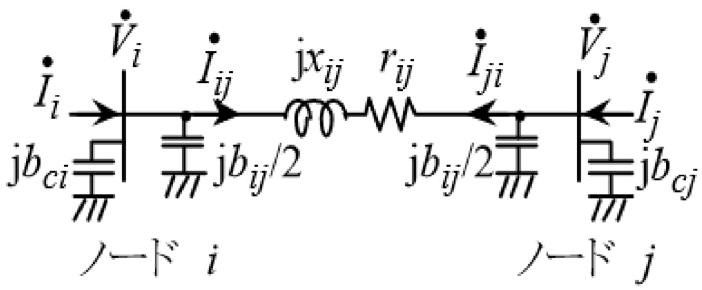

Figure7.2 Equivalent expression of π-shaped equivalent circuit

7.2. Linear Relation of Power System Network

Furthermore, if we write this for all (1 to n) i, it becomes as follows.

$$\dot{\boldsymbol{I}} = \dot{\boldsymbol{Y}}\dot{\boldsymbol{V}}$$

Where,

$$\dot{\boldsymbol{I}} = \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_n \end{bmatrix}, \quad \dot{\boldsymbol{V}} = \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \vdots \\ \dot{V}_n \end{bmatrix}, \quad \dot{\boldsymbol{Y}} = \{Y_{ij}\}$$

Y_{ij} *is* element in square matrix.

I, V, Y are called injection current vector, node voltage vector, node admittance matrix, respectively. Eq. (8) is extremely useful as the effective value model of the network in power system engineering. It is used for stability (stability of synchronous operation of multiple synchronous machines) analysis and evaluation of various phenomena having a time domain longer than that.

Branch constants (with a minus sign) appear in the form of the second equation in Eq. (6) for the off-diagonal elements of the node admittance matrix Y. From this, if there is no branch between two nodes, the corresponding Y off-diagonal element will be zero. As we will see later, the proportion of these zero elements increases as the system size increases. Therefore, the power flow calculation can be executed fast.

The correlation between power and voltage is also required. If the sign of the reactive power is defined as positive in the direction of flowing into the reactance, the power can be obtained from the following equation,

$$P_i + \mathrm{j}Q_i = \dot{V}_i \sum_{j=1}^{n} \overline{Y}_{ij} \overline{V}_j$$

Where *P* and *Q* are active and reactive power, respectively.

Eq. (10) is the power flow equation we want to solve. Branch current can be calculated from the complex voltage obtained by the power flow calculation, the current $\dot{I}_{ij}$ from node *i* towards node *j* is given by

$$\dot{I}'_{ij} = \mathrm{j}\frac{b_{ij}}{2}\dot{V}_i + \frac{\dot{V}_i - \dot{V}_j}{r_{ij} + \mathrm{j}x_{ij}}$$

Taking into consideration the admittance parts located at both ends in a π-type equivalent circuit, the power flow *Pij* + j*Qij* flowing out from node *i* toward node *j* is,

$$P_{ij} + \mathrm{j}Q_{ij} = \dot{V}_i \overline{I}'_{ij} = \dot{V}_i \left(-\mathrm{j}\frac{b_{ij}}{2}\overline{V}_i + \frac{\overline{V}_i - \overline{V}_j}{r_{ij} - \mathrm{j}x_{ij}} \right)$$

7.3. KNOWN AND UNKNOWN QUANTITIES IN POWER FLOW ANALYSIS

We have to define unknowns and knowns in order to solve above equations. These quantities vary according to node type and have been elaborated in Section 2. For generators, the known and unknown quantities are as follows, Known parameters:

- The Amplitude of the complex voltage of all generators
- Active power output of generators other than slack generator
- Phase angle of complex voltage of slack generator

Unknown parameters:

- Reactive power of all generators
- The phase angle of the complex voltage of the generator other than the slack generator
- Active power output of slack generator

While for loads, the known and unknown quantities are as follows,

Known parameters:

- Active power consumed by all load nodes
- Reactive power consumed by all load nodes

Unknown parameters:

- The Amplitude of the complex voltage of all load nodes
- Phase angle of complex voltage of all load nodes

It is well known that there are two ways to express the voltage: orthogonal coordinate representation divided into real part and imaginary part, and polar representation expressed by Amplitude and phase angle.

Depending on the coordinate system used, the number of unknowns and conditions to be given will differ. For each, nonlinear Table 1 summarizes the formulas of the system of equations and unknowns. The column of "known / unknown distinction" in the table corresponds to what was mentioned in the previous section. n_G is the number of generator nodes, and n_L is the number of other nodes, $n_G + n_L = n$ holds.

7.4. ACTIVE AND REACTIVE POWER FLOW EQUATION

The power flow equation can be rewritten in a polar system as,

$$\boldsymbol{p} = \boldsymbol{f}(\boldsymbol{v})$$

Where *Pi* and *Qi* can be expressed as

$$f_{Pi}(v) = V_i \sum_{j=1}^{n} V_j \left\{ G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right\}$$
$$f_{Qi}(v) = V_i \sum_{j=1}^{n} V_j \left\{ G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right\}$$

and the vector ***v*** is an unknown vector and having a size of $2n_L + n_G - 1$ obtained by vertically arranging the amounts arranged in "unknown" in Table 1, that is, the phase angle of all the nodes except for the slack node and the voltages of all the load nodes.

7.5. REVISED NEWTON-RAPHSON METHOD

Newton-Raphson method is a very well-known iterative method to solve linear and non-linear systems and it can be expressed by the follow equation:

$$\boldsymbol{v} \leftarrow \boldsymbol{v} + \left(\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{v}} \right)^{-1} \left(\boldsymbol{p} - \boldsymbol{f}(\boldsymbol{v}) \right)$$

Solve power flow equations iteratively will find the solution satisfying specified accuracy typically in 4-7 iterations if a good initial guess is provided for the calculation.

Grid has implemented multiple techniques to improve the performance of numerical computations. The section will give a brief introduction of these technologies.

7.6. LU FACTORIZATION, FORWARD AND BACK SUBSTITUTION

One of methods to reduce the cost of finding inverse matrix is LU decomposition. To solve a general linear system $A\mathbf{x} = \mathrm{b}$, the matrix A can be decomposed to $\boldsymbol{A} = \boldsymbol{LU}$, where

$$\boldsymbol{L} = \begin{bmatrix} l_{1,1} & 0 & \cdots & 0 \\ l_{2,1} & l_{2,2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ l_{n,1} & \cdots & l_{n,n-1} & l_{n,n} \end{bmatrix}, \quad \boldsymbol{U} = \begin{bmatrix} 1 & u_{1,2} & \cdots & u_{1,n} \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & u_{n-1,n} \\ 0 & \cdots & 0 & 1 \end{bmatrix}$$

With these lower triangular matrix or upper triangular matrix, we have

$$\boldsymbol{Ly} = \boldsymbol{b}$$
$$\boldsymbol{Ux} = \boldsymbol{y}$$

7.7. POWER SYSTEM OPERATION AND CONTROL

Customer's Load demand in electric power systems is not steady and is subject to change because of the change in human activities with time. Economic production of electric energy is one of the challenging tasks in the power generation sector due to the limited and variant generating resources. A great deal of effort is required to maintain the electric power supply quality and quantity within the requirements of various types of consumers being served.

The requirements of consumers include mainly availability, quality, reliability and reasonable cost for the power. As electric energy can't be stored, the loads should be met by variations in the power generation. It is required to commit enough number of generating units to meet the load demand in real time. In short, the load demands are to be met while operating the power system in the most economic manner.

A modern power system consists of several kinds of generating resources of which Hydro, Thermal and Nuclear sources form the major part. These different generating stations are connected to various load centers through transmission lines. Hydro and nuclear sources need more investment in setting up, which contributes to the fixed cost of power generated.

The cost of thermal power is mainly dependent on the variable cost, majority of which is due to the fuel cost. The economic production of power relies on mainly two stages of scheduling. Long term scheduling which involves resource acquisition and allocation for a long duration, commonly one year in advance and short term planning involving the scheduling for one day or one week.

At a load control center, the load demand profile is studied from the past history or experience and based on that, a pre - dispatch schedule is prepared in advance. This scheduling involves the selection of sources of generation available, depending on the constraints and the amount of thermal power to be generated.

Thermal power is usually used to meet the base load during the peak hours. Since the cost of thermal power is more, proper selection and scheduling of these units has become the essential step in power generation planning. Also, the different thermal generating units have different fuel characteristics and hence the cost of production varies from unit to unit. Apart from this, the cost of generation in any existing power system is not deterministic.

It varies instantaneously. Therefore, economic production of electric energy from a thermal power plant demands the optimum selection of units and also the generation levels considering the stochastic nature of cost. In this thesis, the scheduling is to find thermal power generation of the different generating units and is termed as Economic Dispatch. Through the dispatch solution, generation levels of the units are set for duration of several minutes. Power generation from the different units should be so as to satisfy the different constraints and in the most economic manner

The load on a power system varies instantaneously. Meeting the instantaneous variations of load needs a continuous change in the generation. When a load is suddenly added to the system initially the kinetic energy stored in the rotating parts of the generators will be utilized to meet the same.

Consequently, the speed and hence frequency drops. Then the governor mechanism act to increase the fuel input to the system in order to meet the increased load. The primary governor control alone cannot bring the frequency to the scheduled value.

(Reference:https://shodhganga.inflibnet.ac.in/bitstream/10603/117969/4/chapter202.pdf)

7.8. ECONOMIC LOAD DISPATCH

The Economic Load Dispatch (ELD) can be defined as the process of allocating generation level to the generating units, so that the system load is supplied entirely and most economically. For an interconnected system, it is necessary to minimize the expenses.

The economic load dispatch is used to define the production level of each plant, so that the total cost of generation and transmission is minimum for a prescribed schedule of load. The objective of economic load dispatch is to minimize the overall cost of generation. The method of economic load dispatch for generating units at different loads must have total fuel cost at the minimum point.

In a typical power system, multiple generators are implemented to provide enough total output to satisfy a given total consumer demand. Each of these generating stations can, and usually does, have unique cost-per-hour characteristic for its output operating range.

A station has incremental operating cost for fuel and maintenance; and fixed costs associated with the station itself that can be quite considerable in the case of a nuclear power plant, for example things get even more complicated when utilities try to account for transmission line losses, and the seasonal changes associated with hydroelectric plants.

There are many conventional methods that are used to solve economic load dispatch problem such as Lagrange multiplier methods, lambda iteration method and Newton- Raphson method. In the conventional methods, it is difficult to solve the optimal economic problem if the load changed. It needs to compute the economic load dispatch each time which uses a long time in each of computation loops.

It is a computational process where the total required generation is distribution among the generation units in operation, by minimizing the selected cost criterion, and subjects it to load and operational constraints as well.

Economic Load Dispatch (ELD) is an optimization problem and may be solved by known means of numerical optimization. ELD is the short-term determination of the optimal output of a number of electricity generation facilities, to meet the system demand, at the lowest possible fuel cost, while serving power to the public in a robust and reliable manner. Performing an ELD more frequently (e.g., 5 or 15 minutes rather than each hour) affects the level of costs.

The primary concern of an ELD problem is the minimization of its objective function. The total cost generated that meets the demand and satisfies all other constraints associated is selected as the objective function. In general, the ELD problem can be formulated mathematically as a constrained optimization problem with an objective function of the form, as illustrated in (1):

$$\text{Minimize: } FC_T = \sum_{i=1}^{N} FC_i(P_i)$$

where FC_T is the total generation cost; N is the total number of generating units; FCi is the power generation cost function of the ith unit. A. Classical Smooth Fuel Cost Functions Generally, the fuel cost of a thermal generation unit is considered as a second order polynomial function (Neglecting valve-point effects) and this is called classical and smooth cost function as below.

$$FC_i(P_i) = a_i P_i^2 + b_i P_i + c_i$$

where Pi is the power of the i th generating unit; ai, bi, ci are the fuel cost coefficients of the ith generating unit.

「カリコム省エネルギー推進プロジェクト」
系統安定化シミュレーション委託業務
最終報告書

2022 年 10 月 31 日

環境エネルギー技術研究所株式会社

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1. まえがき

カリブ海の島々は、太陽光エネルギー、風力発電、地熱エネルギー、バイオマスなど、すぐに利用できる再生可能エネルギー資源が大量にあるにもかかわらず、エネルギー部門で多くの課題に直面している。セントクリストファー・ネイビス連邦などの小さな島嶼開発途上国は、政府から補助金を受けているが、経済的にこれは長期的な解決策とは見なされていない。

長期的ではるかに大きな経済的解決策は、再生可能エネルギー技術の導入によりエネルギーミックスを多様化することにより、輸入化石燃料への依存を減らし、カリブの政府の最重要課題である長期的なエネルギー安全保障を確保できる。

ここでは、セントキッツ島のエネルギー部門を分析し、ベースロードをカバーする再生可能エネルギー技術として大規模太陽光発電を設置することにより、エネルギー安全保障をどのように達成できるかを実証することである。

セントキッツ島における再生可能エネルギー、電力需要及び電力系統に関する資料収集を行い、これら資料を用いて、電力系統の解析支援ツールである MicroGrid Designer を使用してカリコム系統安定化シミュレーションを実施した。その解析結果を報告する。

2. 実施項目と結果

2.1. 電力系統解析の基本的事項

電力系統解析の基本についての講義系統解析に使用するソフトウェアとして、作成中のツール *MicroGrid Designer*（仮称） を使用することを前提としていたのでその作業内容を説明する資料を作成し、電力系統解析の基本的事項を交えて、当該プロジェクトのメンバーにて論議した。

2.2. St.Kitts 島における収集資料の精査

第 1 次渡航で収集された St.Kitts 島の発電所・発電機情報、系統構成と系統属性、 及び負荷・再生可能エネルギー(太陽光発電と風力発電)情報についての精査を行い、系統解析に使用可能となりそうなデータを抽出したまた、同時に収集された St.Kitts 島における既実施の系統計画レポート「Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept.2014 by leidos」(以下、参考資料と称す)を主たる参考資料としてレビューを行った。

2.3. St.Kitts 島における系統属性の確定

第 1 次渡航で収集された St.Kitts 島の系統情報には、すぐに使える実用的な数値データが少なかったので、参考資料で述べられていた「PSS/E を使用して潮流計算を実施した」こと

をもとに、本プロジェクトにも PSS/E 用のデータを活用することを提案した。なお、PSS/E は Siemens 社で開発された高額な系統解析ツールである。その結果、PSS/E 用のデータが第２次渡航で収集されたので、これを *MicroGrid Designer* 用のデータに変換することができた。

2.4. St.Kitts 島における系統計画の確認

第３次渡航で St.Kitts 島における発電所・発電機情報、系統構成と系統属性、及び負荷・再生可能エネルギー(太陽光発電)情報についての再確認と変更点の調査・収集がなされたので、これらから MicroGrid Designer による系統解析（多段経済負荷配分と潮流計算）用のデータを作成し、想定であるが、蓄電池付き大型太陽光発電 35MW の導入計画確定発電機６台の追加、地下ケーブルと地上送電線の位置情報と線種の収集および週単位・負荷曲線データの確定を行った。

2.5. St.Kitts 島における系統解析シミュレーション

上記の経緯を経て、今年度業務における最終的な系統解析を行う準備が完成したので、St.Kitts 島・電力系統における最適蓄電池容量の決定と MicroGrid Designer による多段経済負荷配分と潮流計算を実施した。この結果は、MicroGrid Designer が系統需給計画と電圧安定性評価に寄与できるツールであることを実証したと判断される

3. St.Kitts 島における発電機の燃料曲線の作成と ELD 決定

3.1. 発電機燃料費曲線と関連データの作成

日本工営から提供された下記実測データより発電機燃料費曲線を作成した。作成した発電機曲線の対応発電機番号は以下である。

Generator #1、Generator #2、Generator #3、Generator #4、Generator #9
Generator #10、Generator #11、Generator #12。

表 3-1　発電機と燃料効率

			燃料効率							
UNIT	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Generator #1	-	-	-	18.77	17.74	18.08	18.08	18.39	18.81	-
Generator #2	10.46	13.84	15.47	17	17.29	17.79	18.01	16.74	-	-
Generator #3	-	-	-	16.46	16.2	17.48	17.38	18.22	18.15	18.51
Generator #4	-	-	-	16.76	17.18	17.32	17.23	17.76	17.45	-
Generator #9	-	-	-	16.12	15.57	16.44	17.9	17.27	19.29	16.58
Generator #10	10.55	14.07	15.55	16.42	17.18	17.73	17.99	18.18	18.47	18.47
Generator #11	9.23	14.41	14.53	16.65	16.6	17.38	18.47	18.32	18.6	18.24
Generator #12	10.19	13.13	16.42	15.35	17.8	17.38	17.99	18.32	18.22	18.02
Generator #14	-	-	-	-	-	-	-	-	-	-

燃料費曲線と対応する母線番号、シミュレーション用発電機番号は下記に示す。ただし、母線番号の４９～５５での係数は、暫定的に既知の八つの発電機の係数の平均値を取った。

表 3-2　発電機と燃料費係数

Unit	母線番号	発電機番号（シミュレーション用）	燃料費曲線	a（二次）	b（一次）	c（定数）
Generator #1	40	1	y = 0.0336x2 + 0.0436x + 17.72	0.03360	0.04360	17.72000
Generator #2	41	2	y = 0.0197x2 + 0.0344x + 0.0065	0.01970	0.03440	0.00650
Generator #3	42	3	y = 0.0043x2 + 0.0395x + 0.0098	0.00430	0.03950	0.00980
Generator #4	43	4	y = 0.0035x2 + 0.0503x + 0.0031	0.00350	0.05030	0.00310
Generator #9	45	5	y = 0.0247x2 + 0.0173x + 0.0156	0.02470	0.01730	0.01560
Generator #10	46	6	y = 0.001x2 + 0.0483x + 0.0047	0.00100	0.04830	0.00470
Generator #11	47	7	y = 0.0037x2 + 0.0443x + 0.0061	0.00370	0.04430	0.00610
Generator #12	48	8	y = 0.0052x2 + 0.0441x + 0.0057	0.00520	0.04410	0.00570
	49	9		0.01196	0.04023	0.00644
	50	10		0.01196	0.04023	0.00644
	51	11		0.01196	0.04023	0.00644
	52	12		0.01196	0.04023	0.00644
	53	13		0.01196	0.04023	0.00644
	54	14		0.01196	0.04023	0.00644
	55	15		0.01196	0.04023	0.00644

発電機の出力上下限は、日本工営が提供した下記のデータを用いた。CAT1～CAT6 のデータは同じなので、母線番号の４９～５５に入れた。

表 3-3　発電機出力上下限値

Generator	Pgen	Pmin	Pmax	Spinning Reserve	%Loading	Down Reserve	Ramp Capability	
	MW	MW	MW	MW	MW	MW	kW/sec	MW/h
Generator#1	5.80	1.22	6.13	0.00	94.60%	4.58	122.00	439.20
Generator#2	3.34	0.77	3.87	0.52	86.50%	2.58	77.40	278.64
Generator#3	3.50	0.77	3.89	0.39	89.80%	2.72	77.92	280.51
Generator#4	3.60	0.77	3.89	0.29	92.40%	2.82	77.92	280.51
Generator#8	0.00	0.73	3.66	0.00	0.00%	0.00	73.20	263.52
Generator#9	0.00	0.70	3.50	0.00	0.00%	0.00	70.00	252.00
Generator#10	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51
Generator#11	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51
Generator#12	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51
Generator#14	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51
Generator CAT1		0.41	1.65				55.00	198.00
Generator CAT2		0.41	1.65				55.00	198.00
Generator CAT3		0.41	1.65				55.00	198.00
Generator CAT4		0.41	1.65				55.00	198.00
Generator CAT5		0.41	1.65				55.00	198.00
Generator CAT6		0.41	1.65				55.00	198.00
sum	16.24	5.99	27.68					

3.2. 負荷データ

日本工営から受領した負荷データ（20200918_hourly loads_1 週間 x4 ケース分 rev1.xlsx）をベースに、シミュレーション用負荷データを抽出した。

3.3. 経済負荷配分(ELD)シミュレーション結果

シミュレーション結果例を示す。

Example 1　2019 July 2019/7/10　（一日２４時間負荷）

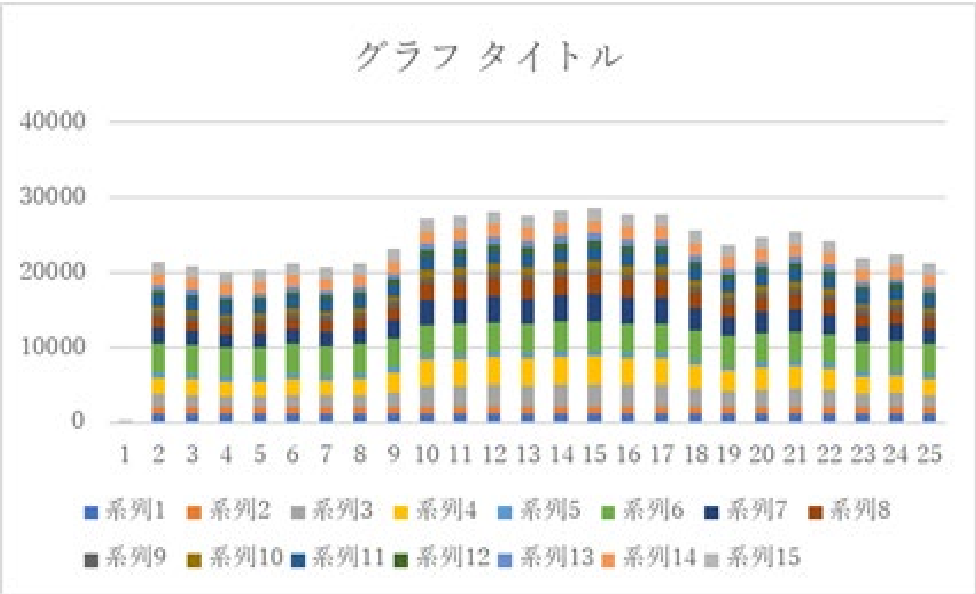


図 3-1　シミュレーション結果（Example 1）

Example 2

2019/7/8 --7/14　一か月１６８時間データ（速度応答制約なし）

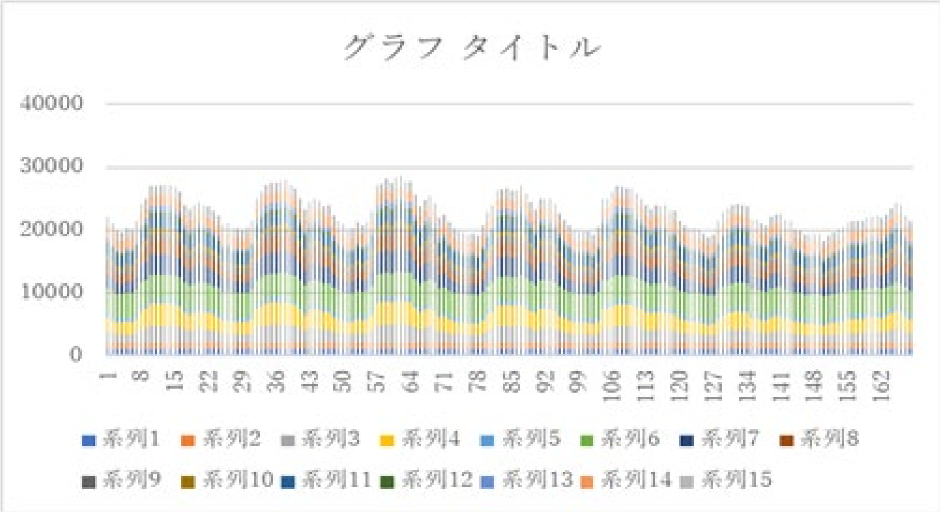


図 3-2　シミュレーション結果（Example 2）

Example 3

2019/7/8 --7/14　一か月１６８時間データデータ

（速度応答制約は定格の２０%仮定、すなわち、最小負荷から満負荷までは５時間という計算）

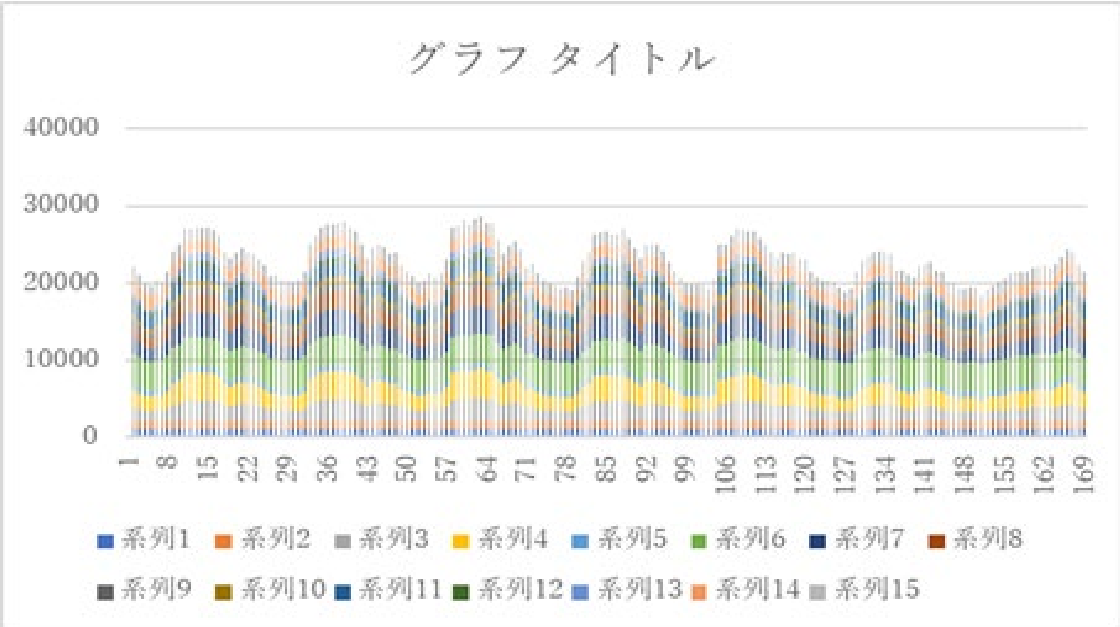


図 3-3　シミュレーション結果（Example 3）

3.4. 結論

これら検証により、カリコム向けのＥＬＤ計算には特に問題がないという結論を得た。

4. St.Kitts 島における潮流解析シミュレーション

4.1. 目的

PSS/E からの変換データをもとに、St.Kitts 島の概略系統構成図を作成し、MicroGrid Designer により潮流計算を実行し、その結果の検討を行った。

PSS/E 用のデータの特徴は、１箇所の発電所から 12 本のフィーダが出るループなしの配電系統であり、各フィーダ末端には小規模太陽光発電、１本のフィーダ中間に一台の大規模風力発電(5.4MW)が設置してあることである。

参考資料には潮流計算結果の詳細は記載されていないので比較はできないが、MicroGrid Designer による潮流計算結果に妥当性が十分あるように判断されるので、現地における PSS/E 用のデータは実際に活用可能であることが明確化された。但し、このデータは６年以上前に作成されているので、以降の系統更新に留意する必要がある。

変換・整理された潮流計算のデータを示す。これを用いた潮流計算シミュレーションを行い、結果評価を行う。

4.2. シミュレーションケース

(1) Case0：PV、BAT（蓄電池）がないケース

発電機の出力分担は負荷の総量を発電機の容量比で配分するものとした。

(2) Case1：PV、BAT（蓄電池）があるケース

PV 出力は 35MW とした。その他発電機出力は Case0 の潮流計算結果を用い、BAT（蓄電池）のノードをスラックとし、この条件での蓄電池必要容量（kW）を計算した。

(3) Case2：PV、BAT（蓄電池）があるケース

Case1 においてその他発電機出力は Case0 の 20%とした。

(3) Case3：PV、BAT（蓄電池）があるケース

Case2 において PV 出力 0%とした。

4.3. データ

（１）系統構成

系統図を PSS のデータより読み取った。図 4-1 に系統図を示す。

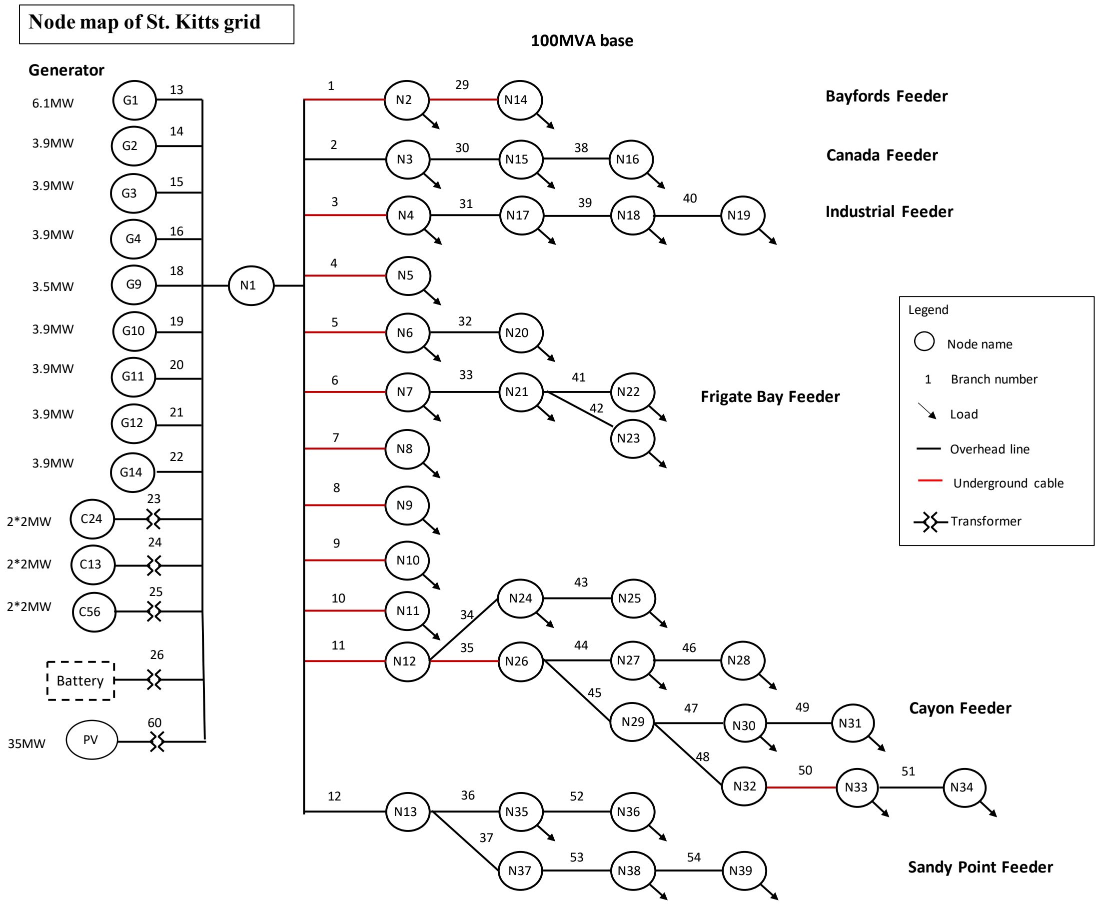


図 4-1　系統図

（２）発電機

発電機データは Generator information.xlsx より入手した。表 4-1 に発電機データを示す。

表 4-1　発電機データ

ノード名	Unit	Engine model	Year installed	Generator Model	Rated Power (MW)	（日本工営追記）Voltage Rate	根拠
G1	G1	Mirlees Blackstone MB430	1999	Leroy Sommer LSA60 B105-14P	6.1	11kV	銘板写真
G2	G2	MAN 18V28/32S	2009	Hyundai	3.9	11kV	単結

G3	G3	MAN 18V28/32S	2008	AVK	3.9	11kV	銘板写真
G4	G4	MAN 18V28/32S	2007	AVK	3.9	11kV	銘板写真
G9	G9	Mirlees Blackstone K8	1987	Brush	3.5	11kV	単結
G10	G10	MAN 18V28/32S	2010	AVK	3.9	11kV	銘板写真
G11	G11	MAN 18V28/32S	2010	AVK	3.9	11kV	銘板写真
G12	G12	MAN 18V28/32S	2011	AVK	3.9	11kV	銘板写真
G14	G14	MAN 18V28/32S	2011	AVK	3.9	11kV	銘板写真
C13	Mobile set 1	Caterpillar 3516	2017	Caterpillar	2	480V	銘板写真、カタログ
	Mobile set 3	Caterpillar 3516	2018	Caterpillar	2	480V	銘板写真、カタログ
C24	Mobile set 2	Caterpillar 3516	2017	Caterpillar	2	480V	銘板写真、カタログ
	Mobile set 4	Caterpillar 3516	2018	Caterpillar	2	480V	銘板写真、カタログ
C56	Mobile set 5	Caterpillar 3516	2019	Caterpillar	2	480V	銘板写真、カタログ
	Mobile set 6	Caterpillar 3516	2019	Caterpillar	2	480V	銘板写真、カタログ

（３）配電線

PSS データより配電線データを読み取った。表 4-2 に配電線データを示す。

表 4-2　配電線データ

Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2
(Up to 5	(Up to 4	(Up to 4	default	(p.u.)	(p.u.)	(p.u.)

digit)	characters)	characters)	= 1			
1	N1	N2		0.9024	0.8624	0
2	N1	N3		0.3319	0.4143	0
3	N1	N4		0.0887	0.0815	0
4	N1	N5		0.0919	0.0844	0
5	N1	N6		0.3422	0.3873	0
6	N1	N7		0.1229	0.1129	0
7	N1	N8		0.1873	0.1721	0
8	N1	N9		3.1699	1.4664	0
9	N1	N10		1.1316	1.0392	0
10	N1	N11		0.3079	0.2827	0
11	N1	N12		0.4534	0.4164	0
12	N1	N13		0.6357	0.5838	0
13	N1	G1		0	0.001	0
14	N1	G2		0	0.001	0
15	N1	G3		0	0.001	0
16	N1	G4		0	0.001	0
18	N1	G9		0	0.001	0
19	N1	G10		0	0.001	0
20	N1	G11		0	0.001	0
21	N1	G12		0	0.001	0
22	N1	G14		0	0.001	0
23	N1	C24		0	0.6	0
24	N1	C13		0	0.6	0
25	N1	C56		0	0.6	0
26	N1	BAT		0	0.6	0
29	N2	N14		1.2189	1.1748	0
30	N3	N15		0.5531	0.4264	0
31	N4	N17		0.1394	0.1281	0
32	N6	N20		0.7286	1.1558	0
33	N7	N21		0.1476	0.1356	0
34	N12	N24		2.479	1.1468	0
35	N12	N26		0.3476	0.3192	0
36	N13	N35		3.0158	2.3139	0
37	N13	N37		0.9404	0.8325	0

38	N15	N16		1.2419	1.0997	0
39	N17	N18		0.09	0.8262	0
40	N18	N19		0.0669	0.0615	0
41	N21	N22		0.1776	0.1632	0
42	N21	N23		0.1956	0.1797	0
43	N24	N25		3.3119	1.5322	0
44	N26	N27		0.9501	0.4395	0
45	N26	N29		1.7516	2.7785	0
46	N27	N28		4.0389	1.8684	0
47	N29	N30		1.1891	1.8862	0
48	N29	N32		3.6489	1.6882	0
49	N30	N31		2.548	1.1788	0
50	N32	N33		1.9684	0.9106	0
51	N33	N34		4.0223	1.8608	0
52	N35	N36		5.0793	2.3498	0
53	N37	N38		1.2729	0.5889	0
54	N38	N39		3.7738	1.7458	0

・ブランチ２４、２５，２６は Catarpillar 発電機用の昇圧変圧器である。2 台の合計は 2*2MW/0.8＝5MVA であるので、変圧器は 5MVA、3%Z と想定する。　100MVA ベースでは 0.03*100/5=0.6pu。

・ブランチ２６の Battery は、今はないものとする。その変圧器は５MVA、３％Z とする。

・ブランチすべてで対地静電容量 Y がゼロである。

・ブランチ 29　R=1.2189pu, X=1.1748pu これは R=1.2189*(11kV^2)/100M=1.47Ω、3.77mH である。線路の L≒1mH と考えればこの配電線は 3.77km になる。妥当な所と考える
・ブランチ 30　R=0.5531pu, X=0.4264pu　これは約 1.7km に相当する。

（４）ノードデータと負荷 PQ

ノードデータと負荷 PQ を表 4-3 に示す。

表 4-3　ノードデータと負荷 PQ　　(100MVAbase)

Node ID	Node type	Pg	Qg	Pl	Ql
(Up to 4 characters)	PQ＝0、PV＝1,Slack＝2	(p.u.)	(p.u.)	(p.u.)	(p.u.)
N1	0			0	0
N2	0	0	0	0.00643	0.00386
N3	0	0	0	0.0047	0.00315
N4	0	0	0	0.00186	0.00119
N5	0	0	0	0.00599	0.00377
N6	0	0	0	0.00126	0.00068
N7	0	0	0	0.00104	-0.0058
N8	0	0	0	0.00575	0.004
N9	0	0	0	0.00635	0.00452
N10	0	0	0	0.0011	0.00233
N11	0	0	0	0.00406	0.00258
N12	0	0	0	0	0
N13	0	0	0	0	0
N14	0	0	0	0.01601	0.00952
N15	0	0	0	0.00919	0.0063
N16	0	0	0	0.00216	-0.00013
N17	0	0	0	0.00722	0.00513
N18	0	0	0	0.00491	0.00285
N19	0	0	0	0.00698	0.00497
N20	0	0	0	0.01723	0.01087
N21	0	0	0	0.00605	0.00377
N22	0	0	0	0.00607	0.00383
N23	0	0	0	0.00606	0.00381
N24	0	0	0	0.00267	0.00202
N25	0	0	0	0.00393	0.00298
N26	0	0	0	0	0
N27	0	0	0	0.00157	0.0012
N28	0	0	0	0.00304	0.00228
N29	0	0	0	0	0
N30	0	0	0	0.00286	0.0021

N31	0	0	0	0.0026	0.00191
N32	0	0	0	0	0
N33	0	0	0	0.00293	0.00215
N34	0	0	0	0.00293	0.00215
N35	0	0	0	0.00197	0.00182
N36	0	0	0	0.00431	0.00407
N37	0	0	0	0	0
N38	0	0	0	0.0022	0.00208
N39	0	0	0	0.00568	0.0054
G1	1	0.02	0	0	0
G2	2	0.013	0	0	0
G3	1	0.013	0	0	0
G4	1	0.013	0	0	0
G9	1	0.012	0	0	0
G10	1	0.0125	0	0	0
G11	1	0.0125	0	0	0
G12	1	0.0125	0	0	0
G14	1	0.0125	0	0	0
C24	1	0.013	0	0	0
C13	1	0.013	0	0	0
C56	1	0.013	0	0	0
BAT	0	0	0	0	0
				0.15711	0.10136

負荷の合計は 15.711MW、10.136Mvar である。

4.4. 潮流計算結果

（1）ケース０　太陽光無し

発電機の出力分担は負荷の総量を発電機の容量比で配分する。

表 4-3 のデータがこのケースである。

①　収束条件等

収束条件 0.0001pu

収束回数　3 回

回路全部の損失 0.00539pu（＝0.539MW）

Nodes		52
Branch:		51
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

②電圧プロファイル

電圧プロファイルを図 4-2 に示す。

末端の N34 ノードの電圧が 0.9pu 以下になっている。対策が必要である。

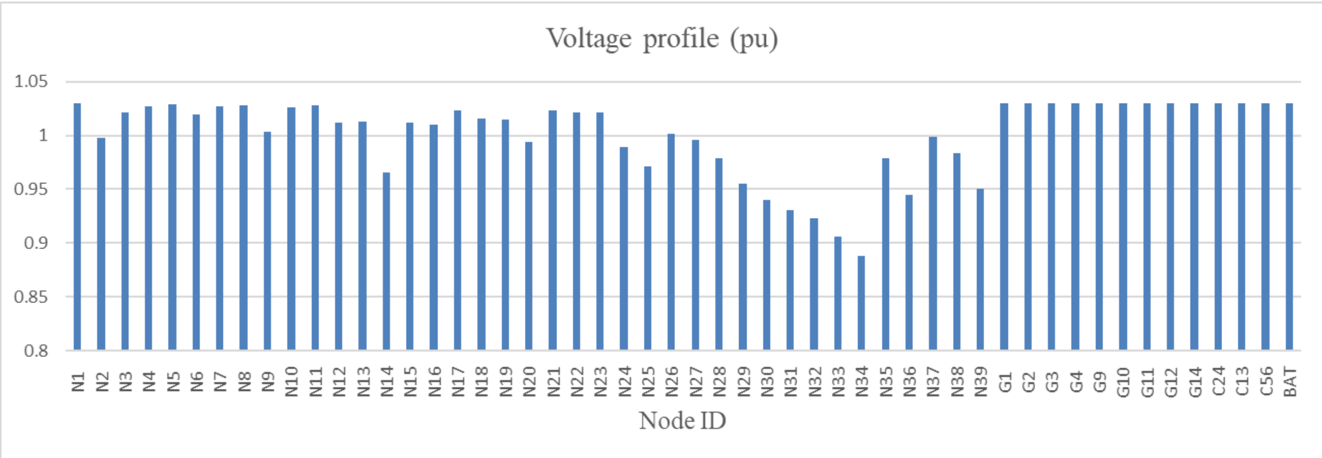


図 4-2　電圧プロファイル

③　線路電流

線路電流を図 4-3 に示す。

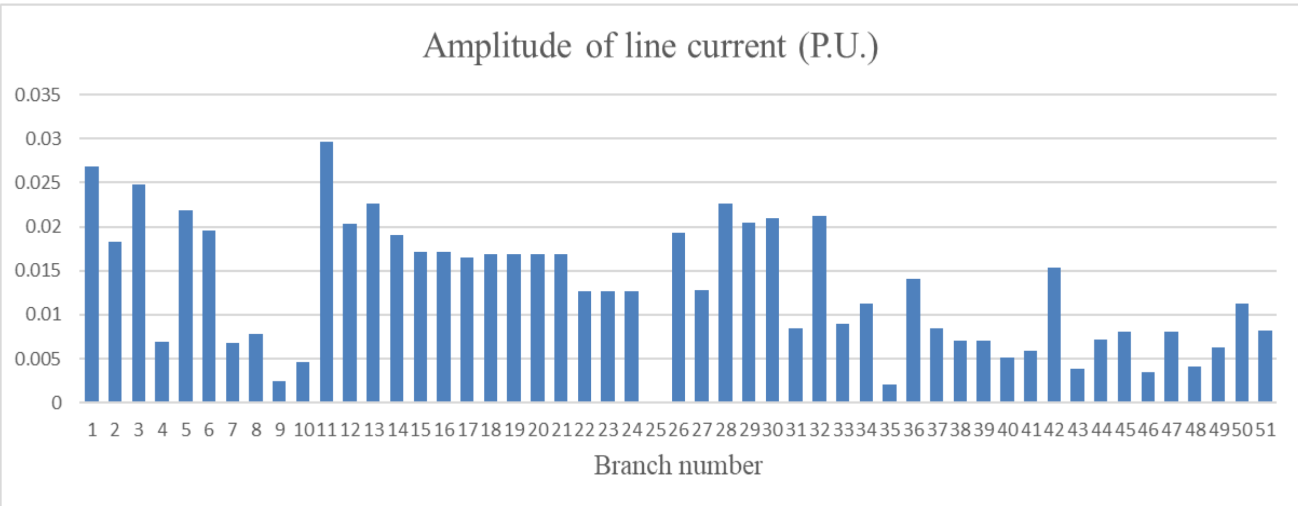


図 4-3　線路電流

④　発電機出力

発電機出力を表 4-4 に示す。

表 4-4　発電機出力　（100MVA ベース）

		電圧指定 V	指定 P(p.u.)	指定 Q(p.u.)	P(p.u.) 結果	Q(p.u.) 結果	
G1	1	1.03	0.02	0	0.02	0.01194	
G2	2	1.03	0.013	0	0.01549	0.01194	スラック
G3	1	1.03	0.013	0	0.013	0.01194	
G4	1	1.03	0.013	0	0.013	0.01194	
G9	1	1.03	0.012	0	0.012	0.01194	
G10	1	1.03	0.0125	0	0.0125	0.01194	
G11	1	1.03	0.0125	0	0.0125	0.01194	
G12	1	1.03	0.0125	0	0.0125	0.01194	
G14	1	1.03	0.0125	0	0.0125	0.01194	
C24	1	1.03	0.013	0	0.013	0.00007	
C13	1	1.03	0.013	0	0.013	0.00007	
C56	1	1.03	0.013	0	0.013	0.00007	
				合計	0.16249	0.10767	

ケース 0 で用いた計算データ：　MGD_PowerFlow_V2_カリコム 2.xlsm

（2）ケース 1　太陽光有、電池有

PV 出力は 35MW とした。発電機出力をケース 0 の潮流計算結果と同じくした場合の必要電池容量を求める。

①　ノードデータ追加･変更

・PV（太陽光）ノード”PV”を追加した。出力を 35MW（0.35p.u.:100 MVA ベース）とした。

･G2 ノードを PV 指定とし､ケース 0 の潮流計算結果から出力を 1.549MW（0.0549p.u.:100 MVA ベース）とした。

・蓄電池ノード”BAT”をスラック指定とした。

ノードデータのうち、追加・変更分を含む、発電機、蓄電池、PV データを表 4-5 に示す。

表 4-5　ノードデータ（発電機、蓄電池、PV データ）

Comments	Node data Input Form for Single Stage Power Flow Analysis								
	Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql
	(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)
	G1	1	1.03	0		0.02	0	0	0
	G2	1	1.03	0		0.01549	0	0	0
	G3	1	1.03	0		0.013	0	0	0
	G4	1	1.03	0		0.013	0	0	0
	G9	1	1.03	0		0.012	0	0	0
	G10	1	1.03	0		0.0125	0	0	0
	G11	1	1.03	0		0.0125	0	0	0
	G12	1	1.03	0		0.0125	0	0	0
	G14	1	1.03	0		0.0125	0	0	0
	C24	1	1.03	0		0.013	0	0	0
	C13	1	1.03	0		0.013	0	0	0
	C56	1	1.03	0		0.013	0	0	0
	BAT	2	1.03	0		0	0	0	0
	PV	0	1	0		0.35			

② ブランチデータ追加

・PV（太陽光）ノード"PV"と、ノード"N1"間の変圧器を追加した（ブランチ番号 60）（表 4-6 参照）。

変圧器は 40MVA、3%Z と想定する。　100MVA ベースでは 0.03*100/40=0.075p.u.。

表 4-6　ブランチデータ（追加分）

Comments	Branch data Input Form for Single Stage Power Flow Analysis							
	Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
	(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
	60	N1	PV		0	0.075		

③ シミュレーション結果

・収束条件等

収束条件 0.0001p.u.

収束回数　3 回

回路全部の損失 0.00539p.u.（＝0.539MW）

Nodes		53
Branch:		52
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

・電圧結果

電圧結果を図 4-4 に示す。

PV 端子電圧（PV ノード）は他発電機と同様な数値 1.03p.u.となっており問題はない。

末端の N34 ノードの電圧が 0.9p.u.以下になっているのはケース 0 と同様である。対策が必要である。

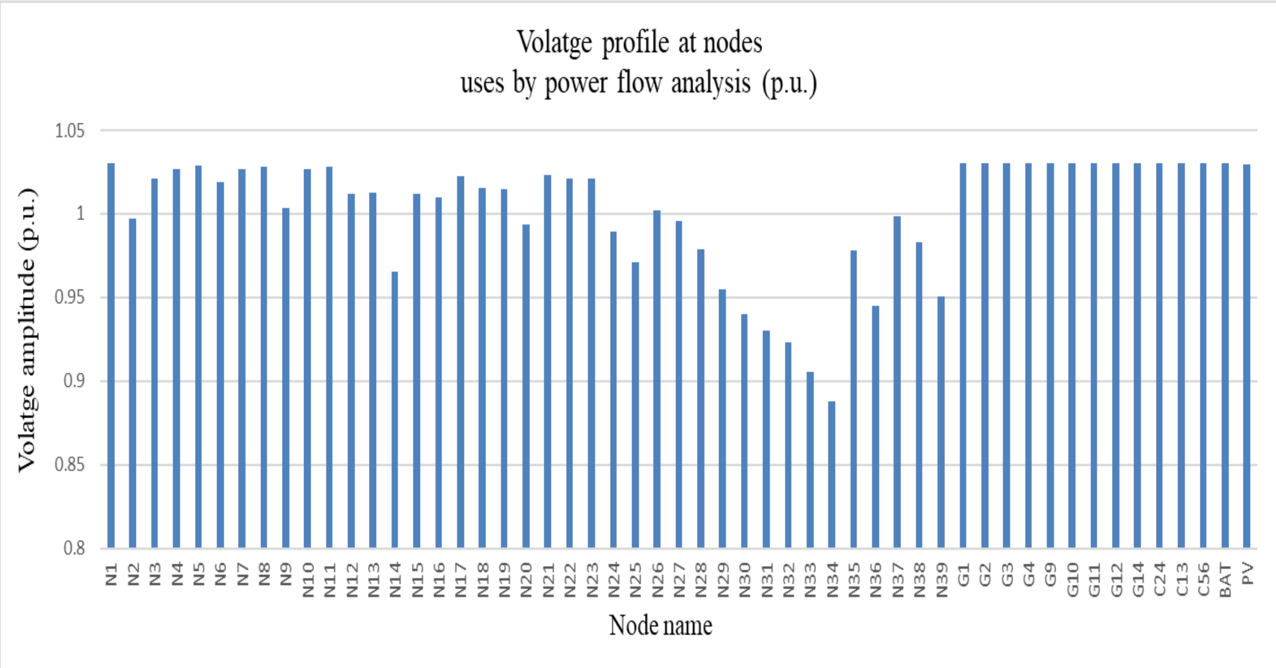


図 4-4 電圧結果

・発電機・PV 出力、蓄電池充放電結果

発電機出力、PV 出力、蓄電池充放電の結果を表 4-7 に示す。

PV 出力 0.35p.u.（35MW）の殆どが蓄電池に充電されていることが分かる。

発電機は無効電力を放出しており遅相運転となっている。しかしいずれも容量以内であり問題ない。

表 4-7　発電機・PV 出力、蓄電池充放電結果

(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	I (p.u.)	Angel (Degree)
G1	1	1.03	1.03	11.42	0.02	0	0.02	0.01666	0.02527	−28.38
G2	1	1.03	1.03	11.42	0.01549	0	0.01549	0.01666	0.02209	−35.67
G3	1	1.03	1.03	11.42	0.013	0	0.013	0.01666	0.02052	−40.62
G4	1	1.03	1.03	11.42	0.013	0	0.013	0.01666	0.02052	−40.62
G9	1	1.03	1.03	11.42	0.012	0	0.012	0.01666	0.01994	−42.82
G10	1	1.03	1.03	11.42	0.0125	0	0.0125	0.01666	0.02022	−41.71
G11	1	1.03	1.03	11.42	0.0125	0	0.0125	0.01666	0.02022	−41.71
G12	1	1.03	1.03	11.42	0.0125	0	0.0125	0.01666	0.02022	−41.71
G14	1	1.03	1.03	11.42	0.0125	0	0.0125	0.01666	0.02022	−41.71
C24	1	1.03	1.03	11.84	0.013	0	0.013	0.00008	0.01262	11.51
C13	1	1.03	1.03	11.84	0.013	0	0.013	0.00008	0.01262	11.51
C56	1	1.03	1.03	11.84	0.013	0	0.013	0.00008	0.01262	11.51
BAT	2	1.03	1.03	0	0	0	−0.35	0.03501	0.3415	−174.29
PV	0	1	1.02967	12.84	0.35	0	0.35	0	0.33992	12.84

・線路電流

ケース 0 とほぼ同じ

・必要電池容量

蓄電池ノード”BAT”をスラック指定とした結果、表 4-6 より P 出力-0.35p.u.（充電）、Q 出力 0.035p.u.（放出）が必要との結果を得た。よって、その他発電機出力をケース 0 と同じとすると、必要電池容量は 0.3517p.u.（35.17MVA）となる。

（3）ケース 2　太陽光有、電池有、発電機出力 20%

PV 出力は 35MW とし、発電機出力をケース 1 の 20%の場合の必要電池容量を求める。負荷の合計 15.711MW に比べ、PV 出力 35MW は大きく、充放電を考えると発電機出力 0%の場合が最も必要電池容量が少なくてすむが、電圧維持、周波数維持を考慮し、発電機出力 20%とした

① ノードデータ追加・変更

ケース 1 で発電機出力を全て 20%とした。

ノードデータのうち、追加・変更分を含む、発電機、蓄電池、PV データを表 4-8 に示す。

表 4-8　ノードデータ（発電機、蓄電池、PV データ）

Comments	Node data Input Form for Single Stage Power Flow Analysis								
	Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql
	(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)
	G1	1	1.03	0		0.004	0	0	0
	G2	1	1.03	0		0.003098	0	0	0
	G3	1	1.03	0		0.0026	0	0	0
	G4	1	1.03	0		0.0026	0	0	0
	G9	1	1.03	0		0.0024	0	0	0
	G10	1	1.03	0		0.0025	0	0	0
	G11	1	1.03	0		0.0025	0	0	0
	G12	1	1.03	0		0.0025	0	0	0
	G14	1	1.03	0		0.0025	0	0	0
	C24	1	1.03	0		0.0026	0	0	0
	C13	1	1.03	0		0.0026	0	0	0
	C56	1	1.03	0		0.0026	0	0	0
	BAT	2	1.03	0			0	0	0
	PV	0	1	0		0.35			

② ブランチデータ

・ケース 1 と変わらず。

③ シミュレーション結果

・収束条件等

収束条件 0.0001p.u.

収束回数　3 回

回路全部の損失 0.00539p.u.（＝0.539MW）

Nodes		53
Branch:		52
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

・電圧結果

電圧結果を図 4-5 に示す。

PV 端子電圧は他発電機と同様な数値 1.03p.u.となっており問題はない。

末端の N34 ノードの電圧が 0.9p.u.以下になっているのはケース 0 と同様である。対策が必要である。

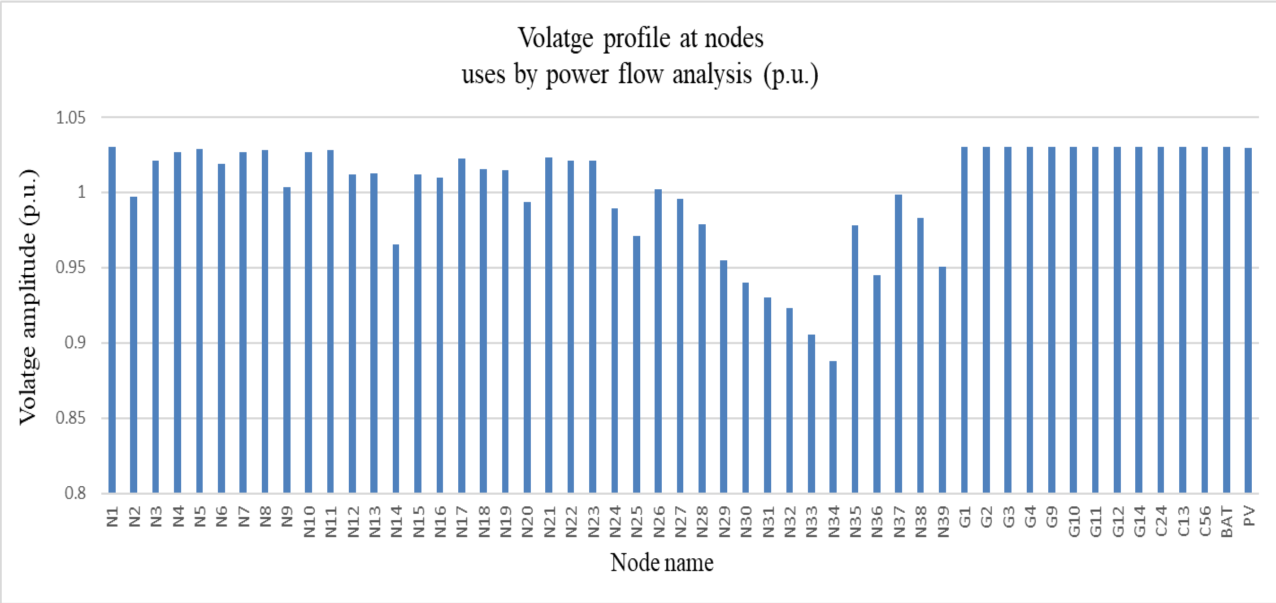


図 4-5 電圧結果

・発電機・PV 出力、蓄電池充放電結果

発電機出力、PV 出力、蓄電池充放電の結果を表 4-9 に示す。

PV 出力 0.35p.u.（35MW）のうち、0.22p.u.(22MW)が蓄電池に充電されていることが分かる。

発電機は無効電力を放出しており遅相運転となっている。しかしいずれも容量以内であり問題ない。

表 4-9　発電機・PV 出力、蓄電池充放電結果

Output Form of Obtained Results for Nodes by Singel Stage Power Flow Anlysis										
Node ID	Node type	Specified voltage	Obtaiened value		Specified P&Q		Obtained P&Q		Injection current	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	I (p.u.)	Angel (Degree)
G1	1	1.03	1.03	7.15	0.004	0	0.004	0.01429	0.01441	−67.21
G2	1	1.03	1.03	7.15	0.003098	0	0.0031	0.01429	0.0142	−70.61
G3	1	1.03	1.03	7.15	0.0026	0	0.0026	0.01429	0.0141	−72.54
G4	1	1.03	1.03	7.15	0.0026	0	0.0026	0.01429	0.0141	−72.54
G9	1	1.03	1.03	7.15	0.0024	0	0.0024	0.01429	0.01407	−73.32
G10	1	1.03	1.03	7.15	0.0025	0	0.0025	0.01429	0.01408	−72.93
G11	1	1.03	1.03	7.15	0.0025	0	0.0025	0.01429	0.01408	−72.93
G12	1	1.03	1.03	7.15	0.0025	0	0.0025	0.01429	0.01408	−72.93
G14	1	1.03	1.03	7.15	0.0025	0	0.0025	0.01429	0.01408	−72.93
C24	1	1.03	1.03	7.23	0.0026	0	0.0026	0.00003	0.00252	6.67
C13	1	1.03	1.03	7.23	0.0026	0	0.0026	0.00003	0.00252	6.67
C56	1	1.03	1.03	7.23	0.0026	0	0.0026	0.00003	0.00252	6.67
BAT	2	1.03	1.03	0	0	0	−0.22001	0.01377	0.21402	−176.42
PV	0	1	1.02967	8.57	0.35	0	0.35	0	0.33991	8.57

・線路電流

ケース 0 とほぼ同じ

・必要電池容量

蓄電池ノード”BAT”をスラック指定とした結果、P 出力-0.22p.u.（充電）、Q 出力 0.014p.u.（放出）が必要との結果を得た。よって、その他発電機出力をケース 0 の 20%とすると、必要電池容量は 0.22p.u.（22.04MVA）となる。

（4）ケース 3　太陽光出力 0%、電池有、発電機出力 20%

発電機出力をケース 2 の場合と同じ（発電機出力 20%）、PV 出力は 0MW とした場合の必要電池容量を求める。ケース 2 で、天候変化等により太陽光出力が 0%となった場合を考える。

① ノードデータ変更

ケース 2 で PV 出力は 0MW とした。

ノードデータのうち、追加・変更分を含む、発電機、蓄電池、PV データを表 4-10 に示す。

表 4-10　ノードデータ（発電機、蓄電池、PV データ）

Comments	Node data Input Form for Single Stage Power Flow Analysis								
	Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql
	(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)
	G1	1	1.03	0		0.004	0	0	0
	G2	1	1.03	0		0.003098	0	0	0
	G3	1	1.03	0		0.0026	0	0	0
	G4	1	1.03	0		0.0026	0	0	0
	G9	1	1.03	0		0.0024	0	0	0
	G10	1	1.03	0		0.0025	0	0	0
	G11	1	1.03	0		0.0025	0	0	0
	G12	1	1.03	0		0.0025	0	0	0
	G14	1	1.03	0		0.0025	0	0	0
	C24	1	1.03	0		0.0026	0	0	0
	C13	1	1.03	0		0.0026	0	0	0
	C56	1	1.03	0		0.0026	0	0	0
	BAT	2	1.03	0			0	0	0
	PV	0	1	0		0			

② ブランチデータ

・ケース 1、ケース 2 と変わらず。

③ シミュレーションン結果

・収束条件等
収束条件 0.0001p.u.
収束回数　3 回
回路全部の損失 0.00539p.u.（＝0.539MW）

Nodes		53
Branch:		52
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

・電圧結果
電圧結果を図 4-6 に示す。
PV 端子電圧は他発電機と同様な数値 1.03p.u.となっており問題はない。
末端の N34 ノードの電圧が 0.9p.u.以下になっているのはケース 0 と同様である。対策が必要である。

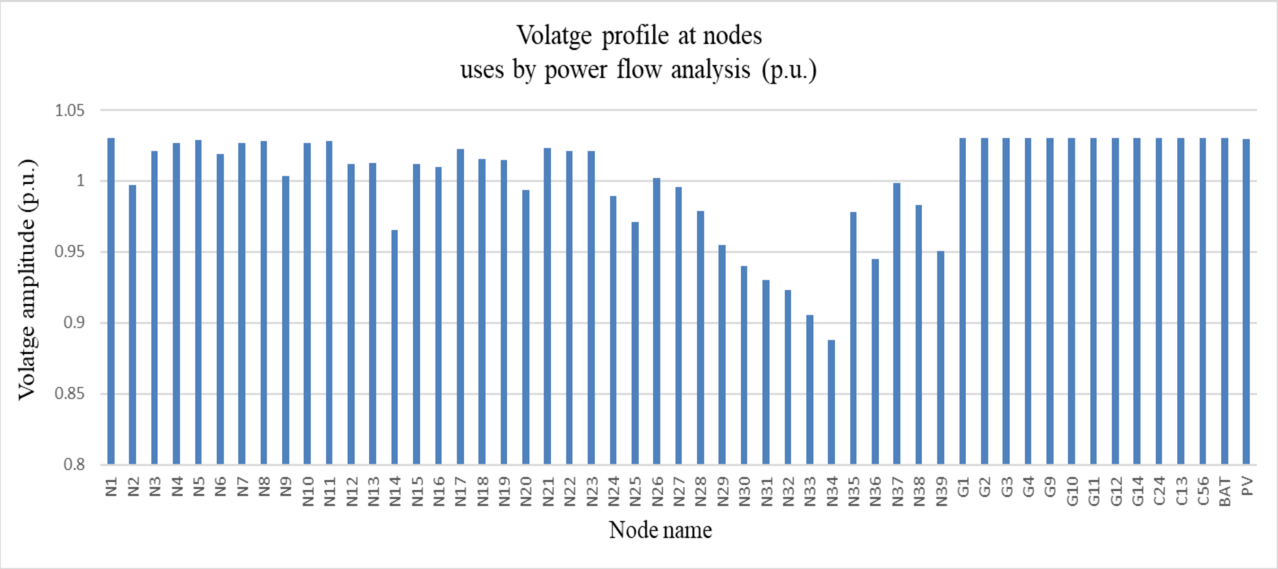


図 4-6　電圧結果

・発電機・PV 出力、蓄電池充放電結果
発電機出力、PV 出力、蓄電池充放電の結果を表 4-11 に示す。
蓄電池が約 0.13p.u.（13MW）放電していることが分かる。
発電機は無効電力を放出しており遅相運転となっている。しかしいずれも容量以内であり問題ない。

表 4-11　発電機・PV 出力、蓄電池充放電結果

Output Form of Obtained Results for Nodes by Singel Stage Power Flow Anlysis										
Node ID	Node type	Specified voltage	Obtaiened value		Specified P&Q		Obtained P&Q		Injection current	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	I (p.u.)	Angel (Degree)
G1	1	1.03	1.03	-4.22	0.004	0	0.004	0.01233	0.01259	-76.25
G2	1	1.03	1.03	-4.22	0.003098	0	0.0031	0.01233	0.01235	-80.11
G3	1	1.03	1.03	-4.22	0.0026	0	0.0026	0.01233	0.01224	-82.31
G4	1	1.03	1.03	-4.22	0.0026	0	0.0026	0.01233	0.01224	-82.31
G9	1	1.03	1.03	-4.22	0.0024	0	0.0024	0.01233	0.0122	-83.2
G10	1	1.03	1.03	-4.22	0.0025	0	0.0025	0.01233	0.01222	-82.76
G11	1	1.03	1.03	-4.22	0.0025	0	0.0025	0.01233	0.01222	-82.76
G12	1	1.03	1.03	-4.22	0.0025	0	0.0025	0.01233	0.01222	-82.76
G14	1	1.03	1.03	-4.22	0.0025	0	0.0025	0.01233	0.01222	-82.76
C24	1	1.03	1.03	-4.13	0.0026	0	0.0026	0.00002	0.00252	-4.63
C13	1	1.03	1.03	-4.13	0.0026	0	0.0026	0.00002	0.00252	-4.63
C56	1	1.03	1.03	-4.13	0.0026	0	0.0026	0.00002	0.00252	-4.63
BAT	2	1.03	1.03	0	0	0	0.12999	0.00481	0.12629	-2.12
PV	0	1	1.02999	-4.22	0	0	0	0	0	0

・線路電流

ケース 0 とほぼ同じ

・必要電池容量

P 出力-0.13p.u.（放電）、Q 出力 0.0048p.u.（放出）が必要との結果を得た。よって、必要電池容量は 0.13p.u.（13MVA）となる。

4.5. 結果

ケース 0 のその他発電機出力（PV を除く発電出力）は総負荷量と同じである。PV 最大出力 35MW として必要電池容量の検討を行った。

（ケース 1）

その他発電機出力をケース 0（総負荷量）と同じとすると、必要電池容量は P0.35p.u.、Q0.035p.u.となった。（P35MW、Q3.5MVar、35.17MVA）

（ケース 2）

その他発電機出力をケース 0（総負荷量）の 20%とすると、必要電池容量は P0.22p.u.、Q0.014p.u.となった。（P22MW、Q1.4MVar、22.04MVA）

（ケース 3）

（ケース 2）において PV 出力を 0%（出力無）とすると、必要電池容量は P0.13p.u.、Q0.0048p.u.となった。（P13MW、Q0.048MVar、13MVA）

負荷の合計 15.711MW に比べ、PV 出力 35MW は大きく、充放電を考えると発電機出力 0%が最も必要電池容量が少なくてすむが、電圧維持、周波数維持を考慮し、発電機出力 20%とした。

よって、発電機出力 20%とし、(ケース 2)、(ケース 3) から必要電池容量を考えると、約 22MVA となる。

4.6. 結論

総負荷量 15.711MW、PV 最大出力 35MW、その他発電機出力を、電圧維持、周波数維持を考え総負荷量の 20%とすると、必要電池容量は約 22MVA となる。

5. St.Kitts 島における蓄電池容量決定シミュレーション

St.Kitts 島における蓄電池容量決定シミュレーションを行った。想定 PV の容量は潮流計算と同じ 35MW とした。潮流計算により、ＰＶ35MW 設置による系統安定性上の問題がないことが確認でき、必要蓄電池容量 (MW) を算出できた。ここでは 24 時間の電池充放電シミュレーションを行い、必要蓄電池容量 (MWh) を算出する。

5.1. 目的

St.Kitts 島の 24 時間の負荷曲線と、PV 曲線を用いて、必要蓄電池容量 (MWh) を算出する。

5.2. シミュレーションデータ

(1) 日負荷データ

日本工営からの入手日負荷データ (図 5-1 参照) から、需要が低い日曜データを用いるものとした (需要が低い程必要蓄電池容量が多めに出る)。　更に潮流計算結果と整合性を保つため、昼間ピーク時の需要を 15.7MW となる様に調整した (全時間帯で、同比率で調整)。

図 5-1　日負荷曲線

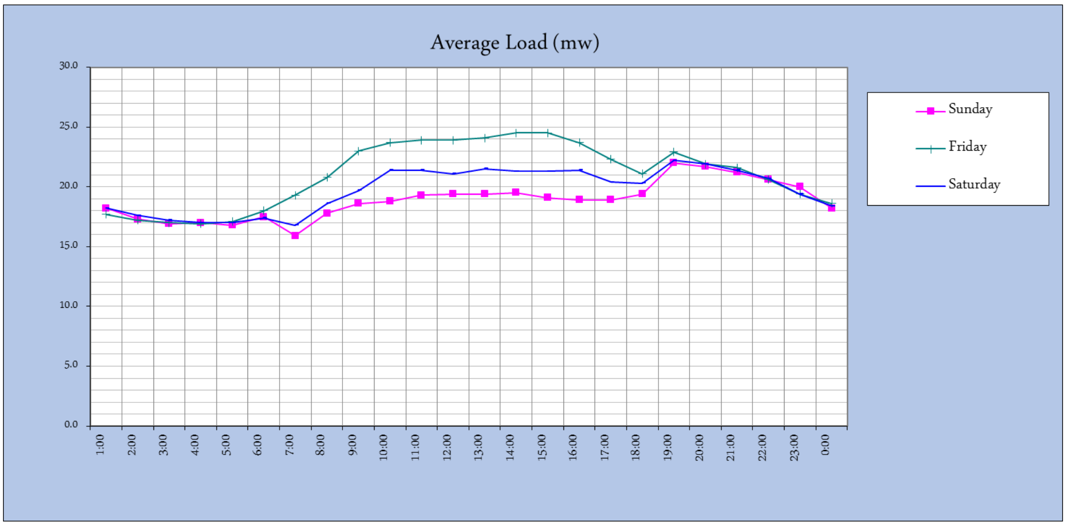


図 5-2 はシミュレーション用に作成した日負荷曲線である。

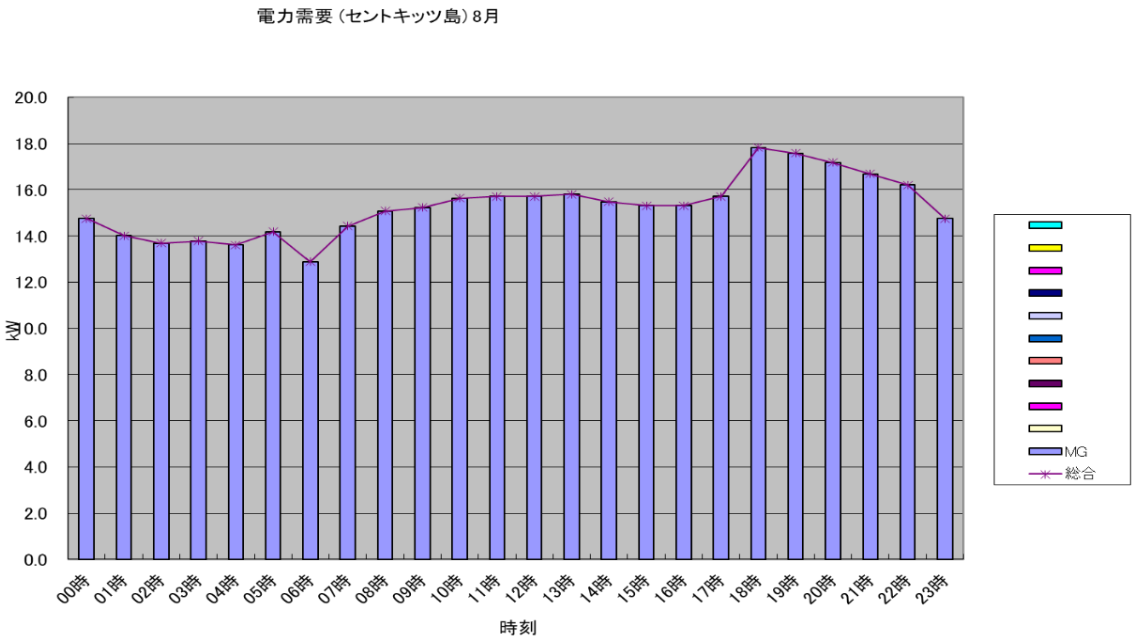


図 5-2　シミュレーション用日負荷曲線

(2) PV データ

日本工営からの入手 PV データから晴天に近い 8 月 1 日データを用いるものとした。更に潮流計算結果と整合性を保つため、最大 PV 出力が 35MW となる様に調整した（図 5-3 参照）。

図 5-3　PV 曲線

5.3. シミュレーション手順

作成した日負荷データ、PV データを用いて、電池充放電シミュレーションを行った。

電池充放電状況は、発電機出力(PV 以外の発電設備)によっても変わってくるので、以下ケースを行った。

ただし、発電機出力は、PV 出力が需要を上まわるときは、最低出力とするものとした。最低出力は潮流計算結果と整合性を保つために、3.2MW とした。

(1) PV 最大出力の場合の検討

① Case1：発電機出力 15MW

② Case2：発電機出力 8MW

③ Case3：発電機出力 5MW

④ Case4：発電機出力 3.2MW

(2) PV 出力 0 の場合の検討

「(1) PV 最大出力の場合の検討」で求めた電池容量を使って下記シミュレーションを行った。

① Case5：発電機出力 15MW

② Case6：発電機出力 10MW

③ Case7：発電機出力 8MW

5.4. シミュレーション結果

(1) PV 最大出力の場合の検討

① Case1：発電機出力 15MW

・充放電結果

充放電結果を図 5-4 に示す。

蓄電池（BT）最大充電量は約 22MW となった。これは潮流計算結果と同結果となった。

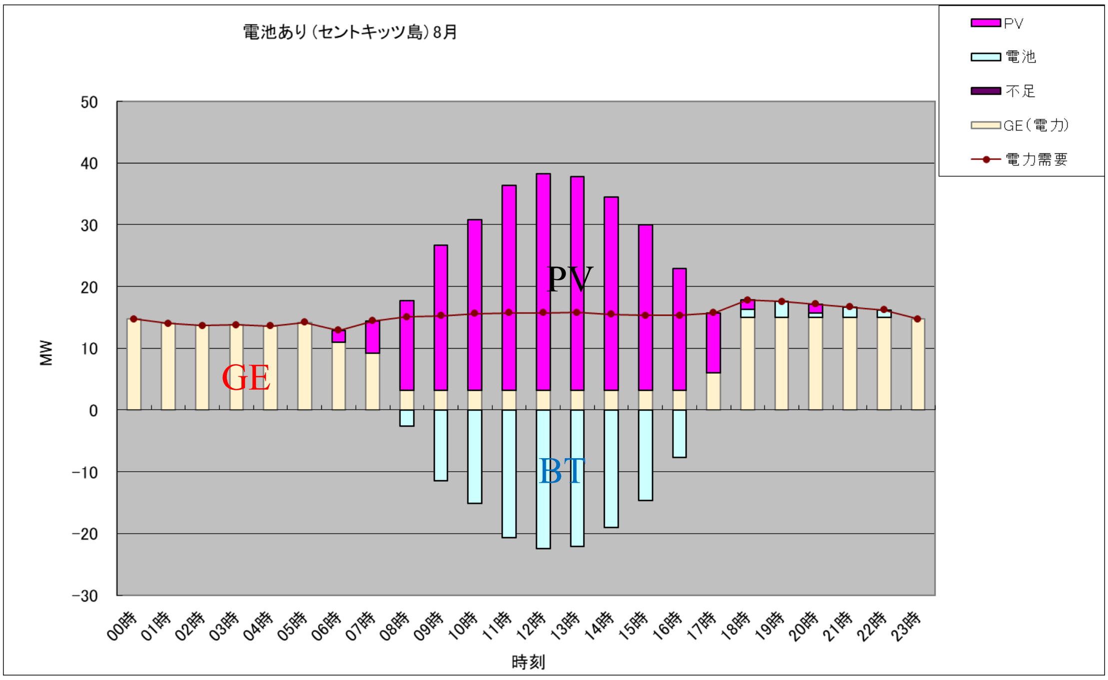


図 5-4　Case1 充放電結果

・SOC 結果

SOC 結果を図 5-5 に示す。最大 SOC は 136 MWh となった。

これは必要蓄電池容量が 136MWh であることを示している。

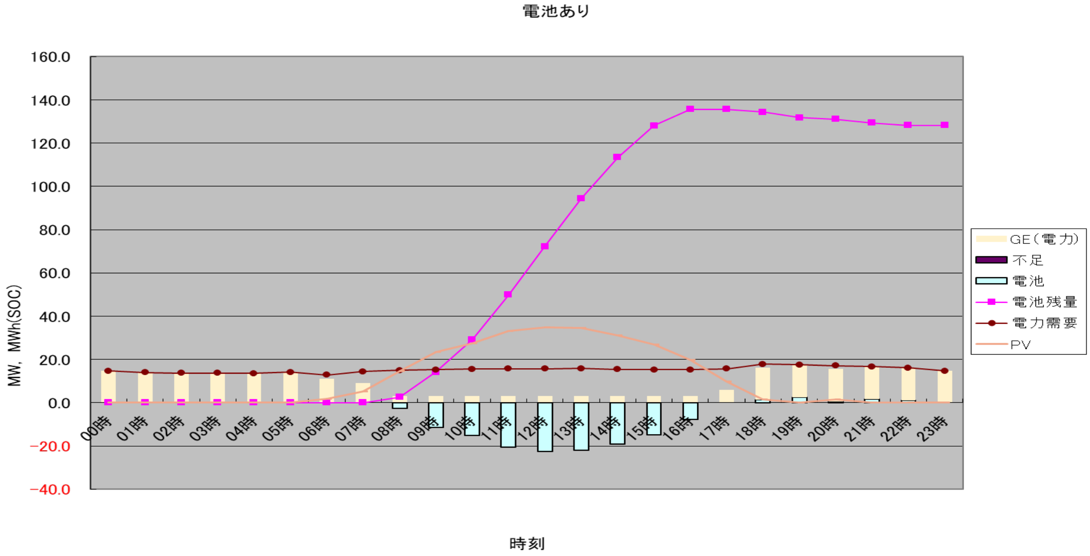


図 5-5　Case1 SOC 結果

また、初期 SOC に対し最終 SOC がかなり大きい。これは晴天時には発電機出力 15MW が過剰気味であることを示している。

② 　Case2：発電機出力 8MW

・充放電結果

充放電結果を図 5-6 に示す。

Case1 と同様に蓄電池（BT）最大充電量は約 22MW となった。

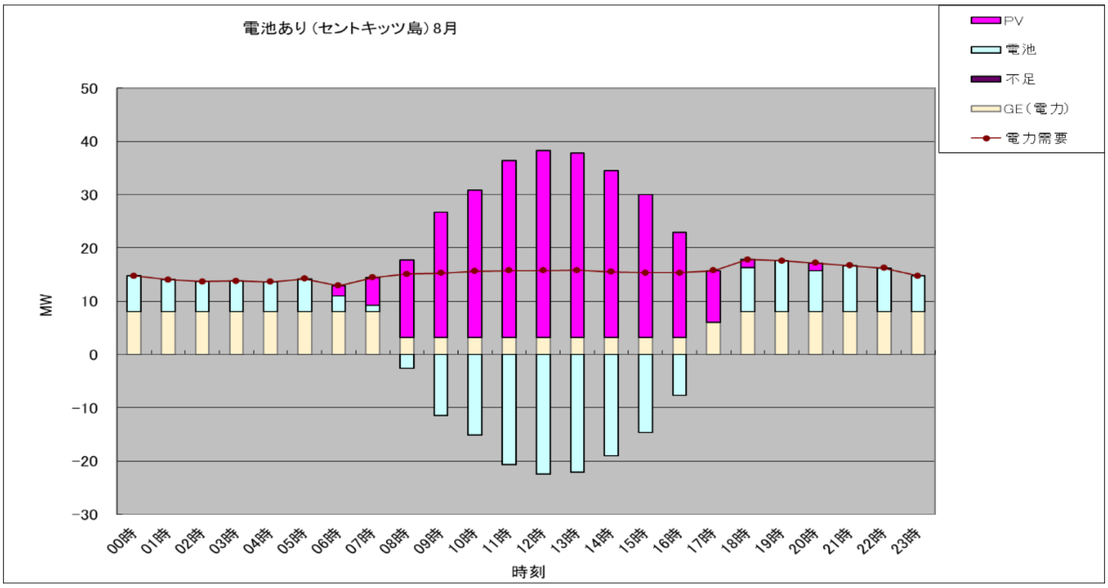


図 5-6　Case2 充放電結果

・SOC 結果

SOC 結果を図 5-7 に示す。

最大 SOC は 136 MWh となった。　このケースからも必要蓄電池容量が 136MWh であることを示している。　また、初期 SOC に対する最終 SOC の差は Case1 に比べ縮まったが、最終 SOC の方が大きい。これは晴天時には発電機出力 8MW は若干、過剰気味であることを示している。

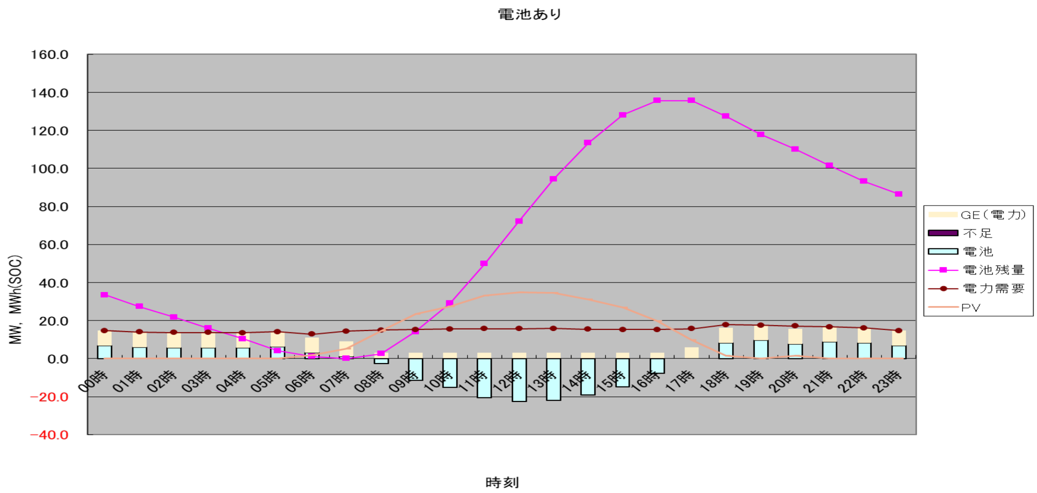


図 5-7　Case2 SOC 結果

③　Case3：発電機出力 5MW

・充放電結果

充放電結果を図 5-8 に示す。

Case1、Case2 と同様に蓄電池（BT）最大充電量は約 22MW となった。

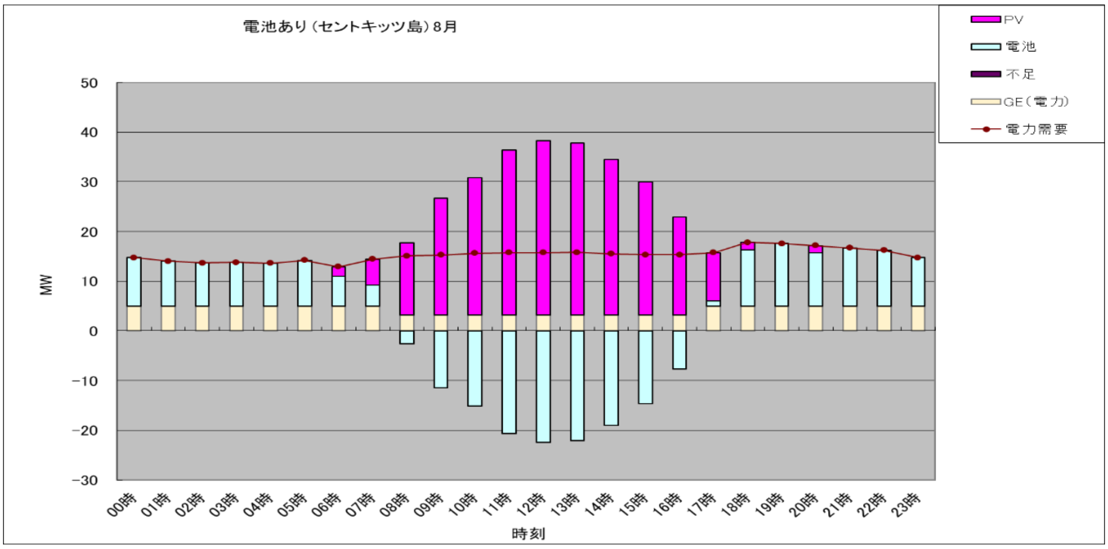


図 5-8　Case3 充放電結果

・SOC 結果

SOC 結果を図 5-9 に示す。

最大 SOC は 136 MWh となった。　このケースからも必要蓄電池容量が 136MWh であることを示している。　また、初期 SOC と最終 SOC は近い値となった。これは晴天時には発電機出力 5MW はほぼ適正であることを示している。

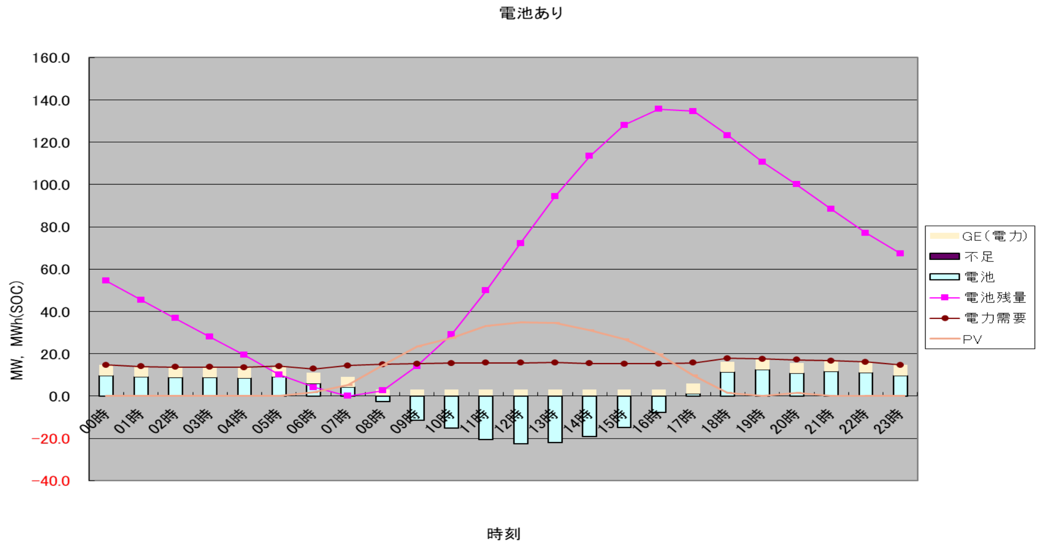


図 5-9　Case3 SOC 結果

④　Case4：発電機出力 3.2MW

・充放電結果

充放電結果を図 5-10 に示す。

Case1、Case2、Case3 と同様に蓄電池（BT）最大充電量は約 22MW となった。

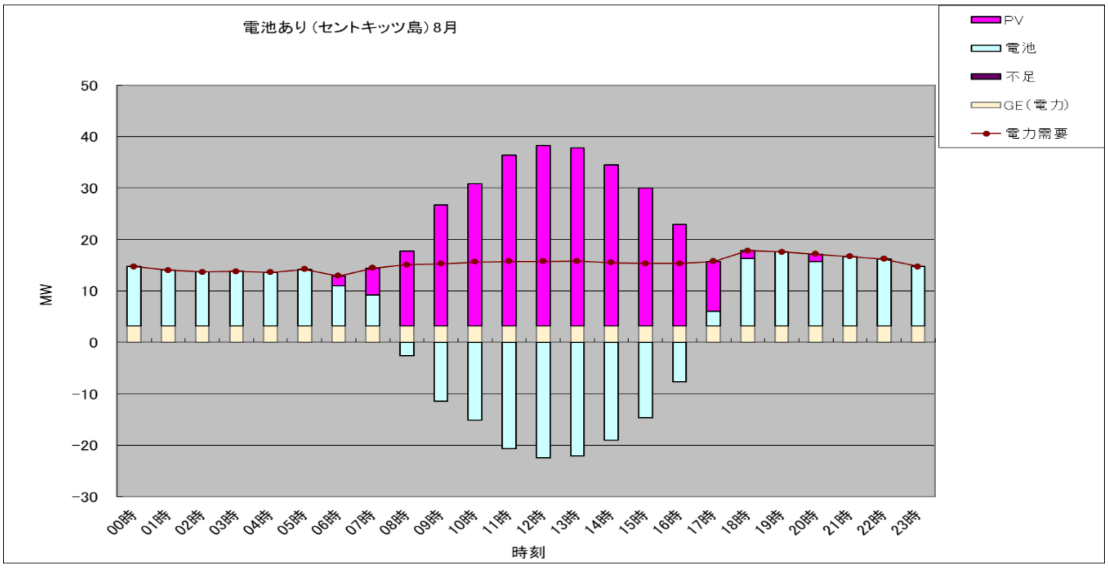


図 5-10　Case4 充放電結果

・SOC 結果

SOC 結果を図 5-11 に示す。

最大 SOC は 136 MWh となった。　このケースからも必要蓄電池容量が 136MWh であることを示している。　また、初期 SOC に比べ、最終 SOC は若干小さくなった。これは晴天時には発電機出力 3.2 は若干小さめであることを示している。

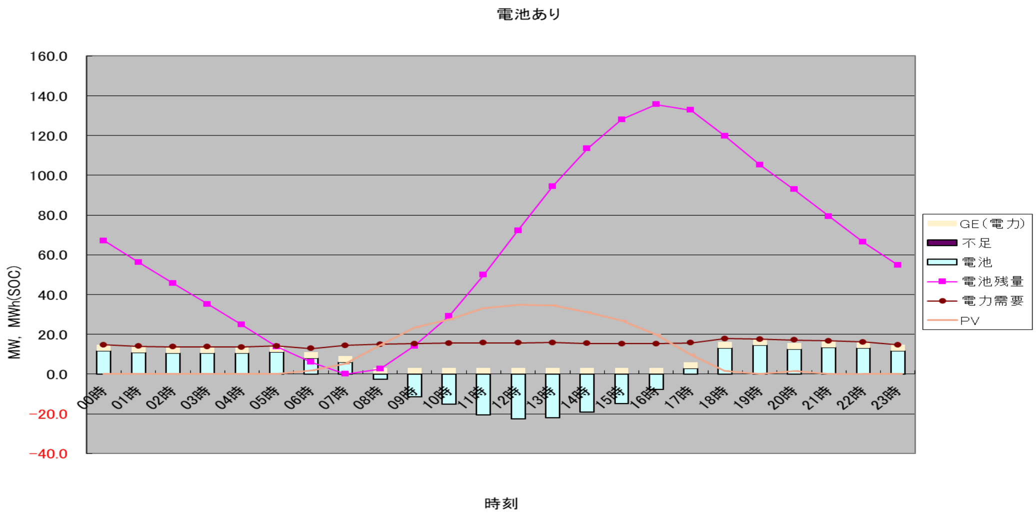


図 5-11　Case4 SOC 結果

(2) PV 出力 0 の場合の検討

最大蓄電池容量を 136MWh として検討した。

①　Case5：発電機出力 15MW

SOC 結果を図 5-12 に示す。

初期 SOC が 15.4MWh となった。初期 SOC が 15.4MWh 以上であれば供給可能である。

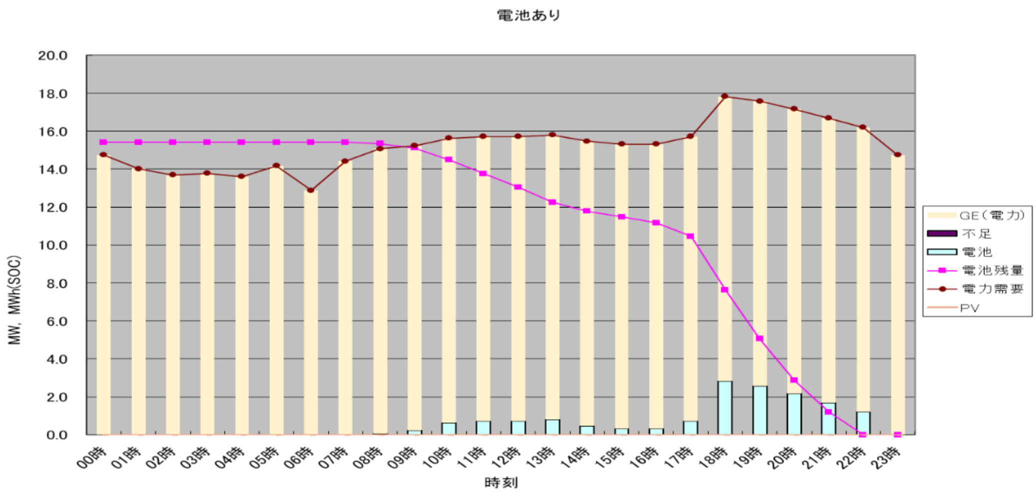


図 5-12　Case5 SOC 結果 1

図 5-13 は、初期 SOC　（前日 23 時の値）を最大蓄電池容量の 136MWh とした場合で

ある。 最終 SOC が 120.6kWh なので、一日の放電量は 15.4MWh となる。このため初期 SOC を 136MW とし、発電機出力 15MW とした場合、PV 出力 0 であっても約 8.8 日間供給可能であることを示す。これは、(8.8（日）=136（kWh）÷15.4（kWh/日）)にて算出される。

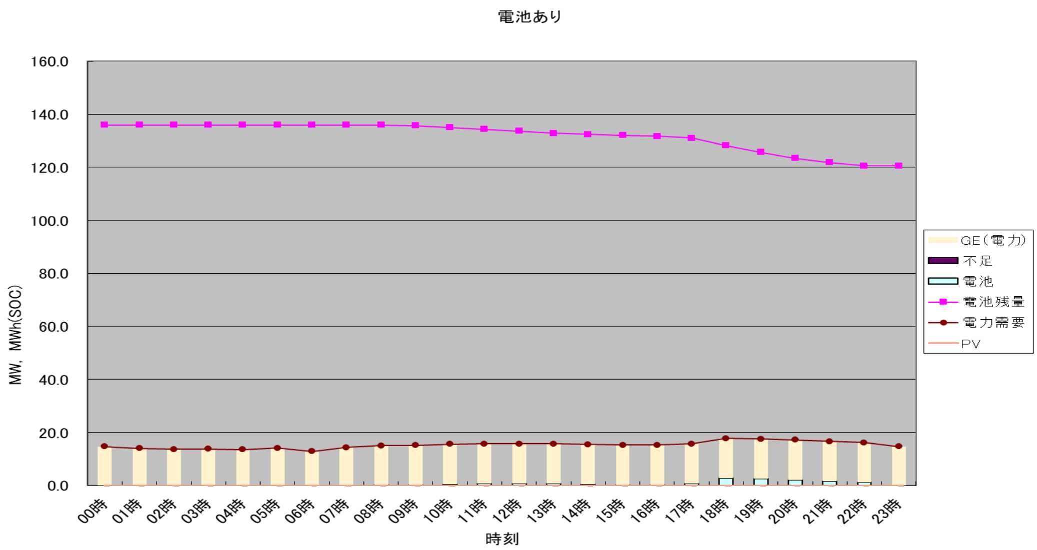


図 5-13　Case5 SOC 結果 2

② Case6：発電機出力 10MW

SOC 結果を図 5-14 に示す。

初期 SOC （前日 23 時の値）を最大蓄電池容量の 136MWh とした。 供給不足はないが最終 SOC は 0 に近くなった。

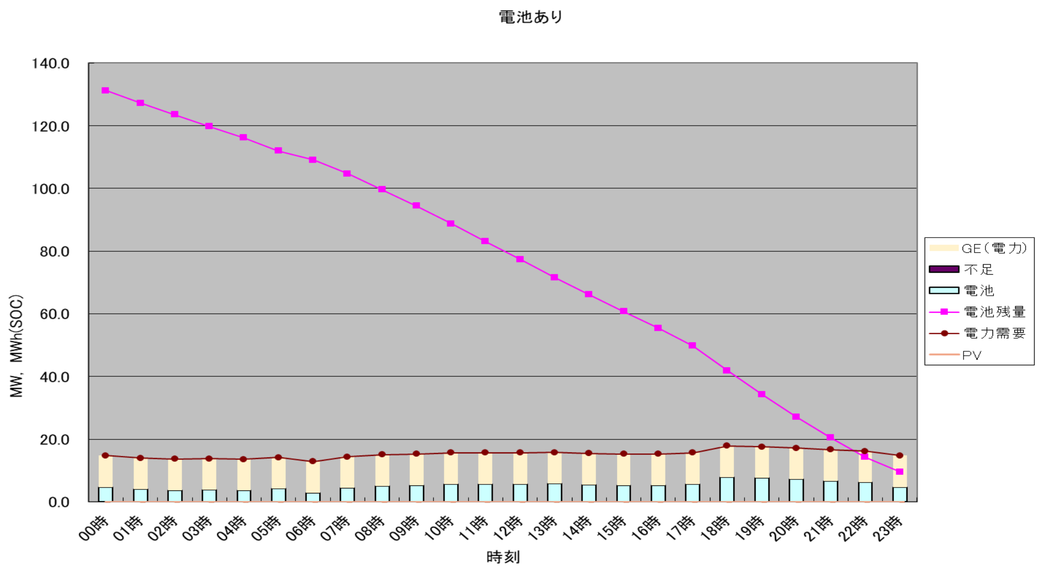


図 5-14　Case6 SOC 結果

③　Case7：発電機出力 8MW

SOC 結果を図 5-15 に示す。

初期 SOC （前日 23 時の値）を最大蓄電池容量の 136MWh とした。 19 時以降に供給不足となる。19 時以降発電機出力を増加する必要がある（図は発電機出力を増加しない場合）。

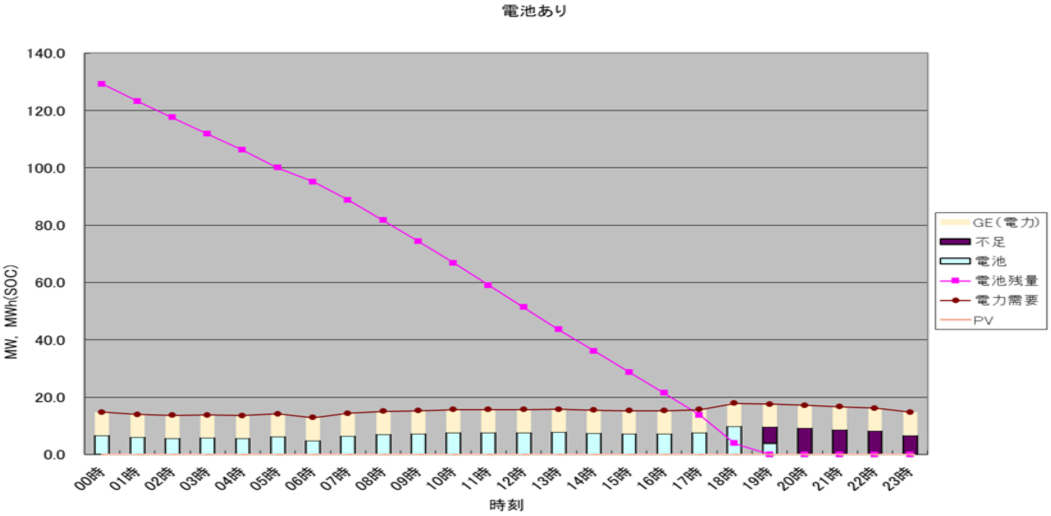


図 5-15　Case7 SOC 結果

5.5. 結果

日本工営からの入手した日負荷データをもとに、潮流計算結果と整合性を保つため、昼間ピーク時の需要を 15.7MW となる様に調整して日負荷データを作成した。PV データも日本工営からの入手データをもとに、潮流計算結果と整合性を保つため、最大 PV 出力が 35MW となる様に調整した。これらデータを用いて、電池充放電シミュレーションによる必要蓄電池容量算定を行った。

シミュレーションは、発電機出力(PV 以外の発電設備)が 15MW、8MW、5MW、3.2MW のケースで行った。この結果、すべてのケースで、必要蓄電池容量は、22MW、136MWh であることが算出された。必要蓄電池容量 22MW は潮流計算結果とも合致している。

PV 出力 0 のケースでは、発電機出力 10MW 以上では 1 日以上電池で供給できることが示された。また、発電機出力 10MW 未満でも、発電機出力を途中から増やす等して十分供給できることが示された。

6. 結論

カリコム諸国においては、長期的で大きな経済的解決策として再生可能エネルギーの導入によりエネルギーミックスを多様化することにより、輸入化石燃料への依存を減らし、カ

リブの政府の最重要課題である長期的なエネルギー安全保障を確保できる。

ここでは、セントキッツ島のエネルギー部門を分析し、ベースロードをカバーする再生可能エネルギー技術として大規模太陽光発電を設置することにより、エネルギー安全保障をどのように達成できるかを実証した。

セントキッツ島における再生可能エネルギー、電力需要及び電力系統に関する資料収集を行い、これら資料を用いて、電力系統の解析支援ツールである MicroGrid Designer を使用してカリコム系統安定化シミュレーションを実施し、その解析結果を示した。

結論として、セントキッツ島において、昼間ピーク負荷量 15.7MW の日負荷曲線、最大出力 35MW の PV 曲線を用いて、電池充放電シミュレーションを行ったところ、必要蓄電池容量は、22MW、136MWh であることが算出された。

必要蓄電池容量 22MW は潮流計算結果とも合致している。また、潮流計算において、35MW 容量の太陽光発電を設置しても、系統に特段の重潮流が発生することもなく、電圧分布も適正値以内に収まることが確認された。

ただし、末端の N34 ノードの電圧が 0.9p.u.以下になるので、電圧調整設備設置等の対策が必要でありことが明らかになった。

実際に、電圧低下が発生しているかの実測と確認が必要である。

計画されている大規模太陽光発電の設置は、この地域の電力安定供給、発電コスト低減、環境負荷の改善に大きく貢献するであろうことが検証できた。

7. 系統解析シミュレーション・ツールの説明（補足）

電力系統シミュレータ MicroGrid Designer は、環境エネルギー技術研究所により開発された（一部開発中の）電力系統エンジニア・実務者向けの送配電系統用数値解析ツールである。その主な用途は、対象とする電力系統において発電機群と計画時間帯の負荷が与えられている場合に、計画時間全体の需給バランスの最適化を行って燃料費を最小とする発電機出力を決定し、引き続き系統の時間帯別潮流計算を行うことにより周波数や電圧の運用安定性を検証する点にあります。発電機群として、再生可能エネルギーや蓄電池も考慮することが可能である。

電力系統分野においては，これまで多数の解析ソフトウェアが開発されているがが、近年のスマートグリッド技術の進展や再生可能エネルギーの導入拡大等に伴い、配電系統における系統解析の高度化と並んで専門外のエンジニアにも利用可能な簡素化されたツールの開発が求められている。

このような状況を考慮して、電力系統シミュレータ MicroGrid Designer は次のようなコンセプトで開発されている。

1 マイクログリッド等の小中規模配電系統を主対象として、より高度な電力需給バラン

ス解析と周波数及び電圧変動解析に寄与する系統解析ツールとする。

2 Excel を使用した入出力及び演算操作インターフェイスにより、ユーザ・フレンドリな機能を与え、専門外のエンジニアにも使いやすいソフトウェアとなっている。

電力需給バランス解析には、実際に運用可能な条件を取り入れた最適化問題としており扱い、一般に知られている効率的解法を使用している。

*MicroGrid Designe*r では、経済負荷配分(ELD: Economic Load Dispatch)と潮流計算(Power flow)を多断面で実行する。

ここで、MicroGrid Designer では、多断面の経済負荷配分を多段経済負荷配分(Multi stage ELD)、また多断面の潮流計算を多段潮流計算(Multi stage Power flow)と、名付けた。

多段経済負荷配分では、対象とする電力系統において発電機群と計画時間帯の総負荷が与えられている場合に、計画時間全体の需給バランスの最適化を行って燃料費を最小とする発電機群の有効電力出力を決定する。

また多段潮流計算では、多段経済負荷配分で決定された発電機群の有効電力出力を使用して、時間帯別潮流計算を逐次的に実行し、母線電圧とブランチ潮流を算定する。

発電機群として、再生可能エネルギー(RES: Renewable Energy Sources)や蓄電池も考慮することが可能である。蓄電池は、充放電量を調整することにより、系統全体の需給インバランスを吸収させる。

MicroGrid Designer は、前記のように、多段経済負荷配分と多段潮流計算を連続して実行する機能を有するツールであるが、1断面に適用すれば、一般的にも使用されている経済負荷配分と潮流計算を単独に実行することができる。

以上、電力系統シミュレータ MicroGrid Designer について概説した。詳細については、英文報告書の ELD, LFC 及び電力潮流解析の定式化と解法において詳しく述べられているので、それを参照して頂きたい。

その他付録と参考資料

ここに述べて業務における実施項目に関する参考資料は付録を参照のこと。

1）中間報告　2020 年 4 月 27 日（付録 A）

2）電力系統解析の定式化と解法の解説資料（付録 B、付録 C、付録 J）

打合せのための説明資料

3）St.Kitts 島における収集資料の精査　（付録 D）

第 1 次渡航で収集された St.Kitts 島の発電所・発電機情報、系統構成と系統属性、 及び負荷・再生可能エネルギー状況

4）St.Kitts 島における系統属性の確定（付録 E）

第 2 次渡航で収集された PSS/E 用のデータと MicroGrid Designer 用に変換されたデータ。

5）St.Kitts 島における潮流計算の追試（付録 A に結果のみ示す）

PSS/E からの変換データをもとに算定された MicroGrid Designer による潮流計算（単期間）５ケースの結果

6）St.Kitts 島における系統計画の確認（付録 F，付録 G，付録 H、付録 I）

第３次渡航で収集された St.Kitts 島における発電所・発電機情報、系統構成と系統属性、及び負荷・再生可能エネルギー(太陽光発電)情報。

8. 付録A:カリコム系統安定化シミュレーション報告(中間)

環境エネルギー技術研究所作成

1. 実施業務の概要

２０１９年度に実施した内容を下記に示す目次に分類して記す。

- 今年度業務における実施項目と進捗状況
- 系統解析シミュレーション・ツールの説明
- 系統解析シミュレーションの暫定的結果
- 成果物と報告書
- 今後(2020 年度以降)に向けた課題等

２. 2019 年度業務における実施項目と進捗状況

1) 電力系統解析の基本的事項

2019 年度の業務に関して、事前に予定されていた項目と中途に追加された項目に関し、その内容と進捗状況を以下のように整理した。

電力系統解析の基本についての講義系統解析に使用するソフトウェアとして、作成中のツール *MicroGrid Designer* (仮称) を使用することを前提としていたのでその作業内容を説明する講義資料を作成し、電力系統解析の基本的事項を交えて、当該プロジェクトのメンバーにて論議した。(2019/07)

2) St.Kitts 島における収集資料の精査

第１次渡航で収集された St.Kitts 島の発電所・発電機情報、系統構成と系統属性、 及び負荷・再生可能エネルギー(太陽光発電と風力発電)情報についての精査を行い、系統解析に使用可能となりそうなデータを抽出したまた、同時に収集された St.Kitts 島における既実施の系統計画レポート「Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept.2014 by leidos」(以下、参考資料と称す)を主たる参考資料としてレビューを行った。

3) St.Kitts 島における系統属性の確定

第１次渡航で収集された St.Kitts 島の系統情報には、すぐに使える実用的な数値データが少なかったので、参考資料で述べられていた「PSS/E を使用して潮流計算を実施した」ことをもとに、本プロジェクトにも PSS/E 用のデータを活用することを提案した。なお、PSS/E は Siemens 社で開発された高額な系統解析ツールである。その結果、PSS/E 用のデータが第

２次渡航で収集されたので、これを *MicroGrid Designer* 用のデータに変換することができた。

4) St.Kitts 島における潮流計算の追試

PSS/E からの変換データをもとに、St.Kitts 島の概略系統構成図を作成し、*MicroGrid Designer* により潮流計算（単期間）５ケース(下記)を実行し、その結果の検討を行った。

PSS/E 用のデータの特徴は、１箇所の発電所から 12 本のフィーダが出るループなしの配電系統であり、各フィーダ末端には小規模太陽光発電、1 本のフィーダ中間に一台の大規模風力発電(5.4MW)が設置してあることである。

参考資料には潮流計算結果の詳細は記載されていないので比較はできないが、*MicroGrid Designer* による潮流計算結果に妥当性が十分あるように判断されるので、現地における PSS/E 用のデータは実際に活用可能であることが明確化された。但し、このデータは６年以上前に作成されているので、以降の系統更新に留意する必要がある。

潮流計算（単断面）を行った５ケースを以下にしめす。

Case0： PSS/E の変換データを直接使用したケース(図１)

Case1：再生可能エネルギー無しパターン：PV, Wind の出力を 0 とするケース

Case 2：ベース条件（図２）

- ・PV500kW(SKELEC サイト)を Bus 4 に接続
- ・PV700kW(空港)を他の火力発電ユニットと同様に、Bus 1 に接続
- ・上記 2 か所以外の PV, Wind の出力を 0 とする

Case3：ベース条件

- ・PV500kW(SKELEC サイト)を Bus 3(Canada_1219)に接続
- ・PV700kW(空港)を他の火力発電ユニットと同様に Bus 1 に接続
- ・上記 2 か所以外の PV, Wind の出力を 0 とする

Case4：既存計画反映 00 (図３)

- ・ベース条件 I に追加して、PV35MW を Bus 1 に接続
- ・蓄電池(BESS)34MWh/5.6MW も同様に、Bus 1 に接続
- ・上記以外の PV, Wind の出力を 0 とする

5) St.Kitts 島における系統計画の確認

第３次渡航で St.Kitts 島における発電所・発電機情報、系統構成と系統属性、及び負荷・再生可能エネルギー(太陽光発電)情報についての再確認と変更点の調査・収集がなされたので、これらから MicroGrid Designer による系統解析（多段経済負荷配分と多段潮流計算）用のデータを作成し、想定であるが、蓄電池付き大型太陽光発電 35MW の導入計画確定発電

機６台の追加、地下ケーブルと地上送電線の位置情報と線種の収集（図４）および週単位・負荷曲線データの確定を行った。

６） St.Kitts 島における系統解析シミュレーション

上記の経緯を経て、今年度業務における最終的な系統解析を行う準備が完成したので、St.Kitts 島・電力系統における最適蓄電池容量の決定と MicroGrid Designer による多段経済負荷配分と多段潮流計算を実施し、一週間単位の需給シナリオに基づいた発電機群と蓄電池の最適ディスパッチ・スケジューリング計画の策定と電圧安定性の検証を行った。詳細内容は、後述の「 系統解析シミュレーションの暫定的結果」にて述べる。この結果は、MicroGrid Designer が系統需給計画と電圧安定性評価に寄与できるツールであることを実証したと判断される

3. 系統解析シミュレーション・ツールの説明

電力系統シミュレータ MicroGrid Designer は、環境エネルギー技術研究所により開発された（一部開発中の）電力系統エンジニア・実務者向けの送配電系統用数値解析ツールである。その主な用途は、対象とする電力系統において発電機群と計画時間帯の負荷が与えられている場合に、計画時間全体の需給バランスの最適化を行って燃料費を最小とする発電機出力を決定し、引き続き系統の時間帯別潮流計算を行うことにより周波数や電圧の運用安定性を検証する点にあります。発電機群として、再生可能エネルギーや蓄電池も考慮することが可能である。

電力系統分野においては，これまで多数の解析ソフトウェアが開発されているがが、近年のスマートグリッド技術の進展や再生可能エネルギーの導入拡大等に伴い、配電系統における系統解析の高度化と並んで専門外のエンジニアにも利用可能な簡素化されたツールの開発が求められている。

このような状況を考慮して、電力系統シミュレータ MicroGrid Designer は次のようなコンセプトで開発されている。

1 マイクログリッド等の小中規模配電系統を主対象として、より高度な電力需給バランス解析と周波数及び電圧変動解析に寄与する系統解析ツールとする。

2 Excel を使用した入出力及び演算操作インターフェイスにより、ユーザ・フレンドリな機能を与え、専門外のエンジニアにも使いやすいソフトウェアとなっている。

電力需給バランス解析には、実際に運用可能な条件を取り入れた最適化問題としており扱い、一般に知られている効率的解法を使用している。

*MicroGrid Designe*r では、経済負荷配分(ELD: Economic Load Dispatch)と潮流計算(Power flow)を多断面で実行する。

ここで、MicroGrid Designer では、多断面の経済負荷配分を多段経済負荷配分(Multi stage

ELD)、また多断面の潮流計算を多段潮流計算(Multi stage Power flow)と、名付けた。

多段経済負荷配分では、対象とする電力系統において発電機群と計画時間帯の総負荷が与えられている場合に、計画時間全体の需給バランスの最適化を行って燃料費を最小とする発電機群の有効電力出力を決定する。

また多段潮流計算では、多段経済負荷配分で決定された発電機群の有効電力出力を使用して、時間帯別潮流計算を逐次的に実行し、母線電圧とブランチ潮流を算定する。

発電機群として、再生可能エネルギー(RES: Renewable Energy Sources)や蓄電池も考慮することが可能である。蓄電池は、充放電量を調整することにより、系統全体の需給インバランスを吸収させる。

MicroGrid Designer は、前記のように、多段経済負荷配分と多段潮流計算を連続して実行する機能を有するツールであるが、1 断面に適用すれば、一般的にも使用されている経済負荷配分と潮流計算を単独に実行することができる。

以上、電力系統シミュレータ MicroGrid Designer について概説した。詳細については、英文報告書の 3 章、4 章、5 章の ELD, LFC 及び電力潮流解析の定式化と解法に詳しく述べられているので、それを参照して頂きたい。

3. 系統解析シミュレーションの暫定的結果

既述した 2019 年度業務における実施(予定)項目と進捗状況及び St.Kitts 島における系統解析シミュレーションについて、その具体的内容を以下に２分類して示す。

・最適蓄電池容量の決定
・*MicroGrid Designer* による系統解析シミュレーション

1) 最適蓄電池容量の決定

大型太陽光発電 35MW の導入においては余剰電力対策が必須であり、そのために大容量蓄電池の併設が通常なされる。その際、最適な蓄電池容量の事前決定が必要要件となる。PV, 蓄電池を考慮した電力需要の均し処理を行うツール（図５）を試作中であり、数値が不明である余裕率や SOC を考慮しない場合の蓄電池の最小必要容量を次のように算定した。

St.Kitts 島の代表的日負荷パターンと太陽光出力をもとに、下記３シナリオに対し、蓄電池の時間最大出力を変えて、それぞれの蓄電池・最小必要容量を試算した。ここで、太陽光の最大出力は、最大負荷 28.8MW よりも大きい 35MW を想定している。

① シナリオ A (最大負荷時) : 最大負荷 28.8MW
② シナリオ B (中負荷時) : 最大負荷 20.0MW
③ シナリオ C (小負荷時) : 最大負荷 10.0MW

なお、太陽光出力が負荷よりも小さいシナリオは、蓄電池の出番がないので除外する。あくまでも想定の下での算定であるが結果は、以下の通りである。

① シナリオ A (最大負荷時) : 最小必要容量 19..943MWh
② シナリオ B (中負荷時) : 最小必要容量 75.548MWh
③ シナリオ C (小負荷時) : 最小必要容量 159.785MWh

試算結果による暫定結論は、以下のとおりである。

① シナリオ A,B,C すべてに対応可能な蓄電池容量は、超過大すぎる。
② シナリオ B,C に対応可能な蓄電池容量も、超過大すぎる。
③ したがって、シナリオ A により蓄電池容量を決定する方が良いが、これによる蓄電池容量ではシナリオ B,C に対応できないので、シナリオ B,C が生じるような状況では、太陽光の出力抑制を実施することで対応しなければならない。
④ シナリオ A で決定された最適な蓄電池・最小必要容量は約 20MWh であり、この最適容量は、蓄電池の最大充放電量 8MW で余剰電力が発生しないように決められている。

以上に示したツールは、蓄電池容量の簡略見積もり用であるので、MicroGrid Designer の多段経済負荷配分を使用して、日単位での最適な蓄電池・最小必要容量の決定もできる（図６）。その結果は、シナリオ A に対し、蓄電池最大充放電量 5.386MW、蓄電池最小容量 14.840MWh であり、MicroGrid Designer の多段済負荷配分の方がより少ない蓄電池最小容量を与えることが実証された。しかし、これは、各種想定の上での結果であり、実運用を踏まえての条件設定の上での再計算が必要である。

2) *MicroGrid Designer* による系統解析シミュレーション

MicroGrid Designer による多段経済負荷配分

一週間単位の需給シナリオに基づいた発電機群と蓄電池の最適ディスパッチ・スケジューリング計画（１時間単位）の策定を下記３ケースに対して実施した。
検討３ケース（図９）では、代表月の１週間; 負荷 profile が異なる。

- case-1: 2019/3/3 2019/3/9 (1 week)
- case-2: 2019/4/7 2019/4/13 (1 week)
- case-3: 2019/7/7 2019/7/13 (1 week) 最大負荷月

ここで、上記３ケースに共通して使用した系統条件として、太陽光発電と余剰電

力対策について述べておく。
・太陽光発電 3 基　(35MW, 0.7MW, 0.5MW)
　これらの発電シナリオとして、天候を考慮した１週間の代表的パターンを使用（図８)。大型太陽光発電（定格 35MW)の最大出力を実効値 25MW に限定。

・余剰電力対策
　太陽光発電からの余剰電力対策として、「蓄電池と需給インバランスを吸収するための調整スラックを設け、この調整スラックを通じて余剰電力を外部へ流す」こととした（図７)。但し、大型太陽光発電の最大出力を 25MW に限定したので、検討３ケースとも調整スラックからの流出はわずかしか発生していない結果が得られている。
　また、蓄電池の充電を昼間時間に制限し、最大出力（最大充放電量）を最適蓄電池容量の決定を参考にして 5MW までとした。これにより、蓄電池の最小必要容量の最大見積りは最大充電量(5MW)*7h＝35MWh となる。但し、シミュレーション結果による実際の（最適な）最小必要容量は、以下の通りであった。

- case-1：最大出力 5.00 MW、最小必要容量 18.16 MWh
- case-2：最大出力 3.97MW、最小必要容量 10.28 MWh
- case-3：最大出力 3.02 MW、最小必要容量 5.65 MWh

　この結果より、検討３ケースにおける蓄電池の最小必要容量は約 18MWh と判断できる根拠が示された。

② MicroGrid Designer による多段潮流計算
　上記の多段経済負荷配分の結果により得られた発電機・蓄電池の有効電力出力を利用して、検討３ケースに対し、一週間（１時間単位 168 断面）の多段潮流計算を実施した。また下記の表に示すように、得られた電圧値の最大・最小より電圧安定性の検証を行い、多少の逸脱はあるが概ね規定範囲内（0.95～1.05p.u.）にあること」を確認した。但し、この表に掲載している電圧値は、St.Kitts 島における最近の系統更新を考慮した系統属性（インピーダンス等）を反映していないデータの下で算定されているので、正確なものではないため、データを確認ののち、本年度に、算定する必要がある。

　多段潮流計算による電圧値と有効電力ロスは、電圧値最小[p.u.]　電圧値最大[p.u.]　有効電力ロス[%]である。

- case-1：0.96087 1.06998 4.699 図 10 参照
- case-2：0.95743 1.07247 4.655 図 11 参照

- case-3 : 0.92619 1.05684 4.591 図 12 参照
-

4. 成果物と報告書

項目「今年度業務における実施項目と進捗状況」にした項目内容
に対応する成果物と報告書は、以下のとおりである。

１）電力系統解析の定式化と解法

レクチャー用の講義資料（英文報告書第 4 章）

２）St.Kitts 島における収集資料の精査

第１次渡航で収集された St.Kitts 島の発電所・発電機情報、系統構成と系統属性、 及び負荷・再生可能エネルギー(太陽光発電と風力発電)情報と系統計画レポート「Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept.2014 by leidos」。

３）St.Kitts 島における系統属性の確定

第２次渡航で収集された PSS/E 用のデータと MicroGrid Designer 用に変換されたデータ。

４）St.Kitts 島における潮流計算の追試

PSS/E からの変換データをもとに算定された MicroGrid Designer による潮流計算（単期間）５ケースの結果(下記の図表に示す)。

５）St.Kitts 島における系統計画の確認

第３次渡航で収集された St.Kitts 島における発電所・発電機情報、系統構成と系統属性、及び負荷・再生可能エネルギー(太陽光発電)情報。

６）St.Kitts 島における系統解析シミュレーション

St.Kitts 島・電力系統における MicroGrid Designer による潮流計算を実施した結果は、英文報告書中にまとめられている。多段潮流計算については、本算定報告末尾に図に示した。

5. 今後（2020 年度以降）に向けた課題等

2020 年度の業務実施においては、St.Kitts 島において収集された系統情報をもとに MicroGrid Designer による系統解析シミュレーションを行い、その適用妥当性の実証と系統計画策定における発電機ディスパッチ・スケジューリングの作成および周波数及び電圧の変動を解析し運用安定性の検証を行う。

重要なベース資料として有効であったものは、PSS/E 用のデータである。これまでの現地におけるデータ収集では、発電機の構成、RE の導入計画、負荷情報等は収集可能であったが、インピーダンス等実際的な系統属性については収集困難な状況にあることが明確になった。したがって、今後他島への展開を行う上では、実際的な系統属性をどう収集するか、PSS/E 用のデータあるいは同等のデータは存在するか、現地カウンターパートから最新の数値情報入りの系統図作成の協力が得られるか等の課題が残されている。

以下には、これから作成するマイクログリッド解析ツールの入出力のイメージを示す。

この解析ツールは、2021 年度後期までに完成させる予定である。

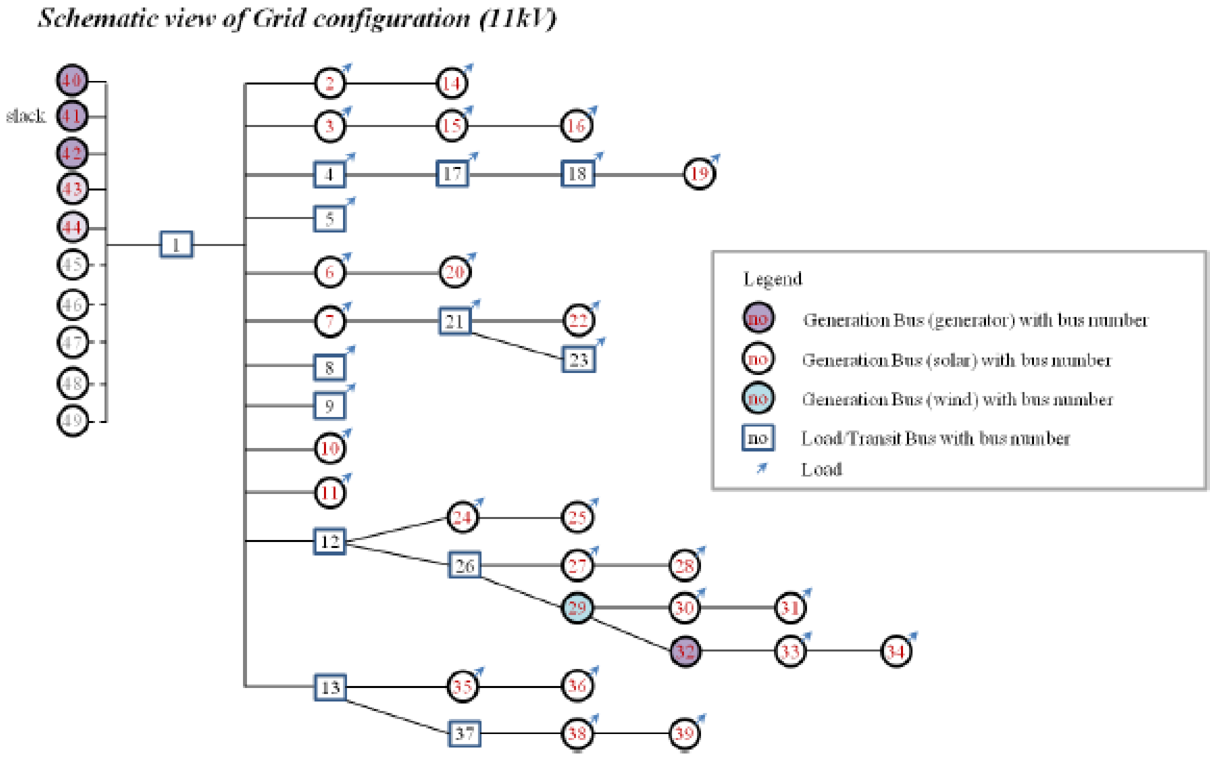


図 1 単期間潮流計算用の概略系統図(case-0)

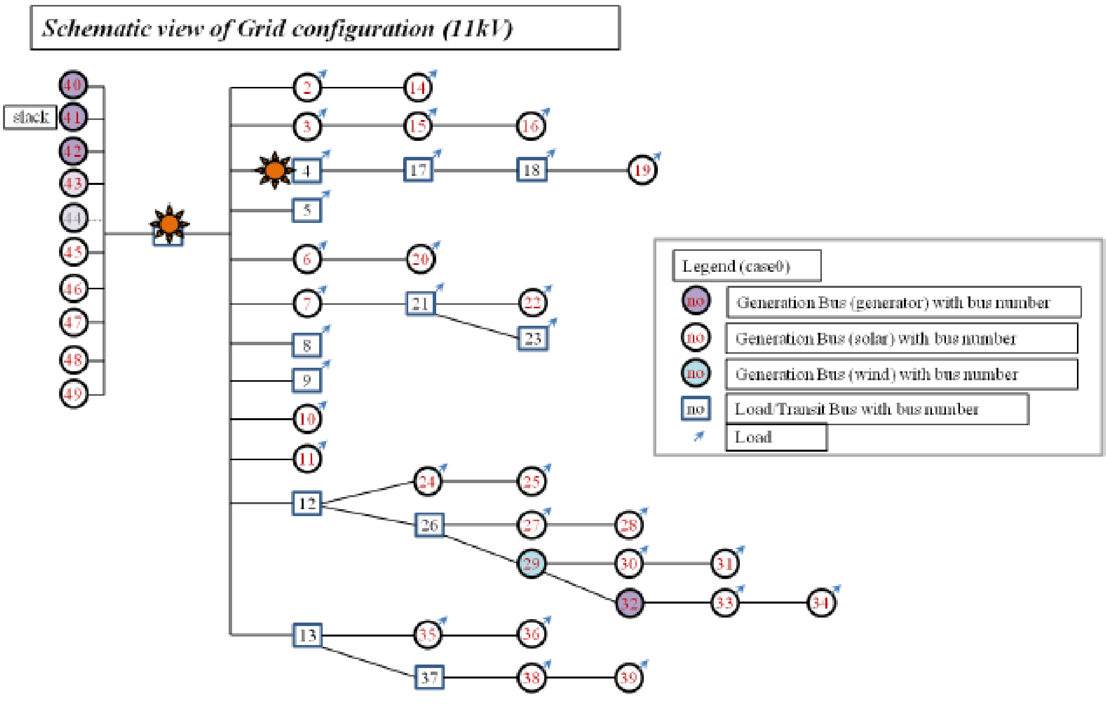


図２　単期間潮流計算用の概略系統図(case-2)

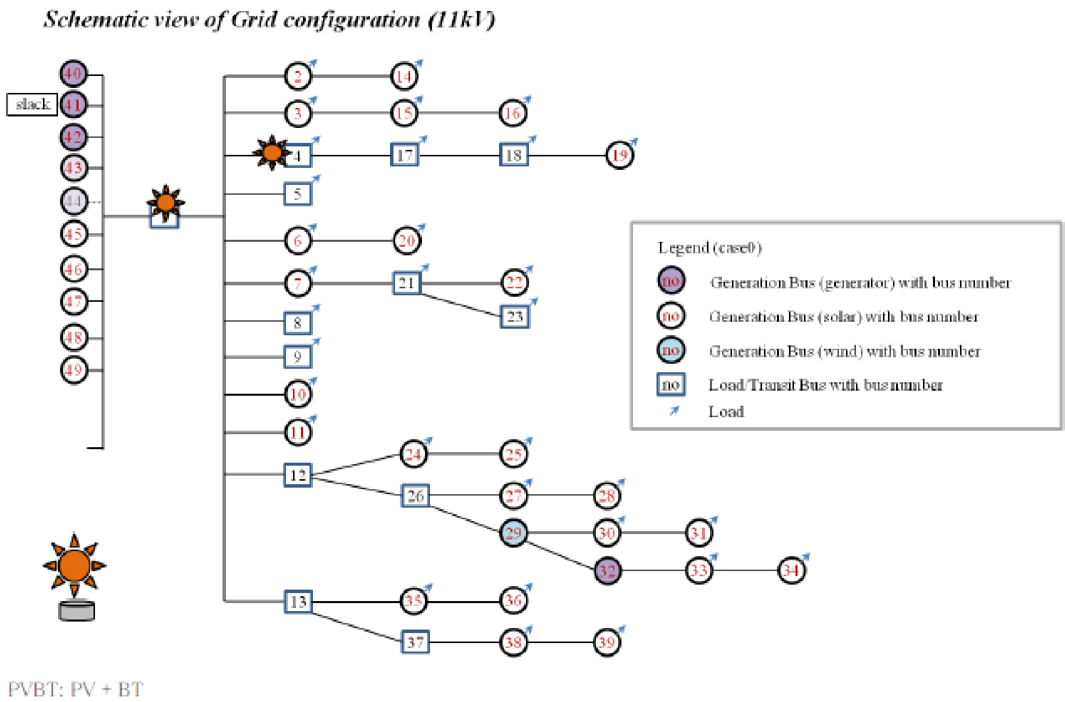


図３　単期間潮流計算用の概略系統図(case-4)

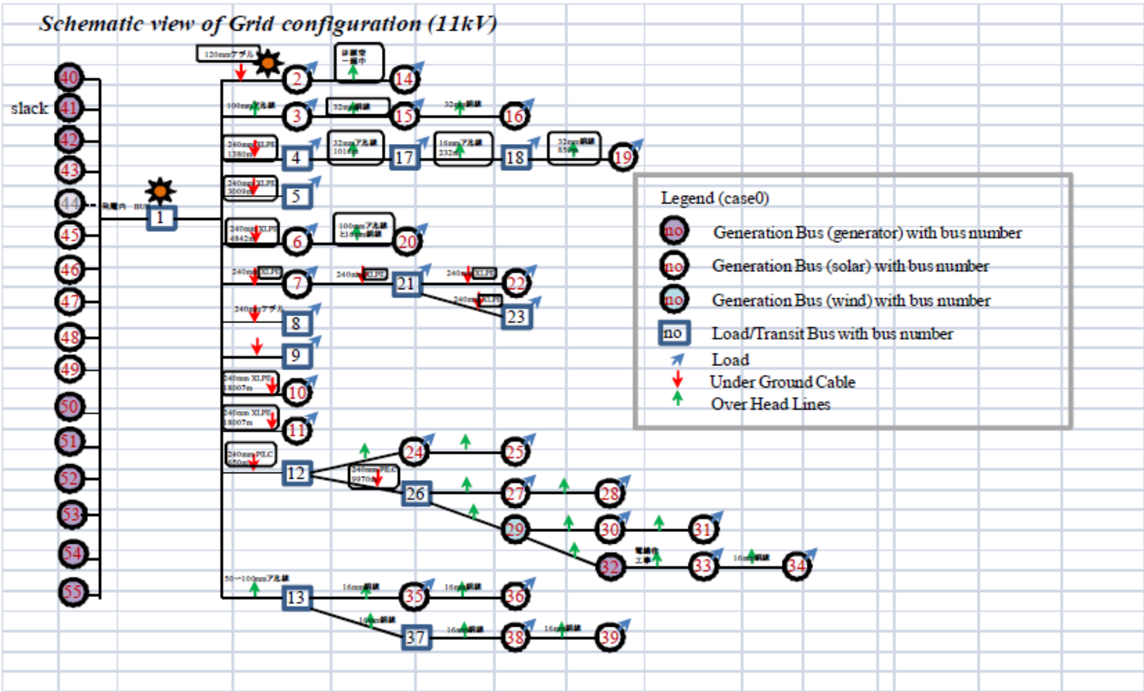


図４　St. Kitts 系統における送電線・線種の調査結果

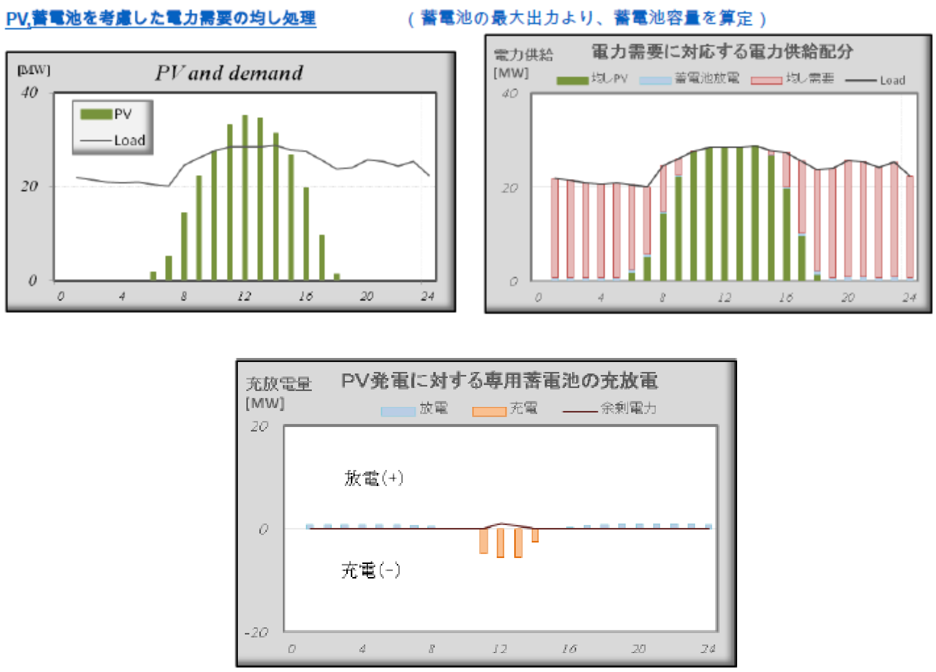
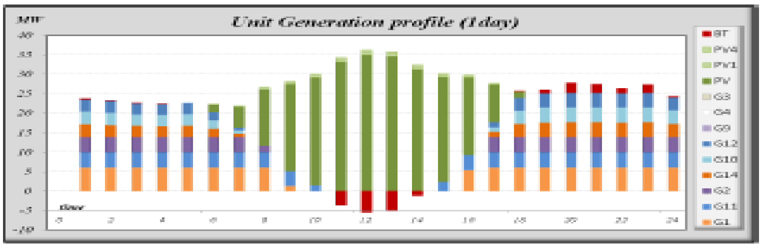


図 5 PV,蓄電池を考慮した電力需要の均し処理のイメージ図



G2(41): slack

time	G2	BT
0		
1	3. 86996	0. 16178
2	3. 86996	0. 16407
3	3. 86996	0. 16749
4	3. 86996	0. 18092
5	3. 86996	0. 00000
6	3. 86996	0. 00000
7	3. 86996	0. 00000
8	1. 65173	0. 00000
9	0. 00001	0. 00000
10	0. 00000	0. 00000
11	0. 00000	−3. 46047
12	0. 00000	−5. 38600
13	0. 00000	−4. 89240
14	0. 00000	−1. 10094
15	0. 00000	0. 00000
16	0. 00001	0. 00000
17	3. 86996	0. 00000
18	3. 86996	0. 17015
19	3. 86996	0. 92989
20	3. 86995	2. 66211
21	3. 86995	2. 33982
22	3. 86996	1. 21355
23	3. 86995	2. 23079
24	3. 86996	0. 16731

5. 38600	蓄電池最大出力[MW]
14. 83981	蓄電池最小容量[MWh]

14. 83981	充電(-)
10. 38788	放電(+)
0. 70000	充放電比

図６　多段経済負荷

配分による最適な蓄電池・最小必要容量の決定のイメージ図

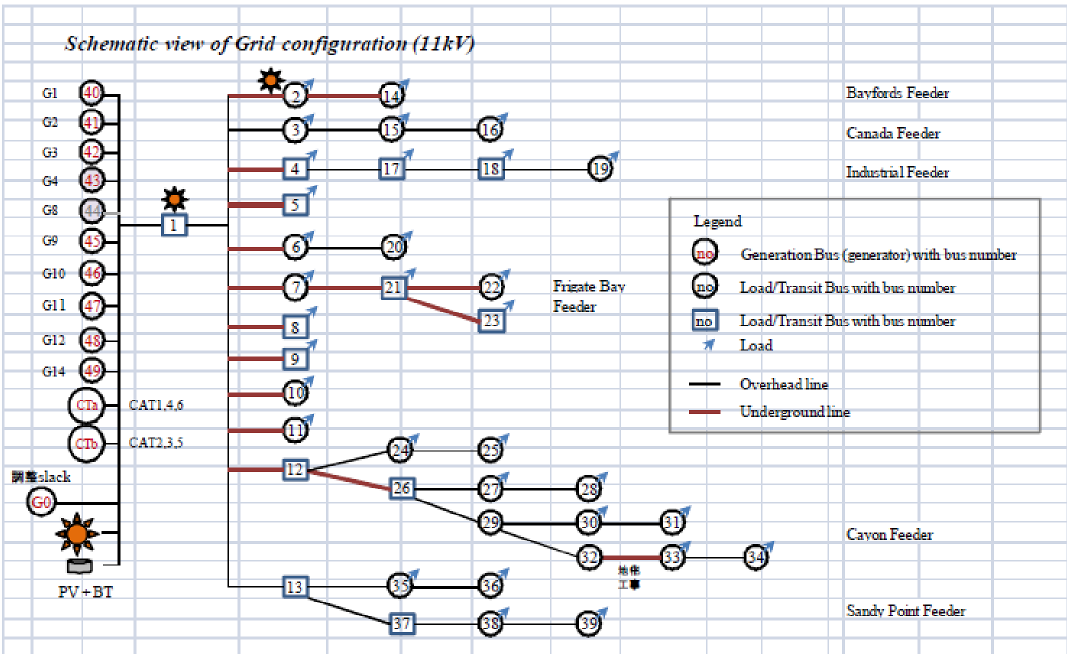
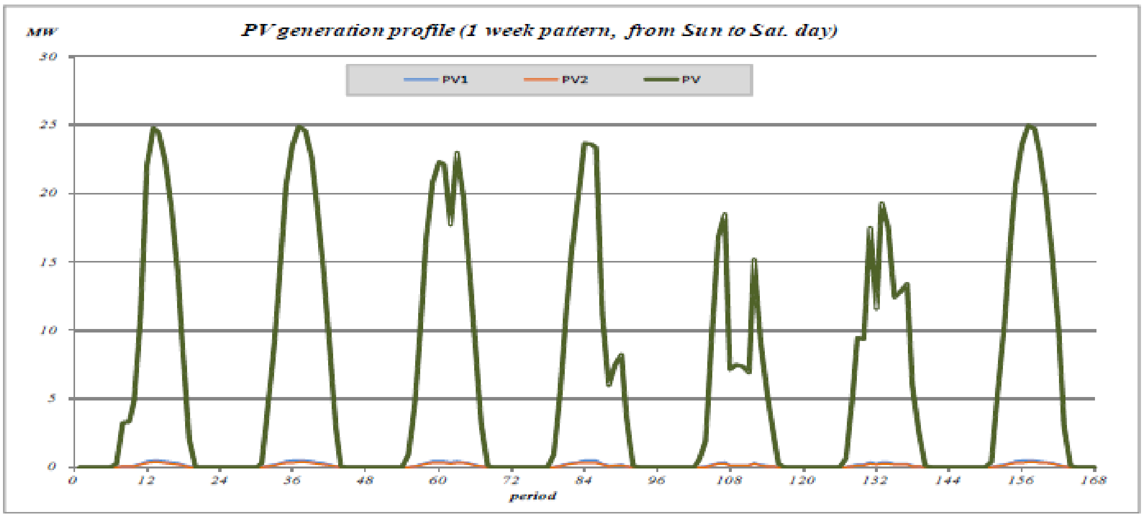


図７　系統解析シミュレーションで使用された概略系統図（現状の系統の確認が必要）



日　Partial Rain
月　Fine
火　Partially Cloud
水　Partial rain
木　Rain
金　Cloudy
土　Fine

図８ 系統解析シミュレーションで使用する太陽光発電のシナリオ例

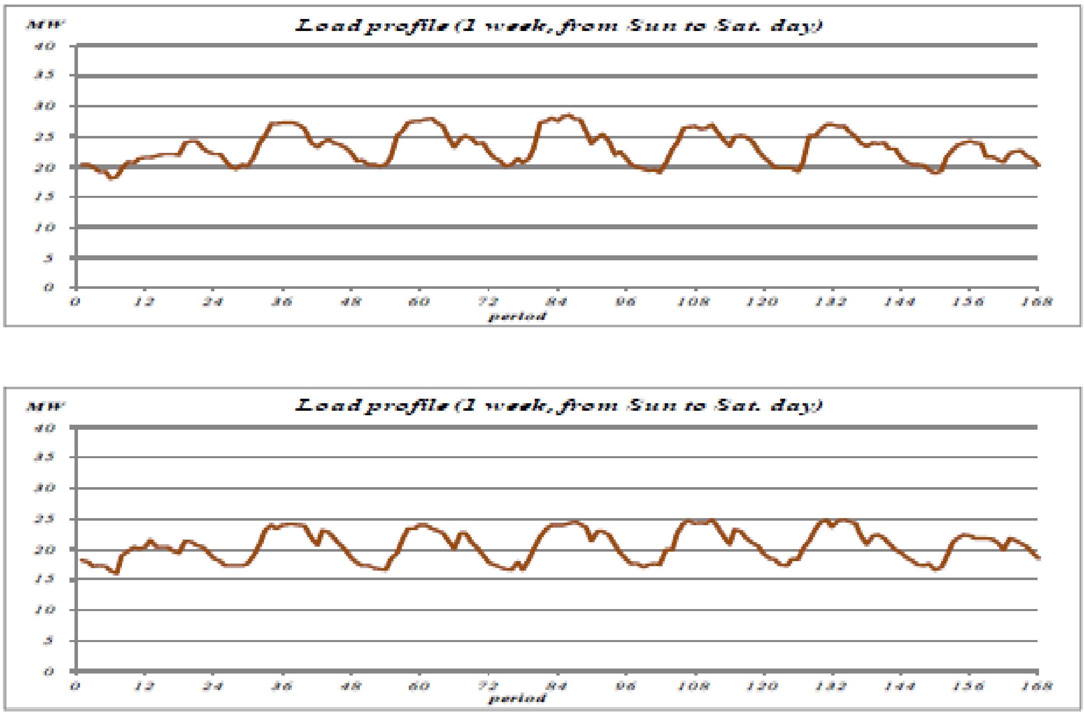


図９　系統解析シミュレーションで使用する負荷パターン(現地より入手)

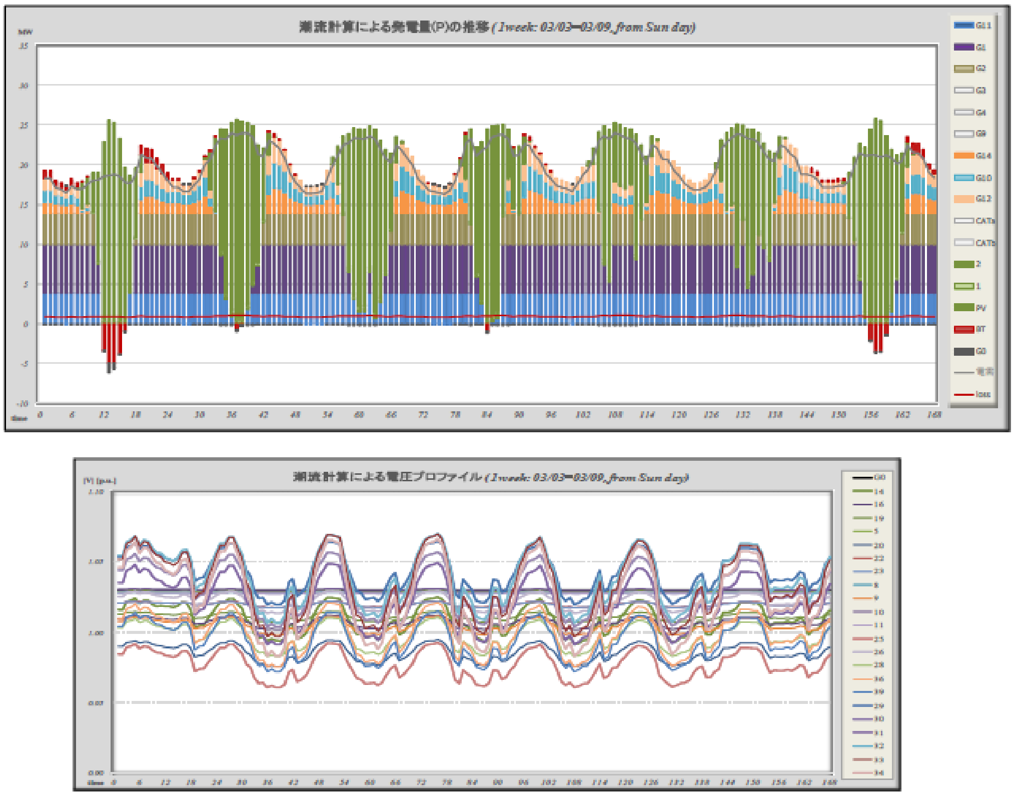


図 10 多段潮流計算による発電機・有効電力出力と母線電圧値の時系列遷移イメージ(case-1)

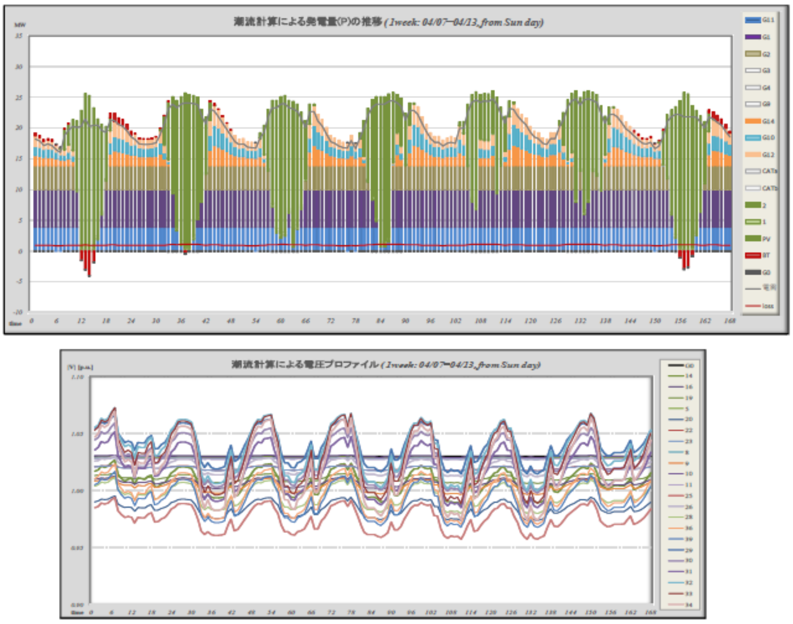


図 11 多段潮流計算による発電機・有効電力出力と母線電圧値の時系列遷移イメージ(case-2)

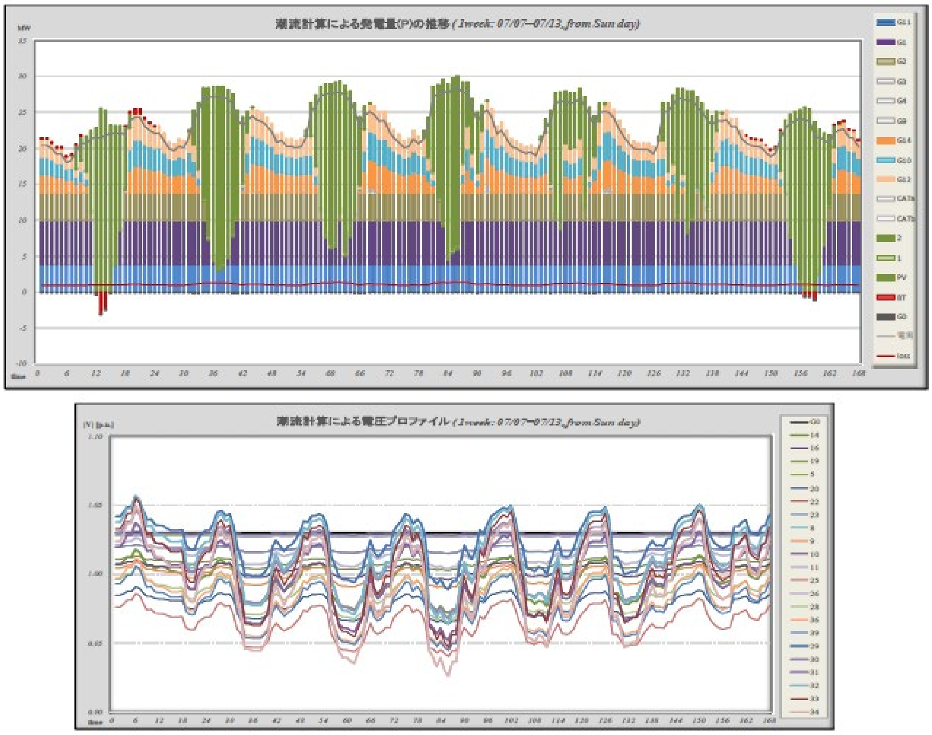


図 12 多段潮流計算による発電機・有効電力出力と母線電圧値の時系列遷移イメージ(case-3)

2019 年 7 月

9. 付録 B:マイクログリッド解析の定式化と解法(打合せ用資料)

環境エネルギー技術研究所

1. 概要

マイクログリッドの解析は，過渡解析と定常解析とに大別される。過渡解析(Transient Analysis)は、系統に大きな変化が生じた瞬間(事故、遮断など)からの系統状態を微小時間単位で追跡するものであり、これには系統状態を表現する微分方程式が使用される。また定常解析(Static Analysis)は、過渡状態が一定時間進み、ある状態に落ち着いた時点での解析であり、その定常値を所定の離散時間断面で数値解析により求めることが要求される。

ここでは、以下の代表的定常解析の一般論について紹介する。

① 潮流計算（Power Flow）

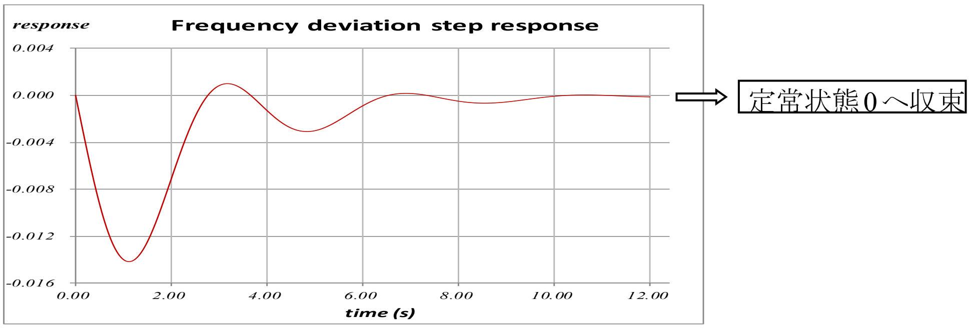
② 経済負荷配分（Economic Load Dispatch）

③ 多段経済負荷配分（Dynamic Economic Load Dispatch）

④ 最適潮流計算（Optimal Power Flow）

⑤ 起動停止計画問題（割愛）

系統に大きな負荷変化が起きてからの周波数偏差の変動解析例(LFC)



2. 交流回路の基本

交流回路は波である電圧、電流を状態量としている。

波は、単振動を表現する微分方程式の解より明らかのように

一般的な数学的表現である Cexp(j(ωt+θ)) の形式で記述できる。

ここで、

$\exp(j(\omega t+\theta)) = \cos(\omega t+\theta) + j\sin(\omega t+\theta)$　Euler の公式

角速度　$\omega = 2\pi f$　f: 周波数，θ: 位相(radian)

C： 振幅(Amplitude)

したがって、交流回路の状態量は複素数であり、ひとつの状態量には２つの状態値がある。すなわち、極座標表現では振幅と角度、直角座標表現では実部と虚部である。

交流用語の複素数表現　（上$\dot{}$記号は複素数を示す）

電圧(Voltage)　$\dot{V} = |\dot{V}|\, e^{j\theta}$

電圧値 $|\dot{V}|$(voltage magnitude)と電圧位相角 θ

電流(Current)　$\dot{I} = |\dot{I}|\, e^{j\delta}$

電力(Power)　$\dot{S} = |\dot{S}|\, e^{j\phi} = P + jQ$

P：有効電力(active power)　　単位: W

Q：無効電力(reactive power)　単位: VAr

インピーダンス(Impedance)　$\dot{Z} = r + jx$

r：抵抗(resistance)

x：誘導抵抗(reactance)

アドミタンス(Admittance)　$\dot{Y} = G + jB$, $\dot{Y} = 1 / \dot{Z}$

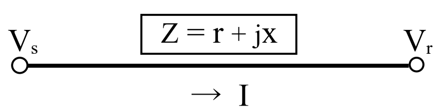
G：コンダクタンス(conductance)

B：サセプタンス(susceptance)

交流回路の基本公式

①オームの法則(Ohm's Law)

- $\dot{V} = \dot{Z}\dot{I}$
- $\dot{I} = \dot{Y}\dot{V}$
- ブランチの電圧降下式： $\dot{V}_s - \dot{V}_r = \dot{Z}\dot{I}$



②キルヒホッフの電流則 (KCL: Kirchhoff's Current Law)

- ノードに流出入する電流の総和は零である。
- ノードに流出入する電力流の総和は零である。

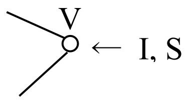
③キルヒホッフの電圧則 (KVL: Kirchhoff's Voltage Law)

- 閉路における電圧変化の総和は零である。

④電力・電圧・電流の関係式

・$\dot{S} = \dot{V}\dot{I}^* = |\dot{V}||\dot{I}| e^{j(\theta - \delta)}$（上*記号は共役複素数を示す; $\dot{I}^* = |\dot{I}| e^{-j\delta}$）
$|\dot{S}| = |\dot{V}||\dot{I}| = \mathrm{sqrt}(P^2 + Q^2)$（皮相電力：単位 VA）
・$\dot{I} = (\dot{S}/\dot{V})^*$

ノードにおける注入電流と注入電力(・S: injected Power,・I : injected Current)

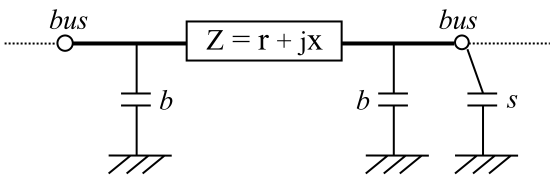


3．マイクログリッドの潮流方程式

送配電マイクログリッドは，需要家の電力需要を賄えるように設計された電力伝送路である。この伝送路は、一定の基準で設定されたノード(母線 : bus)とノード間を結ぶブランチ(枝 : branch)で構成されるネットワークとみなされ、それらの電力・電流の流れと電圧分布を解析するために，ネットワーク構造から導きだされる電力潮流方程式が解かれる。

ネットワークのノードは，発電ノードと負荷ノードに大別され，さらに発電ノードは，複素電圧を指定するスラック母線および発電 P 値と$|\dot{V}|$値を指定する PV 指定母線とに分類されることが一般的である。すべてのノードには、電力負荷(P, Q 値)を指定する。ブランチには，ブランチ属性として Impedance(抵抗とリアクタンス)が与えられる。また，一般の π 型系統モデルでは，ノードおよびブランチに無効電力の供給･吸収を担う Capacitor (Susceptance b or s を有するコンデンサ)を考慮できるようになっている。

送電線の π 型等価回路



このようなモデルで構成される送配電マイクログリッドは，バス群と双方向性を有するブランチ群から構成される無向グラフをもとに，前期の交流回路の基本公式を適用することにより，電力潮流方程式が作成される。具体的には、１本のブランチ *s*–*r* におけるオームの法則 $I_{sr} = (\dot{V}_s - \dot{V}_r)/\dot{Z}_{sr} = (\dot{V}_s - \dot{V}_r)\dot{Y}_{sr}$ を、キルヒホッフの電流則を適用して全体構造へ統合する手続きを繰返し行えばよい。

その結果得られる電力潮流方程式は、以下に示すように、複素変数$\dot{V}_i$ ($i=1...n$)に関する連立(非線形)二次方程式となる。

$\dot{S}_i = \dot{V}_i \dot{I}_i^* = \Sigma_j \dot{V}_i \dot{Y}_{ij}^* \dot{V}_j^*$　($i=1...n$)

ここで, $\dot{V}_i$ はノード i の電圧, $\dot{S}_i = P_i + jQ_i$ はノード i の指定注入電力(発電(+)と負荷(−)の計), $\dot{I}_i$ は同注入電流, $\dot{Y}_{ij}$ は系統全体のアドミッタンス行列の i,j 成分, n はノード数を示す。

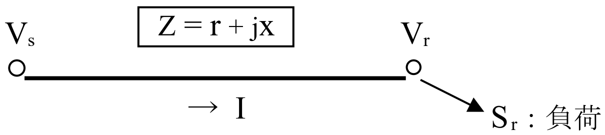
したがって、すべての $\dot{S}$ を与えて電力潮流方程式を解くと全ノード電圧 $\dot{V}$ が求められ、その値を使用して、未知の発電量、ブランチの電流や電力流(Power Flow)、および系統ロスなどが得られる。

但し、潮流方程式はそのままでは解は求めることができないため(不定), スラック母線の導入により一個の複素電圧を指定する必要がある。また, 発電ノードには PV指定母線として発電 P 値と $|\dot{V}|$ 値を指定することがあるので, 実際の変数個数は $2n$ よりも幾分小さくなる。これに応じて、潮流方程式の本数も変数個数と同じになるように減じられる。即ち、スラック母線では発電量 P,Q が未知、PV指定母線では発電量 Q が未知となり、潮流方程式の本数はそれぞれ 0,1 となる。

連立非線形方程式である電力潮流方程式を直接解析的に解く方法はないので, Newton-Raphson 法や Backward/Forward 法など数値演算による繰返し解法が適用される。

4．潮流方程式の解析例

①最も簡単な潮流方程式 (2母線潮流方程式)



オームの法則

$\dot{V}_s - \dot{V}_r = \dot{Z}\dot{I}$,　$\dot{I} = (\dot{V}_s - \dot{V}_r)/\dot{Z}$

受電端 r における注入電力則 (潮流方程式)

$\dot{S}_r = \dot{V}_r \dot{I}^* = \dot{V}_r((\dot{V}_s - \dot{V}_r)/\dot{Z})^* = (\dot{V}_r \dot{V}_s^* - |\dot{V}_r|^2)/\dot{Z}^*$

(具体例)

送電端s(スラック母線)における電圧を基準にし,

$\dot{V}_s = E(\cos(0) + j\sin(0)) = E$　とする。(E:固定)

受電端 r(負荷母線)における電圧を,

$\dot{V}_r = V(\cos\theta + j\sin\theta)$ とおく。

また特に,$\dot{Z} = jx$ (x=1) とすると（抵抗を無視),

$$\dot{S}_r = P + jQ = \{VE(\cos\theta + j\sin\theta) - V^2\}/(-j)$$

$$= VE(j\cos\theta - \sin\theta) - jV^2$$

よって

$$P = -VE\sin\theta$$

$$Q = VE\cos\theta - V^2$$

というV, θに関する２元連立非線形方程式が得られた。

②***MicroGrid Designer*** による解析例

MicroGrid Designer の Power Flow は，Newton-Raphson 法と Backward/Forward 法を採用している。特に大規模送電系統では sparse Newton-Raphson 法に新たな手法を導入して高速に解を求める手法を実現している。対象とする系統の最大規模は、50,000 母線である。

ここでは、小中規模用の dense Newton-Raphson 法を用いて、標準の系統モデルである Ward-Hale 6 母線に対して解析する。

その前に、***MicroGrid Designer*** では入出力データに Per-Unit System (p.u.)を使用しているので、これについて説明しておく。

Per-Unit System

The Per-Unit System (p.u. in short) is widely used in the power system to express values of voltages, currents, powers, and impedances.

For a given quantity, the per-unit value is the value related to a base quantity:

Per-unit value = quantity in some unit / base quantity

Generally, the following two base quantities are given:

・Vbase : The base voltage quantity
・Sbase : The base power quantity

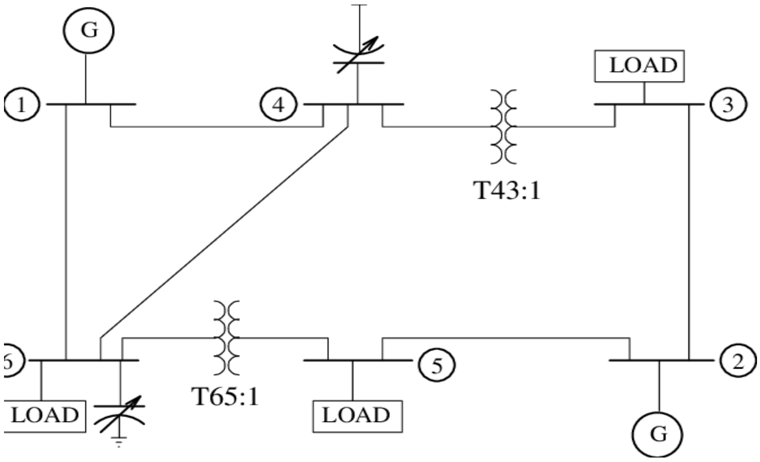
All other base quantities are derived from these two base quantities, using the natural laws of electrical circuits.

Typical base quantities in IEEE test systems
・Vbase : 1～132 kV
・Sbase : 100 MVA

So, voltage magnitude 1.0 in p.u. means 100V actually.
If the power generation and load data (P, Q) are given in units MW and MVAr respectively, conversion of these values into Per-Unit System is simply done

by dividing them by 100(MVA).

Ward-Hale 6 母線モデルと入力データ



入力データ

```
// Node(bus) data
//                        負荷P,Q          発電P,Q     電圧・初期値/指定値
//id type    s   cond    Pl       Ql      Pg     Qg     |V|     θ
   1   G    0.0   VT   -0.25   -0.1                     1.05   0.0
   2   G    0.0   PV   -0.15   -0.05     0.5            1.05   0.0
   3   L    0.0   PQ   -0.275  -0.11                    1.0    0.0
   4   -    0.02  PQ    0.0     0.0                     1.0    0.0
   5   L    0.0   PQ   -0.15   -0.09                    1.0    0.0
   6   L    0.02  PQ   -0.25   -0.15                    1.0    0.0
END

// type - G:発電母線,  L:負荷母線, -:通過・分岐点(負荷0の負荷母線)
// s - susceptance of nodal capacitor (see π型等価回路)
// cond - VT:スラック母線, PV: PV指定母線, PQ: PQ指定母線
//          すべての母線にはPlとQl(通常負値)を指定する。
//          スラック母線には|V|とθを指定する。
//          PV指定母線にはPgと|V|を指定する。
//          PQ指定発電母線にはPgとQg(通常正値)を指定する。
//          PQ指定負荷母線にはPgとQg欄を空白とする。
// なお、 スラック母線の発電量(Pg,Qg)とPV指定母線の発電量(Qg)は
//          潮流計算により決定される。
// 電圧 - 指定値以外はNewton-Raphson法用の初期値とされる。

// Branch data
// name from to     r       x       b     tap
   B1    1   6    0.031   0.259   0.005   0
   B2    1   4    0.020   0.185   0.004   0
   B3    4   6    0.024   0.204   0.005   0
   B4    6   5    0.025   0.150   0.008   2 0.95
   B5    2   5    0.071   0.320   0.007   0
```

```
   B6     2  3   0.006  0.025  0.0     0
   B7     4  3   0.075  0.067  0.0     2 0.97
END

// r - resistance (単位長さ当り* 延長)
// x - reactance  (単位長さ当り* 延長)
// b - half susceptance of branch capacitor (see π型等価回路)
// tap - transformer existence ( 0: not exist, 1,2: exist )
//        変圧器が存在する場合には、そのタップ比を入力する。
//        タップ比は順方向(tap=1)、逆方向(tap=2)に応じた変圧率である。
```

出力データ

Output-1 を参照

４．経済負荷配分(ELD: Economic Load Dispatch)

経済負荷配分は，需要(負荷)予測に基づいて、系統の発電機群に出力指令を与える目的で行われる。経済負荷配分では、総燃料費が最小となるような各発電機の有効電力出力値が決定される。この有効電力出力値は、対象系統の潮流計算を行う際に、PV 指定母線の P 値として使用できる。

経済負荷配分問題は，ある予測時点において、需給バランスを満足させ総燃料費が最小となるような発電機群の有効電力出力を求める最適化問題である。通常、発電機の燃料費には有効電力出力の２次式が使用されるので、経済負荷配分問題は二次計画問題に属する。ただし、発電機の燃料費に有効電力出力の１次式を使用する場合には、同問題は線形計画問題となる。

二次計画問題によるELDの定式化

$\min_{\{P(t)\}} \ \Sigma_i \mathrm{FuelCost}(i)$

$\mathrm{FuelCost}(i) = a_i P_i^2 + b_i P_i + c_i$ for unit-i

Σ_i は発電機(unit)に関する総和を示す(i=1,..,ng, ng:発電機数)。

s.t. $\Sigma_i P_i = D(t)$ (Power balance 制約)

$P_{min,i} \leqq P_i \leqq P_{max,i}$ (P_i の上下限制約)

where

D(t) : demand at a given estimated time-t

P_i : active power generation of unit-i (変数)

$P_{min,i}$, $P_{max,i}$: bounds of P_i for unit-i

経済負荷配分の解法には，二次計画問題専用解法や等λ法などがあるが、***MicroGrid Designer*** では、この二次計画問題のシンプルな構造を利用した超高速厳密解法を採用している。

二次計画問題ELDの解析例

// 入力データ

```
5  // #units

//    a  b  c  Pmin Pmax
G1  10  2  6    0   5
G2   8  4  4    0   5
G3   6  2  2    0   5
G4   4  3  0    0   5
G5   2  1  2    0   5

16  // demand
```

// 出力データ

```
(solution)
 unit  output(P)    Pmin     Pmax      cost
 G1      1.75325    0.00     5.00   40.24523
 G2      2.06656    0.00     5.00   46.43154
 G3      2.92208    0.00     5.00   59.07539
 G4      4.25812    0.00     5.00   85.30058
 G5      5.00000    0.00     5.00   57.00000
 sum   16.00000                    288.05274
```

５．多段経済負荷配分(Dynamic Economic Load Dispatch)

ダイナミック ELD は、前記の単期間 ELD を多期間に拡張したものである。但し、各期間ごとの ELD を順に解く訳ではなく、期間同士の制約を導入して、隣接期間における解の整合性がとれるように改良された手法を採用している。そのため、発電機群の運用可能条件(Operability)を考慮した、長期間の Dispatch スケジューリングが行えるという利点が生じる。また、発電機以外にも、蓄電池や再生可能エネルギーを考慮できるという特徴も合わせ持っている。

ダイナミック ELD は、期間全体を対象とした大規模非線形最適化問題であり、効率的に解く手法が要求される。***MicroGrid Designer*** では当該問題のスパース性を活用した汎用内点法モジュールを使用して、高速に最適解を求めることができる。

多段 ELD の定式化

$\min_{\{P(t)\}}\ \Sigma_t\ \Sigma_i$ FuelCost(t,i)

FuelCost(t,i) = $a_i P_i(t)^2 + b_i P_i(t) + c_i$ for unit-i at time-t

Σ_i は発電機(unit)に関する総和を示す(i=1,..,ng, ng:発電機数)。

Σ_t は期間に関する総和を示す(t=1,..,T, T:期間数)。

s.t. $\Sigma_i P_i(t) = D(t)$ for each time-t（Power balance 制約）

$P_i(t)$の上下限制約：

$P_{min,i}(t) \leqq P_i(t) \leqq P_{max,i}(t)$ for each unit-i at every time-t

where

D(t) : demand at time-t

$P_i(t)$: power generation of unit-i at time-t（変数）

$P_{min,i}(t)$, $P_{max,i}(t)$: bounds of $P_i(t)$ for unit-i at time-t

Ramp constraints:

$rl(i) \leqq P_i(t) - P_i(t-1) \leqq ru(i)$ for each unit-i at every time-t

where rl(i) : max. ramp down < 0,

ru(i): max. ramp up > 0 for unit-i

Inventory constraints:

$\Sigma_t P_i(t) = lot(i)$ or ≦, ≧

where lot(i) : final lot size in a time interval for some unit-i

この制約は、主として蓄電池用として使用される。

ダイナミック ELD の解析例

系統構成

火力発電８機(G1～G8) ： 最大出力 60 ～ 800MW

（入力データ）

初期発電量(MW)、燃料費コスト二次関数係数(a,b,c)

（制約データ）

最小・最大出力(MW), max ramp-down, ramp up (MW/h)

バッテリ１機(BT) ： 最大出力 150MWの簡易蓄電池モデルを採用

（入力データ）

稼働時間帯: 昼間放電(＋)(10-16h), 夜間充電(－)(1-4h,21-24h)

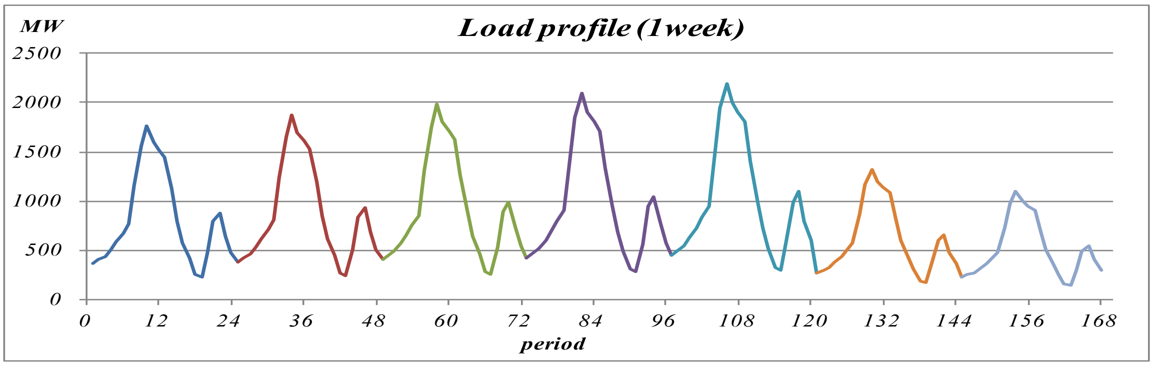
（制約データ）

max. ramp down: −50MW/h, max.ramp up: +50MW/h

総充放電量 ＝ 放電量 － 0.7*充電量 = 0　for every 24 hours

解析対象期間：１週間(168h)、単位期間：1h
解析期間における負荷プロファイル

８機起動停止計画問題で使用した負荷データを利用して作成した。



解析結果

変数 $P_i(t)$ の個数　：1512 = 9*168
変数の上下限制約 ：1512*2
等式制約数 ：168+7 (Power balance 制約+充放電制約)
不等式制約数 ：3008 (Ramp 制約)

計算時間 ：1.80 sec

最適解については、Output-2 と各 unit の発電プロファイルを参照。

（入力データ）

```
168 // T : periods (1 week)
9    // ng: generators

// generator data
//     minG    maxG    rl     ru   cyc    g0      a       b         c
//     (MW)    (MW)      (MW/h)           (MW)          (#/MWh)     (#/h)
 G1     0.0    80.0    -80.   80.   0      0.0    0.0   20.880   213.0
 G2     0.0   250.0   -100. 100.   0      0.0    0.0   18.000   585.62
 G3     0.0   300.0   -100. 100.   0      0.0    0.0   17.460   684.74
 G4     0.0    60.0    -60.   60.   0      0.0    0.0   14.280   252.0
 G5     0.0    60.0    -60.   60.   0      0.0    0.0   18.660   252.0
 G6     0.0   480.0   -120. 120.   0      0.0    0.0   12.660   293.0
 G7   100.0   800.0   -200. 200.   0    300.0    0.0   11.394   305.0
 G8     0.0   300.0   -100. 100.   0      0.0    0.0   10.800   700.0
 BT     0.0     0.0    -50.   50.   1    -10.    0.0    0.0        0.0   // battery
// rl,ru :   max. ramp-down and ramp-up
// cyc :   ramp-constraints are cyclic or not
// g0   :   initial generations used for ramp-constraints
// a,b,c   :   coefficients for fuel cost

// demands (MW)
// Monday
  360.0   400.0   440.0   504.0   584.0   664.0   760.0 1160.0 1560.0 1760.0 1600.0 1520.0
 1440.0 1120.0   800.0   576.0   416.0   256.0   232.0   472.0   792.0   880.0   640.0   480.0
// Tuesday
  382.5   425.0   467.5   535.5   620.5   705.5   807.5 1232.5 1657.5 1870.0 1700.0 1615.0
 1530.0 1190.0   850.0   612.0   442.0   272.0   246.5   501.5   841.5   935.0   680.0   510.0
// Wednesday
  405.0   450.0   495.0   567.0   657.0   747.0   855.0 1305.0 1755.0 1980.0 1800.0 1710.0
 1620.0 1260.0   900.0   648.0   468.0   288.0   261.0   531.0   891.0   990.0   720.0   540.0
// Thursday
  427.5   475.0   522.5   598.5   693.5   788.5   902.5 1377.5 1852.5 2090.0 1900.0 1805.0
 1710.0 1330.0   950.0   684.0   494.0   304.0   275.5   560.5   940.5 1045.0   760.0   570.0
// Friday
  450.0   500.0   550.0   630.0   730.0   830.0   950.0 1450.0 1950.0 2200.0 2000.0 1900.0
 1800.0 1400.0 1000.0   720.0   520.0   320.0   290.0   590.0   990.0 1100.0   800.0   600.0
// Saturday
  270.0   300.0   330.0   378.0   438.0   498.0   570.0   870.0 1170.0 1320.0 1200.0 1140.0
 1080.0   840.0   600.0   432.0   312.0   192.0   174.0   354.0   594.0   660.0   480.0   360.0
// Sunday
  225.0   250.0   275.0   315.0   365.0   415.0   475.0   725.0   975.0 1100.0 1000.0   950.0
  900.0   700.0   500.0   360.0   260.0   160.0   145.0   295.0   495.0   550.0   400.0   300.0
// generation ranges
repeat 7   step 24
// unit    ts   te    minG    maxG    weight
     BT      10   16     0.0    150.0     1.0    //  放電(+)
     -        1    4   -150.    -0.0      0.7   //  充電(-)
     -       21   24   -150.    -0.0      0.7   //  充電(-)
end
// inventory constraints
```

// unit　ope　lotFinal step
BT = 0.0　24　// 放電量 - 0.7 充電量 = 0 at every 24 hours
end

６．最適潮流計算(OPF: Optimal Power Flow)

経済負荷配分は，負荷予測に基づいて、総燃料費が最小となるような発電機の有効電力出力値を求めるものであった。この場合、系統のネットワーク構成が考慮されず、系統ロスを含めた負荷配分が行えないという欠点がある。

最適潮流計算は、このような経済負荷配分の欠点を補う手法であり，系統の負荷バランス制約の下で､総燃料費が最小となるような発電機の有効電力出力値を求めることができる。また最適潮流計算には、ブランチ電力流の制限(潮流制約)を課して混雑度を抑制する機能、あるいは評価関数を変えて異なる目的の解析を行うなどの機能を与えることができる。

最適潮流計算は、多くの非線形・制約条件を有する大規模な非線形最適化問題であり，その求解には効率的な手法が要求される。***MicroGrid Designer*** ではスパース性を活用した汎用内点法を使用し、さらに GMRES 法を導入しているので、高速に最適解を求めることができる。

最適潮流計算の変数は、発電母線の有効・無効電力と各母線の複素電圧である。なお、最適潮流計算は、経済負荷配分と同様，負荷予測を行った単期間のみを対象とする。

最適潮流計算の定式化（燃料費最小化）

$$\min_{\{V,P,Q\}} \sum_i \mathrm{FuelCost}(i)$$

$$\mathrm{FuelCost}(i) = a_i P_i^2 + b_i P_i + c_i \quad \text{for unit-i}$$

$\sum_i$ は発電機（unit）に関する総和を示す（i=1..ng, ng:発電機数）。

s.t.

（変数の上下限制約）

$P_{min,i} \leqq P_i \leqq P_{max,i}$　（P_i の上下限制約）（i=1..ng）

$Q_{min,i} \leqq Q_i \leqq Q_{max,i}$　（Q_i の上下限制約）（i=1..ng）

$V_{min,j} \leqq V_j \leqq V_{max,j}$ （V_j の上下限制約）(j=1..n, n:#nodes)

where

P_i : active power generation of unit-i

Q_i : reactive power generation of unit-i

V_j : voltage magnitude of node-j

$P_{min,i}$, $P_{max,i}$: bounds of P_i for unit-i

$Q_{min,i}$, $Q_{max,i}$: bounds of Q_i for unit-i

$V_{min,j}$, $V_{max,j}$: bounds of V_j for node-j

(Power balance 制約)

$$\sum_j \dot{V}_i \dot{Y}^*_{ij} \dot{V}_j^* = \dot{G}_i + \dot{L}_i \quad (j=1..n,\ i=1...n)$$

where

$\dot{V}_i$: complex voltage of node-i

$\dot{Y}_{ij}$: complex (i,j) element of nodal Admittance matrix

$\dot{G}_i$: complex generation at node-i

P_k+jQ_k if the node is a generation bus-*k*, 0 otherwize.

$\dot{L}_i$: complex load at node-i (fixed)

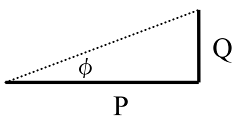
(Power factor 制約)

$\gamma_{min,k} \leqq (Q/P)_k \leqq \gamma_{max,k}$ (k: suset of Generation buses, given)

where

$(Q/P)_k$: reactive/active power ratio at the k-th generation node

$\gamma_{min,k}$, $\gamma_{max,k}$: bounds of the above ratio



力率(Power factor) = cos ϕ

（Branch power flow 制約）

$$|P_{ij}| \leqq P_{max,ij} \quad (i, j : \text{subset of Branches, given})$$

where

P_{ij} : active power flow in branch i-j

$P_{max,ij}$: upper bound of P_{ij}

最適潮流計算の解析例

電気学会が公開している EAST10 機系統モデルを使用して，***MicroGrid Designer*** 最適潮流計算モジュールで燃料費が最小となる最適解を求めた。EAST10 機系統モデルは、関東エリアを 10 発電機 47 母線で模擬した系統である（福島事故の前か？）。

図：EAST10 機系統モデルとインピーダンス・マップ

入力データ：図の後のリスト

出力データ：Output-3

電気学会EAST10機系統モデルとインピーダンス・マップ

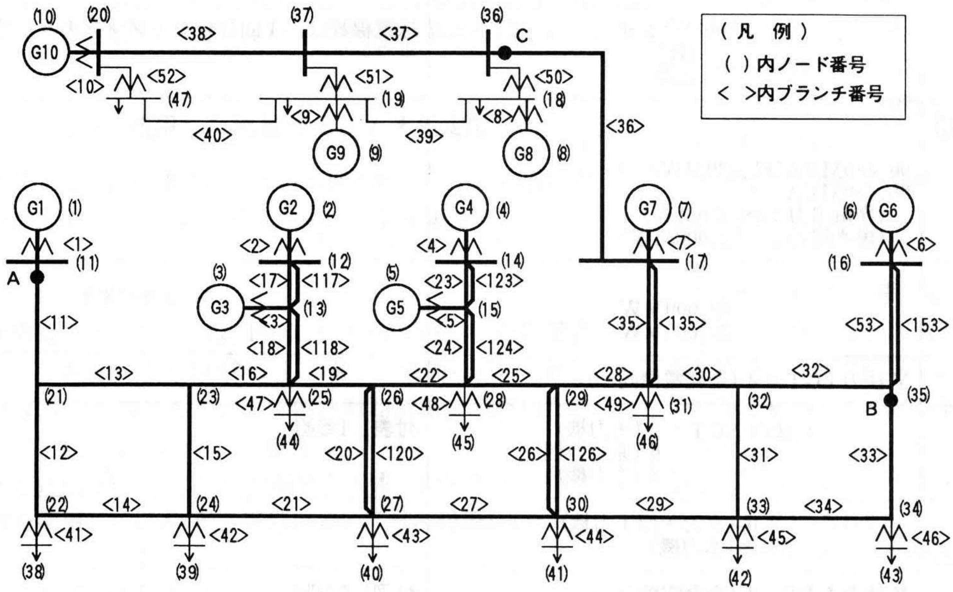
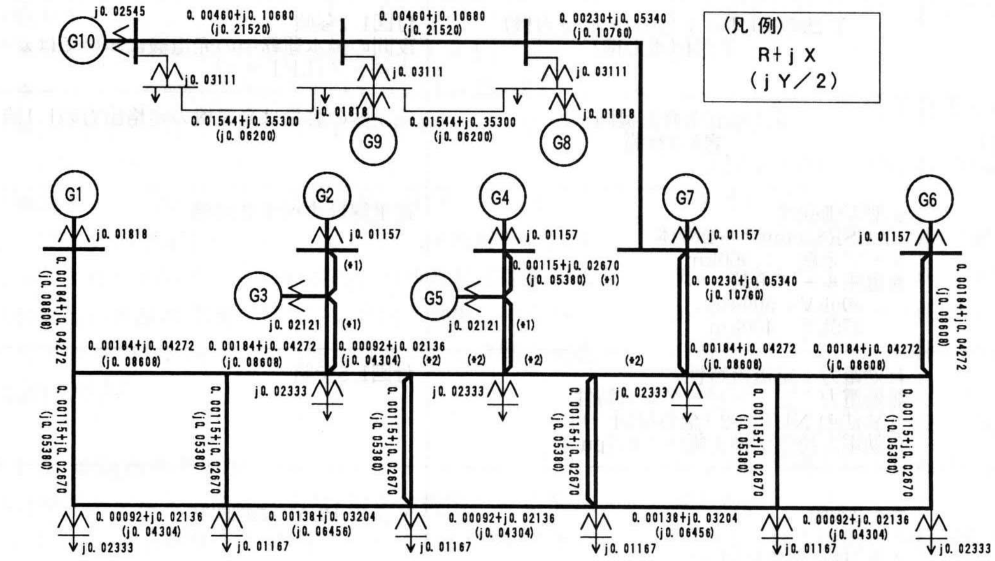


図4.1 電気学会EAST10機系統モデル系統図（ノード番号，ブランチ番号，事故点含む）



注：送電線定数は2回線トータルの値

単位：pu（1000MVAベース）

図4.2 電気学会EAST10機系統モデルインピーダンスマップ

（入力データ）

```
// IEEJ EAST10p (50Hz); 10-machines, 47-bus grid (peak time)
47    // n = #nodes

// Node data
//no type   s cond    Pl       Ql     Pg           Qg          V       T
   1   G   0.0   PQ     0.0      0.0     0.0          0.0        1.007   0   // G01 Thermal
   2   G   0.0   PQ     0.0      0.0     0.00000      0.0        1.005   0   // G02 Nuclear
```

```
    3   G   0.0   VT    0.0       0.0                                   1.020   0   // G03 Hydraulic
(slack)
    4   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.005   0   // G04 Thermal
    5   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.020   0   // G05 Hydraulic
    6   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.005   0   // G06 Thermal
    7   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.020   0   // G07 Nuclear
    8   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.020   0   // G08 Thermal
    9   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.020   0   // G09 Thermal
   10   G   0.0   PQ    0.0       0.0     0.00000     0.0       1.015   0   // G10 Thermal
   11   L   0.0   PQ    0.0       0.0                           1.0     0
   12   L   0.0   PQ    0.0       0.0                           1.0     0
   13   L   0.0   PQ    0.0       0.0                           1.0     0
   14   L   0.0   PQ    0.0       0.0                           1.0     0
   15   L   0.0   PQ    0.0       0.0                           1.0     0
   16   L   0.0   PQ    0.0       0.0                           1.0     0
   17   L   0.0   PQ    0.0       0.0                           1.0     0
   18   L   0.0   PQ   -5.500    -1.050                         1.0     0
   19   L   0.0   PQ   -5.500    -1.413                         1.0     0
   20   L   0.0   PQ    0.0       0.0                           1.0     0
   21   L   0.0   PQ    0.0       0.0                           1.0     0
   22   L   0.0   PQ    0.0       0.0                           1.0     0
   23   L   0.0   PQ    0.0       0.0                           1.0     0
   24   L   0.0   PQ    0.0       0.0                           1.0     0
   25   L   0.0   PQ    0.0       0.0                           1.0     0
   26   L   0.0   PQ    0.0       0.0                           1.0     0
   27   L   0.0   PQ    0.0       0.0                           1.0     0
   28   L   0.0   PQ    0.0       0.0                           1.0     0
   29   L   0.0   PQ    0.0       0.0                           1.0     0
   30   L   0.0   PQ    0.0       0.0                           1.0     0
   31   L   0.0   PQ    0.0       0.0                           1.0     0
   32   L   0.0   PQ    0.0       0.0                           1.0     0
   33   L   0.0   PQ    0.0       0.0                           1.0     0
   34   L   0.0   PQ    0.0       0.0                           1.0     0
   35   L   0.0   PQ    0.0       0.0                           1.0     0
   36   L   0.0   PQ    0.0       0.0                           1.0     0
   37   L   0.0   PQ    0.0       0.0                           1.0     0
   38   L   0.0   PQ   -5.000     1.200                         1.0     0
   39   L   0.0   PQ -10.000      2.416                         1.0     0
   40   L   0.0   PQ -10.000      2.671                         1.0     0
   41   L   0.0   PQ -10.000      2.593                         1.0     0
   42   L   0.0   PQ -10.000      2.378                         1.0     0
   43   L   0.0   PQ   -5.000     1.260                         1.0     0
   44   L   0.0   PQ   -5.000     2.499                         1.0     0
   45   L   0.0   PQ   -5.000     2.480                         1.0     0
   46   L   0.0   PQ   -5.000     2.532                         1.0     0
   47   L   0.0   PQ   -4.000    -1.368                         1.0     0
END

// Branch data
/name frm to        r           x          b        tap         plimit
  B01     11 21   0.001840    0.042720   0.086080   0              0
  B02     21 22   0.001150    0.026700   0.053800   0              0
  B03     21 23   0.001840    0.042720   0.086080   0              0
  B04     22 24   0.000920    0.021360   0.043040   0              0
```

B05	23	24	0.001150	0.026700	0.053800	0		0
B06	25	23	0.001840	0.042720	0.086080	0		0
B07	12	13	0.001150	0.026700	0.053800	0		0
B08	12	13	0.001150	0.026700	0.053800	0		0
B09	13	25	0.001150	0.026700	0.053800	0		0
B10	13	25	0.001150	0.026700	0.053800	0		0
B11	25	26	0.000920	0.021360	0.043040	0		0
B12	26	27	0.001150	0.026700	0.053800	0		0
B13	26	27	0.001150	0.026700	0.053800	0		0
B14	27	24	0.001380	0.032040	0.064560	0		0
B15	28	26	0.000920	0.021360	0.043040	0		0
B16	14	15	0.001150	0.026700	0.053800	0		0
B17	14	15	0.001150	0.026700	0.053800	0		0
B18	15	28	0.001150	0.026700	0.053800	0		0
B19	15	28	0.001150	0.026700	0.053800	0		0
B20	28	29	0.000920	0.021360	0.043040	0		0
B21	29	30	0.001150	0.026700	0.053800	0		0
B22	29	30	0.001150	0.026700	0.053800	0		0
B23	30	27	0.000920	0.021360	0.043040	0		0
B24	31	29	0.000920	0.021360	0.043040	0		0
B25	33	30	0.001380	0.032040	0.064560	0		0
B26	31	32	0.001840	0.042720	0.086080	0		0
B27	32	33	0.001150	0.026700	0.053800	0		0
B28	35	32	0.001840	0.042720	0.086080	0		0
B29	35	34	0.001150	0.026700	0.053800	0		0
B30	34	33	0.000920	0.021360	0.043040	0		0
B31	17	31	0.002300	0.053400	0.107600	0		0
B32	17	31	0.002300	0.053400	0.107600	0		0
B33	36	17	0.002300	0.053400	0.107600	0		0
B34	37	36	0.004600	0.106800	0.215200	0		0
B35	20	37	0.004600	0.106800	0.215200	0		0
B36	19	18	0.015440	0.353000	0.062000	0		0
B37	47	19	0.015440	0.353000	0.062000	0		0
B38	16	35	0.001840	0.042720	0.086080	0		0
B39	16	35	0.001840	0.042720	0.086080	0		0
T01	1	11	0.0000000	0.018180	0.000000	1	1.128210	0
T02	2	12	0.0000000	0.011570	0.000000	1	1.128210	0
T03	3	13	0.0000000	0.021210	0.000000	1	1.070000	0
T04	4	14	0.0000000	0.011570	0.000000	1	1.128210	0
T05	5	15	0.0000000	0.021210	0.000000	1	1.075000	0
T06	6	16	0.0000000	0.011570	0.000000	1	1.128210	0
T07	7	17	0.0000000	0.011570	0.000000	1	1.128210	0
T08	8	18	0.0000000	0.018180	0.000000	1	1.025640	0
T09	9	19	0.0000000	0.018180	0.000000	1	1.025640	0
T10	10	20	0.0000000	0.025450	0.000000	1	1.128210	0
T11	22	38	0.0000000	0.023330	0.000000	1	0.952380	0
T12	24	39	0.0000000	0.011670	0.000000	1	0.952380	0
T13	27	40	0.0000000	0.011670	0.000000	1	0.952380	0
T14	30	41	0.0000000	0.011670	0.000000	1	0.952380	0
T15	33	42	0.0000000	0.011670	0.000000	1	0.952380	0
T16	34	43	0.0000000	0.023330	0.000000	1	0.952380	0
T17	25	44	0.0000000	0.023330	0.000000	1	0.921660	0
T18	28	45	0.0000000	0.023330	0.000000	1	0.921660	0
T19	31	46	0.0000000	0.023330	0.000000	1	0.921660	0

```
 T20     36 18   0.0000000   0.031110   0.000000   1 0.952380   0
 T21     37 19   0.0000000   0.031110   0.000000   1 0.952380   0
 T22     20 47   0.0000000   0.031110   0.000000   1 0.952380   0
END

// Bound constraints for nodal variables
   0.95   1.15   // default min,max of voltage magnitudes   (for all nodes but PV)
  -6.0   15.0    // default min,max of P generation for generation nodes (for VT)
   0.0    0.0    // default min,max of P generation for load nodes
  -6.0   10.0    // default min,max of Q generation for generation nodes (for VT,PV)
   0.0    0.0    // default min,max of Q generation for load nodes

// nodal bounds for voltage magnitudes
/bus   Vmin   Vmax
end

// nodal bounds for P generation
/bus     Pmin     Pmax
    1     1.40     7.00        // G01 Thermal(fossil)
    2    11.00    11.000001 // G02 Nuclear
    3     1.50     6.00        // G03 Hydraulic (slack bus)
    4     3.30    11.00        // G04 Thermal(fossil)
    5     1.50     6.00        // G05 Hydraulic
    6     3.30    11.00        // G06 Thermal(fossil)
    7    11.00    11.000001 // G07 Nuclear
    8     1.75     7.00        // G08 Thermal(fossil)
    9     1.75     7.00        // G09 Thermal(fossil)
   10     1.00     5.00        // G10 Thermal(fossil)
end

// nodal bounds for Q generation
/bus     Qmin     Qmax
    1     0.56     2.73     // G01 Thermal(fossil)
    2    -1.10     4.95     // G02 Nuclear
    3    -0.30     1.50     // G03 Hydraulic (slack bus)
    4    -1.10     5.50     // G04 Thermal(fossil)
    5    -0.30     1.50     // G05 Hydraulic
    6    -1.10     5.50     // G06 Thermal(fossil)
    7    -1.10     4.95     // G07 Nuclear
    8    -1.05     1.05     // G08 Thermal(fossil)
    9    -1.05     1.05     // G09 Thermal(fossil)
   10    -0.25     2.50     // G10 Thermal(fossil)
end

// power factor limits of generations
/bus     pfmin   pfmax     sign
end

// cost coefs for each generator
/bus          a                  b               c              // cost(P) = a*P^2 + b*P + c
```

```
   1    40.0000e-6   2400.0e-6   1170.0e-6   // G01 Thermal(fossil)
   2     0.0000e-6    0.000e-6    0.000e-6   // G02 Nuclear
   3     0.0000e-6    0.000e-6    0.000e-6   // G03 Hydraulic (slack bus)
   4    63.6360e-6   400.00e-6   6050.0e-6   // G04 Thermal(fossil)
   5     0.0000e-6    0.000e-6    0.000e-6   // G05 Hydraulic
   6    63.6360e-6   400.00e-6   6050.0e-6   // G06 Thermal(fossil)
   7     0.0000e-6    0.000e-6    0.000e-6   // G07 Nuclear
   8    38.0000e-6   5000.0e-6   2600.0e-6   // G08 Thermal(fossil)
   9    38.0000e-6   5000.0e-6   2600.0e-6   // G09 Thermal(fossil)
  10     5.0000e-6   5000.0e-6   2000.0e-6   // G10 Thermal(fossil)
end

//note) cost coefs should be scaled for balancing the dual feasibility in IPM formulation.
//        If not, dual feasibility will not be improved and IPM convergence will degrade.
```

以上

補足資料　マイクログリッド等解析用の標準モデル

Output-1　(潮流計算)

```
Power Flow :  No of Equations & Variables = 9

Newton-Raphson ends at iter-4;  cpuTime = 0.031 sec

Nodal   Solution                    (G+L)                            (V:polar/rad)
(G+L)
  1    :  G                            V,T =   1.0500 < +0.0000     I =    0.3139  -
0.2596    P,Q =    0.3296    0.2726
  2    :  G    P    =    0.3500           V  =   1.0500 < -0.0128     I =    0.3333  -
0.0081    P,Q =    0.3500    0.0040   ok
  3     :  L     P,Q  =   -0.2750    -0.1100     V  =   1.0480  <  -0.0182     I  =   -0.2604
0.1097    P,Q =  -0.2750   -0.1100   ok
  4    :  -    P,Q =     0.0000    0.0000     V  =   1.0243  < -0.0220     I  =    0.0000  -
0.0000    P,Q =    0.0000    0.0000   ok
  5     :  L     P,Q  =   -0.1500    -0.0900     V  =   1.0473  <  -0.0452     I  =   -0.1392
0.0923    P,Q =  -0.1500   -0.0900   ok
  6     :  L     P,Q  =   -0.2500    -0.1500     V  =   1.0082  <  -0.0415     I  =   -0.2416
0.1589    P,Q =  -0.2500   -0.1500   ok
            sum      P,Q      =         -0.6750          -0.3500      (load      only)
total P,Q =   0.0046   -0.0734  (loss)

max P,Q mismatch = 5.675e-009  ok
Nodal capacitance flows    (V:rectangular)
  node-4     :  s =  0.0200   V =    1.0240   -0.0225   I =   -0.0004   -0.0205    P,Q =  -
0.0000    0.0210
  node-6     :  s =  0.0200   V =    1.0073   -0.0418   I =   -0.0008   -0.0201    P,Q =
0.0000    0.0203
                                                                      total    P,Q    =
0.0000    0.0413
Branch flows
```

```
  B1      1 --> 6    Re(I) =   0.1787 -->   0.1787 -->   0.1785   Pflow =   0.1876 --
>   0.1860   Ploss =   0.0016
                     Im(I) =  -0.1382 -->  -0.1434 -->  -0.1485   Qflow =   0.1451 --
>   0.1421   Qloss =   0.0030
  B2      1 --> 4    Re(I) =   0.1352 -->   0.1352 -->   0.1351   Pflow =   0.1420 --
>   0.1413   Ploss =   0.0007
                     Im(I) =  -0.1215 -->  -0.1257 -->  -0.1298   Qflow =   0.1275 --
>   0.1299   Qloss =  -0.0023
  B3      4 --> 6    Re(I) =   0.1031 -->   0.1030 -->   0.1028   Pflow =   0.1070 --
>   0.1067   Ploss =   0.0004
                     Im(I) =  -0.0648 -->  -0.0699 -->  -0.0749   Qflow =   0.0640 --
>   0.0712   Qloss =  -0.0072
  B4      6 --> 5    Re(I) =   0.0388 -->   0.0385 -->   0.0362   Pflow =   0.0427 --
>   0.0424   Ploss =   0.0002
                     Im(I) =  -0.0846 -->  -0.0926 -->  -0.0964   Qflow =   0.0836 --
>   0.0991   Qloss =  -0.0155
  B5      2 --> 5    Re(I) =   0.1034 -->   0.1033 -->   0.1030   Pflow =   0.1083 --
>   0.1076   Ploss =   0.0008
                     Im(I) =   0.0187 -->   0.0114 -->   0.0041   Qflow =  -0.0211 --
>  -0.0091   Qloss =  -0.0119
  B6      2 --> 3    Re(I) =   0.2298 -->   0.2298 -->   0.2298   Pflow =   0.2417 --
>   0.2413   Ploss =   0.0003
                     Im(I) =  -0.0268 -->  -0.0268 -->  -0.0268   Qflow =   0.0250 --
>   0.0237   Qloss =   0.0013
  B7      4 --> 3    Re(I) =   0.0316 -->   0.0316 -->   0.0306   Pflow =   0.0342 --
>   0.0337   Ploss =   0.0006
                     Im(I) =  -0.0855 -->  -0.0855 -->  -0.0829   Qflow =   0.0868 --
>   0.0863   Qloss =   0.0005

  branch total P,Q loss = 0.0046  -0.0321,   total P,Q loss = 0.0046  -0.0734  ok
--------------------------------------------------------------------------------------
------------------------------------
```

*) Information about bus(node) solution and power balances

```
sample)
Nodal  Solution              (G+L)                                        (polar/rad)
(G+L)
  1    :  G                          V,T =  1.0000 < +0.0000   I =   0.1642   0.1928
P,Q =   0.1642  -0.1928
  2    :  L   P,Q =   0.2000  -0.2000   V =  1.0137 < -0.1073   I =   0.2173   0.1750
P,Q =   0.2000  -0.2000  ok
  3    :  G   P   =  -0.3500            V =  1.1000 < -0.2384   I =  -0.2591   0.2811
P,Q =  -0.3500  -0.2331  ok
          sum     P,Q     =            0.2000          -0.2000       (L      only)
total P,Q =   0.0142  -0.6259 (loss)

max P,Q mismatch = 3.223e-008  ok
```

*) The complex voltage solution (|V|,angle) for all buses were printed in polar/rad form: |V|∠(phase angle)

*) The complex current injection (I) for each bus were printed in rectangular form,
computed as the sum of branch current flows incident to the bus.

*) The complex power injection (P,Q) for each bus were printed (left: input data; G+L).
The complex power computation (P,Q) for each bus were printed (right: P+jQ = V*conj(I); G+L).
Both powers were compared. If they are nearly equal, 'ok' is printed, '?' otherwise.

*) The difference norm between the both powers for all buses was printed as 'max P,Q mismatch'.
If this value is small enough, 'ok' is printed, '?' otherwise.
*) The sum of complex power in each bus was printed as 'total P,Q'.
This values show the the overall difference between generations and loads,
i.e. the complex power losses (active loss,reactive loss) in the grid.

---

*) Information about power flows and power losses

```
sample)
Nodal capacitance flows  (V:rectangular)
  node-4     :  s =  0.0200  V =   1.0240  -0.0225  I =  -0.0004  -0.0205   P,Q =  -
0.0000   0.0210
```

*) If there exist some shunt capacitors in the buses, the followings will be given for output.
*) The buses with nonzero shunt capacitor susceptance (sus) were picked up for output.
*) The complex voltage solution (V) for each bus were printed in rectangular form.
*) The complex current (Is) for each bus were printed in rectangular form (Is = (j*sus)*V).
*) The complex power computation (P,Q) for each bus were printed (P+jQ = V*conj(Is) → P=0).
*) The sum of the each complex power (P,Q) will be printed as 'total P,Q' if the number of this pickups > 1.

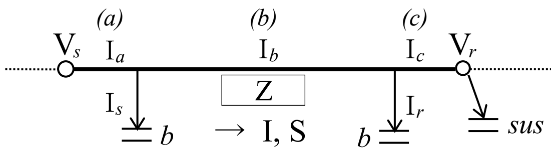
```
sample)
Branch flows
  B1      1       Re(I) =    0.1642 -->    0.1642 -->    0.1588    Pflow =     0.1642 -->
0.1500   Ploss =   0.0142
    -->   2       Im(I) =    0.1928 -->    0.1428 -->    0.0924    Qflow =    -0.1928 -->
-0.1103   Qloss =  -0.0824
  B2      2       Re(I) =    0.3110 -->    0.3110 -->    0.2591    Pflow =     0.3500 -->
0.3500   Ploss =   0.0000
    -->   3       Im(I) =  -0.3373 -->  -0.3373 -->  -0.2811    Qflow =     0.3062 -->
0.2331   Qloss =   0.0731

  branch total P,Q loss = 0.0142  -0.0094,    total P,Q loss = 0.0142  -0.6259  ok
```

*) The complex current flows and complex power flows for all branches were printed in rectangular form.
*) Each branch is separated into 3 parts(*a,b,c*) as shown in the figure below.
*) The complex current flows (I) in the parts(*a,b,c*) were printed in rectangular form (Re,Im).
*) The complex power flows (S) in the parts(*a,c*) were printed in rectangular form (Pflow,Qflow).
*) The complex power loss in the branch were printed in rectangular form (Ploss,Qloss). power loss = $S_a - S_c$
*) The total branch power loss in all branches were printed.
*) Also the total P,Q losses in the grid were printed if some nodal capacitances exist.
total P,Q losses = total branch power loss - total P,Q in ‘Nodal capacitance flows’.
This value was compared with that in ‘Nodal Solution’. If they are nearly equal, 'ok' is printed, '?' otherwise.

*) Output form I_a --> I_b --> I_c S_a --> S_c PowerLoss

```
      branchID     s   Re(I) =  0.1642 -->  0.1642 -->  0.1588   Pflow =  0.1642 -->
0.1500   Ploss =  0.0142
               --> r   Im(I) =  0.1928 -->  0.1428 -->  0.0924   Qflow = -0.1928 -->
-0.1103   Qloss = -0.0824
```

*) π-shaped equivalent citcuit



$$\dot{I}_b = (\dot{V}_s - \dot{V}_r)/\dot{Z}$$

$\dot{I}_a = \dot{I}_b + \dot{I}_s$ $\dot{I}_c = \dot{I}_b - \dot{I}_r$ $\dot{I}_s = \dot{Y}_b \dot{V}_s$, $\dot{I}_r = \dot{Y}_b \dot{V}_r$, $\dot{Y}_b = jb$ *(admittance of the capacitor)*

$\dot{S}_a = \dot{V}_s \dot{I}_a^*$ $\dot{S}_c = \dot{V}_r \dot{I}_c^*$ ($\dot{S} := P + jQ$)

(note) $\dot{I}_a = \dot{I}_c = \dot{I}_b$, if $b = 0$

Output-2 （多段経済負荷配分）

```
solution -----------------------------------------------------
  Objective value = 1788554.711633
  primal bound feasibility  satisfied
  dual   bound feasibility  satisfied
  primal feas. for EQ cons. satisfied
  primal feas. for LE cons. satisfied  (active:152)
--------------------------------------------------------------
```

Dynamic Dispatch Schedule :

Period		G1	G2	G3	G4	G5	G6	G7	G8	BT	sumG	sumCostV	sumCostF
0		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	300.0000	0.0000	-10.0000	290.0000		
1	01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	260.0212	100.0000	-0.0212	360.0000	4042.6896	1005.0000
2	02	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	200.7476	200.0000	-0.7476	400.0000	4447.3261	1005.0000
3	03	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	164.6487	300.0000	-24.6487	440.0000	5116.0189	1005.0000
4	04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	204.6918	300.0000	-0.6918	504.0000	5572.2714	1005.0000
5	05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	284.0000	300.0000	0.0000	584.0000	6475.9131	1005.0000
6	06	0.0000	0.0000	0.0000	0.0000	0.0000	20.0000	344.0000	300.0000	0.0000	664.0000	7412.7569	1298.0000
7	07	0.0000	0.0000	0.0000	0.0000	0.0000	140.0000	400.0000	220.0000	0.0000	760.0000	8706.0228	1298.0000
8	08	0.0000	0.0000	0.0000	0.0000	0.0000	260.0000	600.0000	300.0000	0.0000	1160.0000	13368.0518	1298.0000
9	09	0.0000	0.0000	20.0000	60.0000	0.0000	380.0000	800.0000	300.0000	0.0000	1560.0000	18372.0878	2234.7400
10	10	0.0000	0.0000	70.0000	60.0000	0.0000	480.0000	800.0000	300.0000	50.0000	1760.0000	20511.0971	2234.7400

11	11	0.0000	0.0000	0.0000	20.0000	0.0000	480.0000	800.0000	300.0000	0.0000	1600.0000	18717.6961	1550.0000
12	12	0.0000	0.0000	0.0000	0.0000	0.0000	420.0000	800.0000	300.0000	0.0000	1520.0000	17672.4906	1298.0000
13	13	0.0000	0.0000	0.0000	40.0000	0.0000	300.0000	800.0000	300.0000	0.0000	1440.0000	16724.4822	1550.0000
14	14	0.0000	0.0000	0.0000	0.0000	0.0000	180.0000	640.0000	300.0000	0.0000	1120.0000	12811.0132	1298.0000
15	15	0.0000	0.0000	0.0000	0.0000	0.0000	60.0000	440.0000	300.0000	0.0000	800.0000	9012.9887	1298.0000
16	16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	276.0000	300.0000	0.0000	576.0000	6384.7606	1005.0000
17	17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	160.0000	256.0000	0.0000	416.0000	4587.8491	1005.0000
18	18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	156.0000	0.0000	256.0000	2824.2034	1005.0000
19	19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	132.0000	0.0000	232.0000	2565.0027	1005.0000
20	20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	272.0000	200.0000	0.0000	472.0000	5259.1794	1005.0000
21	21	0.0000	0.0000	0.0000	0.0000	0.0000	20.0000	472.0000	300.0000	-0.0000	792.0000	8871.1993	1298.0000
22	22	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	580.0008	300.0000	-0.0008	880.0000	9848.5720	1005.0000
23	23	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	380.0036	300.0000	-40.0036	640.0000	7569.7849	1005.0000
24	24	0. 0000	0. 0000	0. 0000	0. 0000	0. 0000	0. 0000	185. 3148	300. 0000	−5. 3148	480. 0000	5351. 4896	1005. 0000

— —（略）

136 16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	140.0000	292.0000	0.0000	432.0000	4748.7705	1005.0000
137 17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	120.0000	192.0000	0.0000	312.0000	3440.8851	1005.0000
138 18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	92.0000	0.0000	192.0000	2133.0018	1005.0000
139 19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	74.0000	0.0000	174.0000	1938.6015	1005.0000
140 20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	180.0000	174.0000	0.0000	354.0000	3930.1263	1005.0000
141 21	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	320.0000	274.0000	-0.0000	594.0000	6605.2977	1005.0000
142 22	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	360.0000	300.0000	-0.0000	660.0000	7341.8620	1005.0000
143 23	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	180.0000	300.0000	-0.0000	480.0000	5290.9322	1005.0000
144 24	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	135.0000	225.0000	-0.0000	360.0000	3968.1969	1005.0000
145 01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	125.0000	-0.0000	225.0000	2489.4026	1005.0000
146 02	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	150.0000	-0.0000	250.0000	2759.4033	1005.0000
147 03	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	175.0000	-0.0000	275.0000	3029.4041	1005.0000

148 04 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
215.0000 -0.0000 315.0000 3461.4056 1005.0000
149 05 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
265.0000 0.0000 365.0000 4001.4080 1005.0000
150 06 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 115.0000
300.0000 0.0000 415.0000 4550.3203 1005.0000
151 07 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 275.0000
200.0000 0.0000 475.0000 5293.3616 1005.0000
152 08 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 475.0000
250.0000 0.0000 725.0000 8112.1788 1005.0000
153 09 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 675.0000
300.0000 0.0000 975.0000 10931.0046 1005.0000
154 10 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 800.0000
300.0000 0.0000 1100.0000 12355.2730 1005.0000
155 11 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 700.0000
300.0000 0.0000 1000.0000 11215.8580 1005.0000
156 12 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 650.0000
300.0000 0.0000 950.0000 10646.1513 1005.0000
157 13 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 600.0000
300.0000 0.0000 900.0000 10076.4450 1005.0000
158 14 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 400.0000
300.0000 0.0000 700.0000 7797.6250 1005.0000
159 15 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 200.0000
300.0000 0.0000 500.0000 5518.8130 1005.0000
160 16 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
260.0000 0.0000 360.0000 3947.4078 1005.0000
161 17 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
160.0000 0.0000 260.0000 2867.4036 1005.0000
162 18 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
60.0000 0.0000 160.0000 1787.4014 1005.0000
163 19 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
45.0000 0.0000 145.0000 1625.4012 1005.0000
164 20 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 150.0000
145.0000 0.0000 295.0000 3275.1044 1005.0000
165 21 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 250.0000
245.0000 -0.0000 495.0000 5494.5123 1005.0000
166 22 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 250.0000
300.0000 -0.0000 550.0000 6088.5153 1005.0000
167 23 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
300.0000 -0.0000 400.0000 4379.4100 1005.0000
168 24 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
200.0000 -0.0000 300.0000 3299.4050 1005.0000

sum) 0.0000 915.0000 1995.0000 1475.0000 172.5000 18090.0000 69435.0714
44258.0000 -428.5714 135912.0000 1573739.4516 214815.2600

各 **unit**(G2～G8,BT)の発電プロファイル

*) G1 は燃料費高価のため一度も発電していない(起動停止計画の結果と同じ)。

Output-3 （最適潮流計算）

```
  n = 47, m = 61, ngen = 10, #pfactor = 0, #bpflow = 0, loadFactor = 1.000

Y matrix created;  n = 47, nz = 153 (6.926%), rowwise nzmax = 6

  nVar = 46+46+10+10 = 112 / 188, me = 94, mi = 0+0 = 0,  Sigma = 0.001, red.step =
0.9995

Newton_GMRES-IPM:  tol = 1.00e-008(P) 1.00e-008(D) 1.00e-007(C) 1.00e-011(M)

  iter      myu      Infeas(P)    Infeas(D)    Infeas(C) GMRES  stepLen(P,D)   time(s)
    1   2.109e-002  4.936e+001  8.614e+001  2.419e+002     3   0.0001 0.0000    0.000
    2   2.109e-002  4.943e+001  1.574e+002  2.452e+002    13   0.0000 0.0000    0.015
    3   2.109e-002  4.943e+001  1.574e+002  2.452e+002     2   0.0005 0.0061    0.000
    4   2.098e-002  4.941e+001  4.091e+002  2.437e+002     3   0.0091 0.0006    0.000
    5   2.095e-002  4.879e+001  4.455e+002  2.431e+002     6   0.0003 0.0090    0.016
   .........................................
   33   9.503e-009  8.955e-005  4.984e-003  9.023e-005    20   1.0000 0.6591    0.000
   34   3.210e-009  2.192e-003  1.969e-003  2.995e-005    17   0.9553 0.8046    0.016
   35   5.904e-010  2.798e-003  1.752e-004  5.026e-006    14   0.9501 0.9446    0.000
   36   3.375e-011  1.860e-004  1.384e-005  2.883e-007    14   0.9997 0.8445    0.000
   37   5.232e-012  1.348e-005  8.649e-006  4.509e-008   +21   1.0000 1.0000    0.016

Converged at iter-37;  nK = 206;  nzK = 1868 (4.402%), nzILU = 1814 (4.275%)  fillRate:
```

0.971

total Time = 0.203 sec (aveKKT: 0.001, aveLEQ: 0.003) sumGMRES: 518, memLEQ = 0.072 Mb, MMD(At+A)

FuncCalls: Func = 1, Grad = 37, Hessian = 37

Minimum dispatch cost = 0.158233

```
OPF solution for generations
  Node            kind       V        T(rad)   kind       Pg           Qg           Pl
Ql       Pg+Pl      Qg+Ql   Pfactor
  1       G   PQ :    2    1.043505 -0.129773    2    7.000000    2.097094    0.000000
0.000000   7.000000   2.097094  +0.9579
  2       G   PQ :    2    1.038933  0.105638    2   11.000001    4.059198    0.000000
0.000000  11.000001   4.059198  +0.9382
  3       G   VT :    -    1.020000  0.000000    2    6.000000   -0.300000    0.000000
0.000000   6.000000  -0.300000  -0.9988
  4       G   PQ :    2    1.039096  0.081519    2   11.000000    2.781819    0.000000
0.000000  11.000000   2.781819  +0.9695
  5       G   PQ :    2    1.072063 -0.027571    2    6.000000    1.500000    0.000000
0.000000   6.000000   1.500000  +0.9701
  6       G   PQ :    2    1.039451 -0.051371    2   11.000000    2.823004    0.000000
0.000000  11.000000   2.823004  +0.9686
  7       G   PQ :    2    1.056955  0.078783    2   11.000001    4.888460    0.000000
0.000000  11.000001   4.888460  +0.9138
  8       G   PQ :    2    0.995599  0.302265    2    7.000000    1.050000    0.000000
0.000000   7.000000   1.050000  +0.9889
  9       G   PQ :    2    0.970719  0.398983    2    6.450458    1.050000    0.000000
0.000000   6.450458   1.050000  +0.9870
  10      G   PQ :    2    1.014896  0.444068    2    4.798443    2.500000    0.000000
0.000000   4.798443   2.500000  +0.8869
  #gen: 10                              sum)  81.248903  22.449575

PowerFlow verification of OPF soln
  Node                              (G+L)                                        (polar/rad)
(G+L)
  1     G :  P,Q =    7.0000    2.0971   V =  1.0435 < -0.1298   I =   6.3917  -2.8609
P,Q =   7.0000   2.0971  ok
  2     G :  P,Q =   11.0000    4.0592   V =  1.0389 < +0.1056   I =  10.9407  -2.7689
P,Q =  11.0000   4.0592  ok
  3     G :                           V,T =  1.0200 < +0.0000   I =   5.8824   0.2941
P,Q =   6.0000  -0.3000
  4     G :  P,Q =   11.0000    2.7818   V =  1.0391 < +0.0815   I =  10.7690  -1.8062
P,Q =  11.0000   2.7818  ok
  5     G :  P,Q =    6.0000    1.5000   V =  1.0721 < -0.0276   I =   5.5560  -1.5529
P,Q =   6.0000   1.5000  ok
  6     G :  P,Q =   11.0000    2.8230   V =  1.0395 < -0.0514   I =  10.4291  -3.2557
P,Q =  11.0000   2.8230  ok
  7     G :  P,Q =   11.0000    4.8885   V =  1.0570 < +0.0788   I =  10.7390  -3.7916
P,Q =  11.0000   4.8885  ok
  8     G :  P,Q =    7.0000    1.0500   V =  0.9956 < +0.3023   I =   7.0261   1.0862
P,Q =   7.0000   1.0500  ok
  9     G :  P,Q =    6.4505    1.0500   V =  0.9707 < +0.3990   I =   6.5433   1.5848
```

```
P,Q =   6.4505   1.0500  ok
  10     G :  P,Q =   4.7984   2.5000   V =  1.0149 < +0.4441   I =   5.3277  -0.1932
P,Q =   4.7984   2.5000  ok
  11     - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.2239   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  12     - :  P,Q =   0.0000   0.0000   V =  1.1373 < +0.0100   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  13     - :  P,Q =   0.0000   0.0000   V =  1.1034 < -0.1059   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  14     - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.0130   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  15     - :  P,Q =   0.0000   0.0000   V =  1.1303 < -0.1254   I =  -0.0000   0.0000
P,Q =  -0.0000   0.0000  ok
  16     - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.1459   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  17     - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.0142   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  18     L :  P,Q =  -5.5000  -1.0500   V =  1.0101 < +0.1786   I =  -5.5428   0.0558
P,Q =  -5.5000  -1.0500  ok
  19     L :  P,Q =  -5.5000  -1.4130   V =  0.9835 < +0.2789   I =  -5.7716  -0.1585
P,Q =  -5.5000  -1.4130  ok
  20     - :  P,Q =   0.0000   0.0000   V =  1.0947 < +0.3465   I =  -0.0000  -0.0000
P,Q =  -0.0000   0.0000  ok
  21     - :  P,Q =   0.0000   0.0000   V =  1.1129 < -0.4575   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  22     - :  P,Q =   0.0000   0.0000   V =  1.1175 < -0.5917   I =  -0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  23     - :  P,Q =   0.0000   0.0000   V =  1.1053 < -0.4815   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  24     - :  P,Q =   0.0000   0.0000   V =  1.1183 < -0.6122   I =  -0.0000  -0.0000
P,Q =  -0.0000   0.0000  ok
  25     - :  P,Q =   0.0000   0.0000   V =  1.1014 < -0.2926   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  26     - :  P,Q =   0.0000   0.0000   V =  1.1066 < -0.4059   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  27     - :  P,Q =   0.0000   0.0000   V =  1.1172 < -0.5393   I =   0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  28     - :  P,Q =   0.0000   0.0000   V =  1.1189 < -0.3045   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  29     - :  P,Q =   0.0000   0.0000   V =  1.1173 < -0.4056   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  30     - :  P,Q =   0.0000   0.0000   V =  1.1233 < -0.5290   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  31     - :  P,Q =   0.0000   0.0000   V =  1.1261 < -0.3092   I =   0.0000  -0.0000
P,Q =   0.0000  -0.0000  ok
  32     - :  P,Q =   0.0000   0.0000   V =  1.1216 < -0.4221   I =   0.0000  -0.0000
P,Q =   0.0000  -0.0000  ok
  33     - :  P,Q =   0.0000   0.0000   V =  1.1282 < -0.5514   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  34     - :  P,Q =   0.0000   0.0000   V =  1.1245 < -0.4997   I =  -0.0000  -0.0000
P,Q =  -0.0000   0.0000  ok
  35     - :  P,Q =   0.0000   0.0000   V =  1.1231 < -0.3274   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  36     - :  P,Q =   0.0000   0.0000   V =  1.0917 < +0.1259   I =   0.0000   0.0000
```

```
P,Q =   0.0000  -0.0000  ok
  37     - :  P,Q =    0.0000    0.0000    V =  1.0635 < +0.2621    I =    0.0000    0.0000
P,Q =   0.0000  -0.0000  ok
  38     L :  P,Q =  -5.0000    1.2000    V =  1.0847 < -0.6929    I =  -4.2533    2.0934
P,Q =  -5.0000   1.2000  ok
  39     L :  P,Q = -10.0000    2.4160    V =  1.0856 < -0.7133    I =  -8.4220    4.3440
P,Q = -10.0000   2.4160  ok
  40     L :  P,Q = -10.0000    2.6710    V =  1.0872 < -0.6404    I =  -8.8435    3.5255
P,Q = -10.0000   2.6710  ok
  41     L :  P,Q = -10.0000    2.5930    V =  1.0922 < -0.6290    I =  -8.8002    3.4672
P,Q = -10.0000   2.5930  ok
  42     L :  P,Q = -10.0000    2.3780    V =  1.0945 < -0.6508    I =  -8.5853    3.8065
P,Q = -10.0000   2.3780  ok
  43     L :  P,Q =  -5.0000    1.2600    V =  1.0926 < -0.5995    I =  -4.4290    1.6300
P,Q =  -5.0000   1.2600  ok
  44     L :  P,Q =  -5.0000    2.4990    V =  1.0640 < -0.4008    I =  -5.2432   -0.3292
P,Q =  -5.0000   2.4990  ok
  45     L :  P,Q =  -5.0000    2.4800    V =  1.0792 < -0.4095    I =  -5.1651   -0.2634
P,Q =  -5.0000   2.4800  ok
  46     L :  P,Q =  -5.0000    2.5320    V =  1.0867 < -0.4128    I =  -5.1494   -0.2884
P,Q =  -5.0000   2.5320  ok
  47     L :  P,Q =  -4.0000   -1.3680    V =  0.9934 < +0.2301    I =  -4.2346    0.4225
P,Q =  -4.0000  -1.3680  ok
          sum P,Q = -80.0000  16.1980 (L only)                                        total
P,Q =   1.2489  38.6476 (loss)
                                                                                  max
PQ_mismatch = 3.108e-009  ok

   V = [ 0.9707, 1.1500 ] at node 9, 17,  Theta = [ -0.7133, 0.4441 ] (rad) at node
39, 10

Current/Power flow balance satisfied at all nodes

Test Branch PowerFlow limits;  none
```

10. 付録 C:大規模配電系統潮流計算の高速解法

2020 年 3 月

環境エネルギー技術研究所㈱

１．概要

電力系統における潮流計算手法には，初期の Gauss-Seidel 法，Implicit Zbus Gauss 法を含め，Newton-Raphson 法およびその改良版(Decoupled 法など)，Backward/Forward 法およびその変形版など，多くの解法が提案されている。これらの解法の性能比較については，過去に実施されてはいるが，「時期が古い，大規模系統を対象としていない」などの不十分さがあり,「どの程度の系統規模まで，どれぐらい速く解けるのか」が不明確であった。そこで，本稿では，現在の計算機環境およびソフトウェア技術に基づいて，標準的解法の性能比較をあらためて実施することとする。そのために，これまでに開発された潮流計算のプログラム資産に依存しない新たなプログラムを開発し，これを用いて高速 PC で大規模配電系統向けの数値実験と性能比較を行う。

開発した潮流計算プログラムは,代表的厳密解法である Newton-Raphson 法と Backward/Forward 法である。Newton-Raphson 法では，Jacobian 疎行列の高速 LU 分解，Backward/Forward 法では，グラフ理論に基づいた Topological Ordering による高速 B/F Sweep を採用している。両解法とも，配電系統のトポロジー的特徴である放射性(Radial)または弱ループ性(Weakly-meshed：ループ数が少ないこと)を考慮することが可能である。

２．電力系統の潮流方程式

送配電電力系統は，需要家の電力需要を賄えるように設計された電力伝送路である。この伝送路における電力・電流の流れと電圧分布を解析するために，一定の基準で設定されたノード(母線：bus)とノード間を結ぶブランチ(枝：branch)で構成されるネットワーク構造(属性つきのグラフ)から導きだされる電力潮流方程式が解かれる。ここで，状態量である電力(Power)・電流(Current)・電圧(Voltage)はすべて複素数であり，電力には実数部を示す有効電力(P：Active Power)，虚数部を示す無効電力(Q：Reactive Power)という名称が与えられている。また，複素電圧($\dot{V}$)は，複素数の指数表現である $\dot{V}=|\dot{V}|e^{j\delta}=|\dot{V}|\cos\delta+j|\dot{V}|\sin\delta$ を用いて電圧値$|\dot{V}|$と電圧位相角 δ (radian)で表現されることも多い。ここで，複素数には上ドット記号を添え，j を虚数単位として使用する。

ネットワークのノードは，発電ノードとＰ・Ｑ値を指定する負荷ノードに大別され，さらに発電ノードは，複素電圧を指定する無限大母線(スラック母線)と P 値と$|\dot{V}|$値を指定する PV 母線とに分類されることが一般的である。ブランチには，ブランチ属性として Impedance(抵抗とリアクタンス)が与えられる。また，一般のπ型系統モデルでは，ノードおよびブランチに無効電力の提供・吸収を担う Susceptance を考慮できるようになっている。Susceptance とは，Impedance の逆数である Admittance の虚数部を示し，Susceptance 機能を有する機器を Shunt Capacitor と言う。

このようなモデルで構成される送配電電力系統は，バス群と双方向性を有するブランチ群から構成される無向グラフとしてとらえることができ，このグラフをもとに，以下に示す交流回路の基本式を適用することにより，電力潮流方程式が作成される。

○交流回路の基本式　（上*記号は共役複素数を示す）

①オームの法則(Ohm's Law)

・$\dot{V}=\dot{Z}\dot{I}$　($\dot{V}$:Voltage, $\dot{I}$:Current, $\dot{Z}$:Impedance)

・$\dot{I}=\dot{Y}\dot{V}$　($\dot{V}$:Voltage, $\dot{I}$:Current, $\dot{Y}$:Admittance)

②キルヒホッフの電流則（KCL: Kirchhoff's Current Law）

・ノードに流出入する電流の総和は零である。

・ノードに流出入する電力流の総和は零である。

③キルヒホッフの電圧則（KVL: Kirchhoff's Voltage Law）

・閉路における電圧の総和は零である。

・ブランチ端点 1-->2 の電圧降下式： $\dot{V}_1-\dot{V}_2=\dot{Z}\dot{I}$

④ノードにおける注入電力則

・$\dot{S}=\dot{V}(\dot{I})^*$　($\dot{S}$:injected Power, $\dot{V}$:Voltage, $\dot{I}$:injected Current)

・$\dot{I}=(\dot{S}/\dot{V})^*$

以上の公式より導かれる電力潮流方程式は以下の通りである。

(A) $[\dot{I}]=[\dot{Y}][\dot{V}]$

(B) $\dot{S}_i=\dot{V}_i([\dot{Y}][\dot{V}])_i^*$ （$i=1...n$）

ここで，$[\dot{V}]$は全ノードの電圧ベクトル，$[\dot{I}]$は同注入電流ベクトル，$\dot{S}_i=P_i+jQ_i$ はノード$_i$の指定注入電力（発電＋，負荷－），$[\dot{Y}]$はキルヒホッフの電流則より導かれる系統全体の対称アドミッタンス行列（Y_{bus} matrix），n はノード数を示す。(B)式が電力潮流方程式と称されるノード電圧に関する非線形方程式であり，$\dot{S}_i$を与えてこれを解くとノード電圧が求められる。(A)式は(B)式を作成するために必要な線形交流回路の基本方程式であり，同式よりノード電圧が求められるとノードの注入電流ベクトルが計算できることを示している。このことより，電力系統は線形の交流回路理論が基礎となっているが，電力潮流の非線形性は主として電力値の指定という境界条件より生じることがわかる。

以上で電力潮流方程式の導入を行ったが，実際に潮流方程式を解くには(B)式だけでは

方程式の解は求められず，発電側での境界条件も与える必要がある。そのために考案された方法がスラックバスの導入である。すなわち，少なくとも一個の複素電圧指定ノード（スラック・バス）を与えることにより，電力潮流方程式の不定性を回避できることとなる。また，発電ノードにはPV母線としてＰ値と$|\dot{V}|$値を指定することがあるので，その境界条件も考慮する必要がある。これらの境界条件の原則的な処理方法は，電圧指定があればその電圧変数は固定値とみなし変数からはずすこと，また，電力指定があれば，そのＰ値またはＱ値に関する電力潮流方程式の行を取り除くことである。この結果，電力潮流方程式のサイズ(変数の個数＝方程式の本数)は $2n$ よりも幾分小さくなる。

なお，ここで述べた電力潮流方程式の詳細内容は以下の文献に記述されているので，参照されたい。

出典：東京電力株式会社・インターネット電力講座 Newton-Raphson 法による電力系統の潮流計算

３．電力潮流方程式の解法

前節で述べたように，電力潮流方程式を解くことは，多次元の非線形連立方程式を解くことに等しい。この方程式を直接解析的に解く方法はないので，解法としては数値演算による繰返し法に頼らざるを得ない。そのような手法の多くは，非線形連立方程式を線形近似して，収束条件が満足されるまで繰り返し演算を行うのが通常である。線形近似の方法によって解法が分類され，最も初歩的な解法が，非線形項・非対角項をすべて前回の反復で得られた値で代替し定数項にしてしまう Gauss-Seidel 法である。また，非線形問題の数値解法として一般的に利用される Newton-Raphson 法は，非線形の PQ ミスマッチ関数の勾配情報(Jacobian)によって線形化を行う。さらに別の解法として，電力潮流方程式を線形の交流回路方程式に近似する方法もしばしば利用されており，この線形化を採用した解法として Implicit Zbus Gauss 法や Current Injection 法(電流注入法)が挙げられる。この方法は前記(A)式 $[\dot{Y}][\dot{V}]=[\dot{I}]$ の右辺を前回の反復で得られた電圧 $\dot{V}_p$ で $\dot{I}=(\dot{S}/\dot{V}_p)^*$ と近似して，$[\dot{V}]$ に関する連立一次方程式を繰り返し解くものである。この解法の考えを，行列を使用せず手続き的方法で実現したのが Backward/Forward 法であり，同法では，グラフ探索によってキルヒホッフの法則(KCL,KVL)を直接適用することにより，アドミッタンス行列$[\dot{Y}]$を構成する方法と等価な解を得ることができる。

以上，電力潮流方程式の解法について概説したが，次に Backward/Forward 法について詳述する。

３.１ Backward/Forward 法による電力潮流方程式の解法

Backward/Forward 法は，電力潮流方程式を直接解く送電系統向け伝統的方法（Newton-Raphson 法の系列)の別解法として登場した[1, 7]。この解法は，ループのない放射状配電

系統を対象として，大規模複素行列を操作する複雑な手順を省くことで，シンプルかつ高速な性能を実現することができた。その後，Backward/Forward 法は，ループ構造および電圧制御バス(PV 母線)を考慮できるように拡張され[14, 18]，更に三相不平衡潮流計算にも適用された[26]。これ以外にも，現在まで Backward/Forward 法の変形版が数多く提案されており，それらの内容については詳細なサーベイ論文[47]が発表されているので参照されたい。

以下に，Backward/Forward 法の基本手法と拡張内容について述べる。

３.２ ループ構造のない系統に対する Backward/Forward 法

ループ(サイクル)がない放射状系統とは，木構造のグラフであることを意味する。グラフ理論によると，サイクルがないグラフは，Topological Ordering によって半順序集合に変換できる，すなわち，すべてのノードは，所与の出発点から順序立って訪問でき，逐次処理が可能となるという原理がある。この原理にもとづいて，木の根(root:スラックバス)を出発点として，すべてのノードを逐次訪問しながらキルヒホッフの電圧則による電圧降下計算を行う，という方法が Forward Sweep である。また逆に，すべての木の葉(leaf)を出発点として木の根まで逐次訪問しながらキルヒホッフの電流則による電流加算を行う，という方法が Backward Sweep である。Backward/Forward 法は，この二種類の線形 Sweep を非線形回路に適用した方法であり，次に示す反復処理フローとして実行される。

① すべてのノードにおける電圧($\dot{V}$)の仮定(flat start)

② 収束条件が満足されるまで以下の処理を繰り返す

a) すべてのノードにおける等価注入電流の設定

$\dot{I}_i = (\dot{S}_i / \dot{V}_i)^* - j y_{ci} \dot{V}_i$　(i=$1...n$)　(y_{ci} : *susceptance at node*$_i$)

b) Backward　Sweep による全ノードにおける注入電流の加算とブランチ電流の設定

$\dot{I}_{sr} = \dot{I}_r$　(s: *sending end node*, r: *receiving end node*)

$\dot{I}_s = \dot{I}_s + \dot{I}_r$

c) Forward　Sweep によるすべてのノードにおける電圧降下計算

$\dot{V}_r = \dot{V}_s - \dot{Z}_{sr} \dot{I}_{sr}$　(s: *sending end node*, r: *receiving end node*)

d) すべてのノードにおける電圧増分計算と収束判定

$\| \dot{V}_i - \dot{V}_{iold} \| < \varepsilon$　(i=$1...n$, $i \neq root$)

上記の方法は，Backward Sweep の過程で下流から上流へ電流の積み上げを行うので，Backward/Forward 法の分類としては電流積み上げ法(Current Summation method)と呼ばれている。これに対し，電力流の積み上げを行う電力積み上げ法(Power Summation method)は，次に示す反復処理フローとして実行される。電力積み上げ法の特徴は，ブランチにおける電力ロスを考慮する点であり，これにより電流積み上げ法よりも収束性が改善され

る(後述)。

① すべてのノードにおける電圧($\dot{V}$)の仮定(flat start)

② 収束条件が満足されるまで以下の処理を繰り返す

a) すべてのノードにおける等価注入電力の設定

$\dot{P}_i = \dot{S}_i - \dot{V}_i (j y_{ci} \dot{V}_i)^*$ （$i=1...n$）（y_{ci} : *susceptance at node*$_i$）

b) BackwardSweep による全ノードにおける注入電力の加算とブランチ電流の設定

$\dot{I}_{sr} = (\dot{P}_r / \dot{V}_r)^*$ （*s*: *sending end node, r*: *receiving end node*)

$\dot{P}_s = \dot{P}_s + \dot{P}_r + |\dot{I}_{sr}|^2 \dot{Z}_{sr}$ （右辺第３項は電力ロス）

c) ForwardSweep によるすべてのノードにおける電圧降下計算

$\dot{V}_r = \dot{V}_s - \dot{Z}_{sr} \dot{I}_{sr}$ （*s*: *sending end node, r*: *receiving end node*)

d) すべてのノードにおける電圧増分計算と収束判定

$\| \dot{V}_i - \dot{V}_{iold} \| < \varepsilon$ （$i=1...n, i \neq root$）

ここで，Backward/Forward Sweep を行うブランチ順番を決定する方法には，グラフ探索の手法を用いる。グラフ探索の手法には，分岐を優先する幅優先探索(BFS:Breadth First Search)と連結を優先する深さ優先探索(DFS:Depth First Search)の二種がある。この手法を適用するに当たり，以下の方法が考えられる。

A) Backward/Forward Sweep を行う度に，グラフ探索を行う。

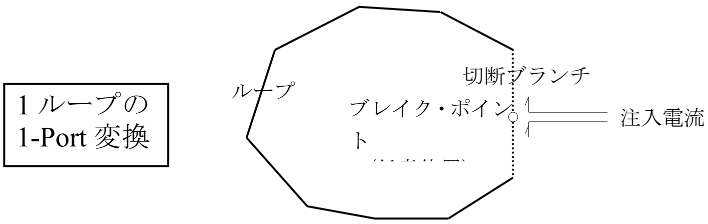
B) 最初に一回グラフ探索を行い，その結果得られるブランチ訪問の順番を格納し，Backward/Forward Sweep の際には，訪問の順番通り，または逆順通りに処理する。

ここでの数値実験では, A)の方法はグラフ探索に要するオーバーヘッドにより計算時間がかなり増大したので，大規模系統では B)の方法を推奨する。特に，系統を無向グラフ(Undirected Graph)として表現するとブランチ数が２倍となるので, その半数のサイズである有向ブランチの訪問順番配列を使用する方にメリットがある。なお, 無向グラフを使用する利点は，複雑な(ループのある)大規模ネットワークになると，中間ブランチ流の向きが不明確となることによるブランチ始点・終点データの入力ミスを防げることにある(有向グラフでは正しい向きを入力しないと到達性が失われる)。特に，複数の配電変電所からのマルチフィーダ系統をスイッチ切替えでラディアル運用している場合には, スイッチの状態による中間ブランチ流の向きの不明確さは顕著となるであろう。

また，BFS と DFS の違いについては，Backward/Forward Sweep に要する計算時間の差異はみられなかったが, グラフ探索そのものに要する時間が大規模系統では, 短い時間ではあるが，DFS の方が数倍～数十倍高速であった。ただし，次に述べるループ構造を有する系統では，ループの発見に BFS と DFS では異なる結果となるので, Backward/Forward Sweep の収束性能に違いが現れる。

３.３ ループ構造を有する系統に対する Backward/Forward 法

ここでは，ループ構造を有する系統をループのない放射状系統に変換して，前述の Backward/Forward 法を適用する Multi-Port Compensation 法[14, 18]に基づいた手法を提案する。Multi-Port Compensation 法は，まず「ループを構成するブランチ群の一つをブレイク・ポイントで切断することにより放射状系統に変換し」,「その潮流計算の結果得られるブレイク・ポイントでの電圧不整合を解消するために当該点における複素電流注入で補充を行う」という考えに基づいている。ループが複数あれば，ブレイク・ポイントもループ数分設け(Multi-Port 変換)，電流注入の補充も同数回考慮する。補充する注入電流量は，線形回路におけるテブナンの定理(Thevenin’s Theorem) を用いて感度行列(Sensitivity matrix)を用意することで求められる。



提案解法では，ループの発見とブレイク・ポイントを設ける切断ブランチの設定は，グラフ理論におけるサイクル発見法を用いて前述したグラフ探索の最中に行う。発見されたループの最後のブランチを切断ブランチとし，このブランチをオープンに設定する。グラフ探索の最中には，各探索ノードに流入接続する唯一のブランチ情報も保存しておき，各ノードからルートへパスを追跡できるようにしておく。この逆向きパスを利用して，ループ数 K のループ・インピーダンスによる感度行列 $\mathbf{Z} = (Z_{ij})$が以下のように作成される。

① 自己インピーダンス: $Z_{ii} = \sum_{l \in S_i} z_l$ *for* $loop_i$ $(i=1...K)$

② 互インピーダンス： $Z_{ij} = \sum_{l \in M_{ij}} z_l \, sign(l)$ *for* $loop_i$ & $loop_j$ $(i,j=1...K, i \neq j)$

ここで，z_l は下記の集合に属するブランチ$_l$ のインピーダンスを示す。

- $S_i = (P_i^+ \cup P_i^-) - (P_i^+ \cap P_i^-) + B_i$
- $M_{ij} = (P_i^+ \cap P_j^+) \cup (P_i^- \cap P_j^-)$ $(sign(l)=+1)$
  $\cup (P_i^+ \cap P_j^-) \cup (P_i^- \cap P_j^+)$ $(sign(l)=-1)$
- B_i ：ループ$_i$ の切断ブランチ
- P_i^+ ：切断ブランチ$_i$ の 1 端点からルートへのパス*(positive path)*を構成するブランチ集合
- P_i^- ：切断ブランチ$_i$ の他端点からルートへのパス*(negative path)*を構成するブランチ集合

この感度行列を利用して，ブレイク・ポイントにおける補充注入電流量の増分は次の連立一次法方程式を解くことで求められる。

$$\mathbf{Z}\,[\dot{I}_d] = [\dot{V}_d]$$

ここで，$[\dot{V}_d]$ はすべてのブレイク・ポイントにおける電圧不整合値ベクトル(切断ブランチ両端の電圧差－切断ブランチにおける電圧降下)，$[\dot{I}_d]$ はすべてのブレイク・ポイントにおける補充注入電流量の増分ベクトルであり，該当する切断ブランチに流れる複素電流として累計される。なお，この方程式のサイズは $2K$ である。

Multi-Port Compensation 法に基づく提案解法では，各反復過程において，上式から求められた切断ブランチの電流をその両端ノードにおける補充注入電力(一方は流入，他方は流出)に公式 $\dot{S} = \dot{V}\,(\dot{I})^*$ で変換し，これを両端ノードにおける元々の注入電力量に加えて，次回の反復に使用する，という処理を行う。

したがって，アルゴリズム上では，Backward/Forward 法の処理枠組みに大きな変化はなく，ループの発見と切断ブランチの設定，感度行列の作成および補充量の計算・加算ルーチンを追加するのみで良い。

３.４ PV 母線を有する系統に対する Backward/Forward 法

Backward/Forward 法に PV母線を導入する試みは，文献[14]で最初になされ，その後 PV 母線の処理にも前述した感度行列を利用するという方式に改良された[18]。さらに，この方法は，収束性の改善という面での進展[25, 35]が見受けられる。

本稿では，文献[18, 35]に基づき，これに若干の修正を行った手法を提案する。Multi-Port Compensation 法にもとづく PV母線処理の基本的アイデアは，各 PV母線とルートノード間に系統に連結しない仮想ブランチ(**Fictitious** branch)を設け，この結果生じる仮想ループ構造に対し前述したループ処理と同じ方法で感度行列を作成する，という点である。PV 母線処理とループ処理との違いは，仮想ブランチにブレイク・ポイントは設けず，その代わりに，PV母線における指定電圧制御のためにその PV母線への無効電力の補充機能を仮想ブランチに付与する，ということにある。すなわち，仮想ブランチは Shunt Capacitor としての役目を担うこととなる。

PV 母線では P, $|\dot{V}|$ 値の指定があるので，前記複素電圧不整合値ベクトルの算定に当たっては，PV 母線における電圧値と指定値との差の実数部のみを使用し，感度行列の作成では，電圧不整合値の虚数部に関する行と P に関与する変数(補充注入電流量の実数部)は除く。したがって，感度行列のサイズは，ループ数を K，PV 母線数を p とすると $2K+p$ となる。これに応じて，感度行列の不要部分を取り除き，行列操作を容易にするために，行と列の並び替え，および補充注入電流量の符号変換を行うと，感度行列の形式は以下のように変換される。

$$\begin{pmatrix} X & R \\ -R & X \end{pmatrix}\begin{pmatrix} -I_i \\ +I_r \end{pmatrix} = \begin{pmatrix} V_r \\ V_i \end{pmatrix} \qquad \boxed{\begin{array}{l} \dot{Z} = R + jX \\ \dot{V} = V_r + jV_i \;\; \dot{I} = I_r + jI_i \end{array}}$$

ここで，左辺行列は変換された感度行列($dim X=K+p, dim R=K$)，左辺ベクトルはすべてのループ・ブレイクポイントとPV母線における補充注入電流量の増分ベクトル，右辺定数項ベクトルは同位置の電圧不整合値ベクトルである。

PV母線における電圧不整合値として，$(|\dot{V}|_{sp}/|\dot{V}|-1)Re(\dot{V})$の改定算定式を使用する[35]。ここで，$\dot{V}$ は Backward/Forward 法の反復過程で得られている PV母線の複素電圧，$|\dot{V}|_{sp}$は当該 PV母線における電圧指定値である。また，上記連立一次方程式より得られる補充注入電流量の増分I_iを用いて，PV母線への無効電力の補充量の増分は $I_i|\dot{V}|^2/Re(\dot{V})$と算定される[35]ので，これを当該仮想ブランチの提供無効電力に加算する。その累計値は，Backward/ Forward 法の次回反復で利用されるよう，当該PV母線における注入無効電力量として設定される。

提案解法では，上記補充量を求めた後，収束の安定性を目的として，各 PV母線の複素電圧$\dot{V}$ を$|\dot{V}|_{sp}$に正規化する処理を追加している。

以上が Multi-Port Compensation 法に基づく PV母線の処理概要であり，原理的にはループ処理と同一であることを示した。したがって，アルゴリズム上では，Backward/Forward 法の処理枠組みに大きな変化はなく，仮想ブランチの 作 成，PV母線を考慮した感度行列の作成および補充量の計算・加算ルーチンを追加するのみで良い。

４．大規模・放射状配電系統の潮流シミュレーション

提案解法を用いて開発したBackward/Forward法とNewton-Raphson法による潮流計算プログラムの性能を確認するために，数値実験を行ったので，以下にその内容を述べる。ここでは放射状配電系統でのシミュレーションについて述べ，ループ構造およびPV母線を有する配電系統でのシミュレーションについては，次節で述べる。なお，開発プログラムはC 言語と C++言語で作成されている。

４.１ シミュレーション用のモデル作成

ループのない仮想的大規模配電系統(Radial Distribution network)を，木構造を有する有向グラフとしてランダムに発生させて，数値実験に使用する。この木の根をスラックバスとし，木の葉を負荷ノード(PQ 指定ノード)，残りは中間通過・分岐点(指定値零 の PQ ノード)とする。負荷ノードのPQ値は範囲P[0.1,1.0], Q[0.0,0.05]からランダムに発生させた。ブランチ属性についてもランダム値を発生させ，抵抗は範囲 R[0.01,0.05]，リアクタンスには対抵抗比 R/X[1.0,10.0]を使用した。ブランチとノードに関与する他の Susceptance 分(Shunt Capacitor)は無視する。スラックバスの電圧位相角は零とし，電圧値については，

暫定推定値としてＰ値総和とＲ値総和の関数として経験的に設定した。但し，その適正な値は評価・算定していないので，この暫定推定値を用いた潮流計算の結果により以下のように補正を行う。

①潮流計算が収束しなければ，電圧崩壊が生じていると判断し，スラックバスの推定電圧値を大きくする。

②潮流計算が収束しノードの電圧位相角がすべて零に近ければ，高圧すぎるスラックバスの推定電圧値を小さくする。

なお，数値実験に使用したブランチ属性の R/X 比は，いわゆる Ill-conditioned と称されている値の範囲(3～5 以上)にあり，Newton-Raphson 法の系列では収束しないことが多いと言われている。

４.２ シミュレーション結果

ノード数 n=500,1000,2000,5000,10000,20000,30000,40000,50000，ブランチ数 n-1 の大規模配電系統を，ランダムに発生させて数値実験を行った。Newton-Raphson 法，Backward/Forward 法ともフラットスタートとし，収束条件は，極座標による Newton-Raphson 法では，PQ 値のミスマッチによる収束誤差として 10^{-4}，直交座標による Backward/Forward 法では，全負荷ノードにおける複素電圧成分の収束増分誤差として 10^{-6}，を与えた。

数値実験の結果を表 1 に示す。すべてのケースにおいて，Backward/Forward 法では解が得られたが，Newton-Raphson 法では n=50000 のケースにおいて，メモリ不足により解が得られなかった。このケースを除き，得られた電圧値の目視比較により，両解法とも許容範囲内でほぼ同一解を与えているものと判断される(実配電系統では潮流多根は存在しないことを証明した論文あり [17])。但し，ノード数が膨大なので完全な照合は行っていない。なお，研究会で報告された 126 母線系統の実行結果では，両解法による電圧分布(電圧値，位相角：単位-度)は少数点以下 4 桁まで完全に一致していた。 数値実験に使用した PC は, Dell Precision T1500(Intel Core i7, 64bit OS, 2.80GHz, 物理メモリ 16GB)である。

表１　大規模配電系統での数値実験の結果

ノード (n)	負荷ノード	スラック電圧	反復回数		最終誤差		実行時間(s)		速度比
			N/R	B/F	N/R	B/F	N/R	B/F	
500	240	5.00	5	12	2.619e-6	5.888e-7	0.031	0.016	1.94
1000	483	10.00	5	14	9.683e-5	7.246e-7	0.062	0.031	2.00
2000	1012	20.00	4	6	1.274e-6	3.812e-7	0.203	0.016	12.69
5000	2510	20.00	6	19	1.985e-7	5.763e-7	1.856	0.031	59.87
10000	5125	30.00	5	8	3.392e-10	4.554e-7	6.147	0.047	130.8
20000	10387	40.00	6	13	3.201e-10	6.207e-7	29.312	0.046	637.2
30000	15920	40.00	6	13	2.474e-10	3.497e-7	65.848	0.093	708.0
40000	21142	50.00	6	16	1.756e-8	5.346e-7	116.610	0.109	1069.8
50000	27346	50.00	—	19	—	5.062e-7	—	0.234	—

注）Backward/Forward 法では，グラフ探索に DFS を使用。
　ただし，DFS による実行時間は上表には含まれていない。

なお，表１に示す結果は，研究会で報告した結果とは以下の点で異なっているので，注意されたい。

① ネットワーク構造の汎用性を高めるため，Backward/Forward 法のプログラムを全面的に改訂した(プログラム名：DnetFlow)。そのためのオーバーヘッドにより，速度性能が劣化した面がある。改訂では，無向グラフの採用，マルチフィーダ系統の考慮，ノード番号からノード名称への変更，孤立ノード群の発見と警告終了，などを取り入れた。

② Backward/Forward 法では，電流積上げ法から電力積上げ法への改訂を行った。

③ Backward/Forward 法では，グラフ探索に DFS と BFS の両方を実装した。

また，下図は，表１に示した結果の中からノード数 n=2000,20000,50000 の場合をピックアップして，Backward/Forward 法における収束状況を図示したものである。横軸が反復回数，縦軸が複素電圧成分の収束増分誤差を示している。同図より，Backward/Forward 法が，ノード数に関係なく多次凸関数的な収束形状を呈していることがわかる。

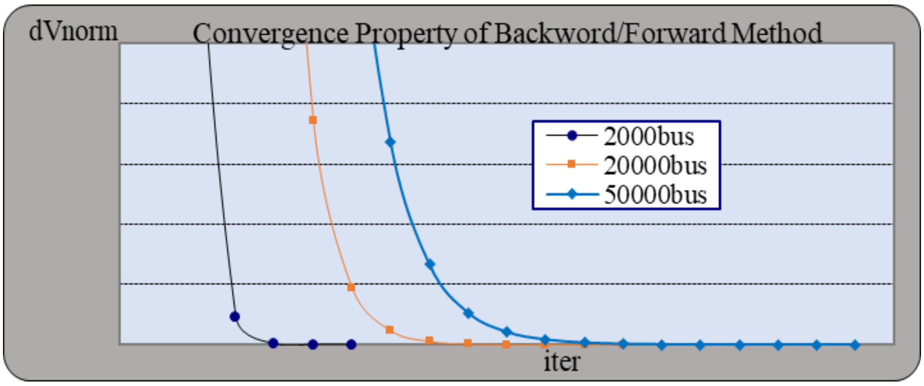


図１　Backward/Forward 法における多次凸関数的な収束形状

４.３ シミュレーションのまとめ

数値実験を行う前の筆者の予想は，「Backward/Forward 法は一回の反復に要する時間は少ないが，反復回数が増大する傾向にある。したがって，トータルでみると，Newton-Raphson 法よりも最良で数倍程度は速くなるであろう。」というものであった。しかしながら，数値実験の結果は，この予想を大幅に上回り，ノード数が多くなるにつれて速度比(表１)が大きく増大する(数万ノードで 100 倍以上)という傾向を示した。

この結果を踏まえ，大規模配電系統には Backward/Forward 法が適していると判定したい。特に，配電系統の再構成問題等では，膨大な回数の潮流計算を要するので，シンプルかつ高速な Backward/Forward 法の採用が成功の鍵とも言えるであろう。

５．Backward/Forward 法による潮流シミュレーションの補足

５.１ 電力積上げ法と電流積上げ法との比較

Backward/Forward 法における電流積み上げ法(Current Summation method)と電力積み上げ法(Power Summation method)による収束性能を比較するため，４.２で使用した大規模配電系統モデルでの数値実験を行った。表２にその結果を示す。数値実験に使用した PC は，Dell Optiplex GX745（Celeron(R) D CPU 3.06GHz，物理メモリ 2.99GB）である。

表２ 大規模配電系統での数値実験による比較結果

ノード (n)	負荷ノード	スラック電圧	反復回数		最終誤差		実行時間(sec)		速度比
			B/F(P)	B/F(C)	B/F(P)	B/F(C)	B/F(P)	B/F(C)	(P)/(C)
500	240	5.00	12	15	5.888e-7	4.595e-7	0.031	0.047	0.66
1000	483	10.00	14	18	7.246e-7	5.226e-7	0.032	0.063	0.51
2000	1012	20.00	6	7	3.812e-7	2.872e-7	0.031	0.032	0.97
5000	2510	20.00	19	23	5.763e-7	5.649e-7	0.110	0.141	0.78
10000	5125	30.00	8	9	4.554e-7	9.374e-7	0.078	0.094	0.83
20000	10387	40.00	13	17	6.207e-7	4.604e-7	0.218	0.297	0.73
30000	15920	40.00	13	16	3.497e-7	7.524e-7	0.312	0.406	0.77
40000	21142	50.00	16	20	5.346e-7	7.147e-7	0.515	0.672	0.77
50000	27346	50.00	19	25	5.062e-7	9.491e-7	0.703	1.016	0.69

（P)電力積上げ法，（C)電流積上げ法

この結果より，電力積み上げ法の方が電流積み上げ法よりも，反復回数と実行時間において優れていることが実証された。

５.２ 弱ループ構造とPV母線を有する系統でのシミュレーション

Multi-Port Compensation 法に基づく提案 Backward/Forward 法の性能を確かめるために，研究会で報告された 126 母線系統で数値実験を行った。この系統に，ループを構成することになるブランチを３本，PV ノードを３個まで追加し，それぞれの組合せに対して潮流計算を行った。ループ・ブランチの候補は，①20-98，②107-122，③42-65 とし，PVノードの候補は A：30，B：77，C：124 とした。すべてのループ・ブランチの属性は r＝0.001,x=0.001 とし，また全PVノードの P,V 値はそれぞれ 1.0 とする。

数値実験での検討ケースは以下の 14 通りである。

ケース０　：　テスト用配電系統
ケース１　：　ループ①を追加
ケース２　：　ループ①②を追加
ケース３　：　ループ①②③を追加
ケース A　：　PVノード A を設定
ケース B　：　PVノード B を設定
ケース C　：　PVノード C を設定
ケース AB　：　PVノード A,B を設定
ケース AC　：　PVノード A,C を設定
ケース BC　：　PVノード B,C を設定
ケース ABC　：　PVノード A,B,C を設定
ケース ABC1　：　PVノード A,B,C を設定し，ループ①を追加
ケース ABC2　：　PVノード A,B,C を設定し，ループ①②を追加
ケース ABC3　：　PVノード A,B,C を設定し，ループ①②③を追加

数値実験の結果を表３に示す。得られた電圧分布は，すべてのケースにおいて Newton/Raphson 法の結果と一致していた。同表に示す反復回数の結果より，Multi-Port

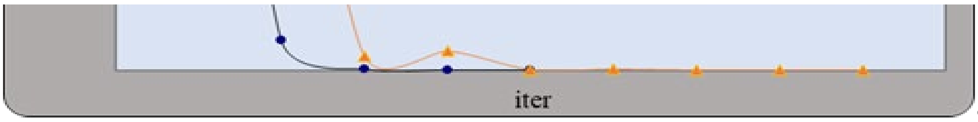
Compensation 法が安定した収束特性を有していることがわかる。また，ループの追加または PV ノードの設定により収束性能が劣化し，その劣化度はループの追加よりも PV ノードの設定の方が大きいことも読み取れる。但し，一例による数値実験であるので，Multi-Port Compensation 法の収束特性に関する結論的見解は控えておく。大規模系統でのさらなる検証が必要であろう。また，原論文[14]では，その手法の収束特性がループの個数と PV ノード数に依存すると記してあるが，今回の数値実験ではそのことを裏付ける顕著な傾向は得られなかった点にも留意する必要がある。

なお，提案 Backward/Forward 法では，電力積み上げ法によるフラットスタート(PVノード除く)を採用し，収束条件として，全負荷ノードにおける複素電圧成分(直交座標)の増分誤差として 10^{-6}，を与えた。数値実験に使用した PC は，Dell Optiplex GX745(Celeron(R) D CPU 3.06GHz，物理メモリ2.99GB)である。

また，下図は，検討ケースのうち，ケース 0 とケース ABC3 について，提案 Backward/Forward 法による収束状況を図示したものである。同図は，ループ構造と PVノードが同時に導入されると，収束形状に部分的不規則性が現れることを示している。但し，ループ構造のみでは不規則性は現れず，PVノード A が関与するケースではすべて不規則性が現れているので，PV ノードの系統内位置が収束性に悪影響を与えることがあると判断できる。

表３ 126 母線配電系統での数値実験の結果

ケース	反復回数	最終誤差 (dV)	PQ mismatch	実行時間 (sec)
0	5	1.340e-7	3.276e-8	0.016
1	5	8.267e-7	3.388e-5	0.015
2	5	8.845e-7	2.114e-5	0.015
3	6	5.068e-8	6.539e-6	0.015
A	9	1.254e-7	9.363e-7	0.015
B	7	8.364e-7	8.508e-7	0.032
C	6	8.187e-7	7.162e-7	0.016
AB	9	1.749e-7	1.372e-6	0.031
AC	9	1.604e-7	1.267e-6	0.031
BC	8	8.497e-7	6.552e-7	0.016
ABC	9	1.867e-7	1.363e-6	0.031
ABC1	9	1.740e-7	1.850e-5	0.031
ABC2	9	1.705e-7	2.217e-5	0.016
ABC3	9	1.650e-7	2.330e-5	0.031

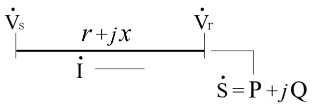


or

ward 法による収束状況

５．３　Backward/Forward 法の収束性について

一般に，電力潮流方程式は，系統がその最大可能負荷点(Maximum Loading Point)を超えると解が存在しない。また，最大可能負荷点に近い重負荷状態となると，数値解法による収束性能が劣化することが知られている。この現象は，Newton-Raphson 法による非線形方程式の解法が，重根解を求める際にヤコビアンの数値的不安定性より振動が生じやすくなる現象と似ている。このことを説明するために，潮流方程式ではPVカーブを用いることが多いので，参考として，下図に示す１ブランチの潮流方程式の解析解とそれによるPVカーブによる図解を示しておく。



交流回路の基本式より，次式が成立する。

$$\dot{I} = (\dot{S}/\dot{V}_r)^*,\ \dot{V}_s = \dot{V}_r + (r+jx)\dot{I}$$

上記両式より，次式が導かれる。

$$\dot{V}_s\dot{V}_r^* = V_r^2 + (rP+xQ) + j(xP-rQ),\quad \text{ここで } V_r^2 = \dot{V}_r\dot{V}_r^*$$

$$Re(\dot{V}_s\dot{V}_r^*) = V_r^2 + (rP+xQ)$$

$$Im(\dot{V}_s\dot{V}_r^*) = xP-rQ$$

上記第２，３式の２乗和をとることにより，次式が得られる。

$$V_s^2V_r^2 = V_r^4 + 2(rP+xQ)V_r^2 + (r^2+x^2)(P^2+Q^2)$$

結局，電力潮流方程式の解析解を与える次の重二次方程式(Biquadratic equation)が得られた。

$$V_r^4 - [V_s^2 - 2(rP + xQ)]V_r^2 + (r^2 + x^2)(P^2 + Q^2) = 0$$

この周知の重二次方程式を解くことにより，終点負荷が与えられた場合における始点電圧に対応する終点電圧を求めることができる。

この方程式において，V_s と Q を固定して V_r と P の関係を示したのが，下図に示す PVカーブである。同図より，V_r の解は通常２個存在し，最大可能負荷点で重根となる。但し，「実配電系統の通常運用では低め解は零に近く，解としては無視できるので多根は生じないと捉えることができる」という主張もある[17]。

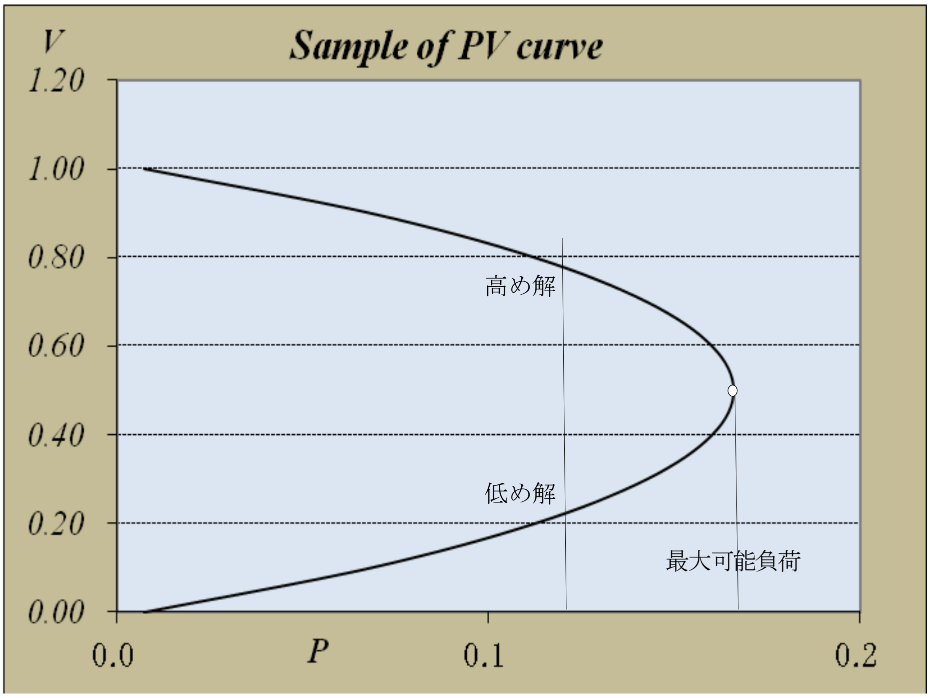
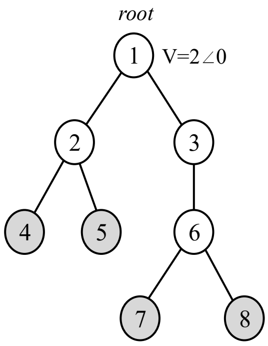


図 3　Vr の解の最大可能負荷点で重根

同様に，V_s と P を固定した V_r と Q の関係も，上図に似た QVカーブとして定義できる。PVカーブと QVカーブの特徴から言えることは，終点負荷 P または Q が小さくなると終点電圧値(高め解)が高くなることである。この事実は，電圧制御のための無効電力補償の原則として活用されている。なお，最大可能負荷点となる条件は，二次方程式 ax^2+bx+c の重根条件 $b^2-4ac=0$ より導かれるので，この左辺値(実行可能解が存在する非負値の場合)を電圧安定性の指標値として利用できる[46]。また，同条件より，所与の V_s と P,Q に対して，電圧崩壊がおこる最大負荷率(Maximum Load Factor)を算定することも可能である[46]。

以上，重負荷状態となると電力潮流方程式の数値解法による収束性能が劣化すること

とその理由について述べた。Backward/Forward 法も例外ではなく，収束性能の劣化が Newton -Raphson 法よりも顕著に現れるようである。この傾向を実際に把握するために，以下に示す簡単な８母線放射状系統で数値実験を行った。



データ

s	t	r	x	Pt	Qt
1	2	0.20	0.40	0.0	0.0
1	3	0.10	0.20	0.0	0.0
2	4	0.15	0.30	-0.6	-0.3
2	5	0.10	0.20	-0.6	-0.3
3	6	0.20	0.40	0.0	0.0
6	7	0.15	0.30	-0.6	-0.3
6	8	0.10	0.20	-0.6	-0.3

この８母線系統は重負荷状態にあり，負荷率(Load Factor)1.02 では解が存在しない。

下図は，この８母線系統で負荷率を 1.0 から 0.9,0.8,0.6 と減少させて，Backward/Forward 法で解いた場合の反復回数と複素電圧成分の増分誤差との関係を示している。

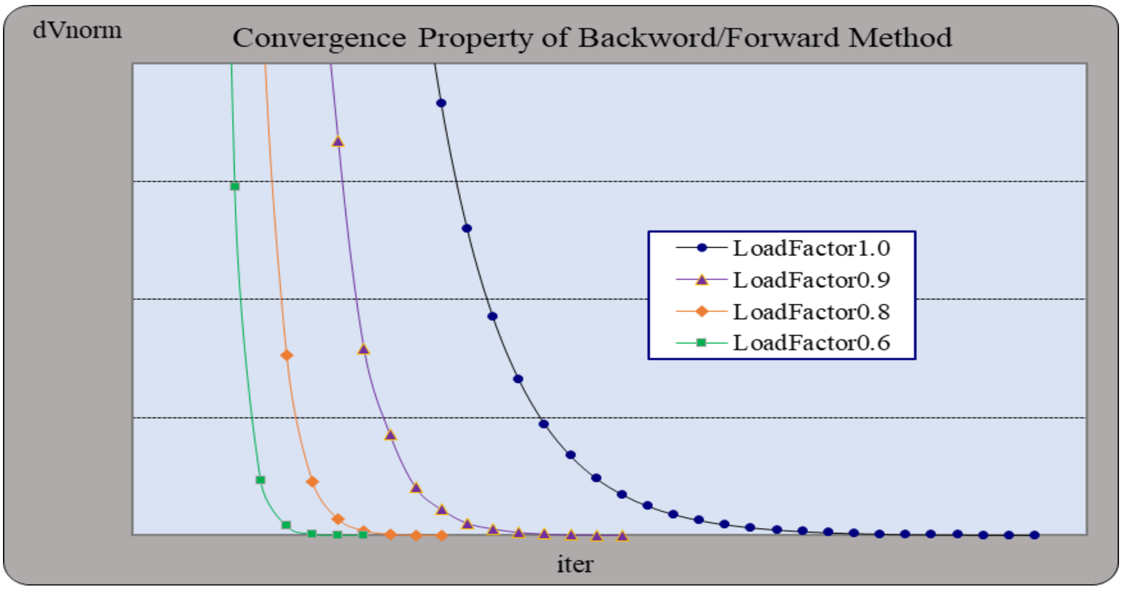


図４　重負荷状態になるにつれての収束性能が劣化状況

同図は，負荷率 0.6,0.8,0.9,1.0 の増大に応じて，反復回数がそれぞれ 9,12,19,35 と増加したことを示しており，(電力積み上げ法による)Backward/Forward 法では重負荷状態になるにつれて収束性能が劣化していくこと，を実証するものである。また，Backward/Forward

法の収束性能が必ずしも系統規模に依存するものではない，すなわち小規模系統の方がより少ない反復回数で収束する訳ではないことも示唆している。なお, 同系統での Newton -Raphson 法による反復回数は，負荷率 0.6,0.8,0.9,1.0 の増大に応じて反復回数がそれぞれ 5,5,6,7 と増加したが，Backward/Forward 法ほどの伸び率ではない。

６．まとめと今後の課題

本稿では, 電力潮流計算手法の基本検討を行い, その代表的解法である Newton-Raphson 法と Backward/Forward 法の実装とノード数 500～50000 の大規模配電系統での数値実験と性能比較を行った。その結果，ループ構造と PV母線のない数万ノード数の大規模配電系統では Backward/Forward 法の方が，Newton-Raphson 法よりも 100 倍以上高速であることが実証された。この高速性は，大規模化する配電系統での潮流計算とその計画・運用問題に Backward/Forward 法が大いに有効であることを示している。この利点を生かすために，ループ運用がなされる，あるいは分散電源が導入された配電系統へ Backward/Forward 法を適用可能とするために, ループ構造と PV母線を取り扱い可能な Multi-Port Compensation 法への機能拡張も行った。126 母線テスト系統における数値実験で Multi-Port Compensation 法は良好な収束性能を示したので，同手法の活用が今後期待できる。

残された課題としては，今回開発した Multi-Port Compensation による Backward/Forward 法を，①各種の負荷モデル(ZIP モデルや電圧依存型負荷モデル)およびその混合モデルを取り扱い可能とすること，②電圧制御装置(変圧器, SVR, SVC など)を考慮できるようにすること，③３相不平衡系統へ適用可能とすること，を挙げておく。

以上

７．代表的参考文献（年次順）

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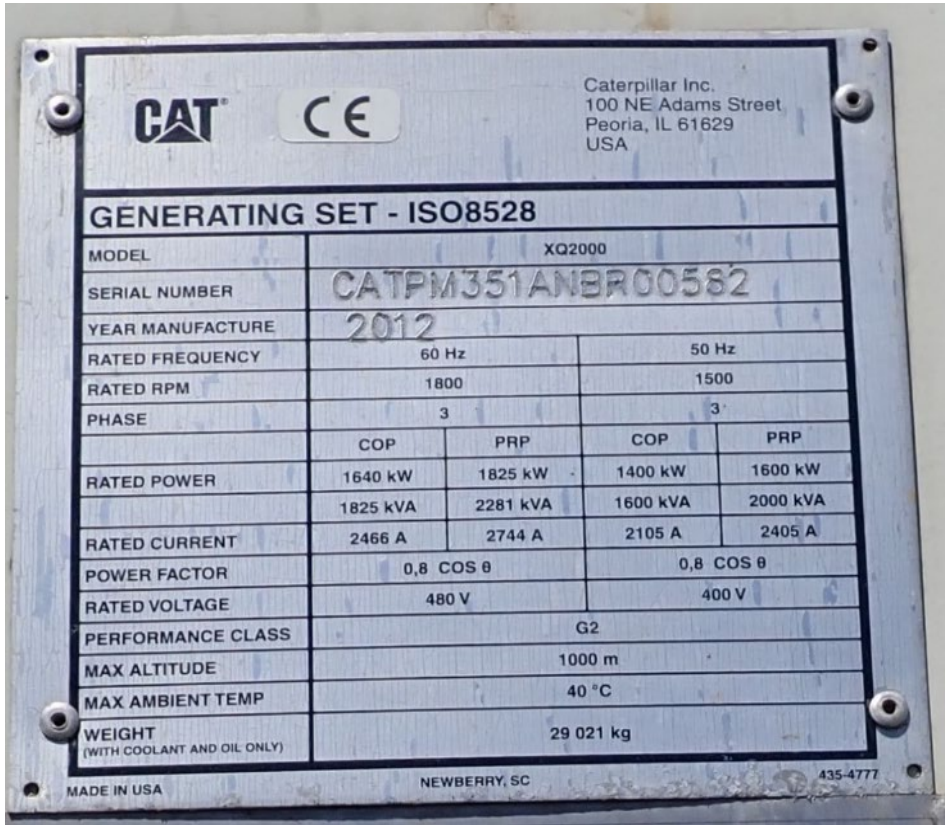
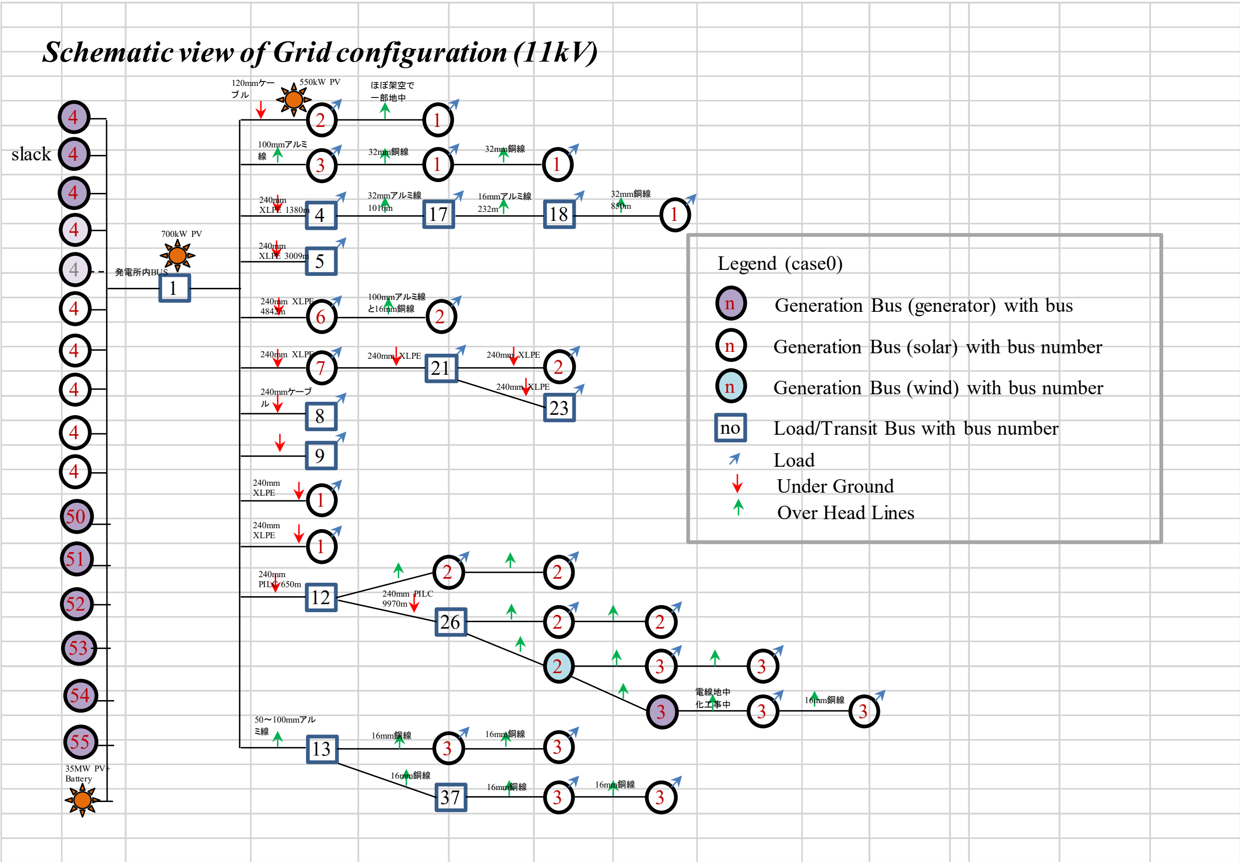
11. 付録 D：CATAPLLER 製発電機データ(現地にて収集、2019 年)

項目	仕様	出展	
台数	6台 （CAT1, CAT2, CAT3, CAT4, CAT5, CAT6）	現地調査にてヒアリング	
型式	Caterpiller製 XQ2000	銘板写真	
定格周波数	60Hz	https://www.cat.com/ja_JP/products/new/power-systems/electric-power/diesel-generator-sets/1000028912.html	
Max MW	1,650 ekW	https://www.cat.com/ja_JP/products/new/power-systems/electric-power/diesel-generator-sets/1000028912.html	
min MW	412.5 ekW(少なくとも25%Loadは可能。それ以下は要調査)	https://s7d2.scene7.com/is/content/Caterpillar/CM20170906-19537-54584	
Rated MW	1,650～2,500ekW （セントキッツでは定格1,650kW）	https://www.cat.com/ja_JP/products/new/power-systems/electric-power/diesel-generator-sets/1000028912.html	
ランプレート	後報		
コスト係数	10729 BTUs/kWh	Historical DataのHeat Rate平均値	
			Kwh/IG
コスト係数計算表			
計測月	計測対象	Heat Rate (Btus / KWh)	Fuel Consumption (kWh/Imperial gallon)
Aug-18	CAT3	10497.5	16.0
Aug-18	CAT4	9601.1	17.5
Sep-18	CAT3	10502.9	16.0
Sep-18	CAT4	9599.7	17.5
Oct-18	CAT1	9602.3	17.5
Oct-18	CAT2	10499.9	16.0
Oct-18	CAT3	10502.8	16.0
Oct-18	CAT4	9601.9	17.5
Nov-18	CAT2	10498.1	16.0
Nov-18	CAT3	10501.3	16.0
Nov-18	CAT4	9602.1	17.5
Dec-18	CAT2	10500.6	16.0
Dec-18	CAT3	10501.7	16.0
Dec-18	CAT4	9597.9	17.5
Jan-19	CAT2	10502.6	16.0
Jan-19	CAT3	10496.8	16.0
Jan-19	CAT4	9598.0	17.5
Feb-19	CAT2	10501.1	16.0
Feb-19	CAT3	10498.9	16.0
Feb-19	CAT4	9599.7	17.5
Mar-19	CAT2	10497.4	16.0
Mar-19	CAT3	10502.0	16.0
Mar-19	CAT4	9602.3	17.5
Apr-19	CAT2	22061.3	
Apr-19	CAT3	10496.9	
Apr-19	CAT4	9597.7	
Average	CAT1	9602.3	17.5
	CAT2	12151.5	16.0
	CAT3	10500.1	16.0
	CAT4	9600.0	17.5
	All	**10598.6**	**16.6**

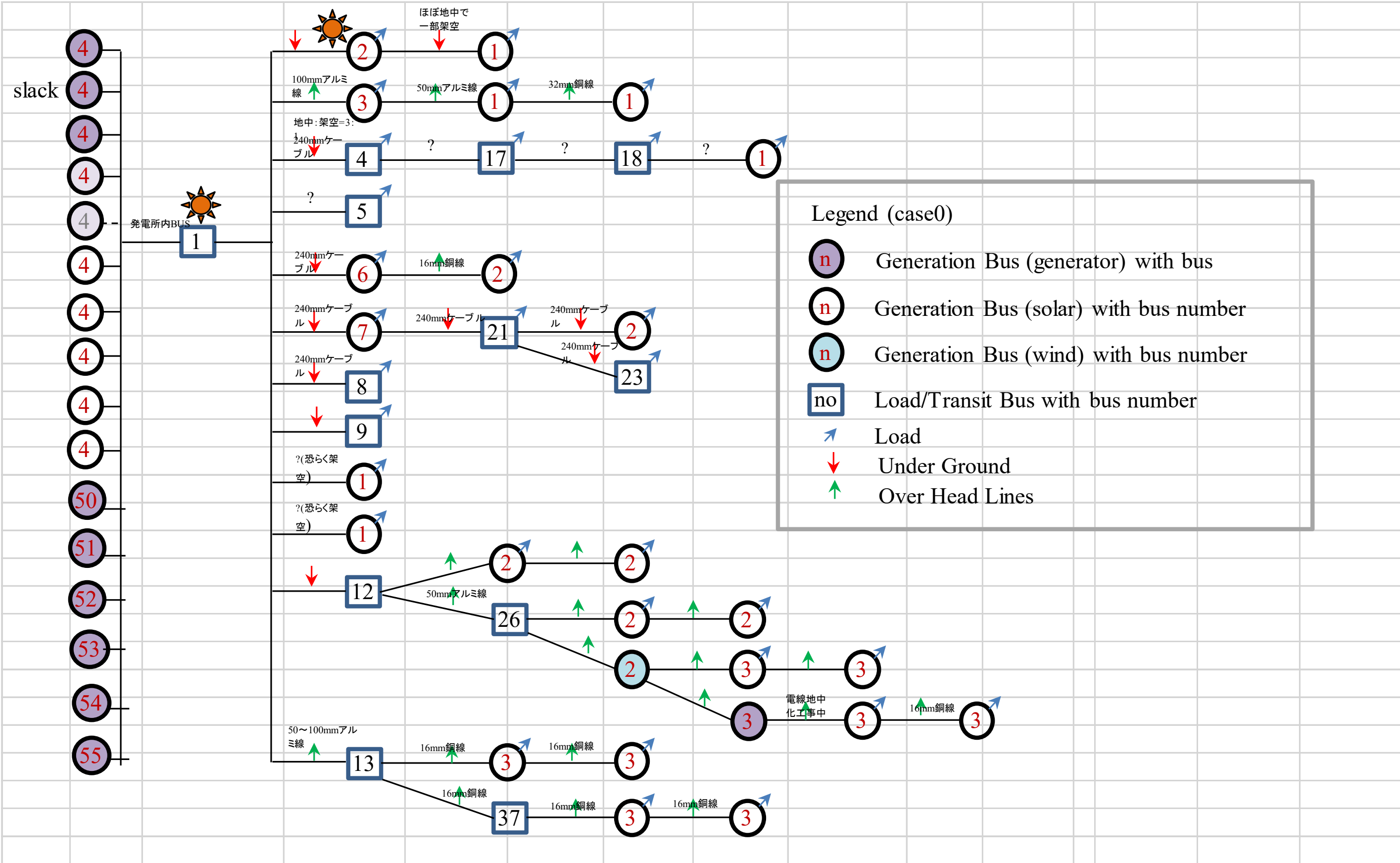

CAT
CE
Caterpillar Inc.
100 NE Adams Street
Peoria, IL 61629
USA
GENERATING SET - ISO8528
MODEL
XQ2000
SERIAL NUMBER
CATPM351ANBR00582
YEAR MANUFACTURE
2012
RATED FREQUENCY
60 Hz
50 Hz
RATED RPM
1800
1500
PHASE
3
3
COP
PRP
COP
PRP
RATED POWER
1640 kW
1825 kW
1400 kW
1600 kW
1825 kVA
2281 kVA
1600 kVA
2000 kVA
RATED CURRENT
2466 A
2744 A
2105 A
2405 A
POWER FACTOR
0,8 COS θ
0,8 COS θ
RATED VOLTAGE
480 V
400 V
PERFORMANCE CLASS
G2
MAX ALTITUDE
1000 m
MAX AMBIENT TEMP
40 °C
WEIGHT
(WITH COOLANT AND OIL ONLY)
29 021 kg
MADE IN USA
NEWBERRY, SC
435-4777


STATION LOAD
FEEDERS
ALL CHANNELS:G9DAQ1 - Google Chrome
192.168.30.171/cgi-bin/moni/allch.cgi
G9 Alt Winding B
82.1
G9 Mech Trip
0
G9 B-Gear Engage
0
G9 L.F.O. A/F Pr
1.63
G9 L.F.O. Tank L
92
G9 Dump Tank L
25
G9 Exh T Diff 1
-14.60
G9 Exh T Diff 2
-9.00
G9 Exh T Diff 3
-2.30
G9 Exh T Diff 4
19.60
G9 Exh T Diff 5
41.50
G9 Exh T Diff 6
17.20
G9 Exh T Diff 7
8.20
G9 Exh T Diff 8
-60.90

12. 付録 E:電線属性(現地にて収集、2019 年)



配電系統図 (rev1)


slack
発電所内BUS
ほぼ地中で一部架空
100mmアルミ線
50mmアルミ線
32mm銅線
地中：架空=3:1
240mmケーブル
16mm銅線
?(恐らく架空)
50mmアルミ線
電線地中化工事中
50～100mmアルミ線
Legend (case0)
Generation Bus (generator) with bus
Generation Bus (solar) with bus number
Generation Bus (wind) with bus number
Load/Transit Bus with bus number
Load
Under Ground
Over Head Lines

配電系統図（rev0)

13. 付録 F：2019 年における hourly loads_1 週間 x3 ケース分(現地にて収集、2019 年)

	Case 1: March							Case 2: April							Case 3: July						
	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	8-Mar	9-Mar	7-Apr	8-Apr	9-Apr	10-Apr	11-Apr	12-Apr	13-Apr	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul
	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday
1:00	18.3	17.2	17.1	16.8	17.4	17.8	18.6	18.2	18.1	17.8	17.5	17.7	18.5	18.7	20.4	22.1	20.9	21.5	20.3	20.8	20.8
2:00	18.3	17.2	16.4	16.6	17.2	17.2	18.2	17.9	17.4	17.3	17.1	17.7	18.3	18.1	20.4	21.1	21.1	20.9	20	20	20.4
3:00	17.1	16.6	16.4	16.5	17	16.8	17.2	17.2	17.3	17.4	16.8	17.1	17.5	17.5	19.9	19.9	20.3	20.1	19.6	19.8	20.3
4:00	16.9	16.6	16.5	16.3	16.6	16.9	17.2	17.4	17.3	16.9	16.7	17.5	17.3	17.4	19.2	19.7	20.3	20.3	19.3	19.8	20.2
5:00	16.5	17.4	16.6	16.7	17.5	17.2	17.2	17.2	17.4	16.8	17.9	17.7	18.3	17.7	19.2	20.3	20.1	21.3	19.5	19.8	19.5
6:00	17.3	18.2	18.3	17.9	18.7	17.9	17.3	16.5	17.6	16.7	16.6	17.5	18.3	16.6	18	20.1	20.3	20.7	19	19.2	18.9
7:00	16.9	20	19.9	19.8	19.4	19.2	17.3	16	18.9	18.3	18.3	19.9	20.1	17.1	18.4	21.5	21.5	21.3	20.7	20.6	19.3
8:00	17	20.7	21.2	22.7	21	22	18	18.9	20.9	19.4	20.1	20	21.4	18.7	19.6	24.1	25.1	23.1	22.9	25.1	21.5
9:00	17.6	22.4	22.5	23.3	23	22.8	19.9	19.7	23.1	21.9	22.1	22.7	23.4	21.1	20.8	25.1	26.1	27.2	24	25.1	22.8
10:00	18	23.3	22.7	21.1	23.6	23.4	21.5	20.3	23.9	23.3	23.4	24.2	24.4	21.8	20.7	27.1	27.2	27.5	26.4	26.1	23.5
11:00	18.1	23.2	23.4	21.7	23.2	23.9	21.1	20.1	23.3	23.3	23.9	24.6	24.8	22.3	21.4	27.1	27.6	28.1	26.5	27	23.9
12:00	18.5	24	23.3	22.3	24	23.7	21.2	20.3	23.9	23.9	23.9	24.2	23.7	22.2	21.5	27.2	27.6	27.6	26.7	26.9	24.2
13:00	18.6	23.7	23.2	23.5	23.8	23.3	21.2	21.5	24.1	24	23.9	24.4	24.6	21.8	21.5	27.2	27.8	28.3	26.3	26.7	24
14:00	18.8	24	23.6	23.7	23.4	23.2	21	20.3	24.1	23.3	24.3	24.3	24.8	21.8	21.8	27.2	27.9	28.6	26.4	26.7	23.8
15:00	18.5	24	23.2	23.8	23.3	22.8	21.2	20.4	24	23.1	24.5	24.8	24.5	21.8	22.1	26.8	27.3	27.8	27	25.8	21.6
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23:00	19	19	18.3	19	19.4	18.8	19.1	19.6	19.8	19.1	19.5	20.5	19.9	19.5	22.5	23.1	23.9	22.5	22.7	23	21.4
0:00	18	17.8	17.6	18.2	18.6	18.8	18.4	18.5	18.7	17.8	18.3	19.3	19.3	18.5	22.1	22.3	22.3	21.3	21.6	21.4	20.2

3Case

	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul	14-Jul	15-Jul
	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday
1:00	21.9	21.3	20.8	21.3	21.1	20.6	20.4	22.1	20.9	21.5	20.3	20.8	20.8	20	20.6
2:00	21.5	20.7	20.5	20.6	22	20.4	20.4	21.1	21.1	20.9	20	20	20.4	19.3	20
3:00	20.9	20.5	20.1	20.3	20.3	20.3	19.9	19.9	20.3	20.1	19.6	19.8	20.3	19.2	20.2
4:00	20.7	20.1	19.9	20.3	20.4	20	19.2	19.7	20.3	20.3	19.3	19.8	20.2	19.5	19.7
5:00	20.9	20.2	20	20.1	20.4	19	19.2	20.3	20.1	21.3	19.5	19.8	19.5	19.5	19.8
6:00	20.5	19.8	19.7	19.9	19.9	19	18	20.1	20.3	20.7	19	19.2	18.9	18.3	19.9
7:00	20.1	21.7	21.3	21.4	20.4	19.4	18.4	21.5	21.5	21.3	20.7	20.6	19.3	19	24
8:00	24.6	24.1	22.3	25.5	24.3	20.6	19.6	24.1	25.1	23.1	22.9	25.1	21.5	19.7	23.3
9:00	26.1	24.5	25.3	26.4	26.7	22.4	20.8	25.1	26.1	27.2	24	25.1	22.8	20.1	25.1
10:00	27.7	26	26.6	27.8	26.7	22.9	20.7	27.1	27.2	27.5	26.4	26.1	23.5	20.5	26.7
11:00	28.4	27.4	26.8	27.7	27.9	24.3	21.4	27.1	27.6	28.1	26.5	27	23.9	21.3	25.9
12:00	28.4	28.3	27.4	28.3	27.1	24.2	21.5	27.2	27.6	27.6	26.7	26.9	24.2	21.5	26
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	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul
	Tuesday	Wednesda	Thursday	Friday	Saturday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday
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2:00	19.8	20.1	20.7	20.9	20.6	20.2	19.7	20.2	21.1	20.3	20.3	20.5	18.7	20.3	19.9	18.3
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7:00	21.1	20.9	21.3	21	19	18.3	19.9	21.2	21.7	20.9	21.9	19.5	17.8	18.9	20.4	19.8
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9:00	25.5	25.2	25.4	24.5	22.6	20.6	25.6	26.1	25.8	23.5	24.3	21.8	22.1	21.2	24.1	23.4
10:00	26.2	26.6	27.1	26	23.4	21	26.1	26.1	26.9	25.4	25.5	23.8	23.9	21.6	25.6	24.9
11:00	26.7	26.6	26.9	26.3	24.2	21	26.5	26.7	26.8	25.1	26.2	23.7	25.1	21.6	26	25.9
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15:00	27.6	27	27.6	26.6	23.2	21.3	27.3	27.5	27.7	23.2	26.3	24	25.7	21.2	25.4	27.2
16:00	26.7	26.2	26.8	26.1	23	21	26.9	26.9	26.7	24.2	24.7	24.4	24.9	18.5	24.2	24
17:00	24.2	24	25.1	24.2	22.9	21.4	24	25.3	24.7	23.7	23.5	23.6	23.3	21.2	23.1	24.1
18:00	22.2	22.5	23.4	22.9	21.9	21.3	23.3	24.3	23.7	22.5	22.9	22.3	22.1	24.5	22.5	22.7
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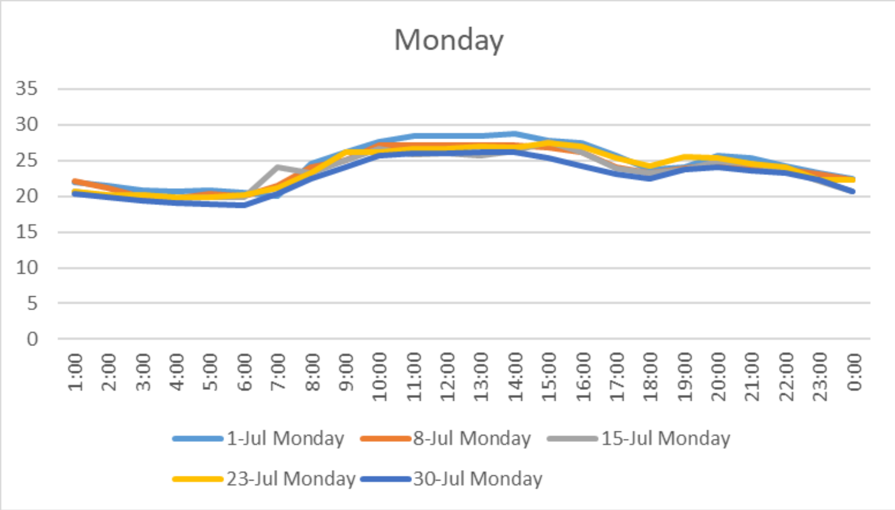
20:00	24.3	24.9	25.4	24.1	23.8	23.5	25.1	25.3	25.1	24	24.2	24	24.7	22.4	24.1	24.7
21:00	23.9	24.6	25.2	23.6	23.7	23.3	24.9	24.5	24.8	23.9	23.8	23.5	24.5	22	23.5	24.3
22:00	23	23.7	24.4	23	23.5	23	24.3	24.1	23.9	22.9	23.7	22.8	22.9	21.4	23.3	23.9
23:00	22.1	22.2	23.2	22.6	22.9	22.3	22.5	22.3	23.1	21.7	22.9	22.1	21.8	19.9	22.3	22.9
0:00	22.1	21	21.9	21.4	22.2	21.7	21.2	22.3	22.5	21.5	21.9	21.4	20.9	19.6	20.6	20.8

1Month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30
25
20
15
10
5
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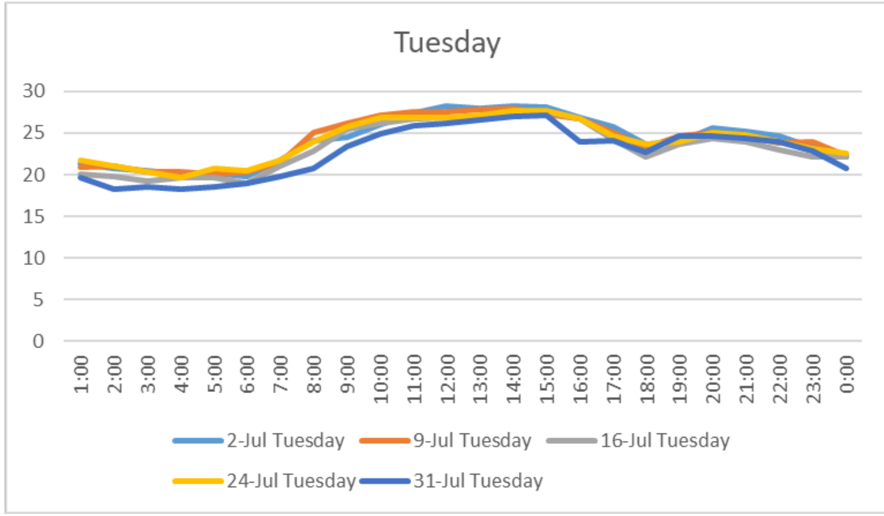
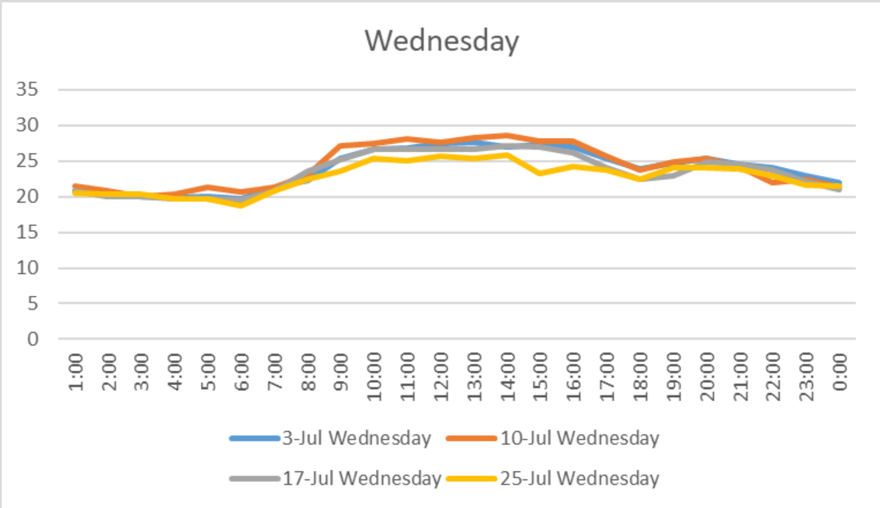
1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 0:00
1-Jul Monday
8-Jul Monday
15-Jul Monday
23-Jul Monday
30-Jul Monday


Tuesday
30
25
20
15
10
5
0
1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 0:00
2-Jul Tuesday
9-Jul Tuesday
16-Jul Tuesday
24-Jul Tuesday
31-Jul Tuesday


Wednesday
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15
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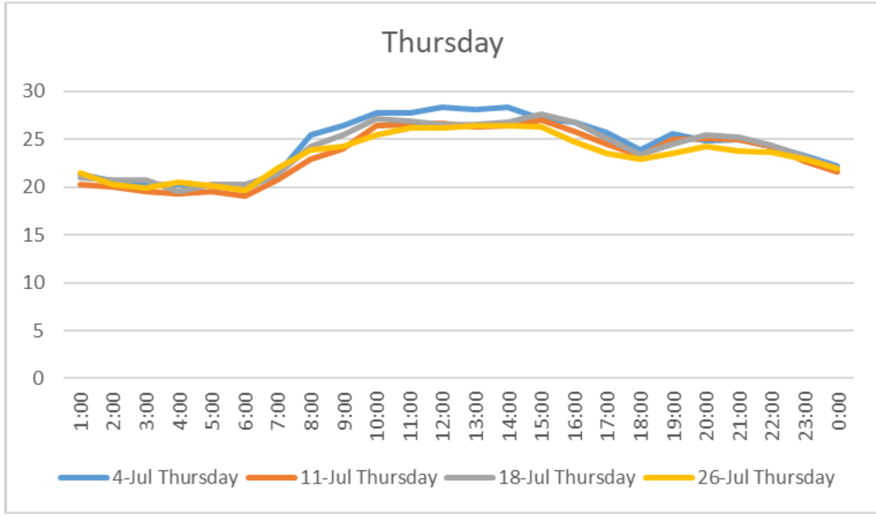
1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 0:00
3-Jul Wednesday
10-Jul Wednesday
17-Jul Wednesday
25-Jul Wednesday


Thursday
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25
20
15
10
5
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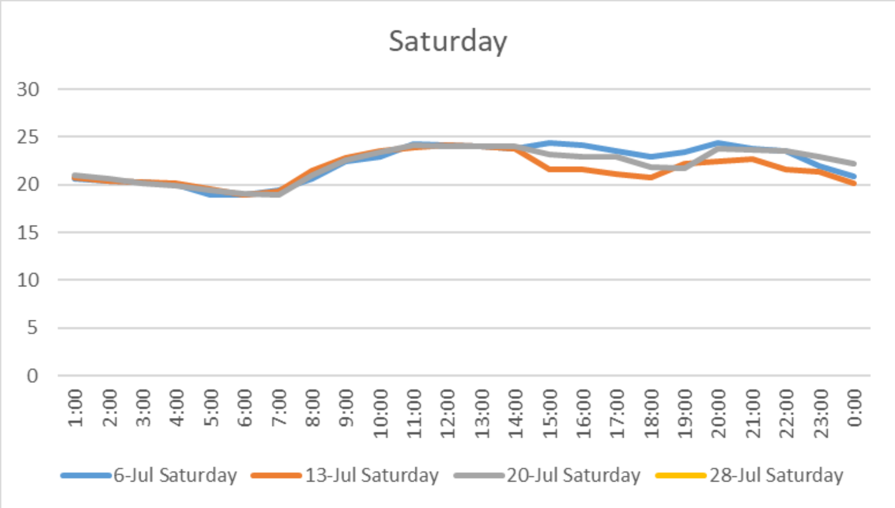
1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 0:00
4-Jul Thursday
11-Jul Thursday
18-Jul Thursday
26-Jul Thursday


Saturday
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1:00
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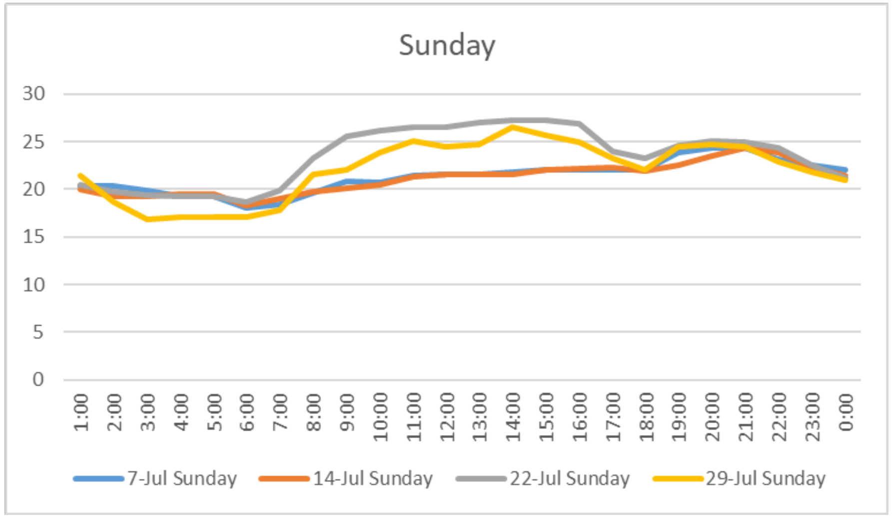
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00
6-Jul Saturday
13-Jul Saturday
20-Jul Saturday
28-Jul Saturday


Sunday
30
25
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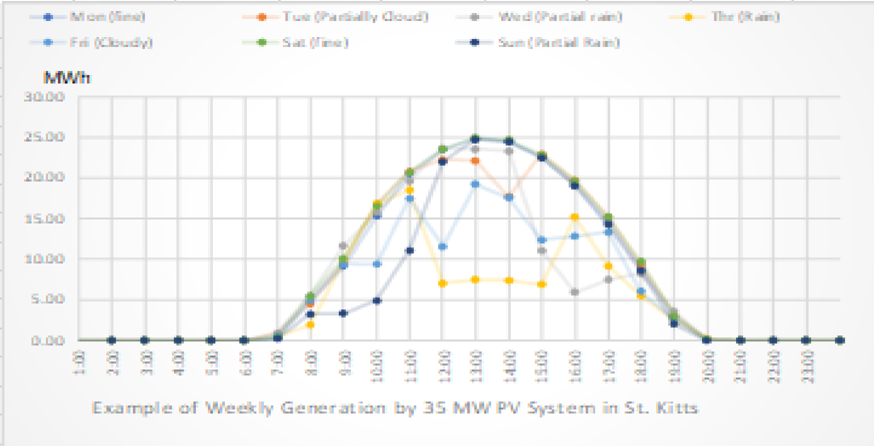
7-Jul Sunday
14-Jul Sunday
22-Jul Sunday
29-Jul Sunday

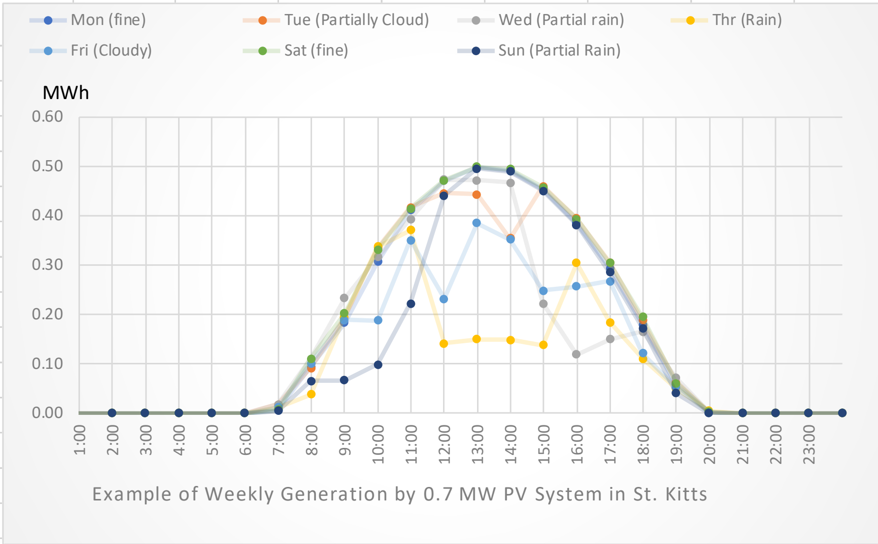
14. 付録 G：太陽光(35MW, 0.7MW, 0.55MW)の 1 週間分の時間ごとの出力プロファイル（想定、2019 年）

Max Irr	330	GTI	6	kWh/m2	Weekly GT	42	kWh/m2				
Total Irr	15119	PV output	4.663	kWh/kWp	35	MW		163.205	MWh/day	1,142.44	MWh/week
					0.7	0.5					
Hourly Generation MWh in an example of a week by 35 MW PV system in St. Kitts											
Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)				
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
7:00	0.30	0.91	0.91	0.53	0.60	0.38	0.23				
8:00	4.68	4.61	5.52	1.89	5.06	5.52	3.25				
9:00	9.14	9.67	11.64	9.82	9.45	10.13	3.32				
10:00	15.34	16.77	15.79	16.85	9.37	16.55	4.91				
11:00	20.55	20.86	19.65	18.51	17.53	20.70	11.11				
12:00	23.50	22.29	23.65	7.10	11.56	23.58	22.06				
13:00	24.86	22.14	23.58	7.48	19.27	24.94	24.78				
14:00	24.56	17.68	23.35	7.41	17.61	24.71	24.48				
15:00	22.67	22.97	11.11	6.88	12.39	22.90	22.52				
16:00	19.27	19.72	5.97	15.19	12.85	19.65	19.04				
17:00	14.66	15.26	7.48	9.22	13.37	15.19	14.28				
18:00	8.99	9.37	8.24	5.52	6.05	9.75	8.61				
19:00	2.87	3.17	3.55	2.49	2.64	3.02	2.04				
20:00	0.08	0.15	0.15	0.23	0.15	0.15	0.00				
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
TOTAL	191.48	185.58	160.57	109.11	137.90	197.14	160.65	1,142.44	MWh		
	5.47	5.30	4.59	3.12	3.94	5.63	4.59				



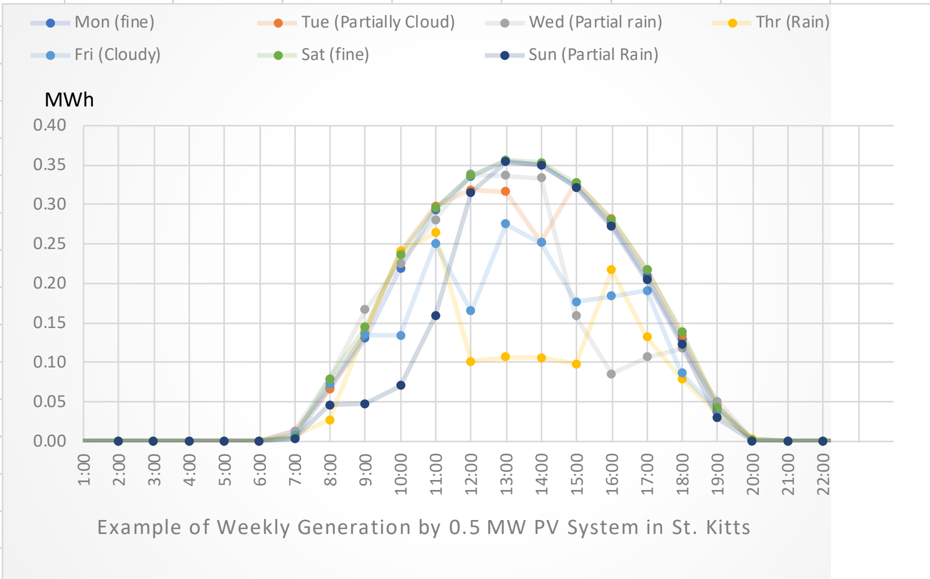
Hourly Generation MWh in an example of a week by 0.7 MW PV system in St. Kitts

Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)		
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
7:00	0.01	0.02	0.02	0.01	0.01	0.01	0.00		
8:00	0.09	0.09	0.11	0.04	0.10	0.11	0.06		
9:00	0.18	0.19	0.23	0.20	0.19	0.20	0.07		
10:00	0.31	0.34	0.32	0.34	0.19	0.33	0.10		
11:00	0.41	0.42	0.39	0.37	0.35	0.41	0.22		
12:00	0.47	0.45	0.47	0.14	0.23	0.47	0.44		
13:00	0.50	0.44	0.47	0.15	0.39	0.50	0.50		
14:00	0.49	0.35	0.47	0.15	0.35	0.49	0.49		
15:00	0.45	0.46	0.22	0.14	0.25	0.46	0.45		
16:00	0.39	0.39	0.12	0.30	0.26	0.39	0.38		
17:00	0.29	0.31	0.15	0.18	0.27	0.30	0.29		
18:00	0.18	0.19	0.16	0.11	0.12	0.19	0.17		
19:00	0.06	0.06	0.07	0.05	0.05	0.06	0.04		
20:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
TOTAL	3.83	3.71	3.21	2.18	2.76	3.94	3.21	22.85	MWh
	0.11	0.11	0.09	0.06	0.08	0.11	0.09		



Hourly Generation MWh in an example of a week by 0.5 MW PV system in St. Kitts

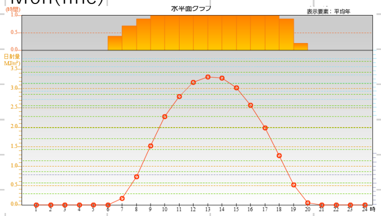
Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)		
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
7:00	0.00	0.01	0.01	0.01	0.01	0.01	0.00		
8:00	0.07	0.07	0.08	0.03	0.07	0.08	0.05		
9:00	0.13	0.14	0.17	0.14	0.13	0.14	0.05		
10:00	0.22	0.24	0.23	0.24	0.13	0.24	0.07		
11:00	0.29	0.30	0.28	0.26	0.25	0.30	0.16		
12:00	0.34	0.32	0.34	0.10	0.17	0.34	0.32		
13:00	0.36	0.32	0.34	0.11	0.28	0.36	0.35		
14:00	0.35	0.25	0.33	0.11	0.25	0.35	0.35		
15:00	0.32	0.33	0.16	0.10	0.18	0.33	0.32		
16:00	0.28	0.28	0.09	0.22	0.18	0.28	0.27		
17:00	0.21	0.22	0.11	0.13	0.19	0.22	0.20		
18:00	0.13	0.13	0.12	0.08	0.09	0.14	0.12		
19:00	0.04	0.05	0.05	0.04	0.04	0.04	0.03		
20:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
TOTAL	2.74	2.65	2.29	1.56	1.97	2.82	2.29	16.32	MWh
	0.08	0.08	0.07	0.04	0.06	0.08	0.07		



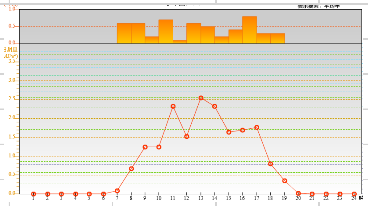
http://app0.infoc.nedo.go.jp/metpv/metpv.html

Hateruma	20-Jun	16-Jul	17-Jun	10-Jun	25-Jun	27-Jun	27-Jun
Time	Mon(fine)	Tue (Parti	Wed (Part	Thr (Rain)	Fri (Cloud	Sat (fine)	Sun (Partial Rain)
1:00	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0
7:00	4	12	12	7	8	5	3
8:00	62	61	73	25	67	73	43
9:00	121	128	154	130	125	134	44
10:00	203	222	209	223	124	219	65
11:00	272	276	260	245	232	274	147
12:00	311	295	313	94	153	312	292
13:00	329	293	312	99	255	330	328
14:00	325	234	309	98	233	327	324
15:00	300	304	147	91	164	303	298
16:00	255	261	79	201	170	260	252
17:00	194	202	99	122	177	201	189
18:00	119	124	109	73	80	129	114
19:00	38	42	47	33	35	40	27
20:00	1	2	2	3	2	2	0
21:00	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0
Max Irr	330	GTI	6	kWh/m2	Weekly G	42	kWh/m2
Total Irr	15119	PV output	4.663	kWh/kWp/day			

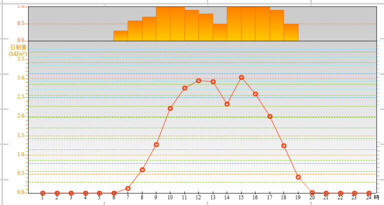
Mon(fine)



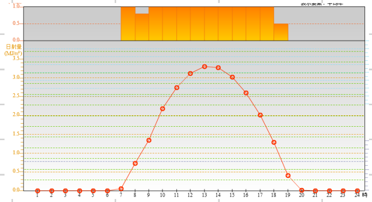
Fri (Cloudy)



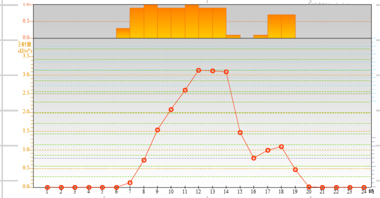
Tue (Partially Cloud)



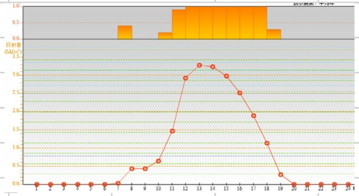
Sat (fine)



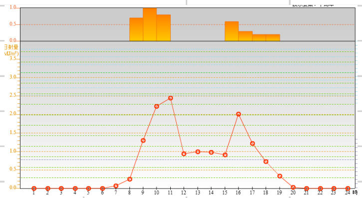
Wed (Partial rain)



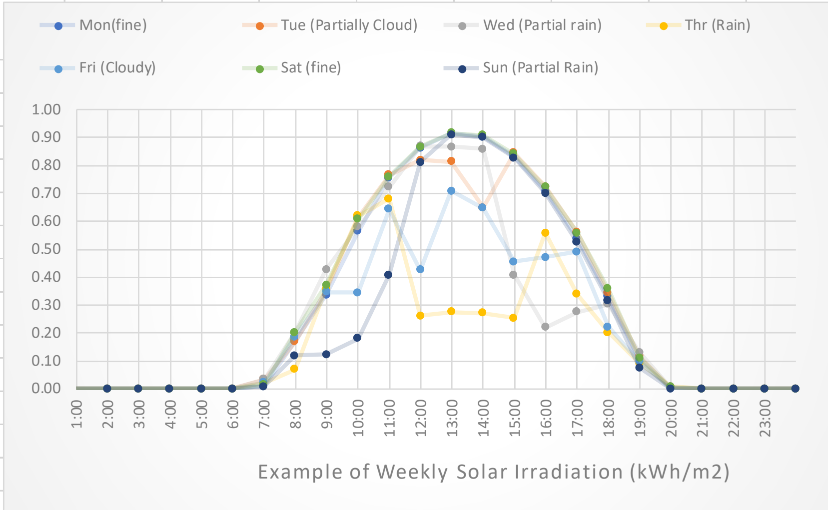
Sun (Partial Rain)

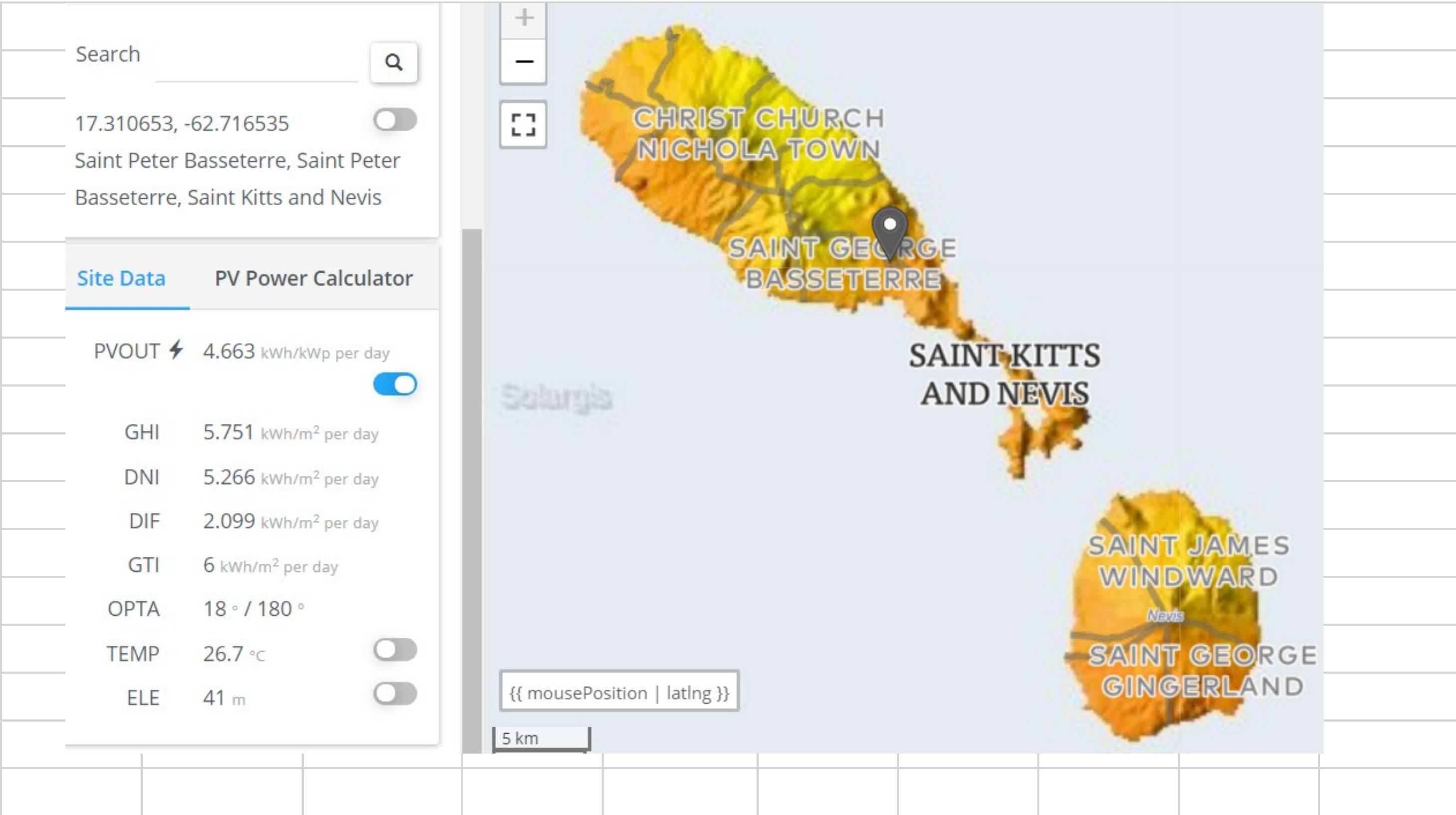


Thr (Rain)

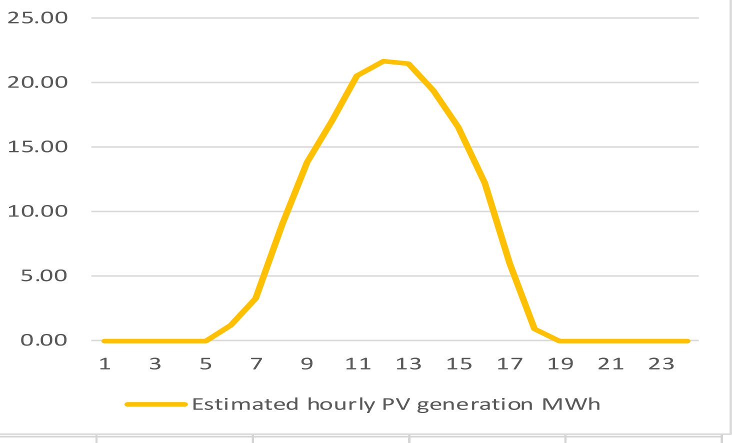


Max Irr	330	GTI	6	kWh/m2	Weekly G	42	kWh/m2	
Total Irr	15119	PV output	4.663	kWh/kWp/day				
kWh/m2								
Hateruma	20-Jun	16-Jul	17-Jun	10-Jun	25-Jun	27-Jun	27-Jun	
Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)	
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
7:00	0.01	0.03	0.03	0.02	0.02	0.01	0.01	
8:00	0.17	0.17	0.20	0.07	0.19	0.20	0.12	
9:00	0.34	0.36	0.43	0.36	0.35	0.37	0.12	
10:00	0.56	0.62	0.58	0.62	0.34	0.61	0.18	
11:00	0.76	0.77	0.72	0.68	0.64	0.76	0.41	
12:00	0.86	0.82	0.87	0.26	0.43	0.87	0.81	
13:00	0.91	0.81	0.87	0.28	0.71	0.92	0.91	
14:00	0.90	0.65	0.86	0.27	0.65	0.91	0.90	
15:00	0.83	0.84	0.41	0.25	0.46	0.84	0.83	
16:00	0.71	0.73	0.22	0.56	0.47	0.72	0.70	
17:00	0.54	0.56	0.28	0.34	0.49	0.56	0.53	
18:00	0.33	0.34	0.30	0.20	0.22	0.36	0.32	
19:00	0.11	0.12	0.13	0.09	0.10	0.11	0.08	
20:00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	7.04	6.82	5.90	4.01	5.07	7.25	5.91	42.00



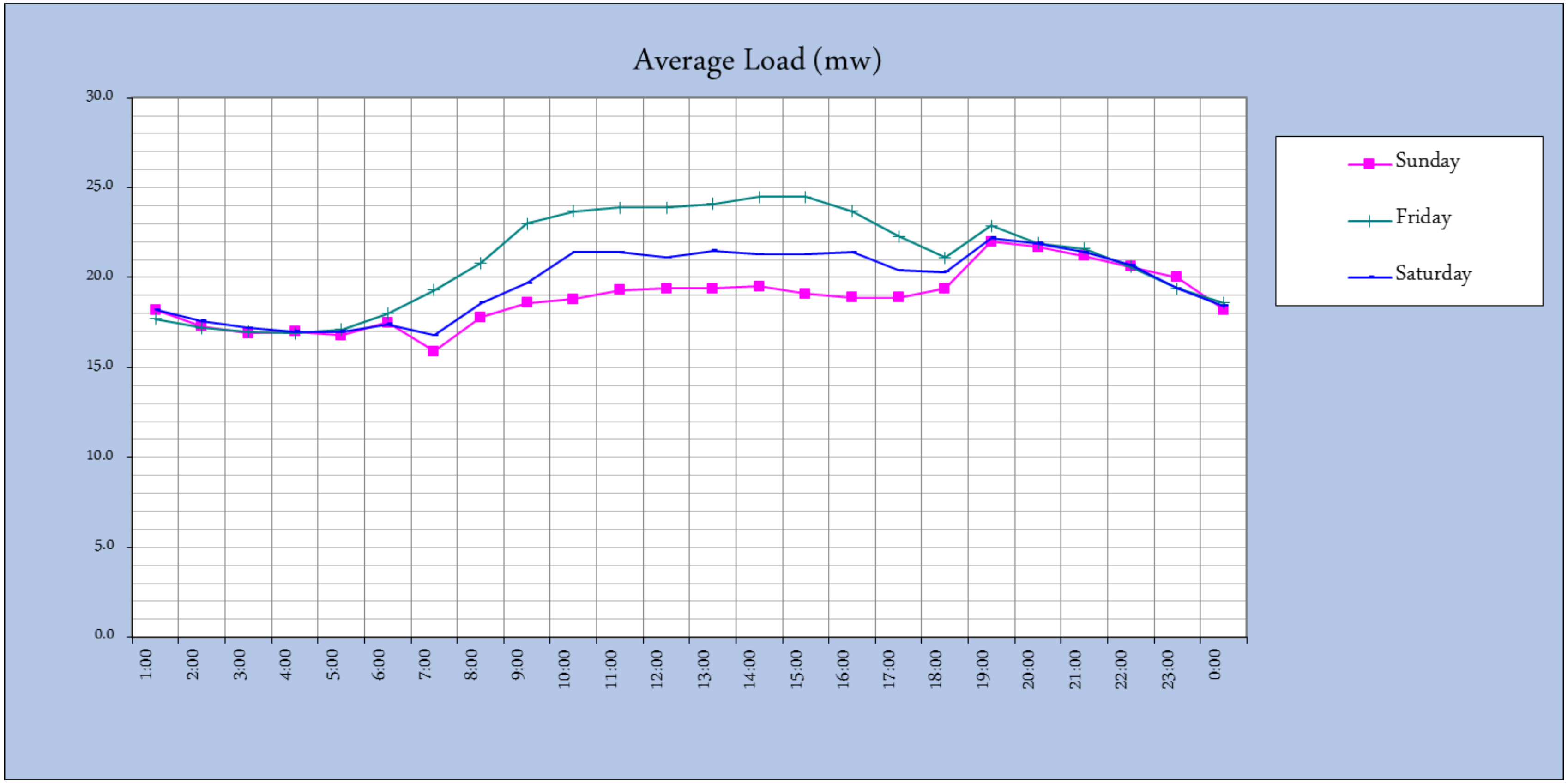

Search
17.310653, -62.716535
Saint Peter Basseterre, Saint Peter Basseterre, Saint Kitts and Nevis
Site Data
PV Power Calculator
PVOUT 4.663 kWh/kWp per day
GHI 5.751 kWh/m² per day
DNI 5.266 kWh/m² per day
DIF 2.099 kWh/m² per day
GTI 6 kWh/m² per day
OPTA 18 ° / 180 °
TEMP 26.7 °C
ELE 41 m
CHRIST CHURCH NICHOLA TOWN
SAINT GEORGE BASSETERRE
SAINT KITTS AND NEVIS
SAINT JAMES WINDWARD
SAINT GEORGE GINGERLAND
{{ mousePosition | latlng }}
5 km

		GTI	6	kWh/m2	
		PV output	4.663	kWh/kWp/day	
Hourly PV generation estimation in St Kitts					
Time	Coeff. Hourly dist. Estimated	Hourly irradiation kWh/m2	Hourly PV kWh/kWp	Estimated hourly PV generation MWh	
1:00	0.00	0.00	0.00	0.00	
2:00	0.00	0.00	0.00	0.00	
3:00	0.00	0.00	0.00	0.00	
4:00	0.00	0.00	0.00	0.00	
5:00	0.00	0.00	0.00	0.00	
6:00	0.05	0.04	0.03	1.15	
7:00	0.14	0.12	0.09	3.23	
8:00	0.39	0.33	0.26	9.00	
9:00	0.60	0.51	0.40	13.85	
10:00	0.74	0.63	0.49	17.08	
11:00	0.89	0.76	0.59	20.54	
12:00	0.94	0.80	0.62	21.70	
13:00	0.93	0.79	0.61	21.47	
14:00	0.84	0.71	0.55	19.39	
15:00	0.72	0.61	0.47	16.62	
16:00	0.53	0.45	0.35	12.23	
17:00	0.26	0.22	0.17	6.00	
18:00	0.04	0.03	0.03	0.92	
19:00	0.00	0.00	0.00	0.00	
20:00	0.00	0.00	0.00	0.00	
21:00	0.00	0.00	0.00	0.00	
22:00	0.00	0.00	0.00	0.00	
23:00	0.00	0.00	0.00	0.00	
0:00	0.00	0.00	0.00	0.00	
TOTAL	7.07	6.00	4.66	163.21	4.66



Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat
1:00	18.2	17.8	17.4	17.7	17.6	17.7	18.2
2:00	17.3	17.2	16.8	17.1	16.8	17.2	17.6
3:00	16.9	16.8	16.8	16.8	16.6	17.0	17.2
4:00	17.0	16.6	16.8	16.6	16.8	16.9	17.0
5:00	16.8	17.0	16.0	16.8	16.8	17.1	17.0
6:00	17.5	17.8	16.6	18.1	18.2	18.0	17.4
7:00	15.9	17.0	18.4	19.3	20.1	19.3	16.8
8:00	17.8	19.4	20.0	20.6	21.8	20.8	18.6
9:00	18.6	21.6	21.6	22.2	21.5	23.0	19.7
10:00	18.8	22.8	23.4	23.5	23.1	23.7	21.4
11:00	19.3	23.0	23.6	23.7	23.3	23.9	21.4
12:00	19.4	23.2	24.0	23.3	23.7	23.9	21.1
13:00	19.4	22.6	23.8	23.4	24.1	24.1	21.5
14:00	19.5	23.2	24.8	24.1	24.0	24.5	21.3
15:00	19.1	22.7	24.2	24.0	23.6	24.5	21.3
16:00	18.9	21.6	23.2	23.2	22.7	23.7	21.4
17:00	18.9	20.8	21.9	22.3	22.1	22.3	20.4
18:00	19.4	18.7	21.2	20.8	21.1	21.1	20.3
19:00	22.0	20.1	23.2	23.4	23.3	22.9	22.2
20:00	21.7	20.9	22.4	23.2	22.7	21.9	21.9
21:00	21.2	20.2	21.7	21.9	22.3	21.6	21.4
22:00	20.6	19.9	20.8	20.8	21.2	20.6	20.7
23:00	20.0	19.2	19.3	19.2	19.6	19.4	19.4
0:00	18.2	18.0	18.1	18.1	18.6	18.6	18.4
DAY PEAK	19.5	23.2	24.8	24.1	24.1	24.5	21.5
NIGHT PEAK	22.0	20.9	23.2	23.4	23.3	22.9	22.2

Load



Average Load (mw)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1:00
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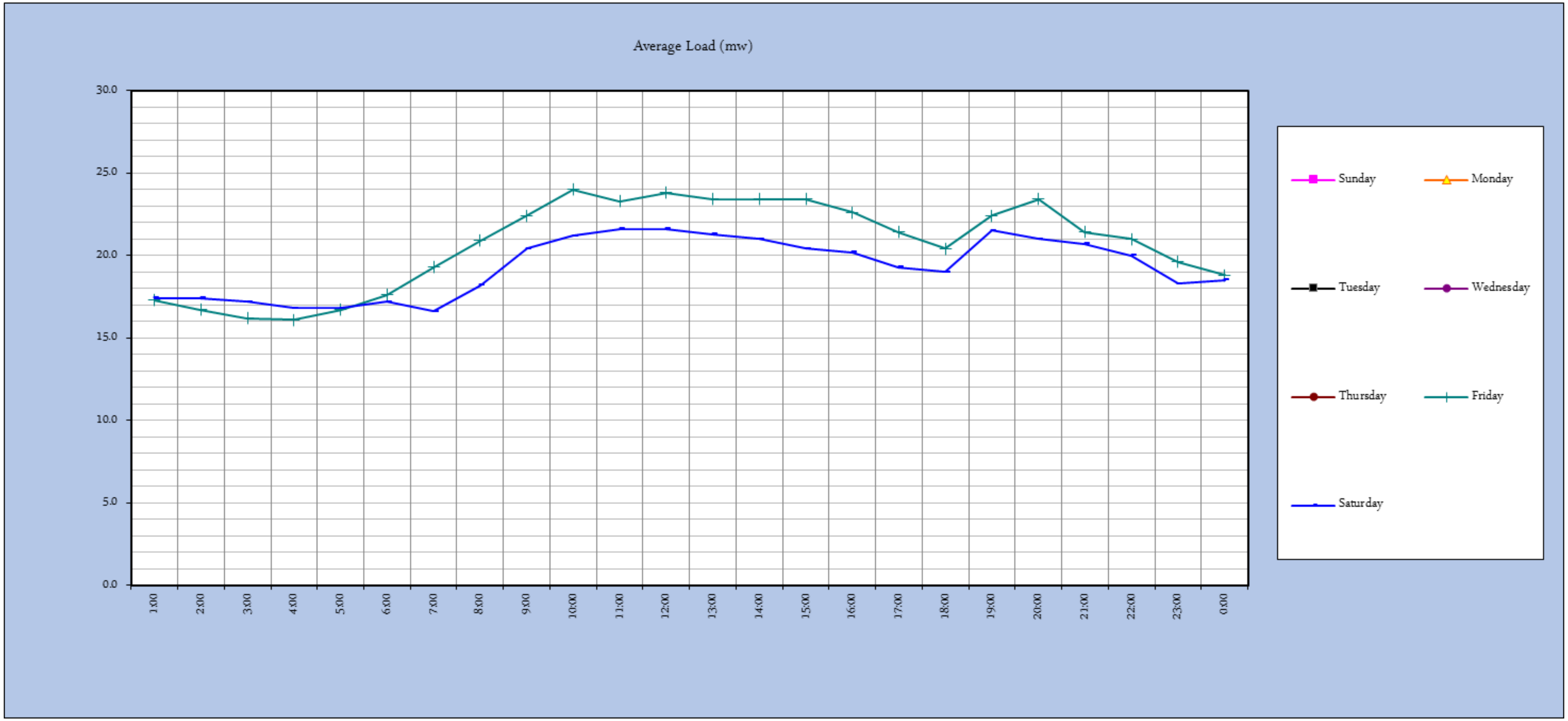
19:00
20:00
21:00
22:00
23:00
0:00
Sunday
Friday
Saturday

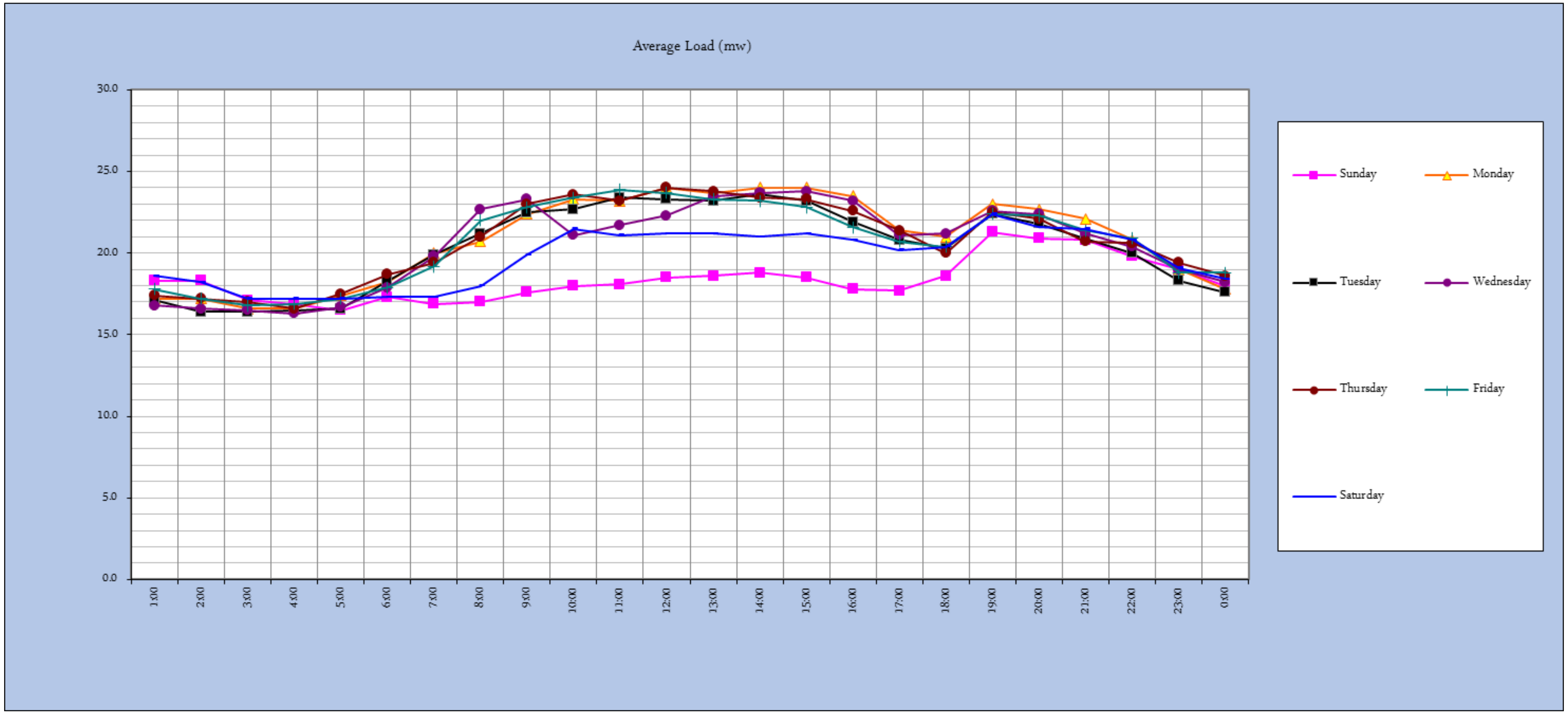
Load

		2019年3月1日				to	2019年3月2日			
	Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
	1:00						17.3	17.4	17.3	17.4
	2:00						16.7	17.4	16.7	17.4
	3:00						16.2	17.2	16.2	17.2
	4:00						16.1	16.8	16.1	16.8
	5:00						16.7	16.8	16.7	16.8
	6:00						17.6	17.2	17.2	17.6
	7:00						19.3	16.6	16.6	19.3
	8:00						20.9	18.2	18.2	20.9
	9:00						22.4	20.4	20.4	22.4
	10:00						24.0	21.2	21.2	24.0
	11:00						23.3	21.6	21.6	23.3
	12:00						23.8	21.6	21.6	23.8
	13:00						23.4	21.3	21.3	23.4
	14:00						23.4	21.0	21.0	23.4
	15:00						23.4	20.4	20.4	23.4
	16:00						22.6	20.2	20.2	22.6
	17:00						21.4	19.3	19.3	21.4
	18:00						20.4	19.0	19.0	20.4
	19:00						22.4	21.5	21.5	22.4
	20:00						23.4	21.0	21.0	23.4
	21:00						21.4	20.7	20.7	21.4
	22:00						21.0	20.0	20.0	21.0
	23:00						19.6	18.3	18.3	19.6
	0:00						18.8	18.5	18.5	18.8
DAY PEAK		0.0	0.0	0.0	0.0	0.0	24.0	21.6		
NIGHT PEAK		0.0	0.0	0.0	0.0	0.0	23.4	21.5		



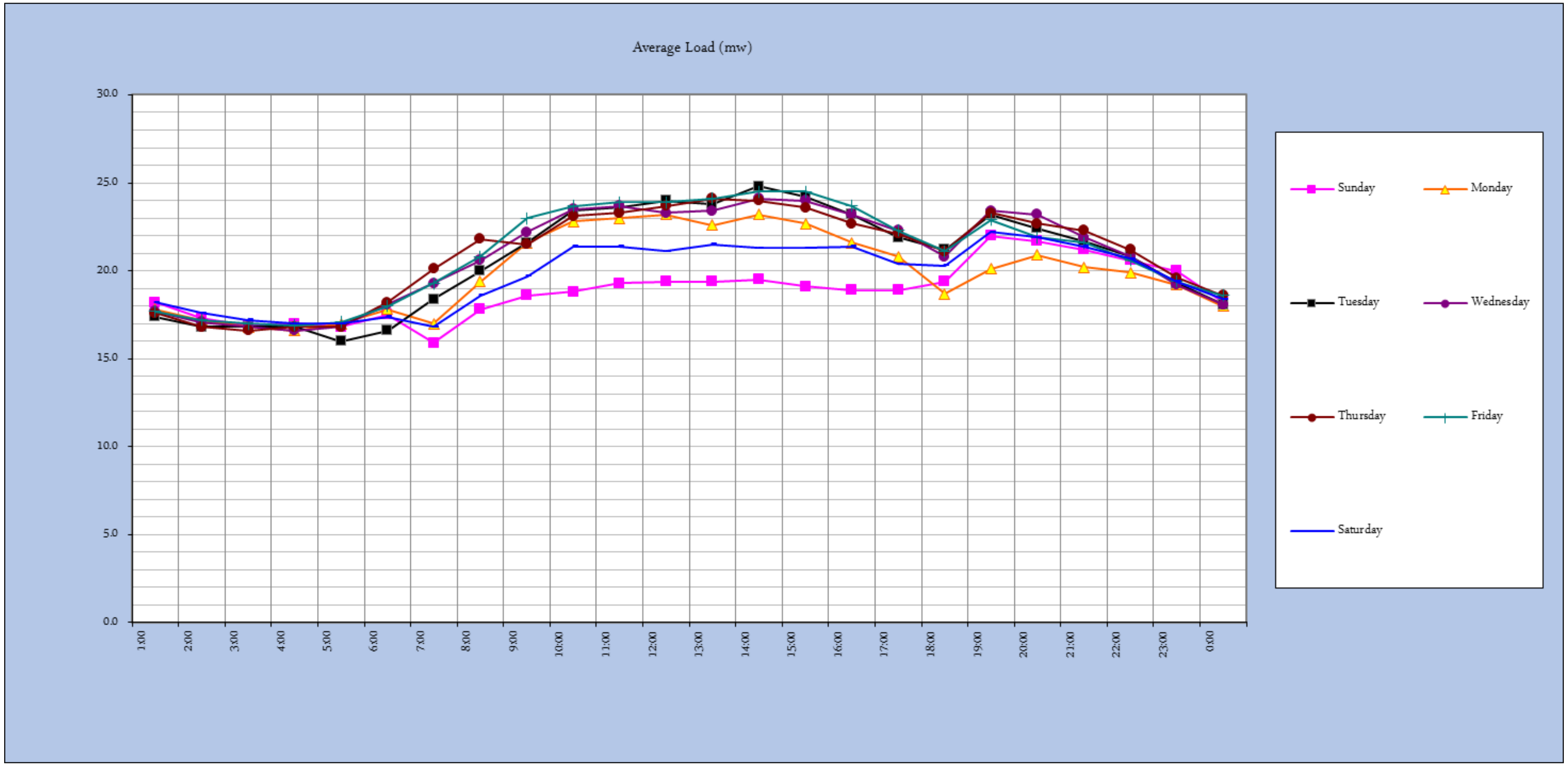
Hourly Load & Averages

		2019年3月3日			to		2019年3月9日		
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.3	17.2	17.1	16.8	17.4	17.8	18.6	16.8	18.6
2:00	18.3	17.2	16.4	16.6	17.2	17.2	18.2	16.4	18.3
3:00	17.1	16.6	16.4	16.5	17.0	16.8	17.2	16.4	17.2
4:00	16.9	16.6	16.5	16.3	16.6	16.9	17.2	16.3	17.2
5:00	16.5	17.4	16.6	16.7	17.5	17.2	17.2	16.5	17.5
6:00	17.3	18.2	18.3	17.9	18.7	17.9	17.3	17.3	18.7
7:00	16.9	20.0	19.9	19.8	19.4	19.2	17.3	16.9	20.0
8:00	17.0	20.7	21.2	22.7	21.0	22.0	18.0	17.0	22.7
9:00	17.6	22.4	22.5	23.3	23.0	22.8	19.9	17.6	23.3
10:00	18.0	23.3	22.7	21.1	23.6	23.4	21.5	18.0	23.6
11:00	18.1	23.2	23.4	21.7	23.2	23.9	21.1	18.1	23.9
12:00	18.5	24.0	23.3	22.3	24.0	23.7	21.2	18.5	24.0
13:00	18.6	23.7	23.2	23.5	23.8	23.3	21.2	18.6	23.8
14:00	18.8	24.0	23.6	23.7	23.4	23.2	21.0	18.8	24.0
15:00	18.5	24.0	23.2	23.8	23.3	22.8	21.2	18.5	24.0
16:00	17.8	23.5	21.9	23.2	22.6	21.6	20.8	17.8	23.5
17:00	17.7	21.4	20.8	21.1	21.4	20.7	20.2	17.7	21.4
18:00	18.6	21.0	20.3	21.2	20.0	20.4	20.4	18.6	21.2
19:00	21.3	23.0	22.4	22.6	22.5	22.4	22.4	21.3	23.0
20:00	20.9	22.7	21.8	22.4	22.1	22.3	21.6	20.9	22.7
21:00	20.8	22.1	20.9	21.2	20.7	21.4	21.5	20.7	22.1
22:00	19.8	20.8	20.0	20.4	20.6	20.9	20.8	19.8	20.9
23:00	19.0	19.0	18.3	19.0	19.4	18.8	19.1	18.3	19.4
0:00	18.0	17.8	17.6	18.2	18.6	18.8	18.4	17.6	18.8
DAY PEAK	18.8	24.0	23.6	23.8	24.0	23.9	21.5		
NIGHT PEAK	21.3	23.0	22.4	22.6	22.5	22.4	22.4		



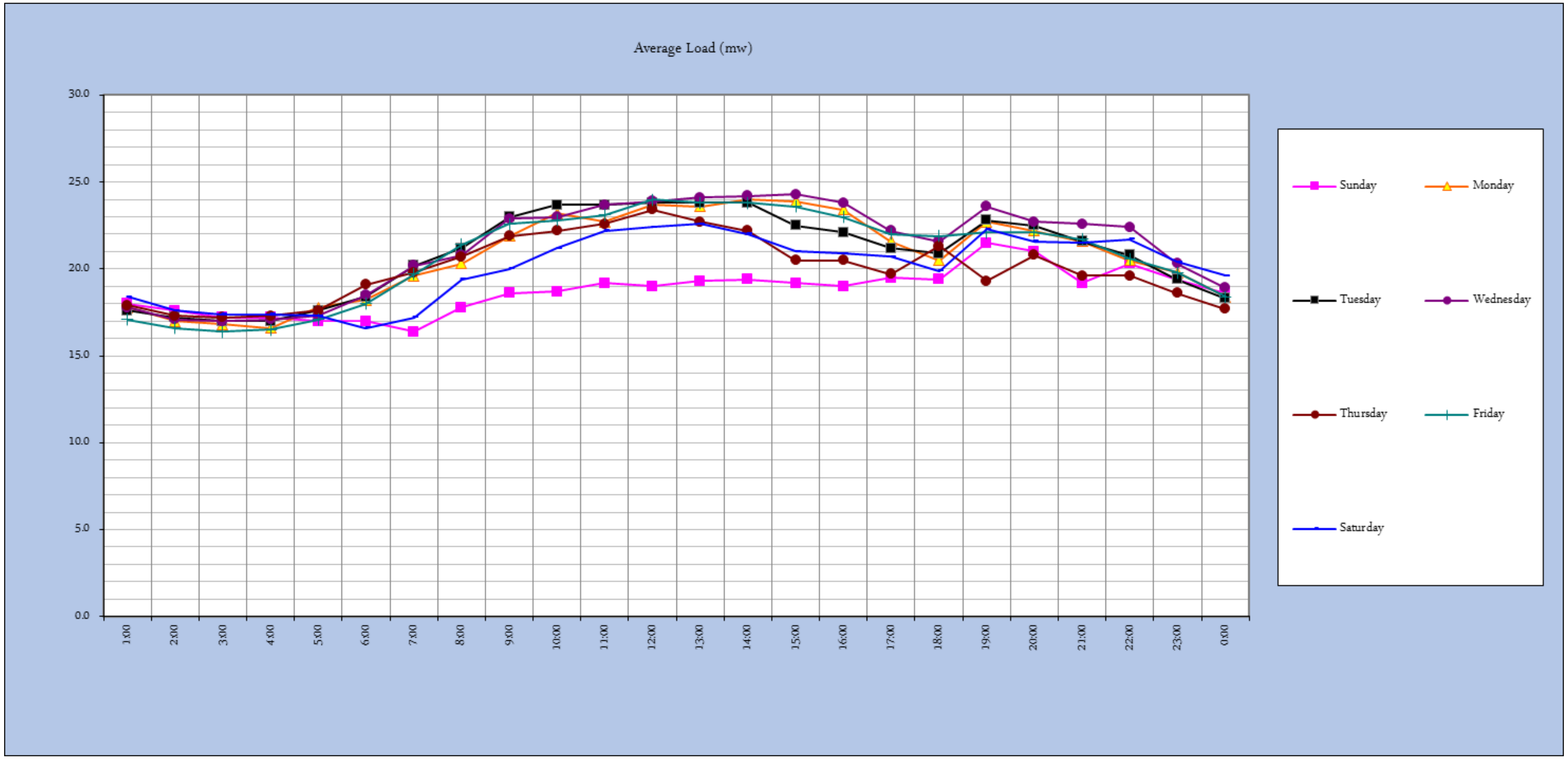
Hourly Load & Averages

		2019年3月10日			to	2019年3月16日			
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.2	17.8	17.4	17.7	17.6	17.7	18.2	17.4	18.2
2:00	17.3	17.2	16.8	17.1	16.8	17.2	17.6	16.8	17.6
3:00	16.9	16.8	16.8	16.8	16.6	17.0	17.2	16.6	17.2
4:00	17.0	16.6	16.8	16.6	16.8	16.9	17.0	16.6	17.0
5:00	16.8	17.0	16.0	16.8	16.8	17.1	17.0	16.0	17.1
6:00	17.5	17.8	16.6	18.1	18.2	18.0	17.4	16.6	18.2
7:00	15.9	17.0	18.4	19.3	20.1	19.3	16.8	15.9	20.1
8:00	17.8	19.4	20.0	20.6	21.8	20.8	18.6	17.8	21.8
9:00	18.6	21.6	21.6	22.2	21.5	23.0	19.7	18.6	23.0
10:00	18.8	22.8	23.4	23.5	23.1	23.7	21.4	18.8	23.7
11:00	19.3	23.0	23.6	23.7	23.3	23.9	21.4	19.3	23.9
12:00	19.4	23.2	24.0	23.3	23.7	23.9	21.1	19.4	24.0
13:00	19.4	22.6	23.8	23.4	24.1	24.1	21.5	19.4	24.1
14:00	19.5	23.2	24.8	24.1	24.0	24.5	21.3	19.5	24.8
15:00	19.1	22.7	24.2	24.0	23.6	24.5	21.3	19.1	24.5
16:00	18.9	21.6	23.2	23.2	22.7	23.7	21.4	18.9	23.7
17:00	18.9	20.8	21.9	22.3	22.1	22.3	20.4	18.9	22.3
18:00	19.4	18.7	21.2	20.8	21.1	21.1	20.3	18.7	21.2
19:00	22.0	20.1	23.2	23.4	23.3	22.9	22.2	20.1	23.4
20:00	21.7	20.9	22.4	23.2	22.7	21.9	21.9	20.9	23.2
21:00	21.2	20.2	21.7	21.9	22.3	21.6	21.4	20.2	22.3
22:00	20.6	19.9	20.8	20.8	21.2	20.6	20.7	19.9	21.2
23:00	20.0	19.2	19.3	19.2	19.6	19.4	19.4	19.2	20.0
0:00	18.2	18.0	18.1	18.1	18.6	18.6	18.4	18.0	18.6
DAY PEAK	19.5	23.2	24.8	24.1	24.1	24.5	21.5		
NIGHT PEAK	22.0	20.9	23.2	23.4	23.3	22.9	22.2		



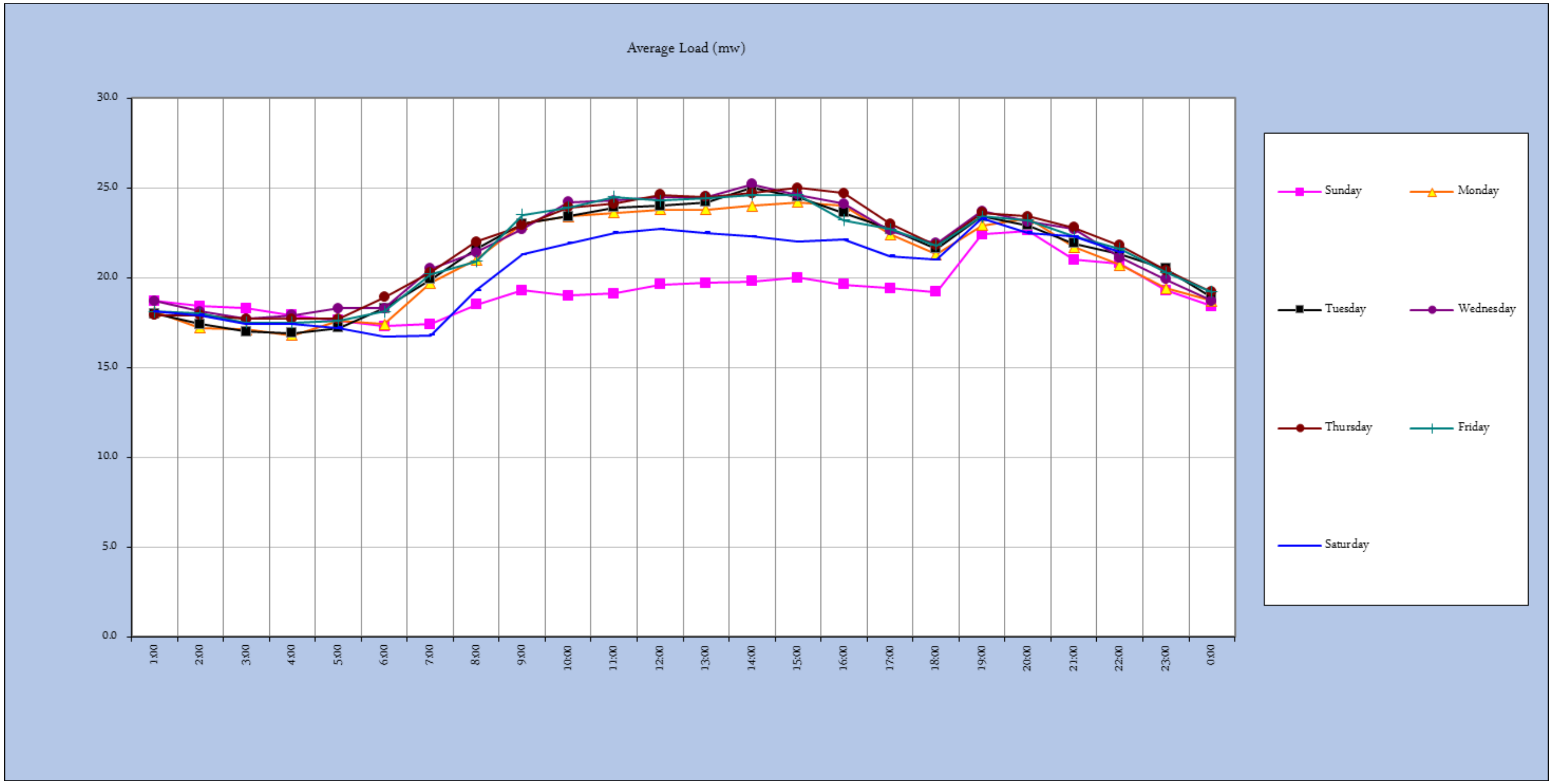
Hourly Load & Averages

		2019年3月17日			to		2019年3月23日		
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.0	17.8	17.6	17.8	17.9	17.1	18.4	17.1	18.4
2:00	17.6	17.0	17.2	17.1	17.3	16.6	17.6	16.6	17.6
3:00	17.2	16.8	17.0	17.0	17.2	16.4	17.4	16.4	17.4
4:00	17.2	16.6	17.0	17.1	17.3	16.5	17.4	16.5	17.4
5:00	17.0	17.8	17.6	17.3	17.6	17.1	17.3	17.0	17.8
6:00	17.0	18.2	18.4	18.5	19.1	18.0	16.6	16.6	19.1
7:00	16.4	19.6	20.2	20.2	19.8	19.7	17.2	16.4	20.2
8:00	17.8	20.3	21.2	20.8	20.7	21.4	19.4	17.8	21.4
9:00	18.6	21.9	23.0	22.9	21.9	22.6	20.0	18.6	23.0
10:00	18.7	23.2	23.7	23.0	22.2	22.8	21.2	18.7	23.7
11:00	19.2	22.7	23.7	23.7	22.6	23.1	22.2	19.2	23.7
12:00	19.0	23.7	23.8	23.9	23.4	24.0	22.4	19.0	24.0
13:00	19.3	23.6	23.8	24.1	22.7	23.8	22.6	19.3	24.1
14:00	19.4	24.0	23.8	24.2	22.2	23.8	22.0	19.4	24.2
15:00	19.2	23.9	22.5	24.3	20.5	23.6	21.0	19.2	24.3
16:00	19.0	23.4	22.1	23.8	20.5	23.0	20.9	19.0	23.8
17:00	19.5	21.6	21.2	22.2	19.7	22.0	20.7	19.5	22.2
18:00	19.4	20.5	20.9	21.6	21.3	21.9	19.9	19.4	21.9
19:00	21.5	22.7	22.8	23.6	19.3	22.1	22.3	19.3	23.6
20:00	21.0	22.2	22.5	22.7	20.8	22.1	21.6	20.8	22.7
21:00	19.2	21.6	21.6	22.6	19.6	21.7	21.5	19.2	22.6
22:00	20.3	20.5	20.8	22.4	19.6	20.6	21.7	19.6	22.4
23:00	19.4	19.8	19.4	20.3	18.6	19.8	20.4	18.6	20.4
0:00	18.6	18.4	18.3	18.9	17.7	18.4	19.6	17.7	19.6
DAY PEAK	17.9	24.0	23.8	24.3	23.4	24.0	22.6		
NIGHT PEAK	21.5	22.7	22.8	23.6	21.3	22.1	22.3		



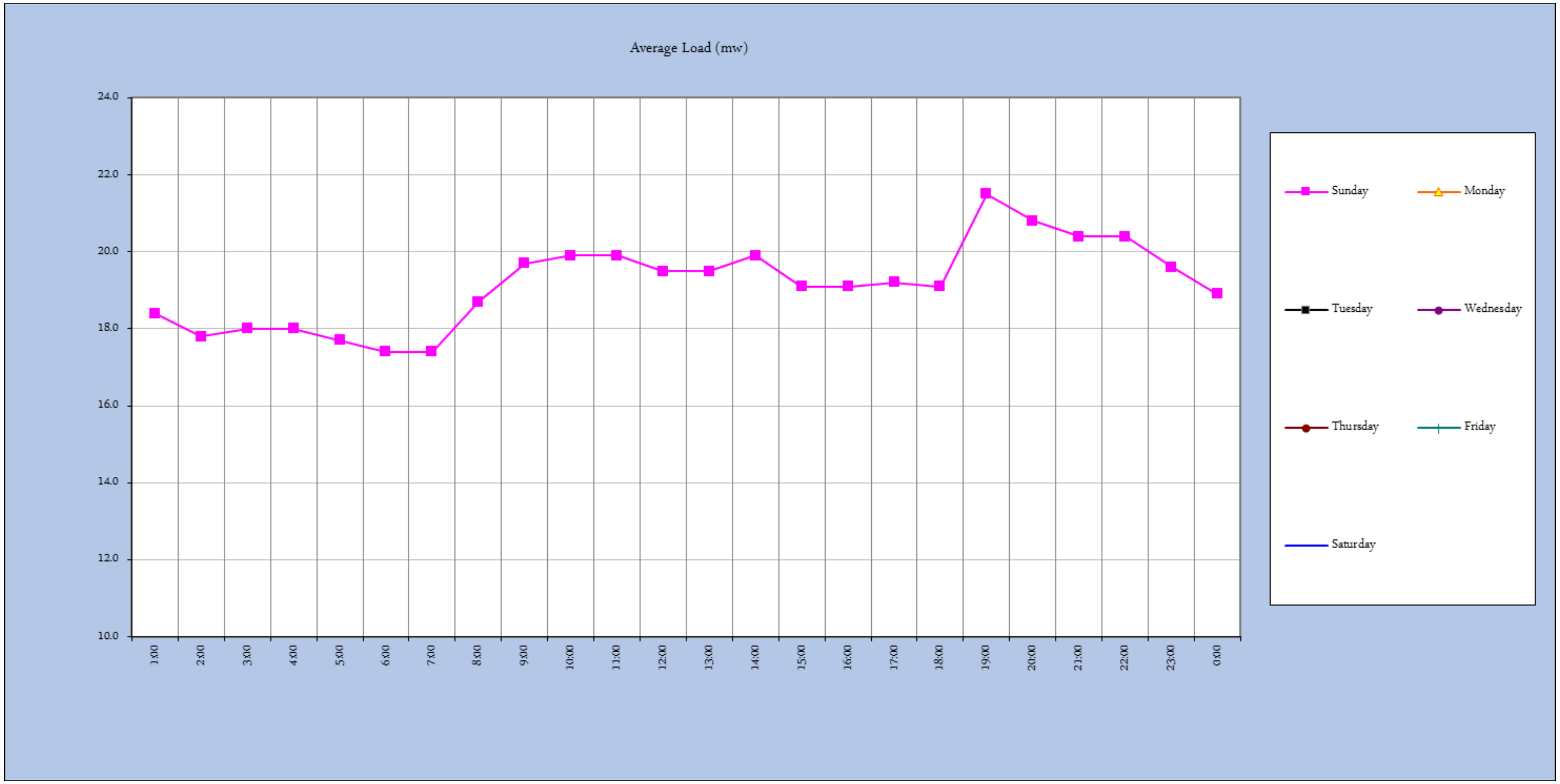
Hourly Load & Averages

			2019年2月24日		to		2019年3月30日		
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.7	18.1	18.0	18.7	17.9	18.1	18.1	17.9	18.7
2:00	18.4	17.2	17.4	18.1	17.9	18.0	17.9	17.2	18.4
3:00	18.3	17.1	17.0	17.7	17.7	17.5	17.4	17.0	18.3
4:00	17.9	16.8	16.9	17.9	17.7	17.5	17.4	16.8	17.9
5:00	17.6	17.6	17.2	18.3	17.7	17.6	17.2	17.2	18.3
6:00	17.3	17.4	18.3	18.3	18.9	18.1	16.7	16.7	18.9
7:00	17.4	19.7	19.9	20.5	20.3	20.2	16.8	16.8	20.5
8:00	18.5	21.0	21.6	21.4	22.0	20.9	19.3	18.5	22.0
9:00	19.3	23.0	23.0	22.7	22.9	23.5	21.3	19.3	23.5
10:00	19.0	23.4	23.4	24.2	23.9	23.9	21.9	19.0	24.2
11:00	19.1	23.6	23.9	24.3	24.1	24.5	22.5	19.1	24.5
12:00	19.6	23.8	24.0	24.5	24.6	24.3	22.7	19.6	24.6
13:00	19.7	23.8	24.2	24.5	24.5	24.4	22.5	19.7	24.5
14:00	19.8	24.0	25.0	25.2	24.7	24.6	22.3	19.8	25.2
15:00	20.0	24.2	24.5	24.6	25.0	24.6	22.0	20.0	25.0
16:00	19.6	24.0	23.6	24.1	24.7	23.2	22.1	19.6	24.7
17:00	19.4	22.4	22.7	22.6	23.0	22.7	21.2	19.4	23.0
18:00	19.2	21.3	21.6	21.9	21.8	21.8	21.0	19.2	21.9
19:00	22.4	22.9	23.4	23.7	23.6	23.4	23.3	22.4	23.7
20:00	22.6	23.3	22.9	23.1	23.4	23.2	22.5	22.5	23.4
21:00	21.0	21.7	21.9	22.7	22.8	22.3	22.3	21.0	22.8
22:00	20.8	20.7	21.3	21.1	21.8	21.6	21.4	20.7	21.8
23:00	19.3	19.4	20.5	19.9	20.4	20.3	20.5	19.3	20.5
0:00	18.4	18.7	18.9	18.7	19.2	19.2	19.4	18.4	19.4
DAY PEAK	20.0	24.2	25.0	25.2	25.0	24.6	22.7		
NIGHT PEAK	22.6	23.3	23.4	23.7	23.6	23.4	23.3		



Hourly Load & Averages

	2019年3月31日								
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.4							18.4	0.0
2:00	17.8							17.8	0.0
3:00	18.0							18.0	0.0
4:00	18.0							18.0	0.0
5:00	17.7							17.7	0.0
6:00	17.4							17.4	0.0
7:00	17.4							17.4	0.0
8:00	18.7							18.7	0.0
9:00	19.7							19.7	0.0
10:00	19.9							19.9	0.0
11:00	19.9							19.9	0.0
12:00	19.5							19.5	0.0
13:00	19.5							19.5	0.0
14:00	19.9							19.9	0.0
15:00	19.1							19.1	0.0
16:00	19.1							19.1	0.0
17:00	19.2							19.2	0.0
18:00	19.1							19.1	0.0
19:00	21.5							21.5	0.0
20:00	20.8							20.8	0.0
21:00	20.4							20.4	0.0
22:00	20.4							20.4	0.0
23:00	19.6							19.6	0.0
0:00	18.9							18.9	0.0
DAY PEAK	19.9	0.0	0.0	0.0	0.0	0.0	0.0		
NIGHT PEAK	21.5	0.0	0.0	0.0	0.0	0.0	0.0		



Hourly Load & Averages

	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
8月1日	0	0	0.05	0.14	0.39	0.63	0.74	0.89	0.94	0.93	0.84	0.72	0.53	0.26	0.04
8月2日	0	0	0	0.01	0.01	0.01	0.01	0.02	0.04	0.09	0.31	0.38	0.27	0.27	0.13
8月3日	0	0	0.04	0.2	0.31	0.58	0.69	0.36	0.44	0.77	0.72	0.57	0.35	0.28	0.11
8月4日	0	0	0.04	0.19	0.43	0.38	0.73	0.89	0.84	0.78	0.87	0.6	0.41	0.28	0.08
8月5日	0	0	0.06	0.18	0.38	0.55	0.7	0.85	0.94	0.97	0.86	0.73	0.5	0.3	0.1
8月6日	0	0	0.06	0.27	0.49	0.7	0.82	0.91	0.78	0.84	0.73	0.63	0.45	0.26	0.08
8月7日	0	0	0.02	0.08	0.35	0.09	0.28	0.55	0.8	0.86	0.6	0.59	0.49	0.28	0.06
8月8日	0	0	0.04	0.16	0.23	0.51	0.47	0.44	0.41	0.36	0.49	0.26	0.27	0.09	0.01
8月9日	0	0	0.01	0.07	0.1	0.15	0.27	0.22	0.22	0.41	0.44	0.2	0.16	0.06	0.03
8月10日	0	0	0	0.01	0.13	0.2	0.11	0.06	0.11	0.2	0.25	0.1	0.11	0.04	0.01
8月11日	0	0	0.03	0.2	0.3	0.51	0.44	0.58	0.64	0.65	0.65	0.53	0.25	0.29	0.06
8月12日	0	0	0.04	0.12	0.38	0.56	0.41	0.67	0.91	0.79	0.8	0.66	0.45	0.25	0.07
8月13日	0	0	0.01	0.09	0.26	0.57	0.81	0.85	0.75	0.87	0.71	0.47	0.39	0.23	0.07
8月14日	0	0	0.02	0.06	0.35	0.57	0.53	0.77	0.92	0.85	0.83	0.51	0.37	0.19	0.06
8月15日	0	0	0.04	0.22	0.35	0.56	0.54	0.55	0.8	0.78	0.66	0.66	0.43	0.22	0.07
8月16日	0	0	0.01	0.13	0.37	0.36	0.39	0.25	0.5	0.23	0.45	0.48	0.32	0.13	0.05
8月17日	0	0	0.02	0.14	0.37	0.38	0.27	0.11	0.18	0.68	0.45	0.66	0.32	0.24	0.07
8月18日	0	0	0.03	0.15	0.46	0.64	0.59	0.25	0.12	0.31	0.39	0.36	0.37	0.13	0.04
8月19日	0	0	0.01	0.05	0.11	0.08	0.54	0.49	0.69	0.23	0.17	0.2	0.18	0.19	0.04
8月20日	0	0	0.04	0.21	0.46	0.63	0.66	0.72	0.77	0.49	0.73	0.44	0.24	0.13	0.03
8月21日	0	0	0.06	0.26	0.48	0.67	0.82	0.88	0.89	0.87	0.84	0.63	0.45	0.27	0.07
8月22日	0	0	0.04	0.21	0.47	0.44	0.63	0.71	0.62	0.67	0.45	0.4	0.25	0.22	0.05
8月23日	0	0	0.02	0.19	0.31	0.61	0.82	0.89	0.95	0.86	0.75	0.53	0.39	0.17	0.05
8月24日	0	0	0.04	0.18	0.42	0.49	0.63	0.74	0.88	0.74	0.66	0.53	0.37	0.16	0.05
8月25日	0	0	0.03	0.2	0.46	0.57	0.64	0.75	0.79	0.72	0.83	0.52	0.44	0.2	0.02
8月26日	0	0	0.05	0.24	0.45	0.55	0.41	0.77	0.64	0.7	0.88	0.53	0.27	0.23	0.03
8月27日	0	0	0.04	0.21	0.34	0.44	0.63	0.82	0.81	0.61	0.79	0.61	0.43	0.21	0.04
8月28日	0	0	0.04	0.21	0.32	0.46	0.74	0.94	0.93	0.81	0.7	0.57	0.29	0.25	0.05
8月29日	0	0	0.05	0.24	0.46	0.66	0.8	0.91	0.97	0.3	0.23	0.44	0.26	0.21	0.04
8月30日	0	0	0.04	0.25	0.36	0.6	0.71	0.9	0.82	0.36	0.49	0.49	0.47	0.2	0.04
8月31日	0	0	0.04	0.23	0.37	0.54	0.76	0.81	0.75	0.91	0.79	0.61	0.4	0.16	0.03

http://k-ichikawa.blog.enjoy.jp/etc/HP/js/sunShine3/ss3H.html

沖縄、2019年8月、全天

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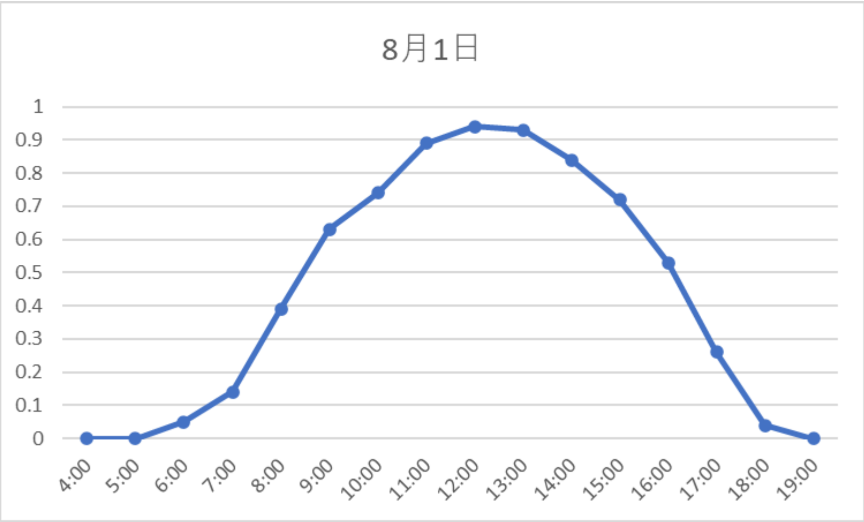
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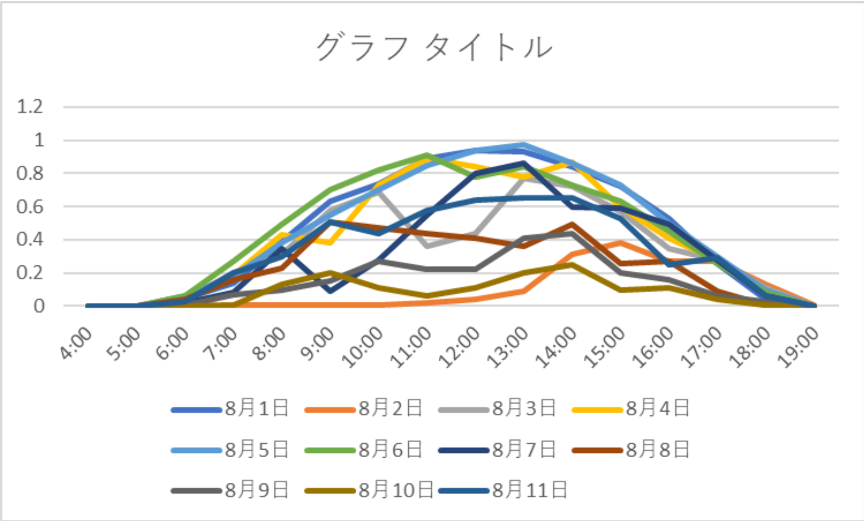
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6月1日	0	0	0.04	0.12	0.25	0.47	0.67	0.68	0.55	0.65	0.75	0.51	0.46	0.11	0.07	0	5.32
2	0	0	0.02	0.11	0.29	0.34	0.44	0.77	0.64	0.38	0.35	0.29	0.22	0.09	0.01	0	3.94
3	0	0.01	0.05	0.13	0.18	0.18	0.1	0.33	0.2	0.55	0.54	0.39	0.35	0.18	0.04	0	3.22
4	0	0	0.07	0.2	0.4	0.37	0.52	0.48	0.46	0.49	0.34	0.17	0.02	0.01	0.01	0	3.54
5	0	0	0.1	0.17	0.2	0.33	0.48	0.6	1	0.95	0.86	0.7	0.51	0.27	0.06	0	6.22
6	0	0.01	0.11	0.25	0.41	0.63	0.84	0.61	0.54	0.68	0.82	0.55	0.32	0.22	0.15	0.01	6.13
7	0	0	0.06	0.3	0.52	0.7	0.84	0.91	1.01	0.97	0.84	0.73	0.53	0.27	0.03	0	7.71
8	0	0	0.03	0.07	0.13	0.28	0.29	0.37	0.32	0.26	0.21	0.16	0.27	0.06	0.02	0	2.46
9	0	0	0.03	0.07	0.26	0.52	0.37	0.59	0.52	0.26	0.12	0.05	0.08	0.1	0.03	0	3.01
10	0	0	0	0	0.02	0.16	0.58	0.29	0.39	0.22	0.42	0.23	0.13	0.06	0.02	0	2.54
11	0	0	0.01	0.04	0.11	0.09	0.07	0.29	0.36	0.54	0.24	0.16	0.23	0.08	0.02	0	2.23
12	0	0	0.06	0.18	0.46	0.73	0.88	0.9	0.66	0.64	0.64	0.51	0.44	0.27	0.09	0.01	6.46
13	0	0	0.04	0.14	0.3	0.34	0.26	0.4	0.47	0.38	0.34	0.18	0.13	0.1	0.02	0	3.1
14	0	0	0.03	0.03	0.02	0.06	0.06	0.28	0.31	0.22	0.33	0.39	0.19	0.1	0.04	0	2.04
15	0	0	0.04	0.31	0.51	0.76	0.85	0.97	1.02	0.99	0.87	0.76	0.51	0.3	0.08	0.01	7.99
16	0	0.01	0.12	0.34	0.55	0.75	0.91	0.99	1.02	0.88	0.81	0.74	0.48	0.24	0.08	0.01	7.93
17	0	0	0.05	0.19	0.19	0.36	0.35	0.37	0.24	0.15	0.14	0.09	0.11	0.08	0.07	0	2.37
18	0	0	0.02	0.14	0.3	0.46	0.26	0.23	0.23	0.11	0.34	0.02	0	0.02	0.06	0	2.19
19	0	0	0.03	0.12	0.21	0.19	0.37	0.36	0.44	0.59	0.57	0.29	0.28	0.23	0.03	0	3.72
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20	0	0	0.01	0.02	0.06	0.08	0.17	0.27	0.11	0.04	0.06	0.04	0.03	0.03	0.01	0	0.94
21	0	0	0.03	0.12	0.27	0.43	0.77	0.42	0.49	0.63	0.6	0.47	0.16	0.13	0.04	0	4.55
22	0	0	0.01	0.04	0.04	0.1	0.09	0.14	0.23	0.2	0.15	0.25	0.17	0.09	0.04	0	1.55
23	0	0	0.01	0.03	0.04	0.13	0.16	0.11	0.16	0.27	0.16	0.14	0.09	0.04	0.01	0	1.35
24	0	0	0.01	0.05	0.08	0.07	0.14	0.15	0.16	0.18	0.22	0.21	0.15	0.1	0.05	0	1.58
25	0	0	0.03	0.07	0.11	0.16	0.41	0.45	0.43	0.43	0.44	0.28	0.2	0.16	0.07	0	3.23
26	0	0	0.01	0.01	0.01	0.05	0.12	0.16	0.47	0.46	0.27	0.35	0.18	0.11	0.07	0	2.27
27	0	0.01	0.07	0.15	0.41	0.68	0.56	0.85	0.83	0.65	0.34	0.21	0.13	0.11	0.04	0	5.04
28	0	0	0.03	0.24	0.48	0.54	0.51	0.62	0.78	0.96	0.73	0.43	0.33	0.15	0.03	0.01	5.81
29	0	0.01	0.09	0.22	0.31	0.57	0.88	0.71	0.76	0.73	0.79	0.74	0.53	0.34	0.14	0.01	6.82
30	0	0	0.06	0.21	0.46	0.48	0.81	0.8	0.76	0.96	0.89	0.64	0.47	0.25	0.13	0.01	6.92

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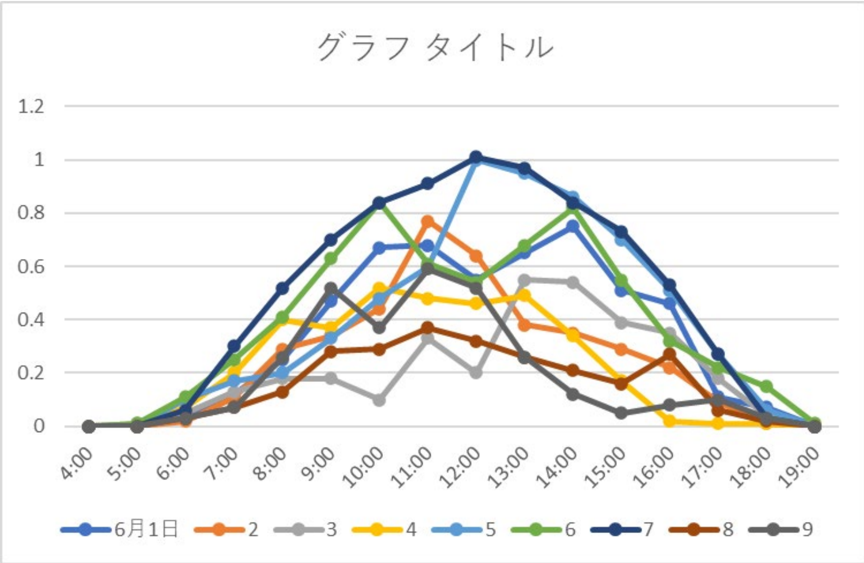

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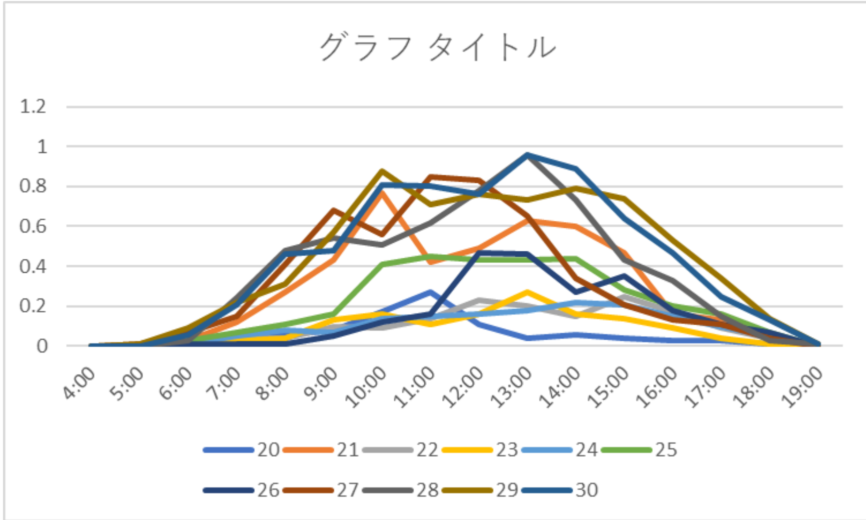

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15. 付録 H：St_Kitts_最低負荷等の別フォーマット(現地にて収集、2019 年)

2.4 Dynamic Stability Analysis

Table 2-8 Dispatch at Minimum Load

Generator	Pgen	Pmin	Pmax	Spinning Reserve	%Loading	Down Reserve
	MW	MW	MW	MW	MW	MW
Generator#1	5.80	1.22	6.13	0.00	94.60%	4.58
Generator#2	3.34	0.77	3.87	0.52	86.50%	2.58
Generator#3	3.50	0.77	3.89	0.39	89.80%	2.72
Generator#4	3.60	0.77	3.89	0.29	92.40%	2.82
Generator#8	0.00	0.73	3.66	0.00	0.00%	0.00
Generator#9	0.00	0.70	3.50	0.00	0.00%	0.00
Generator#10	0.00	0.77	3.89	0.00	0.00%	0.00
Generator#11	0.00	0.77	3.89	0.00	0.00%	0.00
Generator#12	0.00	0.77	3.89	0.00	0.00%	0.00
Generator#14	0.00	0.77	3.89	0.00	0.00%	0.00
Generator CAT1		0.41	1.65			
Generator CAT2		0.41	1.65			
Generator CAT3		0.41	1.65			
Generator CAT4		0.41	1.65			
Generator CAT5		0.41	1.65			
Generator CAT6		0.41	1.65			
sum	16.24	5.99	27.68			

Table 1.3

Existing SKELEC Generation

Ramp Capability	
kW/sec	MW/h
122.00	439.20
77.40	278.64
77.92	280.51
77.92	280.51
73.20	263.52
70.00	252.00
77.92	280.51
77.92	280.51
77.92	280.51
77.92	280.51
55.00	198.00
55.00	198.00
55.00	198.00
55.00	198.00
55.00	198.00
55.00	198.00

April 2019

Generators Fuel Eff (1).docx

Generators Fuel Efficiency (kWh/gal)

UNIT	70%	逆数
Generator#1	18.08	5.531
Generator#2	18.01	5.552
Generator#3	17.38	5.754
Generator#4	17.23	5.804
Generator#9	17.90	5.587
Generator#10	17.99	5.559
Generator#11	18.47	5.414
Generator#12	17.99	5.559
Generator#14	－	
Generator CAT1	17.50	5.715
Generator CAT2	16.00	6.248
Generator CAT3	16.00	6.248
Generator CAT4	17.50	5.715
Generator CAT5	16.00	6.248
Generator CAT6	17.50	5.715

Notes:

Pgen = amount of generation output

Spinning Reserve = Pmax - Pgen

Down Reserve = Pgen - Pmin

CAT1～CAT2のRated Capacityは2MWだが、定格1.65MWで運用中

CAT1～CAT2のPminは要調査。少なくとも25%Loadは問題無しのため。25%Loadの値を入力

CAT1～CAT2のRamp rateは不明のため、30秒で定格となるような値を想定した。

cf.https://www.jadelmas.com/en/brands-products/products-caterpillar-product-line/power-systems/electric-power/diesel-generator-sets/cm32c-inline-generator-set

CAT5, CAT6のGenerators Fuel Efficiencyは、CAT1～4をもとにした推定値

16. 付録 I:20191120St.Kitts ご報告、日本工営様の現地出張結果報告

St. Kitts 島出張 系統解析関係ご報告

2019/11/27 日本工営 新美

1．活動内容概要

・ SKELEC への系統解析関係の現状説明を実施

・ SKELEC へ追加で必要な情報をヒアリング

・ SKELEC と Site visit にて情報収集

・合同調整会議等の場で GridSim（仮称） をアピール（反応は良く、 SKELEC や MPI は協力してくださるとのこと 。 ）

2．収集情報

□Bassetelle の 500kW PV は 8 月頃から運転していない。現在はシャットダウン中。 接続先のフィーダは Bayfords である。

□SKELEC に設置した 1.2MW の太陽光も現在故障により稼働しておらず、保証期間の範囲であるため、全体を撤去し新たに同規模のものを設置することになっている。現在、台湾の業者からの反応を待っているところである。 34MW Laclanche 事業について、ベースは 16MW、 18MW Max で PPA を締結した。16MW を超過した分は SKELEC は電力購入料金を支払わない。 超過分はバッテリーに蓄電し、日没後に売電するよう要求している。

□ 11.3 kV で発電し、末端で 11kV になるように送電している。電圧降下の問題はない。

□ Canon のフィーダの負荷は昼間 2.2 MW、夜間 3.2MW 程度である。 Wind の 5MW が入るとフィーダは限界となる。

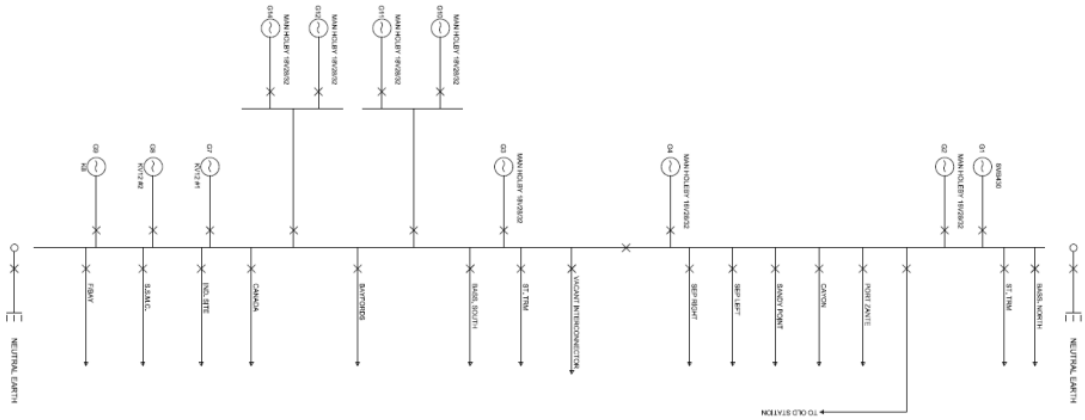
□ シミュレーションに必要なデータは提供する。 Heat Rate, Active power, reactive power,
cost of maintenance など提供可能。

□ 2MW 名板容量、実際出力 1.6MW x 6 units CAT ディーゼル発電機を導入（4 基は 3 月の際に導入済で、 2 基をさらに設置）した。番号は CAT1, CAT2, ...CAT6。全て同じモデル。実際出力を抑えているのは High Speed Diesel でメーカーの推奨による。気温が熱すぎるためか。□ レイドスの最新 F/S 結果はまだ正式に発行されていないため、提供できない

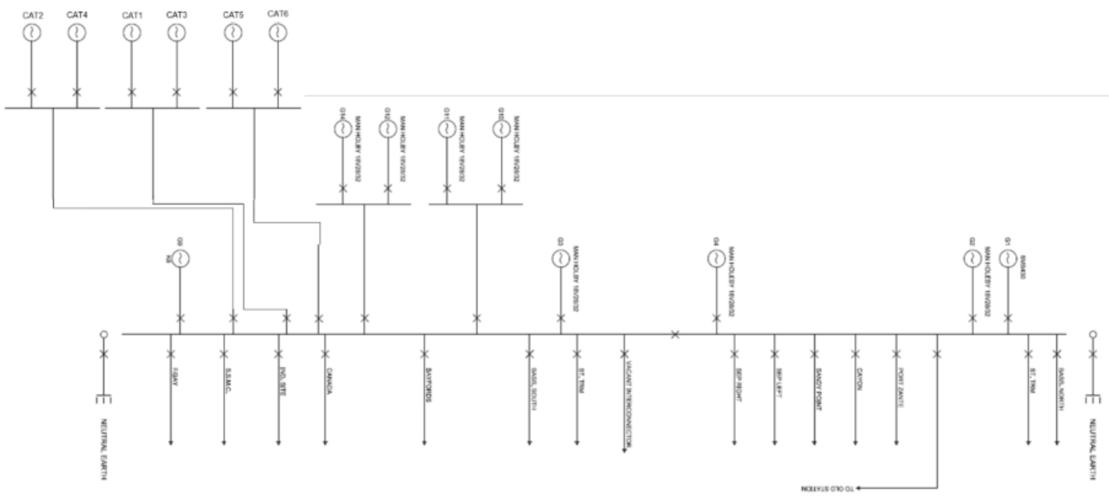
□ 34MW Laclanche 事業におけるインバーターの仕様等はまだ機密なので提供できない

□ Caterpillar 製ディーゼルエンジン発電機 CAT5,6（銘板定格 2MW、実運用定格 1.6MW）
が 2 台増設されており、接続先を示す単結は次図の通りである。

変更前



変更後



- 6 台の Caterpillar 製ディーゼルエンジン発電機は全て同じ仕様とのこと。CAT5 の銘板の写真:
- 10 月 30 日昼間の発電状況
- 各フィーダの負荷は以下の通り。

Feeder	Day Peak	Night Peak
Basseterre North	4.2	4.2
Port zone	1.5	1
Cayon	2	2.8
Sandy Point	1.4	1.8
S.E.P. (Mariott 1)		
S.E.P. (Mariott 2)		
Industrial site	5	1.6
Frigate bay	2.4	2.6
Bassetrre south	4.9	3.1
Bayfords	1.0	1.4
SSMC/Airport	0.8	0.8
CANADA	1.2	1.2

□

Lodge 開閉所は 2 重化構成のリモート制御装置、開閉器のみのシンプルな設計。その他の開閉所も同様な構成。

□ 調相装置は導入していないとのこと

３．系統解析への変更点

・発電機 CAT5,6 の追加

・発電機 G7,G8 の削除

・ 500kW PV の接続先を Bayfords フィーダに変更

・ 34MW Laclanche PV 事業の売電契約 16MW、 18MW Max に基づいたプログラム

・ノードの特異点は、データ異常であったため、他ノードを参考に調整

４．出張スケジュール

10/20 日本発

10/27	St. Kitts 着
10/28	MPI、 SKELEC、 JICA St. Lucia と打合せ
10/29	合同調整会議
10/30	SKELEC と打合せ、 Site visit
10/31	Nevis 島へ渡り関係者と打合せ
11/01	MPI と打合せ予定
11/03	St. Kitts 発
11/11	日本着

以上

17. 付録 J: 大規模送配電系統における高速潮流計算プログラムの解説

環境エネルギー技術研究所㈱

１．背景と経緯

電力系統における潮流計算手法には，送電系統向けの Newton-Raphson 法や配電系統向けの Backward/Forward 法など，多くの解法が提案されている。これらの解法の性能比較については, 過去に実施されてはいるが,「時期が古い, 大規模系統を対象としていない」などの不十分さがあり,「どの程度の系統規模まで，どれぐらい速く解けるのか」が不明確であった。

そこで，2011 年度に，大規模配電系統を対象として，Newton-Raphson 法と Backward/Forward 法の比較シミュレーションを行い, Backward/Forward 法の優位性を実証した。

しかしながら，Backward /Forward 法は弱ループ・ネットワークを取り扱える機能はあるものの，ループが多数存在する送電系統にどの程度適用可能であるかは未知数であった。

また，最適潮流計算を非線形計画問題として厳密に解くには，Newton-Raphson 法的アプローチが不可欠である。このような視点にもとづき，2012 年度に大規模送電系統を対象として，①2011 年度に開発した Newton-Raphson 法による潮流計算の大幅改造と高速化，および②近年の理論的成果と言える「線形方程式の反復法による解法」を Newton-Raphson 法に実装する試み，を行った。

①では，Jacobian 疎行列作成とその LU 分解の高速化(以降、改良 Newton-Raphson 法と称す)，②では，非対称連立一次方程式の代表的反復解法であるリスタート型 GMRES(Generalized Minimal Residual method)法を Newton 方程式に適用した Newton-GMRES 法の実装，を実現した。ここで、両者を EETRI 法と命名する。

２．大規模配電系統におけるシミュレーションの結果（2011,2012 年度）

ループの無い仮想的大規模配電系統(Radial Distribution network)を，木構造を有する有向グラフとしてランダムに発生させて，数値実験に使用した（表 1，2 参照)。この木の根をスラックバスとし，木の葉を負荷ノード(PQ 指定ノード)，残りは中間通過・分岐点(指定値零の PQ ノード)とする。なお、ブランチの R/X 比は[1.0,10.0]を使用し、Susceptance はすべて無視する。

結果として、改良 Newton-Raphson 法では，n=40000 のケースにおいて，2011 年度の結果より約 230 倍の高速性を達成することができた。ただし，その計算時間は Backward/Forward 法の約 4 倍であるので，Backward/Forward 法の優位性は揺るがない。

表１ 大規模配電系統での数値実験の結果（2011 年度）

ノード (n)	負荷ノード	スラック電圧	反復回数		最終誤差(PQmismatch)		実行時間(s)		速度比
			N/R	B/F	N/R	B/F	N/R	B/F	NR/BF
500	240	5.00	5	15	2.619e-6	4.592e-7	0.031	0.016	1.94
1000	483	10.00	5	18	9.683e-5	5.217e-7	0.062	0.015	4.13
2000	1012	20.00	4	7	1.274e-6	2.869e-7	0.203	0.016	12.69
5000	2510	20.00	6	23	1.985e-7	5.688e-7	1.856	0.062	29.94
10000	5125	30.00	5	9	3.392e-10	9.378e-7	6.147	0.015	409.8
20000	10387	40.00	6	17	3.201e-10	4.610e-7	29.312	0.047	623.7
30000	15920	40.00	6	16	2.474e-10	7.494e-7	65.848	0.078	844.2
40000	21142	50.00	6	20	1.756e-8	7.155e-7	116.610	0.125	932.9
50000	27346	50.00	―	25	―	9.499e-7	―	0.188	―

N/R：Newton-Raphson 法

B/F：Backward/Forward 法

表２ 大規模配電系統での数値実験の結果（2012 年度）

ノード (n)	非零要素数	フィルイン率		反復回数		最終誤差(PQmismatch)		実行時間(s)		速度比
		N_R	N_G	N_R	N_G	N_R	N_G	N_R	N_G	N_G/N_R
500	5956	1.279	1.156	5	5	2.619e-6	2.619e-6	0.016	0.031	1.94
1000	11972	1.261	1.138	6	6	2.326e-10	1.845e-8	0.016	0.047	2.94
2000	23908	1.284	1.163	4	4	1.274e-6	1.251e-6	0.015	0.031	2.07
5000	59916	1.281	1.159	6	6	1.985e-7	1.985e-7	0.062	0.140	2.26
10000	119892	1.275	1.155	5	5	3.338e-10	1.002e-8	0.093	0.234	2.52
20000	239876	1.275	1.157	6	6	2.637e-10	3.408e-8	0.249	0.562	2.26
30000	359908	1.276	1.160	6	6	2.710e-10	1.948e-8	0.358	0.874	2.44
40000	479900	1.280	1.162	6	6	1.754e-8	1.323e-6	0.500	1.233	2.47
50000	599876	1.280	1.167	6	6	5.094e-6	5.095e-6	0.656	1.575	2.40

N_R：改良 Newton-Raphson 法

N_G：Newton-GMRES 法

非零要素数：Newton 方程式のヤコビアンにおける非零要素の個数

フィルイン率：完全 LU 分解の非零要素数/上記非零要素数（改良 Newton-Raphson 法）

：不完全 LU 分解の非零要素数/上記非零要素数（Newton-GMRES 法）

ここで、Newton 法による各反復において

①改良 Newton-Raphson 法では、まず完全 LU 分解を行い、その後に一回の求解操作を行う。

②Newton-GMRES 法では、まず不完全 LU 分解を行い，その後の求解操作において GMRES 法による収束改良を複数回行う。不完全 LU 分解は完全 LU 分解より安価であるが、後処理を要する。

３．大規模送電系統におけるシミュレーションの結果（2012 年度）

多数のループを有する仮想的大規模送電系統を，無向グラフとしてランダムに発生させて，数値実験に使用した。ここで，平均のノード次数(接続ブランチ数：degree)2.5 を

与えてランダムグラフを作成し(ノード数をn とすると，ブランチ数 m=1.25n, ループ数 m-n+1), そのノード群を以下のように分類して, 標準π型モデルの送電系統を作成した。

① 入次数(in-degree)の小さいノード順に発電ノードを割り当て，最初の発電ノードをスラック・ノード，以降を PV ノードとする。全体の発電機総数は 51 に固定する。

② 出次数(out-degree)がゼロのノードは，すべて負荷ノード(PQ 指定ノード)とし、その他のノードは，中間通過・分岐点(指定値零の PQ ノード)とする。

なお、ブランチの R/X 比は[1.0,10.0]を使用し、Susceptance は，ブランチとノードにランダムに設定した。

表３ 大規模送電系統での数値実験の結果（2012 年度)

ノード (n)	非零要素数	フィルイン率		反復回数		最終誤差(PQmismatch)		実行時間(s)		速度比
		N_R	N_G	N_R	N_G	N_R	N_G	N_R	N_G	N_G/N_R
500	6398	3.009	1.102	5	5	4.427e-12	9.734e-8	0.031	0.047	1.516
1000	13390	4.133	1.056	5	5	1.582e-11	1.135e-7	0.078	0.078	1.000
2000	27422	6.605	1.045	4	3	1.337e-10	2.945e-6	0.109	0.094	0.862
5000	69406	12.317	1.034	4	4	1.128e-9	3.639e-8	1.029	0.343	0.333
10000	139398	22.954	1.028	4	4	4.610e-9	7.800e-8	7.972	0.842	0.106
20000	279462	40.454	1.019	4	4	2.661e-8	9.036e-7	53.274	2.106	0.040
30000	419450	59.484	1.021	4	4	5.754e-8	2.070e-6	179.541	4.212	0.023
40000	559362	75.681	0.990	4	4	1.198e-7	1.539e-5	401.264	8.986	0.022
50000	699258	82.070	0.952	5	5	3.029e-7	3.410e-7	810.835	30.779	0.038

結果として、ループの無い大規模配電系統では，Newton-GMRES 法は改良 Newton-Raphson 法よりも低速であったが、多くのループを有する大規模送電系統では，Newton-GMRES 法の方が改良 Newton-Raphson 法よりも高速となった。木構造の配電系統では、アドミッタンス行列およびそのヤコビアン行列はバンド形状の行列であり、ヤコビアン行列が効率的に完全 LU 分解できることが，改良 Newton-Raphson 法の方がより高速であった理由と言える。

４．EETRI 法の適用例

① 配電系統における分散電源最適配置問題

126 母線の配電系統での潮流計算(B/F) 159,0544 回を約 31 秒

② 配電系統における時系列依存の確率的潮流計算

126 母線の配電系統での潮流計算(B/F) 288,0000 回を約 87 秒

③ 配電系統における連続型単目的 OPF の各種メタ解法

126 母線の配電系統での潮流計算(改良 Newton-Raphson) 約 1,8200 回を約 17*秒（10-trials)

④ 配電系統における連続型・離散型多目的 OPF のメタ解法

126 母線の配電系統での潮流計算(改良 Newton-Raphson) 1,2951 回を約 12*秒（1−trial)

⑤配電系統におけるスイッチ組合せ問題

126 母線の配電系統での潮流計算(B/F) 163,6290 回を約 29 秒

8. 付録Ａ:カリコム系統安定化シミュレーション報告(中間)

環境エネルギー技術研究所作成

1. 実施業務の概要

２０１９年度に実施した内容を下記に示す目次に分類して記す。

- 今年度業務における実施項目と進捗状況
- 系統解析シミュレーション・ツールの説明
- 系統解析シミュレーションの暫定的結果
- 成果物と報告書
- 今後（2020 年度以降）に向けた課題等

2. 2019 年度業務における実施項目と進捗状況

1) 電力系統解析の基本的事項

2019 年度の業務に関して、事前に予定されていた項目と中途に追加された項目に関し、その内容と進捗状況を以下のように整理した。

電力系統解析の基本についての講義系統解析に使用するソフトウェアとして、作成中のツール *MicroGrid Designer*（仮称） を使用することを前提としていたのでその作業内容を説明する講義資料を作成し、電力系統解析の基本的事項を交えて、当該プロジェクトのメンバーにて論議した。(2019/07)

2) St.Kitts 島における収集資料の精査

第１次渡航で収集された St.Kitts 島の発電所・発電機情報、系統構成と系統属性、 及び負荷・再生可能エネルギー(太陽光発電と風力発電)情報についての精査を行い、系統解析に使用可能となりそうなデータを抽出したまた、同時に収集された St.Kitts 島における既実施の系統計画レポート「Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept.2014 by leidos」(以下、参考資料と称す)を主たる参考資料としてレビューを行った。

3) St.Kitts 島における系統属性の確定

第１次渡航で収集された St.Kitts 島の系統情報には、すぐに使える実用的な数値データが少なかったので、参考資料で述べられていた「PSS/E を使用して潮流計算を実施した」ことをもとに、本プロジェクトにも PSS/E 用のデータを活用することを提案した。なお、PSS/E は Siemens 社で開発された高額な系統解析ツールである。その結果、PSS/E 用のデータが第

２次渡航で収集されたので、これを *MicroGrid Designer* 用のデータに変換することができた。

4) St.Kitts 島における潮流計算の追試

PSS/E からの変換データをもとに、St.Kitts 島の概略系統構成図を作成し、*MicroGrid Designer* により潮流計算（単期間）５ケース(下記)を実行し、その結果の検討を行った。

PSS/E 用のデータの特徴は、１箇所の発電所から 12 本のフィーダが出るループなしの配電系統であり、各フィーダ末端には小規模太陽光発電、１本のフィーダ中間に一台の大規模風力発電(5.4MW)が設置してあることである。

参考資料には潮流計算結果の詳細は記載されていないので比較はできないが、*MicroGrid Designer* による潮流計算結果に妥当性が十分あるように判断されるので、現地における PSS/E 用のデータは実際に活用可能であることが明確化された。但し、このデータは６年以上前に作成されているので、以降の系統更新に留意する必要がある。

潮流計算（単断面）を行った５ケースを以下にしめす。

Case0： PSS/E の変換データを直接使用したケース(図１)

Case1：再生可能エネルギー無しパターン：PV, Wind の出力を 0 とするケース

Case 2：ベース条件（図２）

- PV500kW(SKELEC サイト)を Bus 4 に接続
- PV700kW(空港)を他の火力発電ユニットと同様に、Bus 1 に接続
- 上記 2 か所以外の PV, Wind の出力を 0 とする

Case3：ベース条件

- PV500kW(SKELEC サイト)を Bus 3(Canada_1219)に接続
- PV700kW(空港)を他の火力発電ユニットと同様に Bus 1 に接続
- 上記 2 か所以外の PV, Wind の出力を 0 とする

Case4：既存計画反映 00 (図３)

- ベース条件 I に追加して、PV35MW を Bus 1 に接続
- 蓄電池(BESS)34MWh/5.6MW も同様に、Bus 1 に接続
- 上記以外の PV, Wind の出力を 0 とする

5) St.Kitts 島における系統計画の確認

第３次渡航で St.Kitts 島における発電所・発電機情報、系統構成と系統属性、及び負荷・再生可能エネルギー(太陽光発電)情報についての再確認と変更点の調査・収集がなされたので、これらから MicroGrid Designer による系統解析（多段経済負荷配分と多段潮流計算）用のデータを作成し、想定であるが、蓄電池付き大型太陽光発電 35MW の導入計画確定発電

機６台の追加、地下ケーブルと地上送電線の位置情報と線種の収集（図４）および週単位・負荷曲線データの確定を行った。

６） St.Kitts 島における系統解析シミュレーション

上記の経緯を経て、今年度業務における最終的な系統解析を行う準備が完成したので、St.Kitts 島・電力系統における最適蓄電池容量の決定と MicroGrid Designer による多段経済負荷配分と多段潮流計算を実施し、一週間単位の需給シナリオに基づいた発電機群と蓄電池の最適ディスパッチ・スケジューリング計画の策定と電圧安定性の検証を行った。詳細内容は、後述の「 系統解析シミュレーションの暫定的結果」にて述べる。この結果は、MicroGrid Designer が系統需給計画と電圧安定性評価に寄与できるツールであることを実証したと判断される

3. 系統解析シミュレーション・ツールの説明

電力系統シミュレータ MicroGrid Designer は、環境エネルギー技術研究所により開発された（一部開発中の）電力系統エンジニア・実務者向けの送配電系統用数値解析ツールである。その主な用途は、対象とする電力系統において発電機群と計画時間帯の負荷が与えられている場合に、計画時間全体の需給バランスの最適化を行って燃料費を最小とする発電機出力を決定し、引き続き系統の時間帯別潮流計算を行うことにより周波数や電圧の運用安定性を検証する点にあります。発電機群として、再生可能エネルギーや蓄電池も考慮することが可能である。

電力系統分野においては，これまで多数の解析ソフトウェアが開発されているがが、近年のスマートグリッド技術の進展や再生可能エネルギーの導入拡大等に伴い、配電系統における系統解析の高度化と並んで専門外のエンジニアにも利用可能な簡素化されたツールの開発が求められている。

このような状況を考慮して、電力系統シミュレータ MicroGrid Designer は次のようなコンセプトで開発されている。

1 マイクログリッド等の小中規模配電系統を主対象として、より高度な電力需給バランス解析と周波数及び電圧変動解析に寄与する系統解析ツールとする。

2 Excel を使用した入出力及び演算操作インターフェイスにより、ユーザ・フレンドリな機能を与え、専門外のエンジニアにも使いやすいソフトウェアとなっている。

電力需給バランス解析には、実際に運用可能な条件を取り入れた最適化問題としており扱い、一般に知られている効率的解法を使用している。

*MicroGrid Designe*r では、経済負荷配分(ELD: Economic Load Dispatch)と潮流計算(Power flow)を多断面で実行する。

ここで、MicroGrid Designer では、多断面の経済負荷配分を多段経済負荷配分(Multi stage

ELD)、また多断面の潮流計算を多段潮流計算(Multi stage Power flow)と、名付けた。

多段経済負荷配分では、対象とする電力系統において発電機群と計画時間帯の総負荷が与えられている場合に、計画時間全体の需給バランスの最適化を行って燃料費を最小とする発電機群の有効電力出力を決定する。

また多段潮流計算では、多段経済負荷配分で決定された発電機群の有効電力出力を使用して、時間帯別潮流計算を逐次的に実行し、母線電圧とブランチ潮流を算定する。

発電機群として、再生可能エネルギー(RES: Renewable Energy Sources)や蓄電池も考慮することが可能である。蓄電池は、充放電量を調整することにより、系統全体の需給インバランスを吸収させる。

MicroGrid Designer は、前記のように、多段経済負荷配分と多段潮流計算を連続して実行する機能を有するツールであるが、1断面に適用すれば、一般的にも使用されている経済負荷配分と潮流計算を単独に実行することができる。

以上、電力系統シミュレータ MicroGrid Designer について概説した。詳細については、英文報告書の 3 章、4 章、5 章の ELD, LFC 及び電力潮流解析の定式化と解法に詳しく述べられているので、それを参照して頂きたい。

3. 系統解析シミュレーションの暫定的結果

既述した 2019 年度業務における実施(予定)項目と進捗状況及び St.Kitts 島における系統解析シミュレーションについて、その具体的内容を以下に２分類して示す。

・最適蓄電池容量の決定
・*MicroGrid Designer* による系統解析シミュレーション

1) 最適蓄電池容量の決定

大型太陽光発電 35MW の導入においては余剰電力対策が必須であり、そのために大容量蓄電池の併設が通常なされる。その際、最適な蓄電池容量の事前決定が必要要件となる。PV, 蓄電池を考慮した電力需要の均し処理を行うツール（図５）を試作中であり、数値が不明である余裕率や SOC を考慮しない場合の蓄電池の最小必要容量を次のように算定した。

St.Kitts 島の代表的日負荷パターンと太陽光出力をもとに、下記３シナリオに対し、蓄電池の時間最大出力を変えて、それぞれの蓄電池・最小必要容量を試算した。ここで、太陽光の最大出力は、最大負荷 28.8MW よりも大きい 35MW を想定している。

① シナリオ A (最大負荷時) ： 最大負荷 28.8MW
② シナリオ B (中負荷時) ： 最大負荷 20.0MW
③ シナリオ C (小負荷時) ： 最大負荷 10.0MW

なお、太陽光出力が負荷よりも小さいシナリオは、蓄電池の出番がないので除外する。あくまでも想定の下での算定であるが結果は、以下の通りである。

① シナリオ A (最大負荷時) : 最小必要容量 19..943MWh
② シナリオ B (中負荷時) : 最小必要容量 75.548MWh
③ シナリオ C (小負荷時) : 最小必要容量 159.785MWh

試算結果による暫定結論は、以下のとおりである。

① シナリオ A,B,C すべてに対応可能な蓄電池容量は、超過大すぎる。
② シナリオ B,C に対応可能な蓄電池容量も、超過大すぎる。
③ したがって、シナリオ A により蓄電池容量を決定する方が良いが、これによる蓄電池容量ではシナリオ B,C に対応できないので、シナリオ B,C が生じるような状況では、太陽光の出力抑制を実施することで対応しなければならない。
④ シナリオ A で決定された最適な蓄電池・最小必要容量は約 20MWh であり、この最適容量は、蓄電池の最大充放電量 8MW で余剰電力が発生しないように決められている。

以上に示したツールは、蓄電池容量の簡略見積もり用であるので、MicroGrid Designer の多段経済負荷配分を使用して、日単位での最適な蓄電池・最小必要容量の決定もできる（図６）。その結果は、シナリオ A に対し、蓄電池最大充放電量 5.386MW、蓄電池最小容量 14.840MWh であり、MicroGrid Designer の多段済負荷配分の方がより少ない蓄電池最小容量を与えることが実証された。しかし、これは、各種想定の上での結果であり、実運用を踏まえての条件設定の上での再計算が必要である。

2) *MicroGrid Designer* による系統解析シミュレーション

MicroGrid Designer による多段経済負荷配分

一週間単位の需給シナリオに基づいた発電機群と蓄電池の最適ディスパッチ・スケジューリング計画（１時間単位）の策定を下記３ケースに対して実施した。
検討３ケース（図９）では、代表月の１週間; 負荷 profile が異なる。

- case-1: 2019/3/3 2019/3/9 (1 week)
- case-2: 2019/4/7 2019/4/13 (1 week)
- case-3: 2019/7/7 2019/7/13 (1 week) 最大負荷月

ここで、上記３ケースに共通して使用した系統条件として、太陽光発電と余剰電

力対策について述べておく。
・太陽光発電 3 基　(35MW, 0.7MW, 0.5MW)
　これらの発電シナリオとして、天候を考慮した１週間の代表的パターンを使用（図８）。大型太陽光発電（定格 35MW)の最大出力を実効値 25MW に限定。

・余剰電力対策
　太陽光発電からの余剰電力対策として、「蓄電池と需給インバランスを吸収するための調整スラックを設け、この調整スラックを通じて余剰電力を外部へ流す」こととした（図７）。但し、大型太陽光発電の最大出力を 25MW に限定したので、検討３ケースとも調整スラックからの流出はわずかしか発生していない結果が得られている。
　また、蓄電池の充電を昼間時間に制限し、最大出力（最大充放電量）を最適蓄電池容量の決定を参考にして 5MW までとした。これにより、蓄電池の最小必要容量の最大見積りは最大充電量(5MW)*7h = 35MWh となる。但し、シミュレーション結果による実際の（最適な）最小必要容量は、以下の通りであった。

- case-1： 最大出力 5.00 MW、最小必要容量 18.16 MWh
- case-2： 最大出力 3.97MW、最小必要容量 10.28 MWh
- case-3： 最大出力 3.02 MW、最小必要容量 5.65 MWh

　この結果より、検討３ケースにおける蓄電池の最小必要容量は約 18MWh と判断できる根拠が示された。

② MicroGrid Designer による多段潮流計算
　上記の多段経済負荷配分の結果により得られた発電機・蓄電池の有効電力出力を利用して、検討３ケースに対し、一週間（１時間単位 168 断面）の多段潮流計算を実施した。また下記の表に示すように、得られた電圧値の最大・最小より電圧安定性の検証を行い、多少の逸脱はあるが概ね規定範囲内（0.95～1.05p.u.）にあること」を確認した。但し、この表に掲載している電圧値は、St.Kitts 島における最近の系統更新を考慮した系統属性（インピーダンス等）を反映していないデータの下で算定されているので、正確なものではないため、データを確認ののち、本年度に、算定する必要がある。

　多段潮流計算による電圧値と有効電力ロスは、電圧値最小[p.u.]　電圧値最大[p.u.]　有効電力ロス[%]である。

- case-1：0.96087 1.06998 4.699 図 10 参照
- case-2：0.95743 1.07247 4.655 図 11 参照

- case-3：0.92619 1.05684 4.591 図 12 参照
-

4. 成果物と報告書

項目「今年度業務における実施項目と進捗状況」にした項目内容
に対応する成果物と報告書は、以下のとおりである。

１）電力系統解析の定式化と解法

レクチャー用の講義資料（英文報告書第 4 章）

２）St.Kitts 島における収集資料の精査

第１次渡航で収集された St.Kitts 島の発電所・発電機情報、系統構成と系統属性、 及び負荷・再生可能エネルギー(太陽光発電と風力発電)情報と系統計画レポート「Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept.2014 by leidos」。

３）St.Kitts 島における系統属性の確定

第２次渡航で収集された PSS/E 用のデータと MicroGrid Designer 用に変換されたデータ。

４）St.Kitts 島における潮流計算の追試

PSS/E からの変換データをもとに算定された MicroGrid Designer による潮流計算（単期間）５ケースの結果(下記の図表に示す)。

５）St.Kitts 島における系統計画の確認

第３次渡航で収集された St.Kitts 島における発電所・発電機情報、系統構成と系統属性、及び負荷・再生可能エネルギー(太陽光発電)情報。

６）St.Kitts 島における系統解析シミュレーション

St.Kitts 島・電力系統における MicroGrid Designer による潮流計算を実施した結果は、英文報告書中にまとめられている。多段潮流計算については、本算定報告末尾に図に示した。

5. 今後（2020 年度以降）に向けた課題等

2020 年度の業務実施においては、St.Kitts 島において収集された系統情報をもとに MicroGrid Designer による系統解析シミュレーションを行い、その適用妥当性の実証と系統計画策定における発電機ディスパッチ・スケジューリングの作成および周波数及び電圧の変動を解析し運用安定性の検証を行う。

重要なベース資料として有効であったものは、PSS/E 用のデータである。これまでの現地におけるデータ収集では、発電機の構成、RE の導入計画、負荷情報等は収集可能であったが、インピーダンス等実際的な系統属性については収集困難な状況にあることが明確になった。したがって、今後他島への展開を行う上では、実際的な系統属性をどう収集するか、PSS/E 用のデータあるいは同等のデータは存在するか、現地カウンターパートから最新の数値情報入りの系統図作成の協力が得られるか等の課題が残されている。

以下には、これから作成するマイクログリッド解析ツールの入出力のイメージを示す。

この解析ツールは、2021 年度後期までに完成させる予定である。

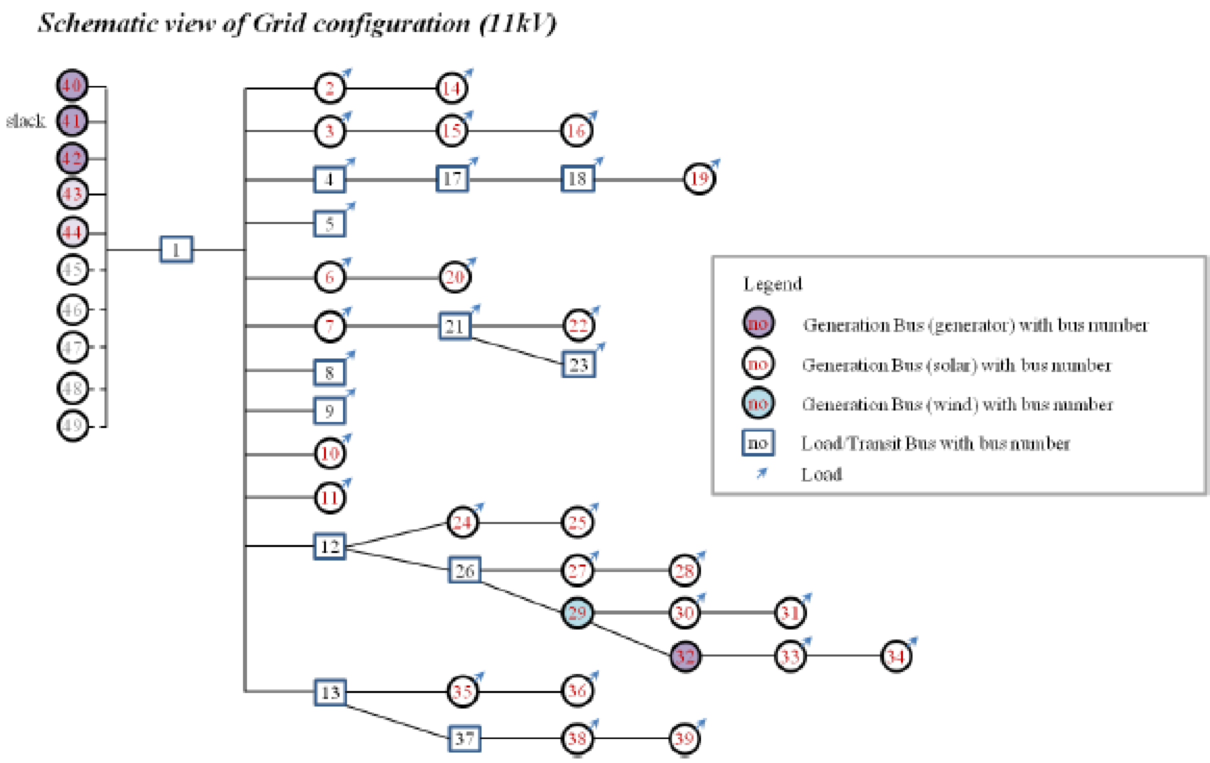


図 1 単期間潮流計算用の概略系統図(case-0)

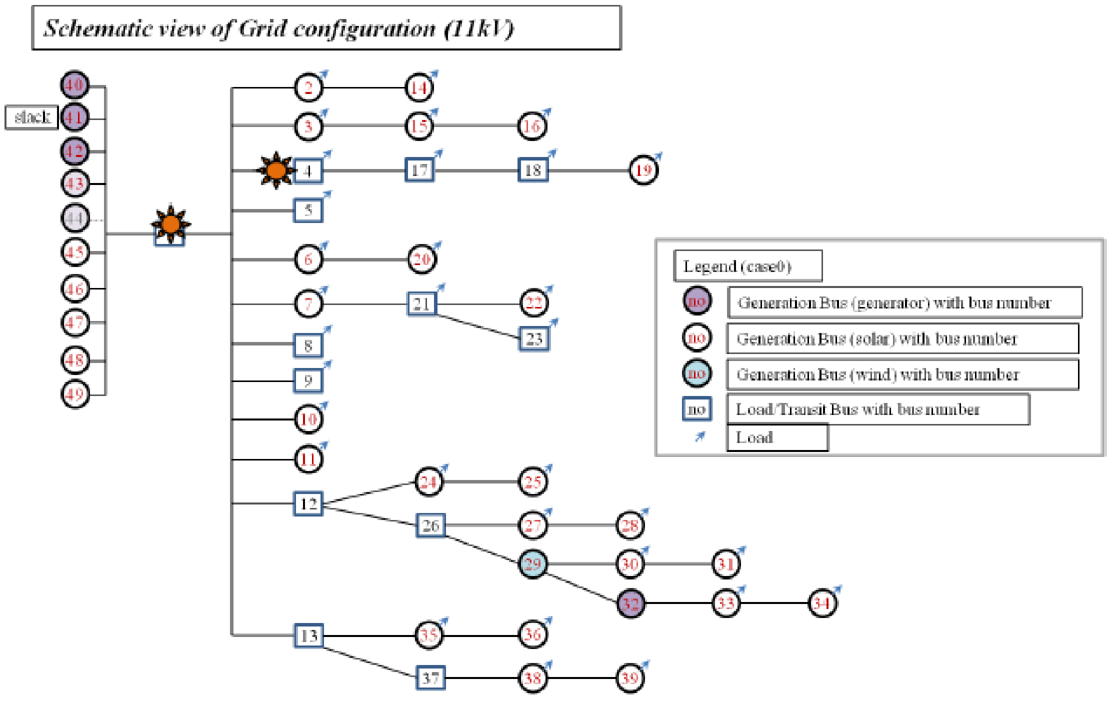


図２　単期間潮流計算用の概略系統図(case-2)

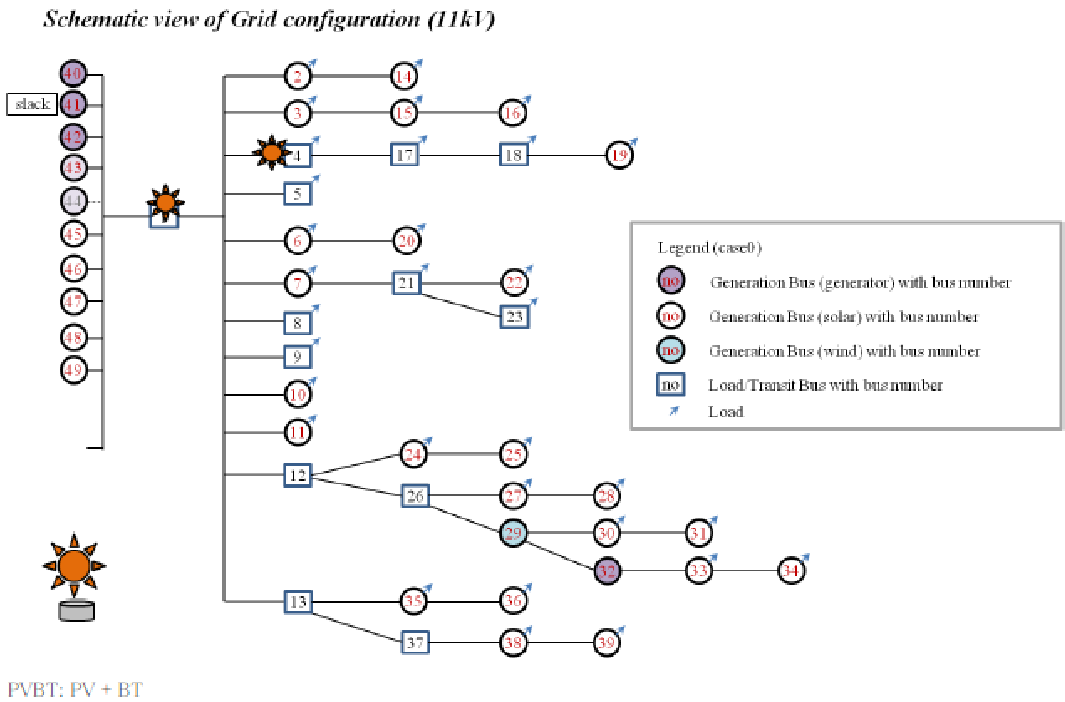


図３　単期間潮流計算用の概略系統図(case-4)

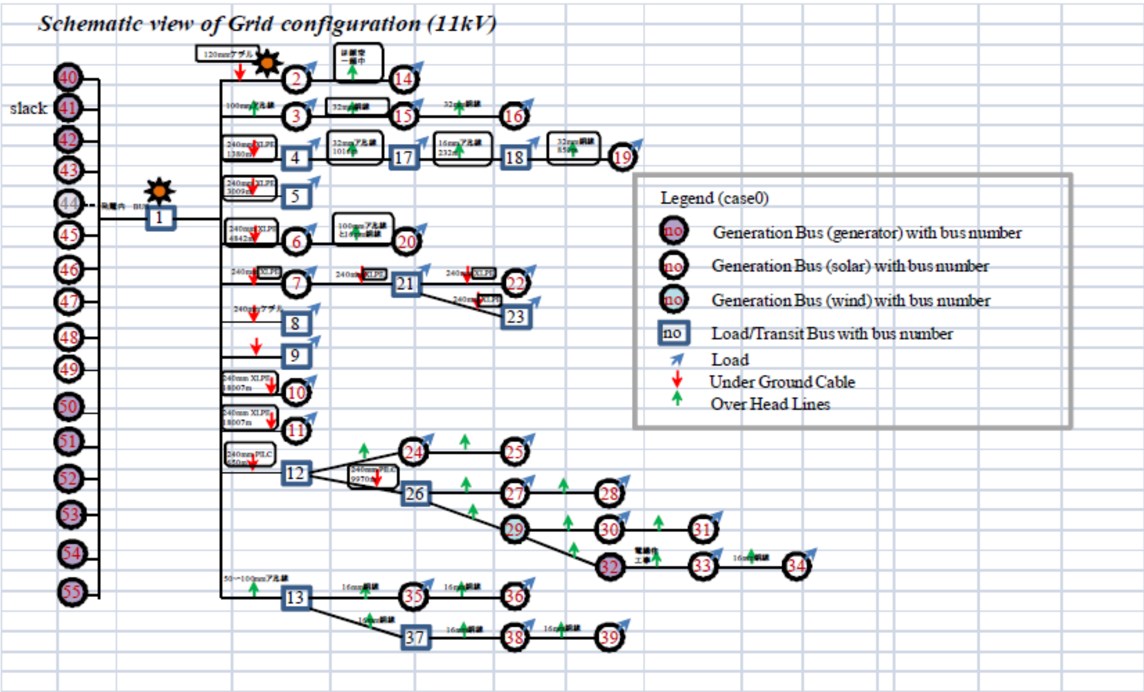


図４　St. Kitts 系統における送電線・線種の調査結果

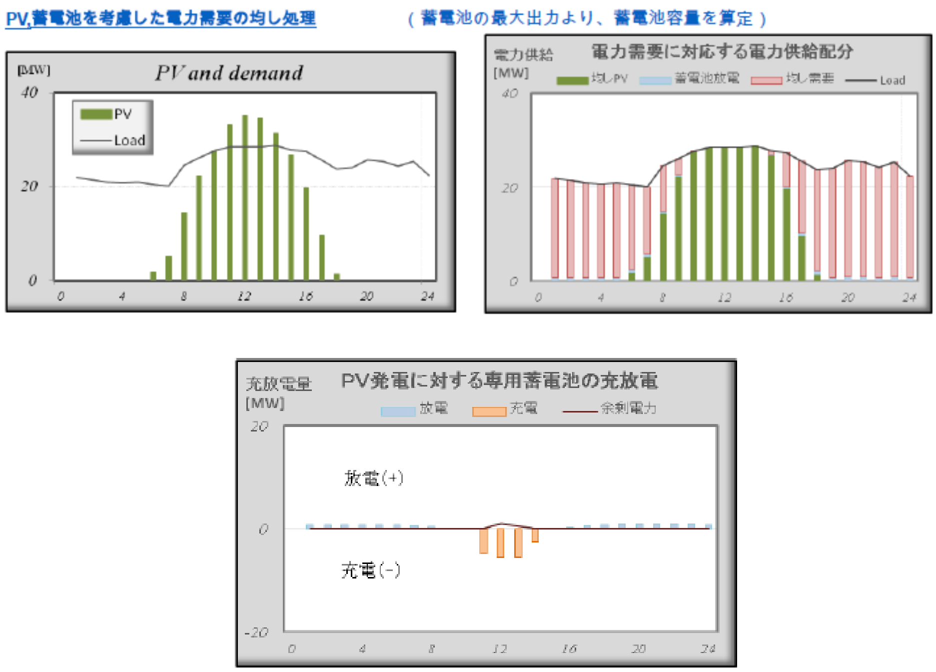
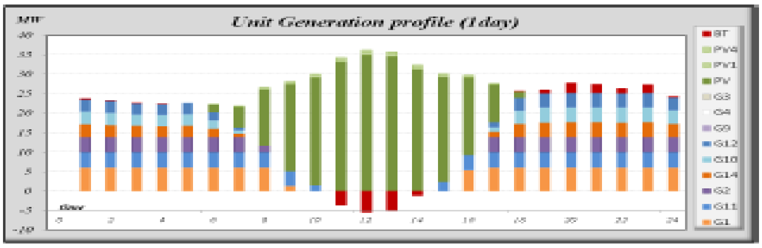


図５ PV,蓄電池を考慮した電力需要の均し処理のイメージ図



G2(41)： slack

time	G2	BT
0		
1	3.86996	0.16178
2	3.86996	0.16407
3	3.86996	0.16749
4	3.86996	0.18092
5	3.86996	0.00000
6	3.86996	0.00000
7	3.86996	0.00000
8	1.65173	0.00000
9	0.00001	0.00000
10	0.00000	0.00000
11	0.00000	−3.46047
12	0.00000	−5.38600
13	0.00000	−4.89240
14	0.00000	−1.10094
15	0.00000	0.00000
16	0.00001	0.00000
17	3.86996	0.00000
18	3.86996	0.17015
19	3.86996	0.92989
20	3.86995	2.66211
21	3.86995	2.33982
22	3.86996	1.21355
23	3.86995	2.23079
24	3.86996	0.16731

5.38600	蓄電池最大出力[MW]
14.83981	蓄電池最小容量[MWh]

14.83981	充電(-)
10.38788	放電(+)
0.70000	充放電比

図６　多段経済負荷

配分による最適な蓄電池・最小必要容量の決定のイメージ図

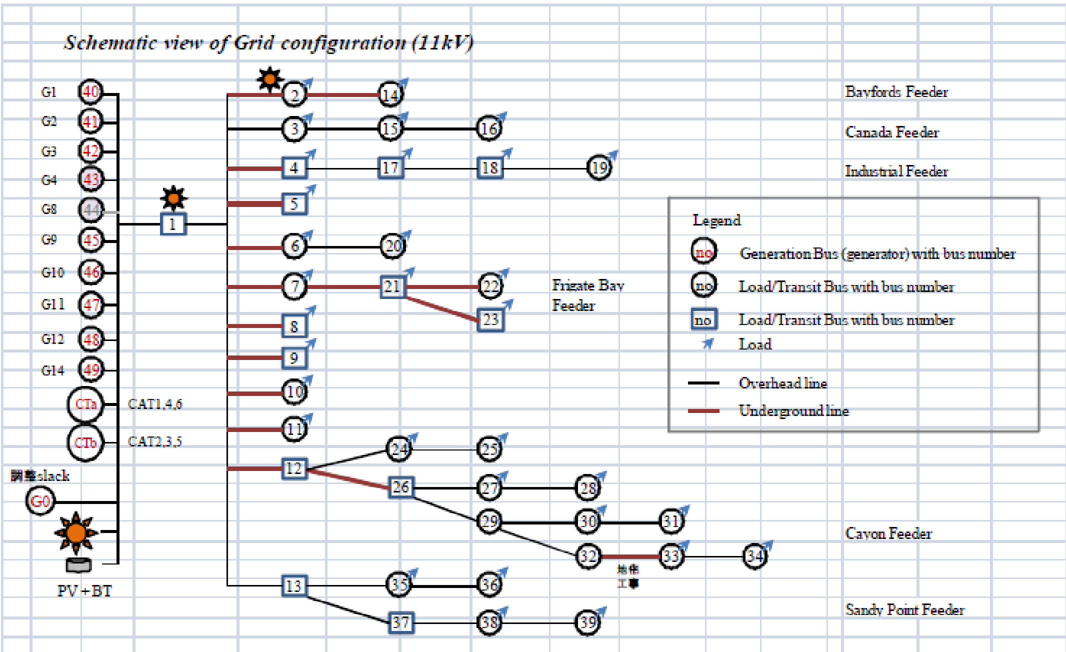
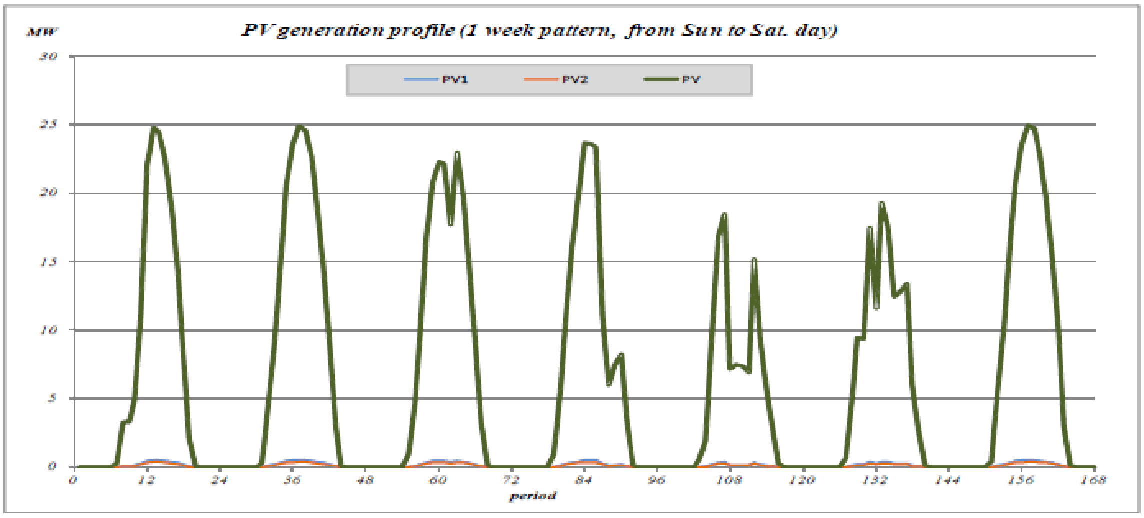


図７　系統解析シミュレーションで使用された概略系統図（現状の系統の確認が必要）



日	Partial Rain
月	Fine
火	Partially Cloud
水	Partial rain
木	Rain
金	Cloudy
土	Fine

図 8 系統解析シミュレーションで使用する太陽光発電のシナリオ例

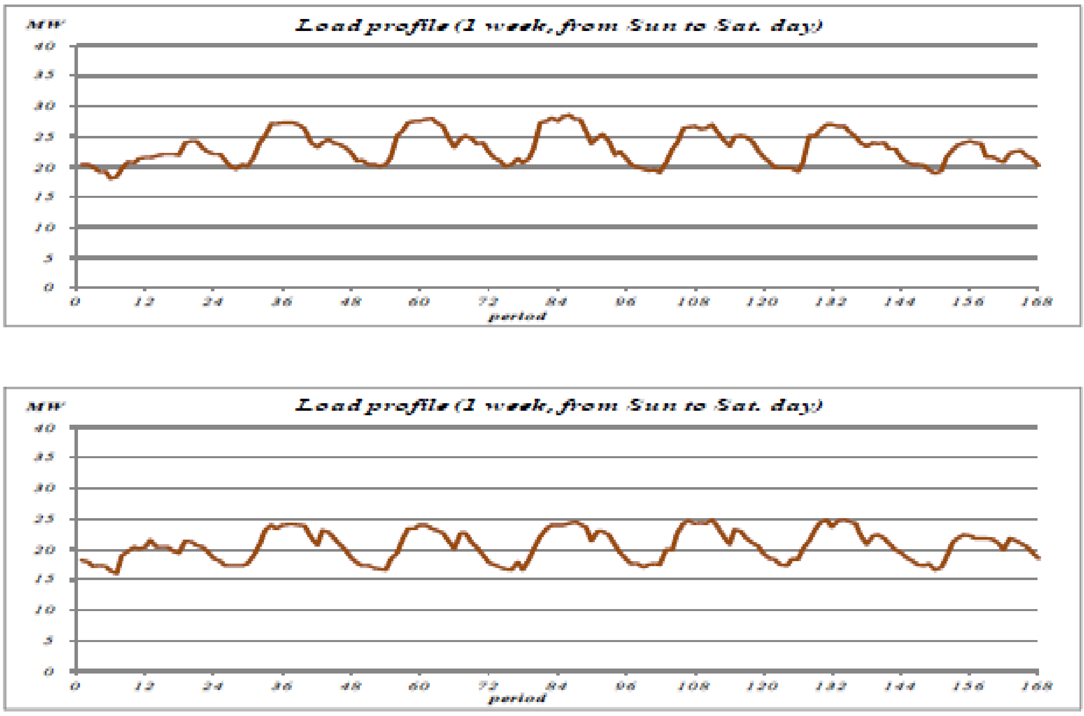


図 9 系統解析シミュレーションで使用する負荷パターン(現地より入手)

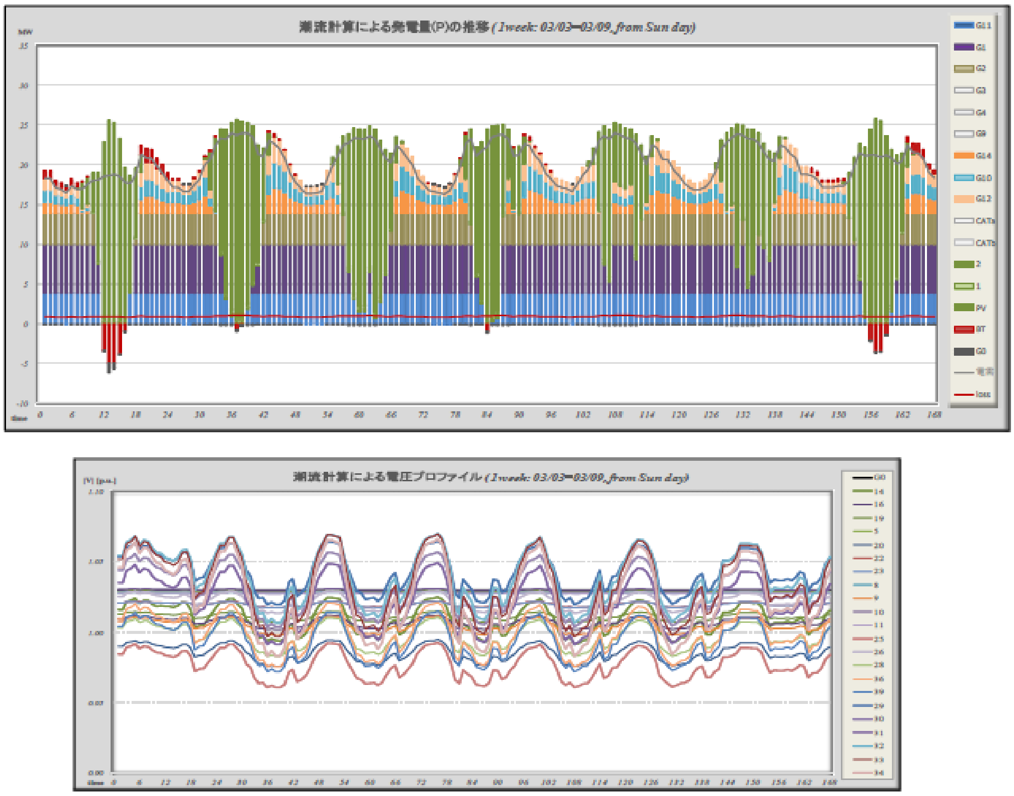


図 10 多段潮流計算による発電機・有効電力出力と母線電圧値の時系列遷移イメージ(case-1)

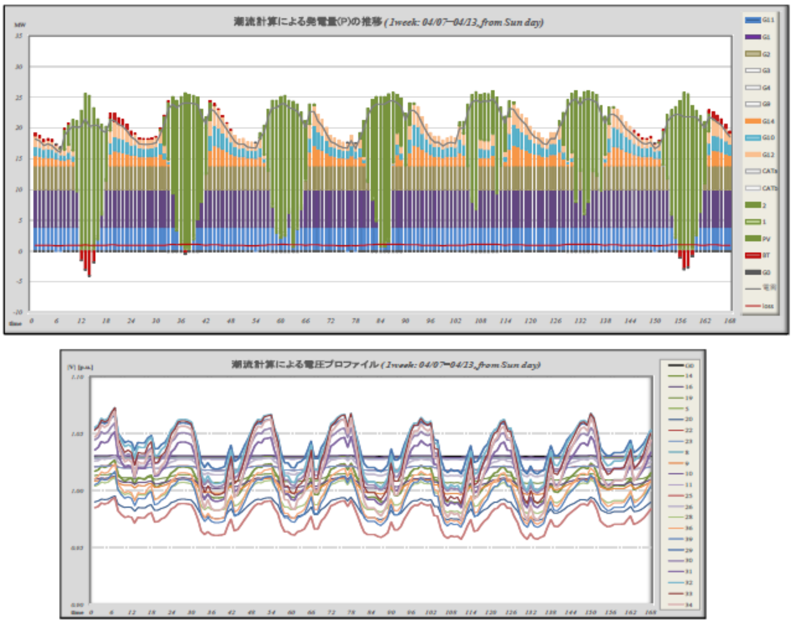


図 11 多段潮流計算による発電機・有効電力出力と母線電圧値の時系列遷移イメージ(case-2)

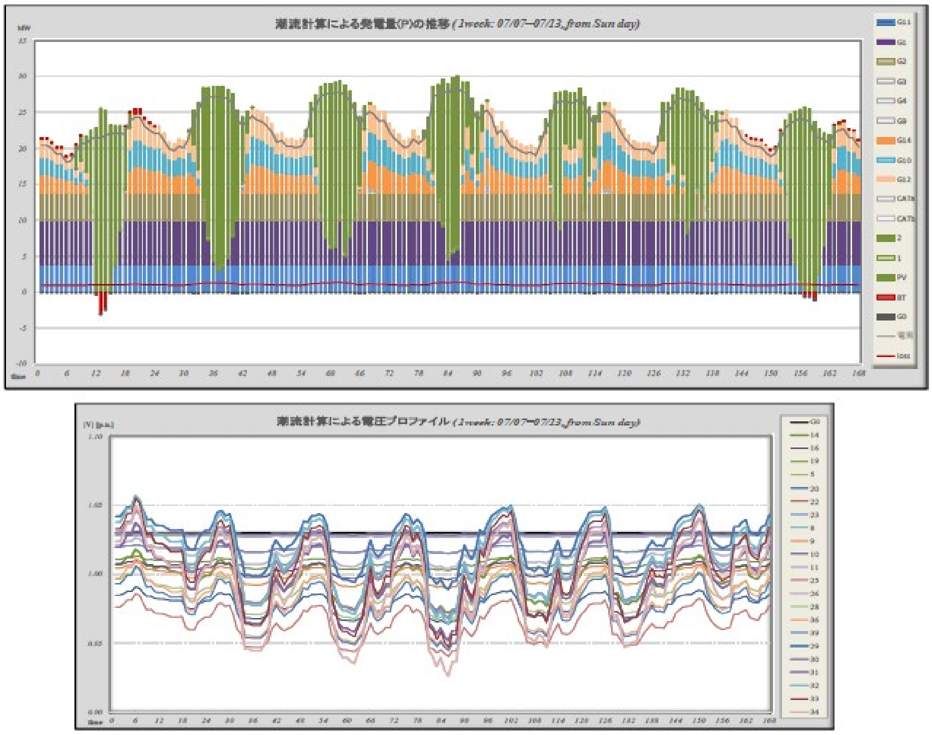


図 12 多段潮流計算による発電機・有効電力出力と母線電圧値の時系列遷移イメージ(case-3)

2019 年 7 月

9. 付録 B:マイクログリッド解析の定式化と解法(打合せ用資料)

環境エネルギー技術研究所

1. 概要

マイクログリッドの解析は，過渡解析と定常解析とに大別される。過渡解析(Transient Analysis)は、系統に大きな変化が生じた瞬間(事故、遮断など)からの系統状態を微小時間単位で追跡するものであり、これには系統状態を表現する微分方程式が使用される。また定常解析(Static Analysis)は、過渡状態が一定時間進み、ある状態に落ち着いた時点での解析であり、その定常値を所定の離散時間断面で数値解析により求めることが要求される。

ここでは、以下の代表的定常解析の一般論について紹介する。

① 潮流計算（Power Flow）

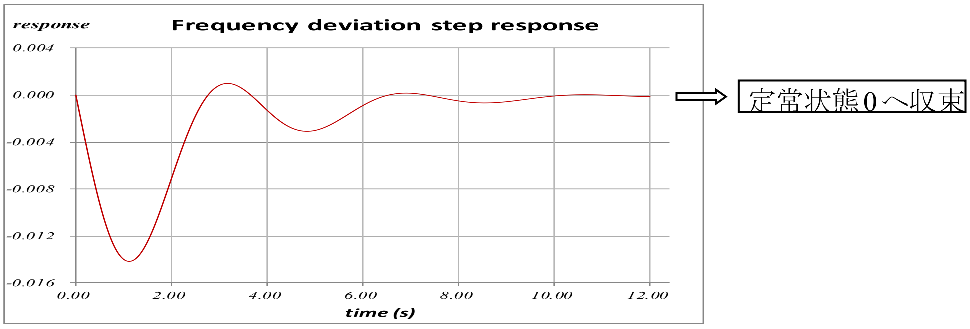
② 経済負荷配分（Economic Load Dispatch）

③ 多段経済負荷配分（Dynamic Economic Load Dispatch）

④ 最適潮流計算（Optimal Power Flow）

⑤ 起動停止計画問題（割愛）

系統に大きな負荷変化が起きてからの周波数偏差の変動解析例(LFC)



2. 交流回路の基本

交流回路は波である電圧、電流を状態量としている。

波は、単振動を表現する微分方程式の解より明らかのように

一般的な数学的表現である Cexp(j(ωt+θ)) の形式で記述できる。

ここで、

$\exp(j(\omega t+\theta)) = \cos(\omega t+\theta) + j\sin(\omega t+\theta)$　Euler の公式

角速度　$\omega = 2\pi f$　f: 周波数, θ: 位相(radian)

C： 振幅(Amplitude)

したがって、交流回路の状態量は複素数であり、ひとつの状態量には２つの状態値がある。すなわち、極座標表現では振幅と角度、直角座標表現では実部と虚部である。

交流用語の複素数表現　（上・記号は複素数を示す）

電圧(Voltage)　$\dot{V} = |\dot{V}| e^{j\theta}$

電圧値 $|\dot{V}|$(voltage magnitude)と電圧位相角 θ

電流(Current)　$\dot{I} = |\dot{I}| e^{j\delta}$

電力(Power)　$\dot{S} = |\dot{S}| e^{j\phi} = P + jQ$

P：有効電力(active power)　単位: W

Q：無効電力(reactive power)　単位: VAr

インピーダンス(Impedance)　$\dot{Z} = r + jx$

r：抵抗(resistance)

x：誘導抵抗(reactance)

アドミタンス(Admittance)　$\dot{Y} = G + jB$, $\dot{Y} = 1/\dot{Z}$

G：コンダクタンス(conductance)

B：サセプタンス(susceptance)

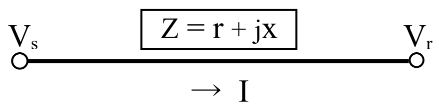
交流回路の基本公式

①オームの法則(Ohm's Law)

・$\dot{V} = \dot{Z}\dot{I}$

・$\dot{I} = \dot{Y}\dot{V}$

・ブランチの電圧降下式： $\dot{V}_s - \dot{V}_r = \dot{Z}\dot{I}$



②キルヒホッフの電流則 (KCL: Kirchhoff's Current Law)

・ノードに流出入する電流の総和は零である。

・ノードに流出入する電力流の総和は零である。

③キルヒホッフの電圧則 (KVL: Kirchhoff's Voltage Law)

・閉路における電圧変化の総和は零である。

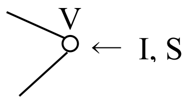
④電力・電圧・電流の関係式

・$\dot{S} = \dot{V}\dot{I}^* = |\dot{V}||\dot{I}|\, e^{j(\theta-\delta)}$（上*記号は共役複素数を示す; $\dot{I}^* = |\dot{I}|\, e^{-j\delta}$）

$|\dot{S}| = |\dot{V}||\dot{I}| = \mathrm{sqrt}(P^2 + Q^2)$（皮相電力：単位 VA）

・$\dot{I} = (\dot{S}/\dot{V})^*$

ノードにおける注入電流と注入電力(・S: injected Power, ・I : injected Current)

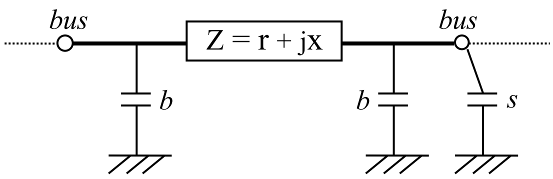


3．マイクログリッドの潮流方程式

送配電マイクログリッドは，需要家の電力需要を賄えるように設計された電力伝送路である。この伝送路は、一定の基準で設定されたノード(母線 : bus)とノード間を結ぶブランチ(枝 : branch)で構成されるネットワークとみなされ、それらの電力・電流の流れと電圧分布を解析するために，ネットワーク構造から導きだされる電力潮流方程式が解かれる。

ネットワークのノードは，発電ノードと負荷ノードに大別され，さらに発電ノードは，複素電圧を指定するスラック母線および発電 P 値と$|\dot{V}|$値を指定する PV 指定母線とに分類されることが一般的である。すべてのノードには、電力負荷(P, Q 値)を指定する。ブランチには，ブランチ属性として Impedance(抵抗とリアクタンス)が与えられる。また，一般の π 型系統モデルでは, ノードおよびブランチに無効電力の供給・吸収を担う Capacitor (Susceptance b or s を有するコンデンサ)を考慮できるようになっている。

送電線の π 型等価回路



このようなモデルで構成される送配電マイクログリッドは，バス群と双方向性を有するブランチ群から構成される無向グラフをもとに，前期の交流回路の基本公式を適用することにより，電力潮流方程式が作成される。具体的には、1 本のブランチ *s-r* におけるオームの法則 $I_{sr} = (\dot{V}_s - \dot{V}_r)/\dot{Z}_{sr} = (\dot{V}_s - \dot{V}_r)\dot{Y}_{sr}$ を、キルヒホッフの電流則を適用して全体構造へ統合する手続きを繰返し行えばよい。

その結果得られる電力潮流方程式は、以下に示すように、複素変数$\dot{V}_i$($i=1...n$)に関する連立(非線形)二次方程式となる。

$$\dot{S}_i = \dot{V}_i \dot{I}_i^* = \Sigma_j \dot{V}_i \dot{Y}_{ij}^* \dot{V}_j^* \quad (i=1 \ldots n)$$

ここで, $\dot{V}_i$ はノード i の電圧, $\dot{S}_i = P_i + jQ_i$ はノードiの指定注入電力(発電(＋)と負荷(－)の計), $\dot{I}_i$ は同注入電流, $\dot{Y}_{ij}$ は系統全体のアドミッタンス行列の i,j 成分, n はノード数を 示す。

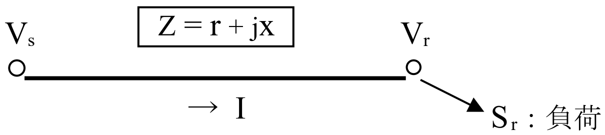
したがって、すべての$\dot{S}$ を与えて電力潮流方程式を解くと全ノード電圧$\dot{V}$ が求められ、その値を使用して、未知の発電量、ブランチの電流や電力流(Power Flow)、および系統ロスなどが得られる。

但し、潮流方程式はそのままでは解は求めることができないため(不定), スラック母線の導入により一個の複素電圧を指定する必要がある。また, 発電ノードには PV指定母線として発電 P 値と$|\dot{V}|$値を指定することがあるので, 実際の変数個数は $2n$ よりも幾分小さくなる。これに応じて、潮流方程式の本数も変数個数と同じになるように減じられる。即ち、スラック母線では発電量 P,Q が未知、PV指定母線では発電量 Q が未知となり、潮流方程式の本数はそれぞれ 0,1 となる。

連立非線形方程式である電力潮流方程式を直接解析的に解く方法はないので, Newton-Raphson 法や Backward/Forward 法など数値演算による繰返し解法が適用される。

4．潮流方程式の解析例

①最も簡単な潮流方程式 (2母線潮流方程式)



オームの法則

$$\dot{V}_s - \dot{V}_r = \dot{Z}\dot{I}, \quad \dot{I} = (\dot{V}_s - \dot{V}_r)/\dot{Z}$$

受電端 r における注入電力則 (潮流方程式)

$$\dot{S}_r = \dot{V}_r \dot{I}^* = \dot{V}_r ((\dot{V}_s - \dot{V}_r)/\dot{Z})^* = (\dot{V}_r \dot{V}_s^* - |\dot{V}_r|^2)/\dot{Z}^*$$

(具体例)

送電端s(スラック母線)における電圧を基準にし,

$\dot{V}_s = E(\cos(0) + j\sin(0)) = E$ とする。(E:固定)

受電端 r (負荷母線)における電圧を,

$\dot{V}_r = V(\cos\theta + j\sin\theta)$ とおく。

また特に,$\dot{Z} = jx$ (x=1) とすると (抵抗を無視),

$$\dot{S}_r = P + jQ = \{VE(\cos\theta + j\sin\theta) - V^2\}/(-j)$$

$$= VE(j\cos\theta - \sin\theta) - jV^2$$

よって

$$P = -VE\sin\theta$$

$$Q = VE\cos\theta - V^2$$

というV, θに関する２元連立非線形方程式が得られた。

②***MicroGrid Designer*** による解析例

MicroGrid Designer の Power Flow は，Newton-Raphson 法と Backward/Forward 法を採用している。特に大規模送電系統では sparse Newton-Raphson 法に新たな手法を導入して高速に解を求める手法を実現している。対象とする系統の最大規模は、50,000 母線である。

ここでは、小中規模用の dense Newton-Raphson 法を用いて、標準の系統モデルである Ward-Hale 6 母線に対して解析する。

その前に、***MicroGrid Designer*** では入出力データに Per-Unit System (p.u.)を使用しているので、これについて説明しておく。

Per-Unit System

The Per-Unit System (p.u. in short) is widely used in the power system to express values of voltages, currents, powers, and impedances.

For a given quantity, the per-unit value is the value related to a base quantity:

Per-unit value = quantity in some unit / base quantity

Generally, the following two base quantities are given:

- Vbase : The base voltage quantity
- Sbase : The base power quantity

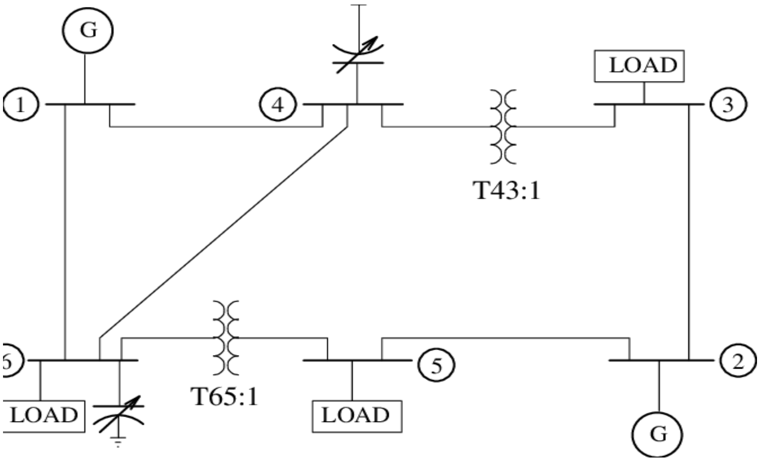
All other base quantities are derived from these two base quantities, using the natural laws of electrical circuits.

Typical base quantities in IEEE test systems
- Vbase : 1～132 kV
- Sbase : 100 MVA

So, voltage magnitude 1.0 in p.u. means 100V actually.
If the power generation and load data (P, Q) are given in units MW and MVAr respectively, conversion of these values into Per-Unit System is simply done

by dividing them by 100(MVA).

Ward-Hale 6 母線モデルと入力データ



入力データ

```
// Node(bus) data
//                     負荷P,Q          発電P,Q    電圧・初期値/指定値
//id type   s  cond   Pl      Ql      Pg    Qg    |V|    θ
   1   G   0.0   VT  -0.25  -0.1                  1.05  0.0
   2   G   0.0   PV  -0.15  -0.05    0.5          1.05  0.0
   3   L   0.0   PQ  -0.275 -0.11                 1.0   0.0
   4   -   0.02  PQ   0.0    0.0                  1.0   0.0
   5   L   0.0   PQ  -0.15  -0.09                 1.0   0.0
   6   L   0.02  PQ  -0.25  -0.15                 1.0   0.0
END

// type - G:発電母線,  L:負荷母線, -:通過・分岐点(負荷0の負荷母線)
// s - susceptance of nodal capacitor (see π型等価回路)
// cond - VT:スラック母線, PV: PV指定母線, PQ: PQ指定母線
//        すべての母線にはPlとQl(通常負値)を指定する。
//        スラック母線には|V|とθを指定する。
//        PV指定母線にはPgと|V|を指定する。
//        PQ指定発電母線にはPgとQg(通常正値)を指定する。
//        PQ指定負荷母線にはPgとQg欄を空白とする。
// なお、 スラック母線の発電量(Pg,Qg)とPV指定母線の発電量(Qg)は
//        潮流計算により決定される。
// 電圧 - 指定値以外はNewton-Raphson法用の初期値とされる。

// Branch data
// name from to    r      x      b    tap
   B1    1  6   0.031  0.259  0.005  0
   B2    1  4   0.020  0.185  0.004  0
   B3    4  6   0.024  0.204  0.005  0
   B4    6  5   0.025  0.150  0.008  2 0.95
   B5    2  5   0.071  0.320  0.007  0
```

```
   B6    2  3   0.006  0.025  0.0    0
   B7    4  3   0.075  0.067  0.0    2 0.97
END

// r - resistance (単位長さ当り* 延長)
// x - reactance  (単位長さ当り* 延長)
// b - half susceptance of branch capacitor (see π型等価回路)
// tap - transformer existence ( 0: not exist, 1,2: exist )
//       変圧器が存在する場合には、そのタップ比を入力する。
//       タップ比は順方向(tap=1)、逆方向(tap=2)に応じた変圧率である。
```

出力データ

Output-1 を参照

4．経済負荷配分(ELD: Economic Load Dispatch)

経済負荷配分は，需要(負荷)予測に基づいて、系統の発電機群に出力指令を与える目的で行われる。経済負荷配分では、総燃料費が最小となるような各発電機の有効電力出力値が決定される。この有効電力出力値は、対象系統の潮流計算を行う際に、PV 指定母線の P 値として使用できる。

経済負荷配分問題は，ある予測時点において、需給バランスを満足させ総燃料費が最小となるような発電機群の有効電力出力を求める最適化問題である。通常、発電機の燃料費には有効電力出力の２次式が使用されるので、経済負荷配分問題は二次計画問題に属する。ただし、発電機の燃料費に有効電力出力の１次式を使用する場合には、同問題は線形計画問題となる。

二次計画問題によるELDの定式化

$\min_{\{P(t)\}} \ \Sigma_i \mathrm{FuelCost}(i)$

$\mathrm{FuelCost}(i) = a_i P_i^2 + b_i P_i + c_i$ for unit-i

Σ_i は発電機(unit)に関する総和を示す(i=1,..,ng, ng:発電機数)。

s.t. $\Sigma_i P_i = D(t)$ (Power balance 制約)

$P_{min,i} \leqq P_i \leqq P_{max,i}$ (P_i の上下限制約)

where

D(t) : demand at a given estimated time-t

P_i : active power generation of unit-i (変数)

$P_{min,i}$, $P_{max,i}$: bounds of P_i for unit-i

経済負荷配分の解法には，二次計画問題専用解法や等λ法などがあるが、***MicroGrid Designer*** では、この二次計画問題のシンプルな構造を利用した超高速厳密解法を採用している。

二次計画問題ELDの解析例

// 入力データ

```
5  // #units

//    a  b  c  Pmin Pmax
G1  10  2  6    0   5
G2   8  4  4    0   5
G3   6  2  2    0   5
G4   4  3  0    0   5
G5   2  1  2    0   5

16  // demand
```

// 出力データ

```
(solution)
 unit  output(P)    Pmin     Pmax      cost
 G1      1.75325    0.00     5.00   40.24523
 G2      2.06656    0.00     5.00   46.43154
 G3      2.92208    0.00     5.00   59.07539
 G4      4.25812    0.00     5.00   85.30058
 G5      5.00000    0.00     5.00   57.00000
 sum   16.00000                    288.05274
```

５．多段経済負荷配分(Dynamic Economic Load Dispatch)

ダイナミック ELD は、前記の単期間 ELD を多期間に拡張したものである。但し、各期間ごとの ELD を順に解く訳ではなく、期間同士の制約を導入して、隣接期間における解の整合性がとれるように改良された手法を採用している。そのため、発電機群の運用可能条件(Operability)を考慮した、長期間の Dispatch スケジューリングが行えるという利点が生じる。また、発電機以外にも、蓄電池や再生可能エネルギーを考慮できるという特徴も合わせ持っている。

ダイナミック ELD は、期間全体を対象とした大規模非線形最適化問題であり、効率的に解く手法が要求される。***MicroGrid Designer*** では当該問題のスパース性を活用した汎用内点法モジュールを使用して、高速に最適解を求めることができる。

多段 ELD の定式化

$\min_{\{P(t)\}}\ \Sigma_t \Sigma_i \mathrm{FuelCost}(t,i)$

$\mathrm{FuelCost}(t,i) = a_i P_i(t)^2 + b_i P_i(t) + c_i$ for unit-i at time-t

Σ_i は発電機(unit)に関する総和を示す(i=1,..,ng, ng:発電機数)。

Σ_t は期間に関する総和を示す(t=1,..,T, T:期間数)。

s.t. $\Sigma_i P_i(t) = D(t)$ for each time-t（Power balance 制約）

$P_i(t)$の上下限制約：

$P_{min,i}(t) \leqq P_i(t) \leqq P_{max,i}(t)$ for each unit-i at every time-t

where

D(t) : demand at time-t

$P_i(t)$: power generation of unit-i at time-t（変数）

$P_{min,i}(t)$, $P_{max,i}(t)$: bounds of $P_i(t)$ for unit-i at time-t

Ramp constraints:

$rl(i) \leqq P_i(t) - P_i(t-1) \leqq ru(i)$ for each unit-i at every time-t

where rl(i) : max. ramp down < 0,

ru(i): max. ramp up > 0 for unit-i

Inventory constraints:

$\Sigma_t P_i(t) = lot(i)$ or ≦, ≧

where lot(i) : final lot size in a time interval for some unit-i

この制約は、主として蓄電池用として使用される。

ダイナミック ELD の解析例

系統構成

火力発電８機(G1～G8) ： 最大出力 60 ～ 800MW

（入力データ）

初期発電量(MW)、燃料費コスト二次関数係数(a,b,c)

（制約データ）

最小・最大出力(MW), max ramp-down, ramp up (MW/h)

バッテリ１機(BT) ： 最大出力 150MWの簡易蓄電池モデルを採用

（入力データ）

稼働時間帯: 昼間放電(＋)(10-16h), 夜間充電(－)(1-4h,21-24h)

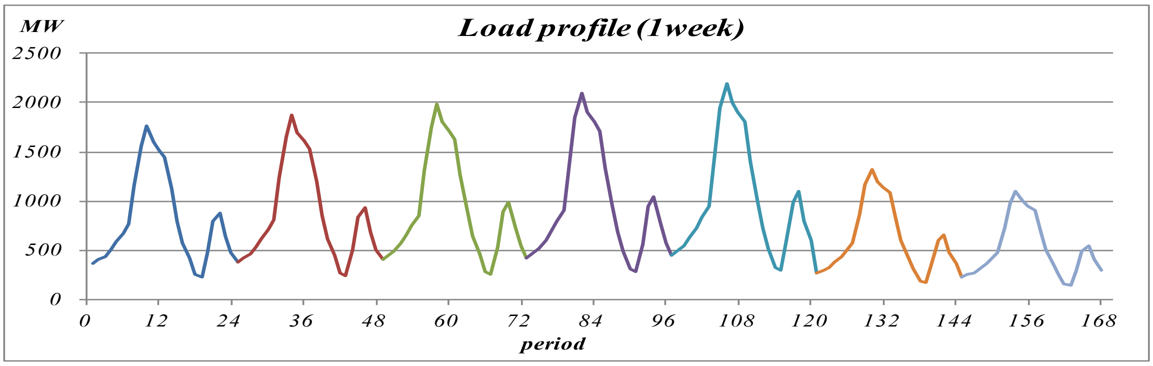
（制約データ）

max. ramp down: −50MW/h, max.ramp up: +50MW/h

総充放電量 ＝ 放電量 － 0.7*充電量 = 0　for every 24 hours

解析対象期間：１週間(168h)、単位期間：1h
解析期間における負荷プロファイル

８機起動停止計画問題で使用した負荷データを利用して作成した。



解析結果

変数 $P_i(t)$ の個数　：1512 = 9*168
変数の上下限制約 ：1512*2
等式制約数 ：168+7 (Power balance 制約+充放電制約)
不等式制約数 ：3008 (Ramp 制約)

計算時間 ：1.80 sec

最適解については、Output-2 と各 unit の発電プロファイルを参照。

(入力データ)

```
168 // T : periods (1 week)
9    // ng: generators

// generator data
//    minG    maxG     rl    ru   cyc    g0      a      b         c
//    (MW)    (MW)     (MW/h)          (MW)          (#/MWh)    (#/h)
 G1     0.0    80.0   -80.   80.   0     0.0    0.0   20.880   213.0
 G2     0.0   250.0  -100. 100.    0     0.0    0.0   18.000   585.62
 G3     0.0   300.0  -100. 100.    0     0.0    0.0   17.460   684.74
 G4     0.0    60.0   -60.   60.   0     0.0    0.0   14.280   252.0
 G5     0.0    60.0   -60.   60.   0     0.0    0.0   18.660   252.0
 G6     0.0   480.0  -120. 120.    0     0.0    0.0   12.660   293.0
 G7   100.0   800.0  -200. 200.    0   300.0    0.0   11.394   305.0
 G8     0.0   300.0  -100. 100.    0     0.0    0.0   10.800   700.0
 BT     0.0     0.0   -50.   50.   1    -10.    0.0    0.0       0.0  // battery
// rl,ru :   max. ramp-down and ramp-up
// cyc :   ramp-constraints are cyclic or not
// g0   :   initial generations used for ramp-constraints
// a,b,c   :   coefficients for fuel cost

// demands (MW)
// Monday
  360.0  400.0  440.0  504.0  584.0  664.0  760.0 1160.0 1560.0 1760.0 1600.0 1520.0
 1440.0 1120.0  800.0  576.0  416.0  256.0  232.0  472.0  792.0  880.0  640.0  480.0
// Tuesday
  382.5  425.0  467.5  535.5  620.5  705.5  807.5 1232.5 1657.5 1870.0 1700.0 1615.0
 1530.0 1190.0  850.0  612.0  442.0  272.0  246.5  501.5  841.5  935.0  680.0  510.0
// Wednesday
  405.0  450.0  495.0  567.0  657.0  747.0  855.0 1305.0 1755.0 1980.0 1800.0 1710.0
 1620.0 1260.0  900.0  648.0  468.0  288.0  261.0  531.0  891.0  990.0  720.0  540.0
// Thursday
  427.5  475.0  522.5  598.5  693.5  788.5  902.5 1377.5 1852.5 2090.0 1900.0 1805.0
 1710.0 1330.0  950.0  684.0  494.0  304.0  275.5  560.5  940.5 1045.0  760.0  570.0
// Friday
  450.0  500.0  550.0  630.0  730.0  830.0  950.0 1450.0 1950.0 2200.0 2000.0 1900.0
 1800.0 1400.0 1000.0  720.0  520.0  320.0  290.0  590.0  990.0 1100.0  800.0  600.0
// Saturday
  270.0  300.0  330.0  378.0  438.0  498.0  570.0  870.0 1170.0 1320.0 1200.0 1140.0
 1080.0  840.0  600.0  432.0  312.0  192.0  174.0  354.0  594.0  660.0  480.0  360.0
// Sunday
  225.0  250.0  275.0  315.0  365.0  415.0  475.0  725.0  975.0 1100.0 1000.0  950.0
  900.0  700.0  500.0  360.0  260.0  160.0  145.0  295.0  495.0  550.0  400.0  300.0
// generation ranges
repeat 7   step 24
// unit    ts   te   minG   maxG   weight
    BT      10   16    0.0   150.0    1.0   // 放電(+)
    -        1    4   -150.   -0.0    0.7   // 充電(-)
    -       21   24   -150.   -0.0    0.7   // 充電(-)
end
// inventory constraints
```

```
    // unit    ope    lotFinal step
BT = 0.0    24    //  放電量  - 0.7 充電量  = 0 at every 24 hours
end
```

６．最適潮流計算(OPF: Optimal Power Flow)

経済負荷配分は，負荷予測に基づいて、総燃料費が最小となるような発電機の有効電力出力値を求めるものであった。この場合、系統のネットワーク構成が考慮されず、系統ロスを含めた負荷配分が行えないという欠点がある。

最適潮流計算は、このような経済負荷配分の欠点を補う手法であり，系統の負荷バランス制約の下で､総燃料費が最小となるような発電機の有効電力出力値を求めることができる。また最適潮流計算には、ブランチ電力流の制限(潮流制約)を課して混雑度を抑制する機能、あるいは評価関数を変えて異なる目的の解析を行うなどの機能を与えることができる。

最適潮流計算は、多くの非線形・制約条件を有する大規模な非線形最適化問題であり，その求解には効率的な手法が要求される。***MicroGrid Designer*** ではスパース性を活用した汎用内点法を使用し、さらに GMRES 法を導入しているので、高速に最適解を求めることができる。

最適潮流計算の変数は、発電母線の有効・無効電力と各母線の複素電圧である。なお、最適潮流計算は、経済負荷配分と同様，負荷予測を行った単期間のみを対象とする。

最適潮流計算の定式化（燃料費最小化）

$$\min_{\{V,P,Q\}} \sum_i \mathrm{FuelCost}(i)$$

$$\mathrm{FuelCost}(i) = a_i P_i^2 + b_i P_i + c_i \quad \text{for unit-i}$$

$\sum_i$ は発電機（unit）に関する総和を示す（i=1..ng, ng:発電機数）。

s.t.

（変数の上下限制約）

$P_{min,i} \leqq P_i \leqq P_{max,i}$　（P_i の上下限制約）（i=1..ng）

$Q_{min,i} \leqq Q_i \leqq Q_{max,i}$　（Q_i の上下限制約）（i=1..ng）

$V_{min,j} \leqq V_j \leqq V_{max,j}$ （V_j の上下限制約）(j=1..n, n:#nodes)

where

P_i : active power generation of unit-i

Q_i : reactive power generation of unit-i

V_j : voltage magnitude of node-j

$P_{min,i}$, $P_{max,i}$: bounds of P_i for unit-i

$Q_{min,i}$, $Q_{max,i}$: bounds of Q_i for unit-i

$V_{min,j}$, $V_{max,j}$: bounds of V_j for node-j

（Power balance 制約）

$\sum_j \dot{V}_i \dot{Y}^*_{ij} \dot{V}_j^* = \dot{G}_i + \dot{L}_i$ (j=1..n, i=1...n)

where

$\dot{V}_i$: complex voltage of node-i

$\dot{Y}_{ij}$: complex (i,j) element of nodal Admittance matrix

$\dot{G}_i$: complex generation at node-i

P_k+jQ_k if the node is a generation bus-*k*, 0 otherwize.

$\dot{L}_i$: complex load at node-i (fixed)

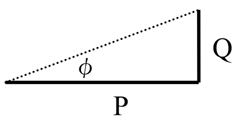
（Power factor 制約）

$\gamma_{min,k} \leqq (Q/P)_k \leqq \gamma_{max,k}$ (k: suset of Generation buses, given)

where

$(Q/P)_k$: reactive/active power ratio at the k-th generation node

$\gamma_{min,k}$, $\gamma_{max,k}$: bounds of the above ratio



力率(Power factor) = cos ϕ

（Branch power flow 制約）

$|P_{ij}| \leqq P_{max,ij}$ (i, j : subset of Branches, given)

where

P_{ij} : active power flow in branch i-j

$P_{max,ij}$: upper bound of P_{ij}

最適潮流計算の解析例

電気学会が公開している EAST10 機系統モデルを使用して，***MicroGrid Designer*** 最適潮流計算モジュールで燃料費が最小となる最適解を求めた。EAST10 機系統モデルは、関東エリアを 10 発電機 47 母線で模擬した系統である（福島事故の前か？）。

図：EAST10 機系統モデルとインピーダンス・マップ

入力データ：図の後のリスト

出力データ：Output-3

電気学会 EAST10 機系統モデルとインピーダンス・マップ

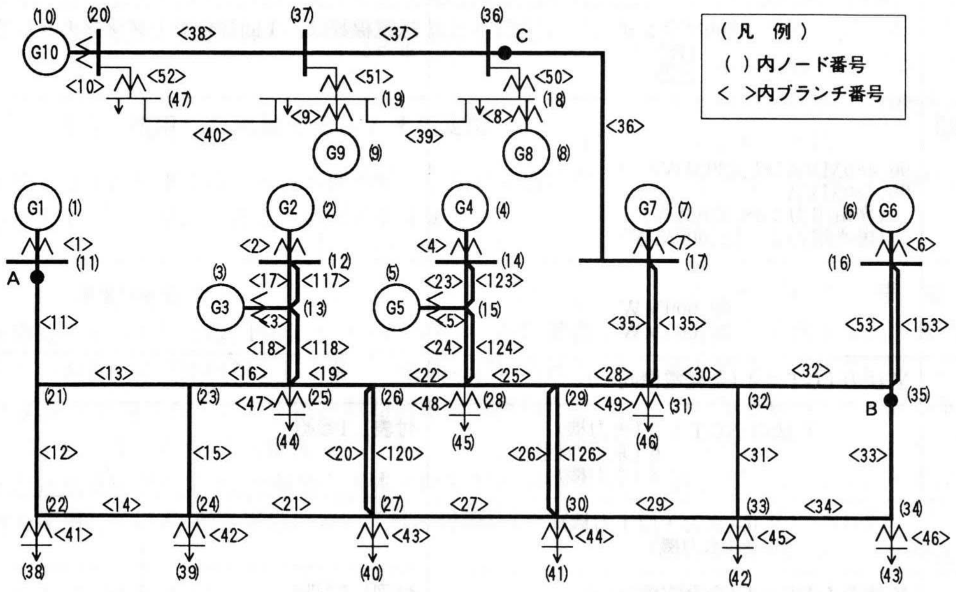
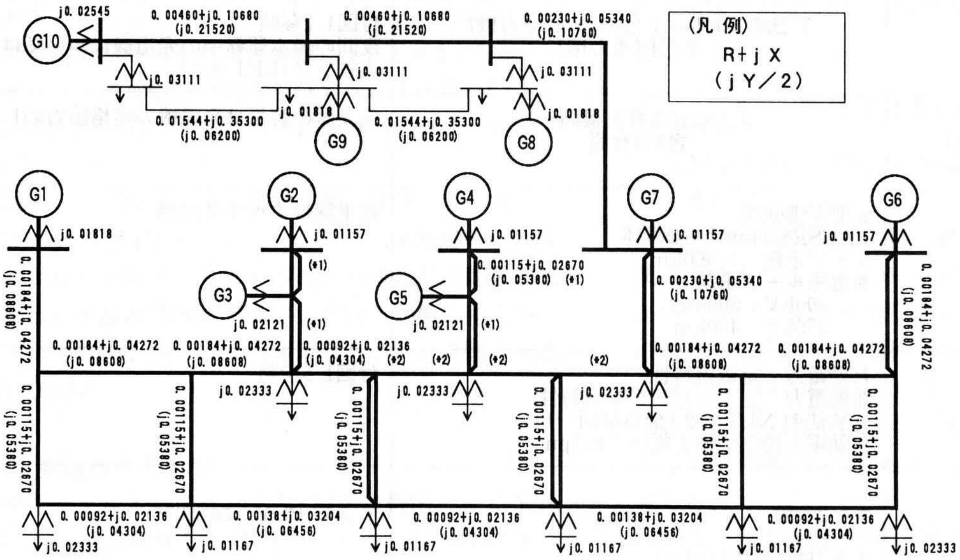


図4.1　電気学会 EAST10機系統モデル系統図（ノード番号，ブランチ番号，事故点含む）



注：送電線定数は2回線トータルの値

単位：pu（1000MVAベース）

図4.2　電気学会 EAST10機系統モデルインピーダンスマップ

（入力データ）

```
// IEEJ EAST10p (50Hz); 10-machines, 47-bus grid (peak time)
47    // n = #nodes

// Node data
//no type   s cond    Pl       Ql     Pg           Qg          V       T
    1   G   0.0   PQ    0.0      0.0     0.0           0.0        1.007    0   // G01 Thermal
    2   G   0.0   PQ    0.0      0.0     0.00000       0.0        1.005    0   // G02 Nuclear
```

```
   3   G   0.0   VT    0.0        0.0                                     1.020   0   // G03 Hydraulic
(slack)
   4   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.005   0   // G04 Thermal
   5   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.020   0   // G05 Hydraulic
   6   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.005   0   // G06 Thermal
   7   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.020   0   // G07 Nuclear
   8   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.020   0   // G08 Thermal
   9   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.020   0   // G09 Thermal
  10   G   0.0   PQ    0.0        0.0     0.00000     0.0        1.015   0   // G10 Thermal
  11   L   0.0   PQ    0.0        0.0                            1.0     0
  12   L   0.0   PQ    0.0        0.0                            1.0     0
  13   L   0.0   PQ    0.0        0.0                            1.0     0
  14   L   0.0   PQ    0.0        0.0                            1.0     0
  15   L   0.0   PQ    0.0        0.0                            1.0     0
  16   L   0.0   PQ    0.0        0.0                            1.0     0
  17   L   0.0   PQ    0.0        0.0                            1.0     0
  18   L   0.0   PQ   -5.500   -1.050                            1.0     0
  19   L   0.0   PQ   -5.500   -1.413                            1.0     0
  20   L   0.0   PQ    0.0        0.0                            1.0     0
  21   L   0.0   PQ    0.0        0.0                            1.0     0
  22   L   0.0   PQ    0.0        0.0                            1.0     0
  23   L   0.0   PQ    0.0        0.0                            1.0     0
  24   L   0.0   PQ    0.0        0.0                            1.0     0
  25   L   0.0   PQ    0.0        0.0                            1.0     0
  26   L   0.0   PQ    0.0        0.0                            1.0     0
  27   L   0.0   PQ    0.0        0.0                            1.0     0
  28   L   0.0   PQ    0.0        0.0                            1.0     0
  29   L   0.0   PQ    0.0        0.0                            1.0     0
  30   L   0.0   PQ    0.0        0.0                            1.0     0
  31   L   0.0   PQ    0.0        0.0                            1.0     0
  32   L   0.0   PQ    0.0        0.0                            1.0     0
  33   L   0.0   PQ    0.0        0.0                            1.0     0
  34   L   0.0   PQ    0.0        0.0                            1.0     0
  35   L   0.0   PQ    0.0        0.0                            1.0     0
  36   L   0.0   PQ    0.0        0.0                            1.0     0
  37   L   0.0   PQ    0.0        0.0                            1.0     0
  38   L   0.0   PQ   -5.000    1.200                            1.0     0
  39   L   0.0   PQ -10.000    2.416                             1.0     0
  40   L   0.0   PQ -10.000    2.671                             1.0     0
  41   L   0.0   PQ -10.000    2.593                             1.0     0
  42   L   0.0   PQ -10.000    2.378                             1.0     0
  43   L   0.0   PQ   -5.000    1.260                            1.0     0
  44   L   0.0   PQ   -5.000    2.499                            1.0     0
  45   L   0.0   PQ   -5.000    2.480                            1.0     0
  46   L   0.0   PQ   -5.000    2.532                            1.0     0
  47   L   0.0   PQ   -4.000   -1.368                            1.0     0
END

// Branch data
/name frm to      r           x           b          tap        plimit
  B01    11 21   0.001840    0.042720   0.086080   0            0
  B02    21 22   0.001150    0.026700   0.053800   0            0
  B03    21 23   0.001840    0.042720   0.086080   0            0
  B04    22 24   0.000920    0.021360   0.043040   0            0
```

B05	23	24	0.001150	0.026700	0.053800	0		0
B06	25	23	0.001840	0.042720	0.086080	0		0
B07	12	13	0.001150	0.026700	0.053800	0		0
B08	12	13	0.001150	0.026700	0.053800	0		0
B09	13	25	0.001150	0.026700	0.053800	0		0
B10	13	25	0.001150	0.026700	0.053800	0		0
B11	25	26	0.000920	0.021360	0.043040	0		0
B12	26	27	0.001150	0.026700	0.053800	0		0
B13	26	27	0.001150	0.026700	0.053800	0		0
B14	27	24	0.001380	0.032040	0.064560	0		0
B15	28	26	0.000920	0.021360	0.043040	0		0
B16	14	15	0.001150	0.026700	0.053800	0		0
B17	14	15	0.001150	0.026700	0.053800	0		0
B18	15	28	0.001150	0.026700	0.053800	0		0
B19	15	28	0.001150	0.026700	0.053800	0		0
B20	28	29	0.000920	0.021360	0.043040	0		0
B21	29	30	0.001150	0.026700	0.053800	0		0
B22	29	30	0.001150	0.026700	0.053800	0		0
B23	30	27	0.000920	0.021360	0.043040	0		0
B24	31	29	0.000920	0.021360	0.043040	0		0
B25	33	30	0.001380	0.032040	0.064560	0		0
B26	31	32	0.001840	0.042720	0.086080	0		0
B27	32	33	0.001150	0.026700	0.053800	0		0
B28	35	32	0.001840	0.042720	0.086080	0		0
B29	35	34	0.001150	0.026700	0.053800	0		0
B30	34	33	0.000920	0.021360	0.043040	0		0
B31	17	31	0.002300	0.053400	0.107600	0		0
B32	17	31	0.002300	0.053400	0.107600	0		0
B33	36	17	0.002300	0.053400	0.107600	0		0
B34	37	36	0.004600	0.106800	0.215200	0		0
B35	20	37	0.004600	0.106800	0.215200	0		0
B36	19	18	0.015440	0.353000	0.062000	0		0
B37	47	19	0.015440	0.353000	0.062000	0		0
B38	16	35	0.001840	0.042720	0.086080	0		0
B39	16	35	0.001840	0.042720	0.086080	0		0
T01	1	11	0.0000000	0.018180	0.000000	1	1.128210	0
T02	2	12	0.0000000	0.011570	0.000000	1	1.128210	0
T03	3	13	0.0000000	0.021210	0.000000	1	1.070000	0
T04	4	14	0.0000000	0.011570	0.000000	1	1.128210	0
T05	5	15	0.0000000	0.021210	0.000000	1	1.075000	0
T06	6	16	0.0000000	0.011570	0.000000	1	1.128210	0
T07	7	17	0.0000000	0.011570	0.000000	1	1.128210	0
T08	8	18	0.0000000	0.018180	0.000000	1	1.025640	0
T09	9	19	0.0000000	0.018180	0.000000	1	1.025640	0
T10	10	20	0.0000000	0.025450	0.000000	1	1.128210	0
T11	22	38	0.0000000	0.023330	0.000000	1	0.952380	0
T12	24	39	0.0000000	0.011670	0.000000	1	0.952380	0
T13	27	40	0.0000000	0.011670	0.000000	1	0.952380	0
T14	30	41	0.0000000	0.011670	0.000000	1	0.952380	0
T15	33	42	0.0000000	0.011670	0.000000	1	0.952380	0
T16	34	43	0.0000000	0.023330	0.000000	1	0.952380	0
T17	25	44	0.0000000	0.023330	0.000000	1	0.921660	0
T18	28	45	0.0000000	0.023330	0.000000	1	0.921660	0
T19	31	46	0.0000000	0.023330	0.000000	1	0.921660	0

```
 T20    36 18   0.0000000   0.031110   0.000000   1 0.952380   0
 T21    37 19   0.0000000   0.031110   0.000000   1 0.952380   0
 T22    20 47   0.0000000   0.031110   0.000000   1 0.952380   0
END

// Bound constraints for nodal variables
    0.95   1.15   // default min,max of voltage magnitudes  (for all nodes but PV)
   -6.0   15.0    // default min,max of P generation for generation nodes (for VT)
    0.0    0.0    // default min,max of P generation for load nodes
   -6.0   10.0    // default min,max of Q generation for generation nodes (for VT,PV)
    0.0    0.0    // default min,max of Q generation for load nodes

// nodal bounds for voltage magnitudes
/bus   Vmin   Vmax
end

// nodal bounds for P generation
/bus     Pmin     Pmax
    1     1.40     7.00       // G01 Thermal(fossil)
    2    11.00    11.000001 // G02 Nuclear
    3     1.50     6.00       // G03 Hydraulic (slack bus)
    4     3.30    11.00       // G04 Thermal(fossil)
    5     1.50     6.00       // G05 Hydraulic
    6     3.30    11.00       // G06 Thermal(fossil)
    7    11.00    11.000001 // G07 Nuclear
    8     1.75     7.00       // G08 Thermal(fossil)
    9     1.75     7.00       // G09 Thermal(fossil)
   10     1.00     5.00       // G10 Thermal(fossil)
end

// nodal bounds for Q generation
/bus     Qmin     Qmax
    1     0.56     2.73     // G01 Thermal(fossil)
    2    -1.10     4.95     // G02 Nuclear
    3    -0.30     1.50     // G03 Hydraulic (slack bus)
    4    -1.10     5.50     // G04 Thermal(fossil)
    5    -0.30     1.50     // G05 Hydraulic
    6    -1.10     5.50     // G06 Thermal(fossil)
    7    -1.10     4.95     // G07 Nuclear
    8    -1.05     1.05     // G08 Thermal(fossil)
    9    -1.05     1.05     // G09 Thermal(fossil)
   10    -0.25     2.50     // G10 Thermal(fossil)
end

// power factor limits of generations
/bus     pfmin   pfmax     sign
end

// cost coefs for each generator
/bus         a               b              c             // cost(P) = a*P^2 + b*P + c
```

```
   1    40.0000e-6   2400.0e-6   1170.0e-6   // G01 Thermal(fossil)
   2     0.0000e-6    0.000e-6    0.000e-6   // G02 Nuclear
   3     0.0000e-6    0.000e-6    0.000e-6   // G03 Hydraulic (slack bus)
   4    63.6360e-6   400.00e-6   6050.0e-6   // G04 Thermal(fossil)
   5     0.0000e-6    0.000e-6    0.000e-6   // G05 Hydraulic
   6    63.6360e-6   400.00e-6   6050.0e-6   // G06 Thermal(fossil)
   7     0.0000e-6    0.000e-6    0.000e-6   // G07 Nuclear
   8    38.0000e-6   5000.0e-6   2600.0e-6   // G08 Thermal(fossil)
   9    38.0000e-6   5000.0e-6   2600.0e-6   // G09 Thermal(fossil)
  10     5.0000e-6   5000.0e-6   2000.0e-6   // G10 Thermal(fossil)
end

//note) cost coefs should be scaled for balancing the dual feasibility in IPM formulation.
//         If not, dual feasibility will not be improved and IPM convergence will degrade.
```

以上

補足資料　マイクログリッド等解析用の標準モデル

Output-1　(潮流計算)

```
Power Flow :  No of Equations & Variables = 9

Newton-Raphson ends at iter-4;  cpuTime = 0.031 sec

Nodal   Solution                      (G+L)                              (V:polar/rad)
(G+L)
  1     :  G                            V,T =   1.0500 < +0.0000     I =    0.3139  -
0.2596    P,Q =   0.3296    0.2726
  2     :  G    P    =    0.3500             V =   1.0500 < -0.0128     I =    0.3333  -
0.0081    P,Q =   0.3500    0.0040   ok
  3     :  L    P,Q  =   -0.2750    -0.1100    V  =   1.0480  <  -0.0182     I  =   -0.2604
0.1097    P,Q =  -0.2750   -0.1100   ok
  4     :  -    P,Q =    0.0000     0.0000    V  =  1.0243 < -0.0220     I =    0.0000  -
0.0000    P,Q =   0.0000    0.0000   ok
  5     :  L    P,Q  =   -0.1500    -0.0900    V  =   1.0473  <  -0.0452     I  =   -0.1392
0.0923    P,Q =  -0.1500   -0.0900   ok
  6     :  L    P,Q  =   -0.2500    -0.1500    V  =   1.0082  <  -0.0415     I  =   -0.2416
0.1589    P,Q =  -0.2500   -0.1500   ok
          sum       P,Q       =            -0.6750          -0.3500       (load       only)
total P,Q =   0.0046   -0.0734  (loss)

max P,Q mismatch = 5.675e-009  ok
Nodal capacitance flows     (V:rectangular)
  node-4      :  s =  0.0200   V =    1.0240   -0.0225   I =   -0.0004   -0.0205    P,Q =  -
0.0000    0.0210
  node-6      :  s =  0.0200   V =    1.0073   -0.0418   I =   -0.0008   -0.0201    P,Q =
0.0000    0.0203
                                                                           total    P,Q    =
0.0000    0.0413
Branch flows
```

```
  B1      1 --> 6    Re(I) =   0.1787 -->   0.1787 -->   0.1785   Pflow =   0.1876 --
>   0.1860   Ploss =   0.0016
                     Im(I) =  -0.1382 -->  -0.1434 -->  -0.1485   Qflow =   0.1451 --
>   0.1421   Qloss =   0.0030
  B2      1 --> 4    Re(I) =   0.1352 -->   0.1352 -->   0.1351   Pflow =   0.1420 --
>   0.1413   Ploss =   0.0007
                     Im(I) =  -0.1215 -->  -0.1257 -->  -0.1298   Qflow =   0.1275 --
>   0.1299   Qloss =  -0.0023
  B3      4 --> 6    Re(I) =   0.1031 -->   0.1030 -->   0.1028   Pflow =   0.1070 --
>   0.1067   Ploss =   0.0004
                     Im(I) =  -0.0648 -->  -0.0699 -->  -0.0749   Qflow =   0.0640 --
>   0.0712   Qloss =  -0.0072
  B4      6 --> 5    Re(I) =   0.0388 -->   0.0385 -->   0.0362   Pflow =   0.0427 --
>   0.0424   Ploss =   0.0002
                     Im(I) =  -0.0846 -->  -0.0926 -->  -0.0964   Qflow =   0.0836 --
>   0.0991   Qloss =  -0.0155
  B5      2 --> 5    Re(I) =   0.1034 -->   0.1033 -->   0.1030   Pflow =   0.1083 --
>   0.1076   Ploss =   0.0008
                     Im(I) =   0.0187 -->   0.0114 -->   0.0041   Qflow =  -0.0211 --
>  -0.0091   Qloss =  -0.0119
  B6      2 --> 3    Re(I) =   0.2298 -->   0.2298 -->   0.2298   Pflow =   0.2417 --
>   0.2413   Ploss =   0.0003
                     Im(I) =  -0.0268 -->  -0.0268 -->  -0.0268   Qflow =   0.0250 --
>   0.0237   Qloss =   0.0013
  B7      4 --> 3    Re(I) =   0.0316 -->   0.0316 -->   0.0306   Pflow =   0.0342 --
>   0.0337   Ploss =   0.0006
                     Im(I) =  -0.0855 -->  -0.0855 -->  -0.0829   Qflow =   0.0868 --
>   0.0863   Qloss =   0.0005

  branch total P,Q loss = 0.0046  -0.0321,   total P,Q loss = 0.0046  -0.0734  ok
--------------------------------------------------------------------------------------
------------------------------------
```

***) Information about bus(node) solution and power balances**

```
sample)
Nodal  Solution               (G+L)                                      (polar/rad)
(G+L)
  1    :  G                        V,T =  1.0000 < +0.0000   I =   0.1642   0.1928
P,Q =   0.1642  -0.1928
  2    :  L   P,Q =   0.2000  -0.2000   V =  1.0137 < -0.1073   I =   0.2173   0.1750
P,Q =   0.2000  -0.2000  ok
  3    :  G   P   =  -0.3500            V =  1.1000 < -0.2384   I =  -0.2591   0.2811
P,Q =  -0.3500  -0.2331  ok
          sum     P,Q     =             0.2000          -0.2000      (L     only)
total P,Q =   0.0142  -0.6259 (loss)

max P,Q mismatch = 3.223e-008  ok
```

*) The complex voltage solution (|V|,angle) for all buses were printed in polar/rad form: |V|∠(phase angle)

*) The complex current injection (I) for each bus were printed in rectangular form,
computed as the sum of branch current flows incident to the bus.

*) The complex power injection (P,Q) for each bus were printed (left: input data; G+L).
The complex power computation (P,Q) for each bus were printed (right: P+jQ = V*conj(I); G+L).
Both powers were compared. If they are nearly equal, 'ok' is printed, '?' otherwise.

*) The difference norm between the both powers for all buses was printed as 'max P,Q mismatch'. If this value is small enough, 'ok' is printed, '?' otherwise.
*) The sum of complex power in each bus was printed as 'total P,Q'. This values show the the overall difference between generations and loads, i.e. the complex power losses (active loss,reactive loss) in the grid.

---

*) Information about power flows and power losses

```
sample)
Nodal capacitance flows  (V:rectangular)
  node-4    :  s =  0.0200  V =   1.0240  -0.0225  I =  -0.0004  -0.0205   P,Q =  -
0.0000   0.0210
```

*) If there exist some shunt capacitors in the buses, the followings will be given for output.
*) The buses with nonzero shunt capacitor susceptance (sus) were picked up for output.
*) The complex voltage solution (V) for each bus were printed in rectangular form.
*) The complex current (Is) for each bus were printed in rectangular form (Is = (j*sus)*V).
*) The complex power computation (P,Q) for each bus were printed (P+jQ = V*conj(Is) → P=0).
*) The sum of the each complex power (P,Q) will be printed as 'total P,Q' if the number of this pickups > 1.

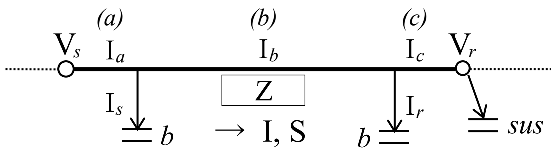
```
sample)
Branch flows
  B1     1       Re(I) =    0.1642 -->    0.1642 -->    0.1588    Pflow =     0.1642 -->
0.1500   Ploss =   0.0142
    -->  2       Im(I) =    0.1928 -->    0.1428 -->    0.0924    Qflow =    -0.1928 -->
-0.1103   Qloss =  -0.0824
  B2     2       Re(I) =    0.3110 -->    0.3110 -->    0.2591    Pflow =     0.3500 -->
0.3500   Ploss =   0.0000
    -->  3       Im(I) =   -0.3373 -->   -0.3373 -->   -0.2811    Qflow =     0.3062 -->
0.2331   Qloss =   0.0731

  branch total P,Q loss = 0.0142  -0.0094,    total P,Q loss = 0.0142  -0.6259  ok
```

*) The complex current flows and complex power flows for all branches were printed in rectangular form.
*) Each branch is separated into 3 parts(*a,b,c*) as shown in the figure below.
*) The complex current flows (I) in the parts(*a,b,c*) were printed in rectangular form (Re,Im).
*) The complex power flows (S) in the parts(*a,c*) were printed in rectangular form (Pflow,Qflow).
*) The complex power loss in the branch were printed in rectangular form (Ploss,Qloss). power loss = $S_a - S_c$
*) The total branch power loss in all branches were printed.
*) Also the total P,Q losses in the grid were printed if some nodal capacitances exist.
total P,Q losses = total branch power loss - total P,Q in 'Nodal capacitance flows'.
This value was compared with that in 'Nodal Solution'. If they are nearly equal, 'ok' is printed, '?' otherwise.

```
  *) Output form                 Ia   -->    Ib   -->    Ic                   Sa   -->
Sc     PowerLoss
       branchID     s   Re(I) =  0.1642 -->  0.1642 -->  0.1588   Pflow =  0.1642 -->
0.1500   Ploss =  0.0142
                --> r   Im(I) =  0.1928 -->  0.1428 -->  0.0924   Qflow = -0.1928 -->
-0.1103   Qloss = -0.0824
```

*) π-shaped equivalent citcuit



$$\dot{I}_b = (\dot{V}_s - \dot{V}_r)\,/\,\dot{Z}$$

$\dot{I}_a = \dot{I}_b + \dot{I}_s$ $\qquad$ $\dot{I}_c = \dot{I}_b - \dot{I}_r$ $\quad$ $\dot{I}_s = \dot{Y}_b \dot{V}_s,\ \dot{I}_r = \dot{Y}_b \dot{V}_r,\ \dot{Y}_b = jb$ *(admittance of the capacitor)*

$\dot{S}_a = \dot{V}_s\, \dot{I}_a^*$ $\qquad$ $\dot{S}_c = \dot{V}_r\, \dot{I}_c^*$ $\quad$ $(\dot{S} := P + jQ)$

(note) $\dot{I}_a = \dot{I}_c = \dot{I}_b$, if $b = 0$

Output-2 （多段経済負荷配分）

```
solution --------------------------------------------------------
  Objective value = 1788554.711633
  primal bound feasibility  satisfied
  dual   bound feasibility  satisfied
  primal feas. for EQ cons. satisfied
  primal feas. for LE cons. satisfied  (active:152)
-----------------------------------------------------------------
```

Dynamic Dispatch Schedule :

Period	G1	G2	G3	G4	G5	G6	G7	G8	BT	sumG	sumCostV	sumCostF
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	300.0000	0.0000	-10.0000	290.0000		
1 01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	260.0212	100.0000	-0.0212	360.0000	4042.6896	1005.0000
2 02	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	200.7476	200.0000	-0.7476	400.0000	4447.3261	1005.0000
3 03	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	164.6487	300.0000	-24.6487	440.0000	5116.0189	1005.0000
4 04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	204.6918	300.0000	-0.6918	504.0000	5572.2714	1005.0000
5 05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	284.0000	300.0000	0.0000	584.0000	6475.9131	1005.0000
6 06	0.0000	0.0000	0.0000	0.0000	0.0000	20.0000	344.0000	300.0000	0.0000	664.0000	7412.7569	1298.0000
7 07	0.0000	0.0000	0.0000	0.0000	0.0000	140.0000	400.0000	220.0000	0.0000	760.0000	8706.0228	1298.0000
8 08	0.0000	0.0000	0.0000	0.0000	0.0000	260.0000	600.0000	300.0000	0.0000	1160.0000	13368.0518	1298.0000
9 09	0.0000	0.0000	20.0000	60.0000	0.0000	380.0000	800.0000	300.0000	0.0000	1560.0000	18372.0878	2234.7400
10 10	0.0000	0.0000	70.0000	60.0000	0.0000	480.0000	800.0000	300.0000	50.0000	1760.0000	20511.0971	2234.7400

11 11 0.0000 0.0000 0.0000 20.0000 0.0000 480.0000 800.0000
300.0000 0.0000 1600.0000 18717.6961 1550.0000
12 12 0.0000 0.0000 0.0000 0.0000 0.0000 420.0000 800.0000
300.0000 0.0000 1520.0000 17672.4906 1298.0000
13 13 0.0000 0.0000 0.0000 40.0000 0.0000 300.0000 800.0000
300.0000 0.0000 1440.0000 16724.4822 1550.0000
14 14 0.0000 0.0000 0.0000 0.0000 0.0000 180.0000 640.0000
300.0000 0.0000 1120.0000 12811.0132 1298.0000
15 15 0.0000 0.0000 0.0000 0.0000 0.0000 60.0000 440.0000
300.0000 0.0000 800.0000 9012.9887 1298.0000
16 16 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 276.0000
300.0000 0.0000 576.0000 6384.7606 1005.0000
17 17 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 160.0000
256.0000 0.0000 416.0000 4587.8491 1005.0000
18 18 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
156.0000 0.0000 256.0000 2824.2034 1005.0000
19 19 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
132.0000 0.0000 232.0000 2565.0027 1005.0000
20 20 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 272.0000
200.0000 0.0000 472.0000 5259.1794 1005.0000
21 21 0.0000 0.0000 0.0000 0.0000 0.0000 20.0000 472.0000
300.0000 -0.0000 792.0000 8871.1993 1298.0000
22 22 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 580.0008
300.0000 -0.0008 880.0000 9848.5720 1005.0000
23 23 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 380.0036
300.0000 -40.0036 640.0000 7569.7849 1005.0000
24 24 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 185.3148
300.0000 −5.3148 480.0000 5351.4896 1005.0000
— —
— — — — — — —（略）
136 16 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 140.0000
292.0000 0.0000 432.0000 4748.7705 1005.0000
137 17 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 120.0000
192.0000 0.0000 312.0000 3440.8851 1005.0000
138 18 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
92.0000 0.0000 192.0000 2133.0018 1005.0000
139 19 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
74.0000 0.0000 174.0000 1938.6015 1005.0000
140 20 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 180.0000
174.0000 0.0000 354.0000 3930.1263 1005.0000
141 21 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 320.0000
274.0000 -0.0000 594.0000 6605.2977 1005.0000
142 22 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 360.0000
300.0000 -0.0000 660.0000 7341.8620 1005.0000
143 23 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 180.0000
300.0000 -0.0000 480.0000 5290.9322 1005.0000
144 24 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 135.0000
225.0000 -0.0000 360.0000 3968.1969 1005.0000
145 01 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
125.0000 -0.0000 225.0000 2489.4026 1005.0000
146 02 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
150.0000 -0.0000 250.0000 2759.4033 1005.0000
147 03 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 100.0000
175.0000 -0.0000 275.0000 3029.4041 1005.0000

148 04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	215.0000	-0.0000	315.0000	3461.4056	1005.0000
149 05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	265.0000	0.0000	365.0000	4001.4080	1005.0000
150 06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	115.0000	300.0000	0.0000	415.0000	4550.3203	1005.0000
151 07	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	275.0000	200.0000	0.0000	475.0000	5293.3616	1005.0000
152 08	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	475.0000	250.0000	0.0000	725.0000	8112.1788	1005.0000
153 09	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	675.0000	300.0000	0.0000	975.0000	10931.0046	1005.0000
154 10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	800.0000	300.0000	0.0000	1100.0000	12355.2730	1005.0000
155 11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	700.0000	300.0000	0.0000	1000.0000	11215.8580	1005.0000
156 12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	650.0000	300.0000	0.0000	950.0000	10646.1513	1005.0000
157 13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	600.0000	300.0000	0.0000	900.0000	10076.4450	1005.0000
158 14	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	400.0000	300.0000	0.0000	700.0000	7797.6250	1005.0000
159 15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	200.0000	300.0000	0.0000	500.0000	5518.8130	1005.0000
160 16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	260.0000	0.0000	360.0000	3947.4078	1005.0000
161 17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	160.0000	0.0000	260.0000	2867.4036	1005.0000
162 18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	60.0000	0.0000	160.0000	1787.4014	1005.0000
163 19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	45.0000	0.0000	145.0000	1625.4012	1005.0000
164 20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	150.0000	145.0000	0.0000	295.0000	3275.1044	1005.0000
165 21	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	250.0000	245.0000	-0.0000	495.0000	5494.5123	1005.0000
166 22	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	250.0000	300.0000	-0.0000	550.0000	6088.5153	1005.0000
167 23	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	300.0000	-0.0000	400.0000	4379.4100	1005.0000
168 24	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	100.0000	200.0000	-0.0000	300.0000	3299.4050	1005.0000
sum)	0.0000	915.0000	1995.0000	1475.0000	172.5000	18090.0000	69435.0714	44258.0000	-428.5714	135912.0000	1573739.4516	214815.2600

各 **unit**(G2～G8,BT)の発電プロファイル

*) G1 は燃料費高価のため一度も発電していない(起動停止計画の結果と同じ)。

Output-3 (最適潮流計算)

```
  n = 47, m = 61, ngen = 10, #pfactor = 0, #bpflow = 0, loadFactor = 1.000

Y matrix created;  n = 47, nz = 153 (6.926%), rowwise nzmax = 6

  nVar = 46+46+10+10 = 112 / 188, me = 94, mi = 0+0 = 0,  Sigma = 0.001, red.step =
0.9995

Newton_GMRES-IPM:  tol = 1.00e-008(P) 1.00e-008(D) 1.00e-007(C) 1.00e-011(M)

  iter      myu      Infeas(P)   Infeas(D)   Infeas(C) GMRES  stepLen(P,D)   time(s)
   1   2.109e-002  4.936e+001  8.614e+001  2.419e+002    3   0.0001 0.0000    0.000
   2   2.109e-002  4.943e+001  1.574e+002  2.452e+002   13   0.0000 0.0000    0.015
   3   2.109e-002  4.943e+001  1.574e+002  2.452e+002    2   0.0005 0.0061    0.000
   4   2.098e-002  4.941e+001  4.091e+002  2.437e+002    3   0.0091 0.0006    0.000
   5   2.095e-002  4.879e+001  4.455e+002  2.431e+002    6   0.0003 0.0090    0.016
   .........................................
   33  9.503e-009  8.955e-005  4.984e-003  9.023e-005   20   1.0000 0.6591    0.000
   34  3.210e-009  2.192e-003  1.969e-003  2.995e-005   17   0.9553 0.8046    0.016
   35  5.904e-010  2.798e-003  1.752e-004  5.026e-006   14   0.9501 0.9446    0.000
   36  3.375e-011  1.860e-004  1.384e-005  2.883e-007   14   0.9997 0.8445    0.000
   37  5.232e-012  1.348e-005  8.649e-006  4.509e-008  +21   1.0000 1.0000    0.016

Converged at iter-37;  nK = 206;  nzK = 1868 (4.402%), nzILU = 1814 (4.275%)  fillRate:
```

```
0.971

  total Time = 0.203 sec ( aveKKT: 0.001, aveLEQ: 0.003 )  sumGMRES: 518,  memLEQ =
0.072 Mb, MMD(At+A)

  FuncCalls: Func = 1, Grad = 37, Hessian = 37

  Minimum dispatch cost = 0.158233

OPF solution for generations
  Node          kind       V        T(rad)   kind       Pg          Qg          Pl
Ql       Pg+Pl      Qg+Ql   Pfactor
  1       G   PQ :    2    1.043505 -0.129773    2    7.000000    2.097094    0.000000
0.000000   7.000000   2.097094  +0.9579
  2       G   PQ :    2    1.038933  0.105638    2   11.000001    4.059198    0.000000
0.000000  11.000001   4.059198  +0.9382
  3       G   VT :    -    1.020000  0.000000    2    6.000000   -0.300000    0.000000
0.000000   6.000000  -0.300000  -0.9988
  4       G   PQ :    2    1.039096  0.081519    2   11.000000    2.781819    0.000000
0.000000  11.000000   2.781819  +0.9695
  5       G   PQ :    2    1.072063 -0.027571    2    6.000000    1.500000    0.000000
0.000000   6.000000   1.500000  +0.9701
  6       G   PQ :    2    1.039451 -0.051371    2   11.000000    2.823004    0.000000
0.000000  11.000000   2.823004  +0.9686
  7       G   PQ :    2    1.056955  0.078783    2   11.000001    4.888460    0.000000
0.000000  11.000001   4.888460  +0.9138
  8       G   PQ :    2    0.995599  0.302265    2    7.000000    1.050000    0.000000
0.000000   7.000000   1.050000  +0.9889
  9       G   PQ :    2    0.970719  0.398983    2    6.450458    1.050000    0.000000
0.000000   6.450458   1.050000  +0.9870
  10      G   PQ :    2    1.014896  0.444068    2    4.798443    2.500000    0.000000
0.000000   4.798443   2.500000  +0.8869
  #gen: 10                              sum)  81.248903  22.449575

PowerFlow verification of OPF soln
  Node                                (G+L)                                (polar/rad)
(G+L)
  1      G :  P,Q =   7.0000   2.0971   V =  1.0435 < -0.1298   I =   6.3917  -2.8609
P,Q =   7.0000   2.0971  ok
  2      G :  P,Q =  11.0000   4.0592   V =  1.0389 < +0.1056   I =  10.9407  -2.7689
P,Q =  11.0000   4.0592  ok
  3      G :                        V,T =  1.0200 < +0.0000   I =   5.8824   0.2941
P,Q =   6.0000  -0.3000
  4      G :  P,Q =  11.0000   2.7818   V =  1.0391 < +0.0815   I =  10.7690  -1.8062
P,Q =  11.0000   2.7818  ok
  5      G :  P,Q =   6.0000   1.5000   V =  1.0721 < -0.0276   I =   5.5560  -1.5529
P,Q =   6.0000   1.5000  ok
  6      G :  P,Q =  11.0000   2.8230   V =  1.0395 < -0.0514   I =  10.4291  -3.2557
P,Q =  11.0000   2.8230  ok
  7      G :  P,Q =  11.0000   4.8885   V =  1.0570 < +0.0788   I =  10.7390  -3.7916
P,Q =  11.0000   4.8885  ok
  8      G :  P,Q =   7.0000   1.0500   V =  0.9956 < +0.3023   I =   7.0261   1.0862
P,Q =   7.0000   1.0500  ok
  9      G :  P,Q =   6.4505   1.0500   V =  0.9707 < +0.3990   I =   6.5433   1.5848
```

```
P,Q =   6.4505   1.0500  ok
  10    G :  P,Q =   4.7984   2.5000   V =  1.0149 < +0.4441   I =   5.3277  -0.1932
P,Q =   4.7984   2.5000  ok
  11    - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.2239   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  12    - :  P,Q =   0.0000   0.0000   V =  1.1373 < +0.0100   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  13    - :  P,Q =   0.0000   0.0000   V =  1.1034 < -0.1059   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  14    - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.0130   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  15    - :  P,Q =   0.0000   0.0000   V =  1.1303 < -0.1254   I =  -0.0000   0.0000
P,Q =  -0.0000   0.0000  ok
  16    - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.1459   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  17    - :  P,Q =   0.0000   0.0000   V =  1.1500 < -0.0142   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  18    L :  P,Q =  -5.5000  -1.0500   V =  1.0101 < +0.1786   I =  -5.5428   0.0558
P,Q =  -5.5000  -1.0500  ok
  19    L :  P,Q =  -5.5000  -1.4130   V =  0.9835 < +0.2789   I =  -5.7716  -0.1585
P,Q =  -5.5000  -1.4130  ok
  20    - :  P,Q =   0.0000   0.0000   V =  1.0947 < +0.3465   I =  -0.0000  -0.0000
P,Q =  -0.0000   0.0000  ok
  21    - :  P,Q =   0.0000   0.0000   V =  1.1129 < -0.4575   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  22    - :  P,Q =   0.0000   0.0000   V =  1.1175 < -0.5917   I =  -0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  23    - :  P,Q =   0.0000   0.0000   V =  1.1053 < -0.4815   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  24    - :  P,Q =   0.0000   0.0000   V =  1.1183 < -0.6122   I =  -0.0000  -0.0000
P,Q =  -0.0000   0.0000  ok
  25    - :  P,Q =   0.0000   0.0000   V =  1.1014 < -0.2926   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  26    - :  P,Q =   0.0000   0.0000   V =  1.1066 < -0.4059   I =   0.0000  -0.0000
P,Q =   0.0000   0.0000  ok
  27    - :  P,Q =   0.0000   0.0000   V =  1.1172 < -0.5393   I =   0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  28    - :  P,Q =   0.0000   0.0000   V =  1.1189 < -0.3045   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  29    - :  P,Q =   0.0000   0.0000   V =  1.1173 < -0.4056   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  30    - :  P,Q =   0.0000   0.0000   V =  1.1233 < -0.5290   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  31    - :  P,Q =   0.0000   0.0000   V =  1.1261 < -0.3092   I =   0.0000  -0.0000
P,Q =   0.0000  -0.0000  ok
  32    - :  P,Q =   0.0000   0.0000   V =  1.1216 < -0.4221   I =   0.0000  -0.0000
P,Q =   0.0000  -0.0000  ok
  33    - :  P,Q =   0.0000   0.0000   V =  1.1282 < -0.5514   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  34    - :  P,Q =   0.0000   0.0000   V =  1.1245 < -0.4997   I =  -0.0000  -0.0000
P,Q =  -0.0000   0.0000  ok
  35    - :  P,Q =   0.0000   0.0000   V =  1.1231 < -0.3274   I =  -0.0000   0.0000
P,Q =  -0.0000  -0.0000  ok
  36    - :  P,Q =   0.0000   0.0000   V =  1.0917 < +0.1259   I =   0.0000   0.0000
```

```
P,Q =   0.0000  -0.0000  ok
  37    - :  P,Q =   0.0000   0.0000   V =  1.0635 < +0.2621   I =   0.0000   0.0000
P,Q =   0.0000  -0.0000  ok
  38    L :  P,Q =  -5.0000   1.2000   V =  1.0847 < -0.6929   I =  -4.2533   2.0934
P,Q =  -5.0000   1.2000  ok
  39    L :  P,Q = -10.0000   2.4160   V =  1.0856 < -0.7133   I =  -8.4220   4.3440
P,Q = -10.0000   2.4160  ok
  40    L :  P,Q = -10.0000   2.6710   V =  1.0872 < -0.6404   I =  -8.8435   3.5255
P,Q = -10.0000   2.6710  ok
  41    L :  P,Q = -10.0000   2.5930   V =  1.0922 < -0.6290   I =  -8.8002   3.4672
P,Q = -10.0000   2.5930  ok
  42    L :  P,Q = -10.0000   2.3780   V =  1.0945 < -0.6508   I =  -8.5853   3.8065
P,Q = -10.0000   2.3780  ok
  43    L :  P,Q =  -5.0000   1.2600   V =  1.0926 < -0.5995   I =  -4.4290   1.6300
P,Q =  -5.0000   1.2600  ok
  44    L :  P,Q =  -5.0000   2.4990   V =  1.0640 < -0.4008   I =  -5.2432  -0.3292
P,Q =  -5.0000   2.4990  ok
  45    L :  P,Q =  -5.0000   2.4800   V =  1.0792 < -0.4095   I =  -5.1651  -0.2634
P,Q =  -5.0000   2.4800  ok
  46    L :  P,Q =  -5.0000   2.5320   V =  1.0867 < -0.4128   I =  -5.1494  -0.2884
P,Q =  -5.0000   2.5320  ok
  47    L :  P,Q =  -4.0000  -1.3680   V =  0.9934 < +0.2301   I =  -4.2346   0.4225
P,Q =  -4.0000  -1.3680  ok
         sum P,Q = -80.0000  16.1980 (L only)                                    total
P,Q =   1.2489  38.6476 (loss)
                                                                           max
PQ_mismatch = 3.108e-009  ok

   V = [ 0.9707, 1.1500 ] at node 9, 17,  Theta = [ -0.7133, 0.4441 ] (rad) at node
39, 10

Current/Power flow balance satisfied at all nodes

Test Branch PowerFlow limits;  none
```

10. 付録 C:大規模配電系統潮流計算の高速解法

2020 年 3 月

環境エネルギー技術研究所㈱

１．概要

電力系統における潮流計算手法には，初期の Gauss-Seidel 法，Implicit Zbus Gauss 法を含め，Newton-Raphson 法およびその改良版(Decoupled 法など)，Backward/Forward 法およびその変形版など，多くの解法が提案されている。これらの解法の性能比較については，過去に実施されてはいるが，「時期が古い，大規模系統を対象としていない」などの不十分さがあり,「どの程度の系統規模まで，どれぐらい速く解けるのか」が不明確であった。そこで，本稿では，現在の計算機環境およびソフトウェア技術に基づいて，標準的解法の性能比較をあらためて実施することとする。そのために，これまでに開発された潮流計算のプログラム資産に依存しない新たなプログラムを開発し，これを用いて高速 PC で大規模配電系統向けの数値実験と性能比較を行う。

開発した潮流計算プログラムは, 代表的厳密解法である Newton-Raphson 法と Backward/Forward 法である。Newton-Raphson 法では，Jacobian 疎行列の高速 LU 分解，Backward/Forward 法では，グラフ理論に基づいた Topological Ordering による高速 B/F Sweep を採用している。両解法とも，配電系統のトポロジー的特徴である放射性(Radial)または弱ループ性(Weakly-meshed：ループ数が少ないこと)を考慮することが可能である。

２．電力系統の潮流方程式

送配電電力系統は，需要家の電力需要を賄えるように設計された電力伝送路である。この伝送路における電力・電流の流れと電圧分布を解析するために，一定の基準で設定されたノード(母線：bus)とノード間を結ぶブランチ(枝：branch)で構成されるネットワーク構造(属性つきのグラフ)から導きだされる電力潮流方程式が解かれる。ここで，状態量である電力(Power)・電流(Current)・電圧(Voltage)はすべて複素数であり，電力には実数部を示す有効電力(P：Active Power)，虚数部を示す無効電力(Q：Reactive Power)という名称が与えられている。また，複素電圧($\dot{V}$)は，複素数の指数表現である $\dot{V}=|\dot{V}|e^{j\delta}=|\dot{V}|\cos\delta+j|\dot{V}|\sin\delta$ を用いて電圧値$|\dot{V}|$と電圧位相角 δ (radian)で表現されることも多い。ここで，複素数には上ドット記号を添え，j を虚数単位として使用する。

ネットワークのノードは，発電ノードとP・Q値を指定する負荷ノードに大別され，さらに発電ノードは，複素電圧を指定する無限大母線(スラック母線)と P 値と$|\dot{V}|$値を指定する PV 母線とに分類されることが一般的である。ブランチには，ブランチ属性として Impedance(抵抗とリアクタンス)が与えられる。また，一般の π 型系統モデルでは，ノードおよびブランチに無効電力の提供・吸収を担う Susceptance を考慮できるようになっている。Susceptance とは，Impedance の逆数である Admittance の虚数部を示し，Susceptance 機能を有する機器を Shunt Capacitor と言う。

このようなモデルで構成される送配電電力系統は，バス群と双方向性を有するブランチ群から構成される無向グラフとしてとらえることができ，このグラフをもとに，以下に示す交流回路の基本式を適用することにより，電力潮流方程式が作成される。

〇交流回路の基本式　（上*記号は共役複素数を示す）

①オームの法則(Ohm's Law)

・ $\dot{V} = \dot{Z}\dot{I}$　($\dot{V}$:Voltage, $\dot{I}$:Current, $\dot{Z}$:Impedance)

・ $\dot{I} = \dot{Y}\dot{V}$　($\dot{V}$:Voltage, $\dot{I}$:Current, $\dot{Y}$:Admittance)

②キルヒホッフの電流則（KCL: Kirchhoff's Current Law）

・ノードに流出入する電流の総和は零である。

・ノードに流出入する電力流の総和は零である。

③キルヒホッフの電圧則（KVL: Kirchhoff's Voltage Law）

・閉路における電圧の総和は零である。

・ブランチ端点 1-->2 の電圧降下式： $\dot{V}_1 - \dot{V}_2 = \dot{Z}\dot{I}$

④ノードにおける注入電力則

・ $\dot{S} = \dot{V}(\dot{I})^*$　($\dot{S}$:injected Power, $\dot{V}$:Voltage, $\dot{I}$:injected Current)

・ $\dot{I} = (\dot{S}/\dot{V})^*$

以上の公式より導かれる電力潮流方程式は以下の通りである。

(A) $[\dot{I}] = [\dot{Y}][\dot{V}]$

(B) $\dot{S}_i = \dot{V}_i([\dot{Y}][\dot{V}])_i^*$　($i=1...n$)

ここで，$[\dot{V}]$は全ノードの電圧ベクトル，$[\dot{I}]$は同注入電流ベクトル，$\dot{S}_i = P_i + jQ_i$ はノード$_i$の指定注入電力（発電+，負荷−），$[\dot{Y}]$はキルヒホッフの電流則より導かれる系統全体の対称アドミッタンス行列（Y_{bus} matrix），n はノード数を示す。(B)式が電力潮流方程式と称されるノード電圧に関する非線形方程式であり，$\dot{S}_i$を与えてこれを解くとノード電圧が求められる。(A)式は(B)式を作成するために必要な線形交流回路の基本方程式であり，同式よりノード電圧が求められるとノードの注入電流ベクトルが計算できることを示している。このことより，電力系統は線形の交流回路理論が基礎となっているが，電力潮流の非線形性は主として電力値の指定という境界条件より生じることがわかる。

以上で電力潮流方程式の導入を行ったが，実際に潮流方程式を解くには(B)式だけでは

方程式の解は求められず，発電側での境界条件も与える必要がある。そのために考案された方法がスラックバスの導入である。すなわち，少なくとも一個の複素電圧指定ノード（スラック・バス）を与えることにより，電力潮流方程式の不定性を回避できることとなる。また，発電ノードにはPV母線としてP値と$|\dot{V}|$値を指定することがあるので，その境界条件も考慮する必要がある。これらの境界条件の原則的な処理方法は，電圧指定があればその電圧変数は固定値とみなし変数からはずすこと，また，電力指定があれば，そのP値またはQ値に関する電力潮流方程式の行を取り除くことである。この結果，電力潮流方程式のサイズ(変数の個数＝方程式の本数)は $2n$ よりも幾分小さくなる。

なお，ここで述べた電力潮流方程式の詳細内容は以下の文献に記述されているので，参照されたい。

出典：東京電力株式会社・インターネット電力講座 Newton-Raphson 法による電力系統の潮流計算

３．電力潮流方程式の解法

前節で述べたように，電力潮流方程式を解くことは，多次元の非線形連立方程式を解くことに等しい。この方程式を直接解析的に解く方法はないので，解法としては数値演算による繰返し法に頼らざるを得ない。そのような手法の多くは，非線形連立方程式を線形近似して，収束条件が満足されるまで繰り返し演算を行うのが通常である。線形近似の方法によって解法が分類され，最も初歩的な解法が，非線形項・非対角項をすべて前回の反復で得られた値で代替し定数項にしてしまう Gauss-Seidel 法である。また，非線形問題の数値解法として一般的に利用される Newton-Raphson 法は，非線形の PQ ミスマッチ関数の勾配情報(Jacobian)によって線形化を行う。さらに別の解法として，電力潮流方程式を線形の交流回路方程式に近似する方法もしばしば利用されており，この線形化を採用した解法として Implicit Zbus Gauss 法や Current Injection 法(電流注入法)が挙げられる。この方法は前記(A)式 $[\dot{Y}][\dot{V}]=[\dot{I}]$ の右辺を前回の反復で得られた電圧 $\dot{V}_p$ で $\dot{I}=(\dot{S}/\dot{V}_p)^*$ と近似して，$[\dot{V}]$ に関する連立一次方程式を繰り返し解くものである。この解法の考えを，行列を使用せず手続き的方法で実現したのが Backward/Forward 法であり，同法では，グラフ探索によってキルヒホッフの法則(KCL,KVL)を直接適用することにより，アドミッタンス行列$[\dot{Y}]$を構成する方法と等価な解を得ることができる。

以上，電力潮流方程式の解法について概説したが，次に Backward/Forward 法について詳述する。

３.１ Backward/Forward 法による電力潮流方程式の解法

Backward/Forward 法は，電力潮流方程式を直接解く送電系統向け伝統的方法（Newton-Raphson 法の系列）の別解法として登場した[1, 7]。この解法は，ループのない放射状配電

系統を対象として，大規模複素行列を操作する複雑な手順を省くことで，シンプルかつ高速な性能を実現することができた。その後，Backward/Forward 法は，ループ構造および電圧制御バス(PV 母線)を考慮できるように拡張され[14, 18]，更に三相不平衡潮流計算にも適用された[26]。これ以外にも，現在まで Backward/Forward 法の変形版が数多く提案されており，それらの内容については詳細なサーベイ論文[47]が発表されているので参照されたい。

以下に，Backward/Forward 法の基本手法と拡張内容について述べる。

３.２　ループ構造のない系統に対する Backward/Forward 法

ループ(サイクル)がない放射状系統とは，木構造のグラフであることを意味する。グラフ理論によると，サイクルがないグラフは，Topological Ordering によって半順序集合に変換できる，すなわち，すべてのノードは，所与の出発点から順序立って訪問でき，逐次処理が可能となるという原理がある。この原理にもとづいて，木の根(root:スラックバス)を出発点として，すべてのノードを逐次訪問しながらキルヒホッフの電圧則による電圧降下計算を行う，という方法が Forward Sweep である。また逆に，すべての木の葉(leaf)を出発点として木の根まで逐次訪問しながらキルヒホッフの電流則による電流加算を行う，という方法が Backward Sweep である。Backward/Forward 法は，この二種類の線形 Sweep を非線形回路に適用した方法であり，次に示す反復処理フローとして実行される。

① すべてのノードにおける電圧($\dot{V}$)の仮定(flat start)

② 収束条件が満足されるまで以下の処理を繰り返す

a) すべてのノードにおける等価注入電流の設定

$\dot{I}_i = (\dot{S}_i / \dot{V}_i)^* - j y_{ci} \dot{V}_i$ （$i=1...n$）（y_{ci} : *susceptance at node*$_i$）

b) Backward　Sweep による全ノードにおける注入電流の加算とブランチ電流の設定

$\dot{I}_{sr} = \dot{I}_r$ （*s*: *sending end node, r*: *receiving end node*）

$\dot{I}_s = \dot{I}_s + \dot{I}_r$

c) Forward　Sweep によるすべてのノードにおける電圧降下計算

$\dot{V}_r = \dot{V}_s - \dot{Z}_{sr} \dot{I}_{sr}$ （*s*: *sending end node, r*: *receiving end node*）

d) すべてのノードにおける電圧増分計算と収束判定

$\| \dot{V}_i - \dot{V}_{iold} \| < \varepsilon$ （$i=1...n, i \neq root$）

上記の方法は，Backward Sweep の過程で下流から上流へ電流の積み上げを行うので，Backward/Forward 法の分類としては電流積み上げ法(Current Summation method)と呼ばれている。これに対し，電力流の積み上げを行う電力積み上げ法(Power Summation method)は，次に示す反復処理フローとして実行される。電力積み上げ法の特徴は，ブランチにおける電力ロスを考慮する点であり，これにより電流積み上げ法よりも収束性が改善され

る(後述)。

① すべてのノードにおける電圧($\dot{V}$)の仮定(flat start)

② 収束条件が満足されるまで以下の処理を繰り返す

a) すべてのノードにおける等価注入電力の設定

$\dot{P}_i = \dot{S}_i - \dot{V}_i (j y_{ci} \dot{V}_i)^*$ （$i=1...n$）（y_{ci} : *susceptance at node*$_i$）

b) BackwardSweep による全ノードにおける注入電力の加算とブランチ電流の設定

$\dot{I}_{sr} = (\dot{P}_r / \dot{V}_r)^*$ （*s*: *sending end node, r*: *receiving end node*）

$\dot{P}_s = \dot{P}_s + \dot{P}_r + |\dot{I}_{sr}|^2 \dot{Z}_{sr}$ （右辺第３項は電力ロス）

c) ForwardSweep によるすべてのノードにおける電圧降下計算

$\dot{V}_r = \dot{V}_s - \dot{Z}_{sr} \dot{I}_{sr}$ （*s*: *sending end node, r*: *receiving end node*）

d) すべてのノードにおける電圧増分計算と収束判定

$\| \dot{V}_i - \dot{V}_{iold} \| < \varepsilon$ （$i=1...n, i \neq root$）

ここで，Backward/Forward Sweep を行うブランチ順番を決定する方法には，グラフ探索の手法を用いる。グラフ探索の手法には，分岐を優先する幅優先探索(BFS:Breadth First Search)と連結を優先する深さ優先探索(DFS:Depth First Search)の二種がある。この手法を適用するに当たり，以下の方法が考えられる。

A) Backward/Forward Sweep を行う度に，グラフ探索を行う。

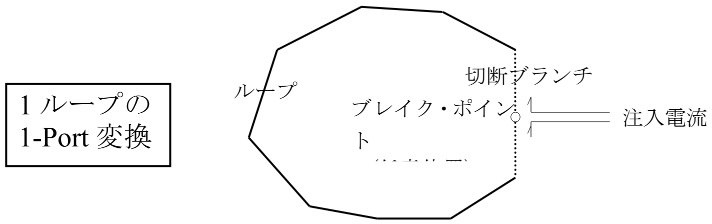
B) 最初に一回グラフ探索を行い，その結果得られるブランチ訪問の順番を格納し，Backward/Forward Sweep の際には，訪問の順番通り，または逆順通りに処理する。

ここでの数値実験では, A)の方法はグラフ探索に要するオーバーヘッドにより計算時間がかなり増大したので，大規模系統では B)の方法を推奨する。特に，系統を無向グラフ(Undirected Graph)として表現するとブランチ数が２倍となるので, その半数のサイズである有向ブランチの訪問順番配列を使用する方にメリットがある。なお, 無向グラフを使用する利点は，複雑な(ループのある)大規模ネットワークになると，中間ブランチ流の向きが不明確となることによるブランチ始点・終点データの入力ミスを防げることにある(有向グラフでは正しい向きを入力しないと到達性が失われる)。特に，複数の配電変電所からのマルチフィーダ系統をスイッチ切替えでラディアル運用している場合には,スイッチの状態による中間ブランチ流の向きの不明確さは顕著となるであろう。

また，BFS と DFS の違いについては，Backward/Forward Sweep に要する計算時間の差異はみられなかったが, グラフ探索そのものに要する時間が大規模系統では, 短い時間ではあるが，DFS の方が数倍～数十倍高速であった。ただし，次に述べるループ構造を有する系統では，ループの発見に BFS と DFS では異なる結果となるので，Backward/Forward Sweep の収束性能に違いが現れる。

３.３ ループ構造を有する系統に対する Backward/Forward 法

ここでは，ループ構造を有する系統をループのない放射状系統に変換して，前述の Backward/Forward 法を適用する Multi-Port Compensation 法[14, 18]に基づいた手法を提案する。Multi-Port Compensation 法は，まず「ループを構成するブランチ群の一つをブレイク・ポイントで切断することにより放射状系統に変換し」,「その潮流計算の結果得られるブレイク・ポイントでの電圧不整合を解消するために当該点における複素電流注入で補充を行う」という考えに基づいている。ループが複数あれば，ブレイク・ポイントもループ数分設け(Multi-Port 変換)，電流注入の補充も同数回考慮する。補充する注入電流量は，線形回路におけるテブナンの定理(Thevenin’s Theorem)を用いて感度行列(Sensitivity matrix)を用意することで求められる。



提案解法では，ループの発見とブレイク・ポイントを設ける切断ブランチの設定は，グラフ理論におけるサイクル発見法を用いて前述したグラフ探索の最中に行う。発見されたループの最後のブランチを切断ブランチとし，このブランチをオープンに設定する。グラフ探索の最中には，各探索ノードに流入接続する唯一のブランチ情報も保存しておき，各ノードからルートへパスを追跡できるようにしておく。この逆向きパスを利用して，ループ数 K のループ・インピーダンスによる感度行列 $\mathbf{Z} = (Z_{ij})$ が以下のように作成される。

① 自己インピーダンス: $Z_{ii} = \sum_{l \in S_i} z_l$ *for* $loop_i$ $(i=1...K)$

② 互インピーダンス： $Z_{ij} = \sum_{l \in M_{ij}} z_l \, sign(l)$ *for* $loop_i$ & $loop_j$ $(i,j=1...K, i \neq j)$

ここで，z_l は下記の集合に属するブランチ$_l$ のインピーダンスを示す。

- $S_i = (P_i^+ \cup P_i^-) - (P_i^+ \cap P_i^-) + B_i$
- $M_{ij} = (P_i^+ \cap P_j^+) \cup (P_i^- \cap P_j^-)$ $(sign(l)=+1)$
  $\cup (P_i^+ \cap P_j^-) \cup (P_i^- \cap P_j^+)$ $(sign(l)=-1)$
- B_i ：ループ$_i$ の切断ブランチ
- P_i^+ ：切断ブランチ$_i$ の１端点からルートへのパス*(positive path)*を構成するブランチ集合
- P_i^- ：切断ブランチ$_i$ の他端点からルートへのパス*(negative path)*を構成するブランチ集合

この感度行列を利用して，ブレイク・ポイントにおける補充注入電流量の増分は次の連立一次法方程式を解くことで求められる。

$$\mathbf{Z}\,[\dot{I}_d] = [\dot{V}_d]$$

ここで，$[\dot{V}_d]$ はすべてのブレイク・ポイントにおける電圧不整合値ベクトル(切断ブランチ両端の電圧差−切断ブランチにおける電圧降下)，$[\dot{I}_d]$ はすべてのブレイク・ポイントにおける補充注入電流量の増分ベクトルであり，該当する切断ブランチに流れる複素電流として累計される。なお，この方程式のサイズは *2K* である。

Multi-Port Compensation 法に基づく提案解法では，各反復過程において，上式から求められた切断ブランチの電流をその両端ノードにおける補充注入電力(一方は流入，他方は流出)に公式 $\dot{S} = \dot{V}\,(\dot{I})^*$ で変換し，これを両端ノードにおける元々の注入電力量に加えて，次回の反復に使用する，という処理を行う。

したがって，アルゴリズム上では，Backward/Forward 法の処理枠組みに大きな変化はなく，ループの発見と切断ブランチの設定，感度行列の作成および補充量の計算・加算ルーチンを追加するのみで良い。

３．４ PV 母線を有する系統に対する Backward/Forward 法

Backward/Forward 法に PV母線を導入する試みは，文献[14]で最初になされ，その後 PV 母線の処理にも前述した感度行列を利用するという方式に改良された[18]。さらに，この方法は，収束性の改善という面での進展[25, 35]が見受けられる。

本稿では，文献[18, 35]に基づき，これに若干の修正を行った手法を提案する。Multi-Port Compensation 法にもとづく PV母線処理の基本的アイデアは，各 PV母線とルートノード間に系統に連結しない仮想ブランチ(**Fictitious** branch)を設け，この結果生じる仮想ループ構造に対し前述したループ処理と同じ方法で感度行列を作成する，という点である。PV 母線処理とループ処理との違いは，仮想ブランチにブレイク・ポイントは設けず，その代わりに，PV母線における指定電圧制御のためにその PV母線への無効電力の補充機能を仮想ブランチに付与する，ということにある。すなわち，仮想ブランチは Shunt Capacitor としての役目を担うこととなる。

PV 母線では P, $|\dot{V}|$値の指定があるので，前記複素電圧不整合値ベクトルの算定に当たっては，PV 母線における電圧値と指定値との差の実数部のみを使用し，感度行列の作成では，電圧不整合値の虚数部に関する行と P に関与する変数(補充注入電流量の実数部)は除く。したがって，感度行列のサイズは，ループ数を *K*，PV 母線数を *p* とすると *2K+p* となる。これに応じて，感度行列の不要部分を取り除き，行列操作を容易にするために，行と列の並び替え，および補充注入電流量の符号変換を行うと，感度行列の形式は以下のように変換される。

$$\begin{pmatrix} X & R \\ -R & X \end{pmatrix}\begin{pmatrix} -I_i \\ +I_r \end{pmatrix} = \begin{pmatrix} V_r \\ V_i \end{pmatrix} \qquad \boxed{\begin{array}{l} \dot{Z} = R + jX \\ \dot{V} = V_r + jV_i \quad \dot{I} = I_r + jI_i \end{array}}$$

ここで，左辺行列は変換された感度行列($dim\,X=K+p, dim\,R=K$)，左辺ベクトルはすべてのループ・ブレイクポイントとPV母線における補充注入電流量の増分ベクトル，右辺定数項ベクトルは同位置の電圧不整合値ベクトルである。

PV母線における電圧不整合値として，$(|\dot{V}|_{sp}/|\dot{V}|-1)Re(\dot{V})$の改定算定式を使用する[35]。ここで，$\dot{V}$はBackward/Forward法の反復過程で得られているPV母線の複素電圧，$|\dot{V}|_{sp}$は当該PV母線における電圧指定値である。また，上記連立一次方程式より得られる補充注入電流量の増分I_iを用いて，PV母線への無効電力の補充量の増分は$I_i|\dot{V}|^2/Re(\dot{V})$と算定される[35]ので，これを当該仮想ブランチの提供無効電力に加算する。その累計値は，Backward/ Forward法の次回反復で利用されるよう，当該PV母線における注入無効電力量として設定される。

提案解法では，上記補充量を求めた後，収束の安定性を目的として，各PV母線の複素電圧$\dot{V}$を$|\dot{V}|_{sp}$に正規化する処理を追加している。

以上がMulti-Port Compensation法に基づくPV母線の処理概要であり，原理的にはループ処理と同一であることを示した。したがって，アルゴリズム上では，Backward/Forward法の処理枠組みに大きな変化はなく，仮想ブランチの作成，PV母線を考慮した感度行列の作成および補充量の計算・加算ルーチンを追加するのみで良い。

４．大規模・放射状配電系統の潮流シミュレーション

提案解法を用いて開発したBackward/Forward法とNewton-Raphson法による潮流計算プログラムの性能を確認するために，数値実験を行ったので，以下にその内容を述べる。ここでは放射状配電系統でのシミュレーションについて述べ，ループ構造およびPV母線を有する配電系統でのシミュレーションについては，次節で述べる。なお，開発プログラムはC言語とC++言語で作成されている。

４.１　シミュレーション用のモデル作成

ループのない仮想的大規模配電系統(Radial Distribution network)を，木構造を有する有向グラフとしてランダムに発生させて，数値実験に使用する。この木の根をスラックバスとし，木の葉を負荷ノード(PQ指定ノード)，残りは中間通過・分岐点(指定値零の PQ ノード)とする。負荷ノードのPQ値は範囲P[0.1,1.0], Q[0.0,0.05]からランダムに発生させた。ブランチ属性についてもランダム値を発生させ，抵抗は範囲R[0.01,0.05]，リアクタンスには対抵抗比R/X[1.0,10.0]を使用した。ブランチとノードに関与する他のSusceptance分(Shunt Capacitor)は無視する。スラックバスの電圧位相角は零とし，電圧値については，

暫定推定値としてＰ値総和とＲ値総和の関数として経験的に設定した。但し，その適正な値は評価・算定していないので，この暫定推定値を用いた潮流計算の結果により以下のように補正を行う。

①潮流計算が収束しなければ，電圧崩壊が生じていると判断し，スラックバスの推定電圧値を大きくする。

②潮流計算が収束しノードの電圧位相角がすべて零に近ければ，高圧すぎるスラックバスの推定電圧値を小さくする。

なお，数値実験に使用したブランチ属性の R/X 比は，いわゆる Ill-conditioned と称されている値の範囲(3～5 以上)にあり，Newton-Raphson 法の系列では収束しないことが多いと言われている。

４.２ シミュレーション結果

ノード数 n=500,1000,2000,5000,10000,20000,30000,40000,50000，ブランチ数 n-1 の大規模配電系統を，ランダムに発生させて数値実験を行った。Newton-Raphson 法，Backward/Forward 法ともフラットスタートとし，収束条件は，極座標による Newton-Raphson 法では，PQ 値のミスマッチによる収束誤差として 10^{-4}，直交座標による Backward/Forward 法では，全負荷ノードにおける複素電圧成分の収束増分誤差として 10^{-6}，を与えた。

数値実験の結果を表 1 に示す。すべてのケースにおいて，Backward/Forward 法では解が得られたが，Newton-Raphson 法では n=50000 のケースにおいて，メモリ不足により解が得られなかった。このケースを除き，得られた電圧値の目視比較により，両解法とも許容範囲内でほぼ同一解を与えているものと判断される(実配電系統では潮流多根は存在しないことを証明した論文あり [17])。但し，ノード数が膨大なので完全な照合は行っていない。なお，研究会で報告された 126 母線系統の実行結果では，両解法による電圧分布(電圧値，位相角：単位-度)は少数点以下 4 桁まで完全に一致していた。 数値実験に使用した PC は, Dell Precision T1500(Intel Core i7, 64bit OS, 2.80GHz, 物理メモリ 16GB)である。

表１　大規模配電系統での数値実験の結果

ノード (n)	負荷ノード	スラック電圧	反復回数		最終誤差		実行時間(s)		速度比
			N/R	B/F	N/R	B/F	N/R	B/F	
500	240	5.00	5	12	2.619e-6	5.888e-7	0.031	0.016	1.94
1000	483	10.00	5	14	9.683e-5	7.246e-7	0.062	0.031	2.00
2000	1012	20.00	4	6	1.274e-6	3.812e-7	0.203	0.016	12.69
5000	2510	20.00	6	19	1.985e-7	5.763e-7	1.856	0.031	59.87
10000	5125	30.00	5	8	3.392e-10	4.554e-7	6.147	0.047	130.8
20000	10387	40.00	6	13	3.201e-10	6.207e-7	29.312	0.046	637.2
30000	15920	40.00	6	13	2.474e-10	3.497e-7	65.848	0.093	708.0
40000	21142	50.00	6	16	1.756e-8	5.346e-7	116.610	0.109	1069.8
50000	27346	50.00	—	19	—	5.062e-7	—	0.234	—

注） Backward/Forward 法では，グラフ探索に DFS を使用。
ただし，DFS による実行時間は上表には含まれていない。

なお，表１に示す結果は，研究会で報告した結果とは以下の点で異なっているので，注意されたい。

①ネットワーク構造の汎用性を高めるため，Backward/Forward 法のプログラムを全面的に改訂した(プログラム名：DnetFlow)。そのためのオーバーヘッドにより，速度性能が劣化した面がある。改訂では，無向グラフの採用，マルチフィーダ系統の考慮，ノード番号からノード名称への変更，孤立ノード群の発見と警告終了，などを取り入れた。

②Backward/Forward 法では，電流積上げ法から電力積上げ法への改訂を行った。

③Backward/Forward 法では，グラフ探索に DFS と BFS の両方を実装した。

また，下図は，表１に示した結果の中からノード数 n=2000,20000,50000 の場合をピックアップして，Backward/Forward 法における収束状況を図示したものである。横軸が反復回数，縦軸が複素電圧成分の収束増分誤差を示している。同図より，Backward/Forward 法が，ノード数に関係なく多次凸関数的な収束形状を呈していることがわかる。

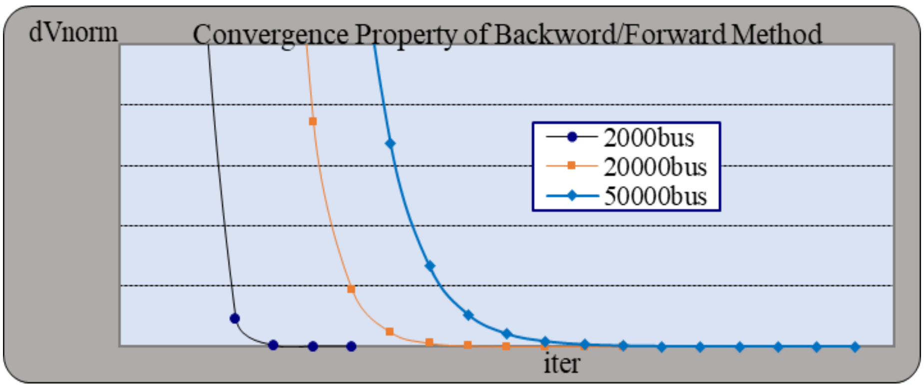


図１　Backward/Forward 法における多次凸関数的な収束形状

４.３ シミュレーションのまとめ

数値実験を行う前の筆者の予想は,「Backward/Forward 法は一回の反復に要する時間は少ないが，反復回数が増大する傾向にある。したがって，トータルでみると，Newton-Raphson 法よりも最良で数倍程度は速くなるであろう。」というものであった。しかしながら，数値実験の結果は，この予想を大幅に上回り，ノード数が多くなるにつれて速度比(表１)が大きく増大する(数万ノードで 100 倍以上)という傾向を示した。

この結果を踏まえ，大規模配電系統には Backward/Forward 法が適していると判定したい。特に，配電系統の再構成問題等では，膨大な回数の潮流計算を要するので，シンプルかつ高速な Backward/Forward 法の採用が成功の鍵とも言えるであろう。

５. Backward/Forward 法による潮流シミュレーションの補足

５.１ 電力積上げ法と電流積上げ法との比較

Backward/Forward 法における電流積み上げ法(Current Summation method)と電力積み上げ法(Power Summation method)による収束性能を比較するため，４.２で使用した大規模配電系統モデルでの数値実験を行った。表２にその結果を示す。数値実験に使用した PC は，Dell Optiplex GX745（Celeron(R) D CPU 3.06GHz，物理メモリ 2.99GB）である。

表２ 大規模配電系統での数値実験による比較結果

ノード (n)	負荷ノード	スラック電圧	反復回数		最終誤差		実行時間(sec)		速度比
			B/F(P)	B/F(C)	B/F(P)	B/F(C)	B/F(P)	B/F(C)	(P)/(C)
500	240	5.00	12	15	5.888e-7	4.595e-7	0.031	0.047	0.66
1000	483	10.00	14	18	7.246e-7	5.226e-7	0.032	0.063	0.51
2000	1012	20.00	6	7	3.812e-7	2.872e-7	0.031	0.032	0.97
5000	2510	20.00	19	23	5.763e-7	5.649e-7	0.110	0.141	0.78
10000	5125	30.00	8	9	4.554e-7	9.374e-7	0.078	0.094	0.83
20000	10387	40.00	13	17	6.207e-7	4.604e-7	0.218	0.297	0.73
30000	15920	40.00	13	16	3.497e-7	7.524e-7	0.312	0.406	0.77
40000	21142	50.00	16	20	5.346e-7	7.147e-7	0.515	0.672	0.77
50000	27346	50.00	19	25	5.062e-7	9.491e-7	0.703	1.016	0.69

（P)電力積上げ法，（C)電流積上げ法

この結果より，電力積み上げ法の方が電流積み上げ法よりも，反復回数と実行時間において優れていることが実証された。

５.２ 弱ループ構造とPV母線を有する系統でのシミュレーション

Multi-Port Compensation 法に基づく提案 Backward/Forward 法の性能を確かめるために，研究会で報告された 126 母線系統で数値実験を行った。この系統に，ループを構成することになるブランチを３本，PV ノードを３個まで追加し，それぞれの組合せに対して潮流計算を行った。ループ・ブランチの候補は，①20-98，②107-122，③42-65 とし，PVノードの候補は A：30，B：77，C：124 とした。すべてのループ・ブランチの属性は r＝0.001,x=0.001 とし，また全PVノードの P,V 値はそれぞれ 1.0 とする。

数値実験での検討ケースは以下の 14 通りである。

ケース 0 ： テスト用配電系統
ケース 1 ： ループ①を追加
ケース 2 ： ループ①②を追加
ケース 3 ： ループ①②③を追加
ケース A ： PVノード A を設定
ケース B ： PVノード B を設定
ケース C ： PVノード C を設定
ケース AB ： PVノード A, B を設定
ケース AC ： PVノード A, C を設定
ケース BC ： PVノード B, C を設定
ケース ABC ： PVノード A,B, C を設定
ケース ABC1 ： PVノード A,B, C を設定し，ループ①を追加
ケース ABC2 ： PVノード A,B, C を設定し，ループ①②を追加
ケース ABC3 ： PVノード A,B, C を設定し，ループ①②③を追加

数値実験の結果を表３に示す。得られた電圧分布は，すべてのケースにおいて Newton/Raphson 法の結果と一致していた。同表に示す反復回数の結果より，Multi-Port

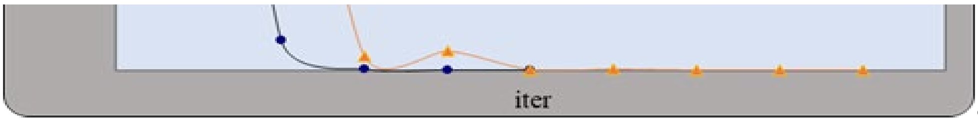
Compensation 法が安定した収束特性を有していることがわかる。また，ループの追加または PV ノードの設定により収束性能が劣化し，その劣化度はループの追加よりも PV ノードの設定の方が大きいことも読み取れる。但し，一例による数値実験であるので，Multi-Port Compensation 法の収束特性に関する結論的見解は控えておく。大規模系統でのさらなる検証が必要であろう。また，原論文[14]では，その手法の収束特性がループの個数と PV ノード数に依存すると記してあるが，今回の数値実験ではそのことを裏付ける顕著な傾向は得られなかった点にも留意する必要がある。

なお，提案 Backward/Forward 法では，電力積み上げ法によるフラットスタート(PV ノード除く)を採用し，収束条件として，全負荷ノードにおける複素電圧成分(直交座標)の増分誤差として 10^{-6}，を与えた。数値実験に使用した PC は，Dell Optiplex GX745(Celeron(R) D CPU 3.06GHz，物理メモリ 2.99GB)である。

また，下図は，検討ケースのうち，ケース 0 とケース ABC3 について，提案 Backward/Forward 法による収束状況を図示したものである。同図は，ループ構造と PV ノードが同時に導入されると，収束形状に部分的不規則性が現れることを示している。但し，ループ構造のみでは不規則性は現れず，PV ノード A が関与するケースではすべて不規則性が現れているので，PV ノードの系統内位置が収束性に悪影響を与えることがあると判断できる。

表３ 126 母線配電系統での数値実験の結果

ケース	反復回数	最終誤差 (dV)	PQ mismatch	実行時間 (sec)
0	5	1.340e-7	3.276e-8	0.016
1	5	8.267e-7	3.388e-5	0.015
2	5	8.845e-7	2.114e-5	0.015
3	6	5.068e-8	6.539e-6	0.015
A	9	1.254e-7	9.363e-7	0.015
B	7	8.364e-7	8.508e-7	0.032
C	6	8.187e-7	7.162e-7	0.016
AB	9	1.749e-7	1.372e-6	0.031
AC	9	1.604e-7	1.267e-6	0.031
BC	8	8.497e-7	6.552e-7	0.016
ABC	9	1.867e-7	1.363e-6	0.031
ABC1	9	1.740e-7	1.850e-5	0.031
ABC2	9	1.705e-7	2.217e-5	0.016
ABC3	9	1.650e-7	2.330e-5	0.031

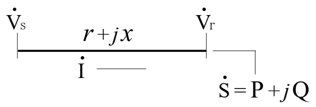


or

ward 法による収束状況

５．３　Backward/Forward 法の収束性について

一般に，電力潮流方程式は，系統がその最大可能負荷点(Maximum Loading Point)を超えると解が存在しない。また，最大可能負荷点に近い重負荷状態となると，数値解法による収束性能が劣化することが知られている。この現象は，Newton-Raphson 法による非線形方程式の解法が，重根解を求める際にヤコビアンの数値的不安定性より振動が生じやすくなる現象と似ている。このことを説明するために，潮流方程式では PVカーブを用いることが多いので，参考として，下図に示す１ブランチの潮流方程式の解析解とそれによる PVカーブによる図解を示しておく。



交流回路の基本式より，次式が成立する。

$$\dot{I} = (\dot{S}/\dot{V}_r)^*,\ \dot{V}_s = \dot{V}_r + (r+jx)\dot{I}$$

上記両式より，次式が導かれる。

$$\dot{V}_s\dot{V}_r^* = V_r^2 + (rP+xQ) + j(xP-rQ),\quad ここで\ V_r^2 = \dot{V}_r\dot{V}_r^*$$

$$Re(\dot{V}_s\dot{V}_r^*) = V_r^2 + (rP+xQ)$$

$$Im(\dot{V}_s\dot{V}_r^*) = xP-rQ$$

上記第２，３式の２乗和をとることにより，次式が得られる。

$$V_s^2V_r^2 = V_r^4 + 2(rP+xQ)V_r^2 + (r^2+x^2)(P^2+Q^2)$$

結局，電力潮流方程式の解析解を与える次の重二次方程式(Biquadratic equation)が得られた。

$$V_r^4 - [V_s^2 - 2(rP + xQ)]V_r^2 + (r^2 + x^2)(P^2 + Q^2) = 0$$

この周知の重二次方程式を解くことにより，終点負荷が与えられた場合における始点電圧に対応する終点電圧を求めることができる。

この方程式において，V_s と Q を固定して V_r と P の関係を示したのが，下図に示す PVカーブである。同図より，V_r の解は通常２個存在し，最大可能負荷点で重根となる。但し，「実配電系統の通常運用では低め解は零に近く，解としては無視できるので多根は生じないと捉えることができる」という主張もある[17]。

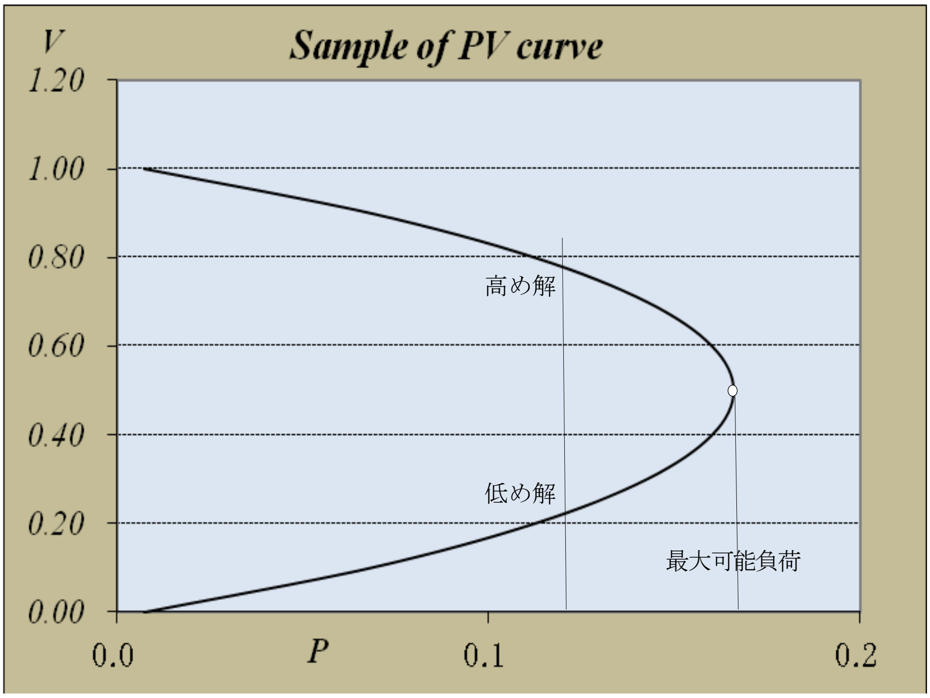
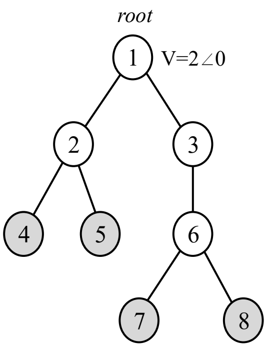


図 3　Vr の解の最大可能負荷点で重根

同様に，V_s と P を固定した V_r と Q の関係も，上図に似た QVカーブとして定義できる。PVカーブと QVカーブの特徴から言えることは，終点負荷 P または Q が小さくなると終点電圧値(高め解)が高くなることである。この事実は，電圧制御のための無効電力補償の原則として活用されている。なお，最大可能負荷点となる条件は，二次方程式 ax^2+bx+c の重根条件 $b^2-4ac=0$ より導かれるので，この左辺値(実行可能解が存在する非負値の場合)を電圧安定性の指標値として利用できる[46]。また，同条件より，所与の V_s と P,Q に対して，電圧崩壊がおこる最大負荷率(Maximum Load Factor)を算定することも可能である[46]。

以上，重負荷状態となると電力潮流方程式の数値解法による収束性能が劣化すること

とその理由について述べた。Backward/Forward 法も例外ではなく，収束性能の劣化が Newton -Raphson 法よりも顕著に現れるようである。この傾向を実際に把握するために，以下に示す簡単な８母線放射状系統で数値実験を行った。



データ

s	t	r	x	Pt	Qt
1	2	0.20	0.40	0.0	0.0
1	3	0.10	0.20	0.0	0.0
2	4	0.15	0.30	-0.6	-0.3
2	5	0.10	0.20	-0.6	-0.3
3	6	0.20	0.40	0.0	0.0
6	7	0.15	0.30	-0.6	-0.3
6	8	0.10	0.20	-0.6	-0.3

この８母線系統は重負荷状態にあり，負荷率(Load Factor)1.02 では解が存在しない。

下図は，この８母線系統で負荷率を 1.0 から 0.9,0.8,0.6 と減少させて，Backward/Forward 法で解いた場合の反復回数と複素電圧成分の増分誤差との関係を示している。

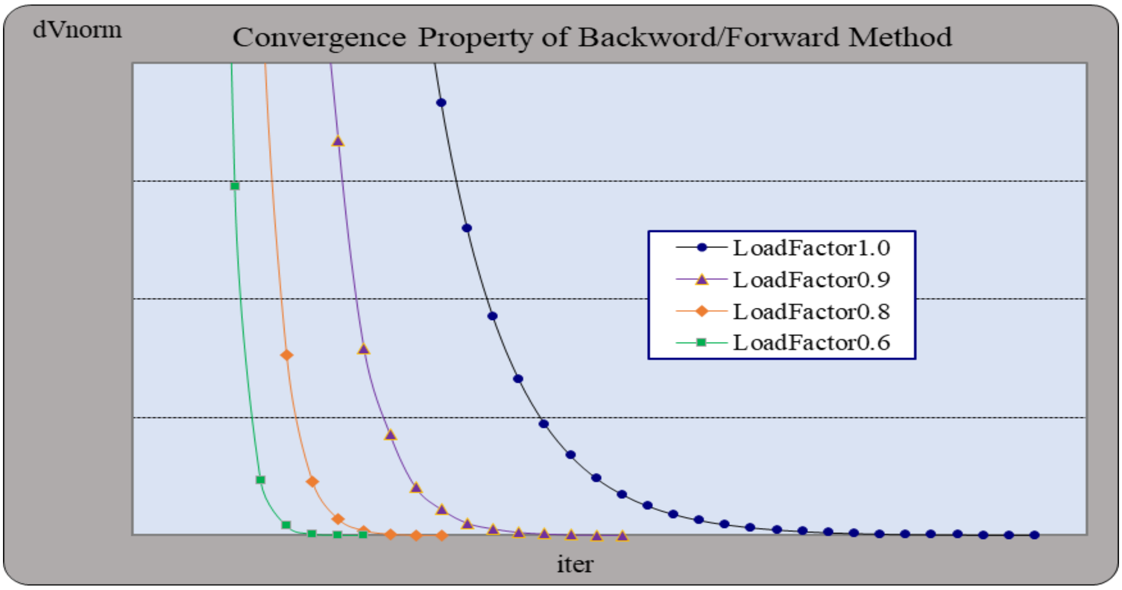


図４　重負荷状態になるにつれての収束性能が劣化状況

同図は，負荷率 0.6,0.8,0.9,1.0 の増大に応じて，反復回数がそれぞれ 9,12,19,35 と増加したことを示しており，(電力積み上げ法による)Backward/Forward 法では重負荷状態になるにつれて収束性能が劣化していくこと，を実証するものである。また，Backward/Forward

法の収束性能が必ずしも系統規模に依存するものではない，すなわち小規模系統の方がより少ない反復回数で収束する訳ではないことも示唆している。なお, 同系統での Newton -Raphson 法による反復回数は，負荷率 0.6,0.8,0.9,1.0 の増大に応じて反復回数がそれぞれ 5,5,6,7 と増加したが，Backward/Forward 法ほどの伸び率ではない。

６. まとめと今後の課題

本稿では, 電力潮流計算手法の基本検討を行い, その代表的解法である Newton-Raphson 法と Backward/Forward 法の実装とノード数 500～50000 の大規模配電系統での数値実験と性能比較を行った。その結果，ループ構造と PV母線のない数万ノード数の大規模配電系統では Backward/Forward 法の方が，Newton-Raphson 法よりも 100 倍以上高速であることが実証された。この高速性は，大規模化する配電系統での潮流計算とその計画・運用問題に Backward/Forward 法が大いに有効であることを示している。この利点を生かすために, ループ運用がなされる，あるいは分散電源が導入された配電系統へ Backward/Forward 法を適用可能とするために, ループ構造と PV母線を取り扱い可能な Multi-Port Compensation 法への機能拡張も行った。126 母線テスト系統における数値実験で Multi-Port Compensation 法は良好な収束性能を示したので，同手法の活用が今後期待できる。

残された課題としては，今回開発した Multi-Port Compensation による Backward/Forward 法を，①各種の負荷モデル(ZIP モデルや電圧依存型負荷モデル)およびその混合モデルを取り扱い可能とすること，②電圧制御装置(変圧器, SVR, SVC など)を考慮できるようにすること，③３相不平衡系統へ適用可能とすること，を挙げておく。

以上

７. 代表的参考文献（年次順）

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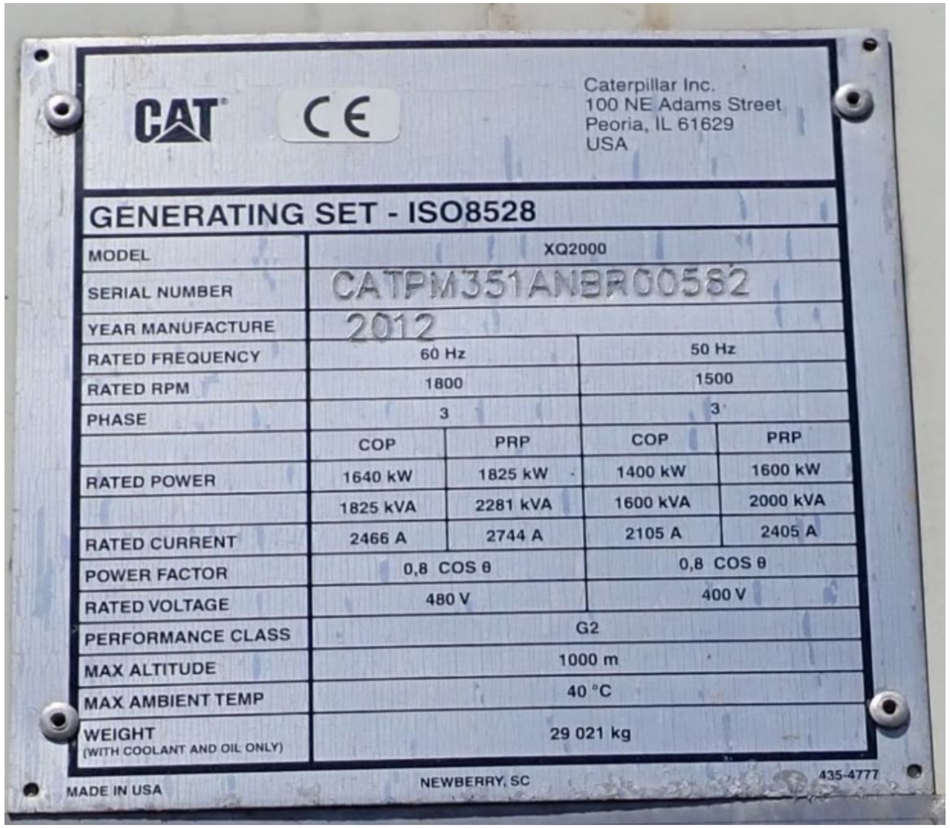
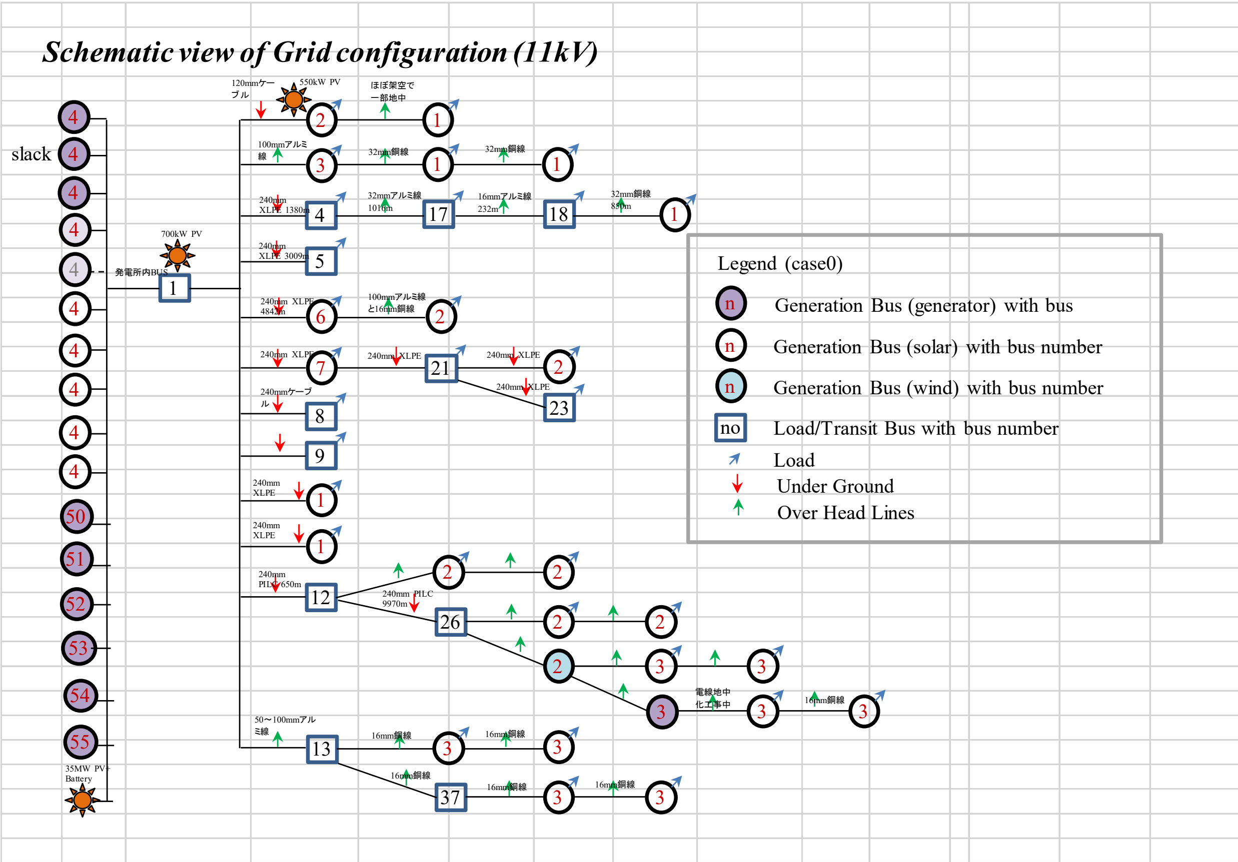
11. 付録 D：CATAPLLER 製発電機データ(現地にて収集、2019 年)

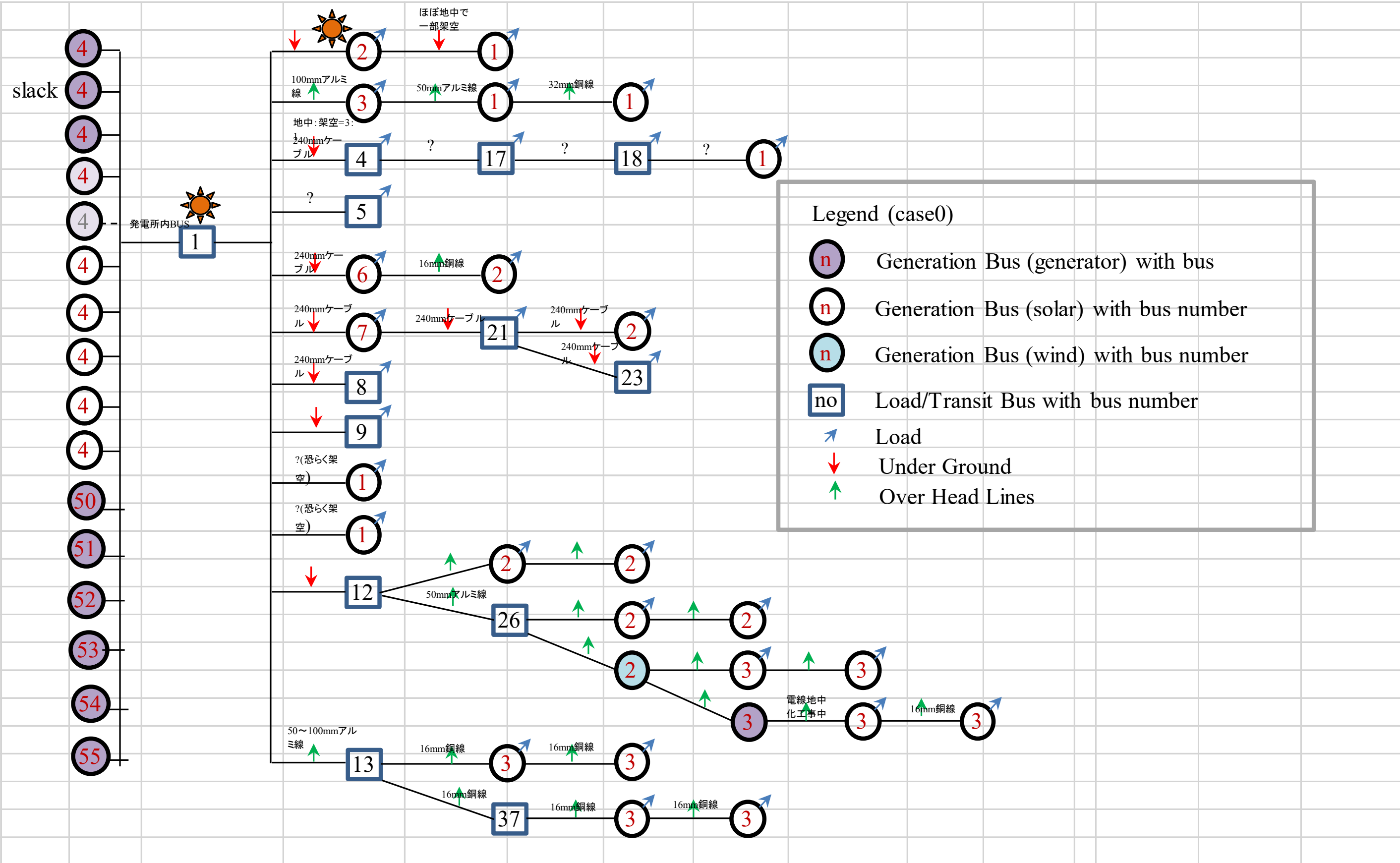
項目	仕様	出展	
台数	6台 （CAT1, CAT2, CAT3, CAT4, CAT5, CAT6）	現地調査にてヒアリング	
型式	Caterpiller製 XQ2000	銘板写真	
定格周波数	60Hz	https://www.cat.com/ja_JP/products/new/power-systems/electric-power/diesel-generator-sets/1000028912.html	
Max MW	1,650 ekW	https://www.cat.com/ja_JP/products/new/power-systems/electric-power/diesel-generator-sets/1000028912.html	
min MW	412.5 ekW(少なくとも25%Loadは可能。それ以下は要調査)	https://s7d2.scene7.com/is/content/Caterpillar/CM20170906-19537-54584	
Rated MW	1,650～2,500ekW （セントキッツでは定格1,650kW）	https://www.cat.com/ja_JP/products/new/power-systems/electric-power/diesel-generator-sets/1000028912.html	
ランプレート	後報		
コスト係数	10729 BTUs/kWh	Historical DataのHeat Rate平均値	
			Kwh/IG
コスト係数計算表			
計測月	計測対象	Heat Rate (Btus / KWh)	Fuel Consumption (kWh/Imperial gallon)
Aug-18	CAT3	10497.5	16.0
Aug-18	CAT4	9601.1	17.5
Sep-18	CAT3	10502.9	16.0
Sep-18	CAT4	9599.7	17.5
Oct-18	CAT1	9602.3	17.5
Oct-18	CAT2	10499.9	16.0
Oct-18	CAT3	10502.8	16.0
Oct-18	CAT4	9601.9	17.5
Nov-18	CAT2	10498.1	16.0
Nov-18	CAT3	10501.3	16.0
Nov-18	CAT4	9602.1	17.5
Dec-18	CAT2	10500.6	16.0
Dec-18	CAT3	10501.7	16.0
Dec-18	CAT4	9597.9	17.5
Jan-19	CAT2	10502.6	16.0
Jan-19	CAT3	10496.8	16.0
Jan-19	CAT4	9598.0	17.5
Feb-19	CAT2	10501.1	16.0
Feb-19	CAT3	10498.9	16.0
Feb-19	CAT4	9599.7	17.5
Mar-19	CAT2	10497.4	16.0
Mar-19	CAT3	10502.0	16.0
Mar-19	CAT4	9602.3	17.5
Apr-19	CAT2	22061.3	
Apr-19	CAT3	10496.9	
Apr-19	CAT4	9597.7	
Average	CAT1	9602.3	17.5
	CAT2	12151.5	16.0
	CAT3	10500.1	16.0
	CAT4	9600.0	17.5
	All	**10598.6**	**16.6**


CAT
CE
Caterpillar Inc.
100 NE Adams Street
Peoria, IL 61629
USA
GENERATING SET - ISO8528
MODEL XQ2000
SERIAL NUMBER CATPM351ANBR00582
YEAR MANUFACTURE 2012
RATED FREQUENCY 60 Hz 50 Hz
RATED RPM 1800 1500
PHASE 3 3
COP PRP COP PRP
RATED POWER 1640 kW 1825 kW 1400 kW 1600 kW
1825 kVA 2281 kVA 1600 kVA 2000 kVA
RATED CURRENT 2466 A 2744 A 2105 A 2405 A
POWER FACTOR 0,8 COS θ 0,8 COS θ
RATED VOLTAGE 480 V 400 V
PERFORMANCE CLASS G2
MAX ALTITUDE 1000 m
MAX AMBIENT TEMP 40 °C
WEIGHT (WITH COOLANT AND OIL ONLY) 29 021 kg
MADE IN USA
NEWBERRY, SC
435-4777

12. 付録 E：電線属性(現地にて収集、2019 年)



配電系統図（rev1）


slack
発電所内BUS
ほぼ地中で
一部架空
100mmアルミ線
50mmアルミ線
32mm銅線
240mmケーブル
16mm銅線
?(恐らく架空)
50mmアルミ線
50～100mmアルミ線
電線地中化工事中
Legend (case0)
Generation Bus (generator) with bus
Generation Bus (solar) with bus number
Generation Bus (wind) with bus number
Load/Transit Bus with bus number
Load
Under Ground
Over Head Lines

配電系統図（rev0）

13. 付録 F：2019 年における hourly loads_1 週間 x3 ケース分(現地にて収集、2019 年)

	Case 1: March							Case 2: April							Case 3: July						
	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	8-Mar	9-Mar	7-Apr	8-Apr	9-Apr	10-Apr	11-Apr	12-Apr	13-Apr	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul
	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday
1:00	18.3	17.2	17.1	16.8	17.4	17.8	18.6	18.2	18.1	17.8	17.5	17.7	18.5	18.7	20.4	22.1	20.9	21.5	20.3	20.8	20.8
2:00	18.3	17.2	16.4	16.6	17.2	17.2	18.2	17.9	17.4	17.3	17.1	17.7	18.3	18.1	20.4	21.1	21.1	20.9	20	20	20.4
3:00	17.1	16.6	16.4	16.5	17	16.8	17.2	17.2	17.3	17.4	16.8	17.1	17.5	17.5	19.9	19.9	20.3	20.1	19.6	19.8	20.3
4:00	16.9	16.6	16.5	16.3	16.6	16.9	17.2	17.4	17.3	16.9	16.7	17.5	17.3	17.4	19.2	19.7	20.3	20.3	19.3	19.8	20.2
5:00	16.5	17.4	16.6	16.7	17.5	17.2	17.2	17.2	17.4	16.8	17.9	17.7	18.3	17.7	19.2	20.3	20.1	21.3	19.5	19.8	19.5
6:00	17.3	18.2	18.3	17.9	18.7	17.9	17.3	16.5	17.6	16.7	16.6	17.5	18.3	16.6	18	20.1	20.3	20.7	19	19.2	18.9
7:00	16.9	20	19.9	19.8	19.4	19.2	17.3	16	18.9	18.3	18.3	19.9	20.1	17.1	18.4	21.5	21.5	21.3	20.7	20.6	19.3
8:00	17	20.7	21.2	22.7	21	22	18	18.9	20.9	19.4	20.1	20	21.4	18.7	19.6	24.1	25.1	23.1	22.9	25.1	21.5
9:00	17.6	22.4	22.5	23.3	23	22.8	19.9	19.7	23.1	21.9	22.1	22.7	23.4	21.1	20.8	25.1	26.1	27.2	24	25.1	22.8
10:00	18	23.3	22.7	21.1	23.6	23.4	21.5	20.3	23.9	23.3	23.4	24.2	24.4	21.8	20.7	27.1	27.2	27.5	26.4	26.1	23.5
11:00	18.1	23.2	23.4	21.7	23.2	23.9	21.1	20.1	23.3	23.3	23.9	24.6	24.8	22.3	21.4	27.1	27.6	28.1	26.5	27	23.9
12:00	18.5	24	23.3	22.3	24	23.7	21.2	20.3	23.9	23.9	23.9	24.2	23.7	22.2	21.5	27.2	27.6	27.6	26.7	26.9	24.2
13:00	18.6	23.7	23.2	23.5	23.8	23.3	21.2	21.5	24.1	24	23.9	24.4	24.6	21.8	21.5	27.2	27.8	28.3	26.3	26.7	24
14:00	18.8	24	23.6	23.7	23.4	23.2	21	20.3	24.1	23.3	24.3	24.3	24.8	21.8	21.8	27.2	27.9	28.6	26.4	26.7	23.8
15:00	18.5	24	23.2	23.8	23.3	22.8	21.2	20.4	24	23.1	24.5	24.8	24.5	21.8	22.1	26.8	27.3	27.8	27	25.8	21.6
16:00	17.8	23.5	21.9	23.2	22.6	21.6	20.8	20.4	23.8	22.7	24.1	23.8	24.2	21.7	22.1	26.2	26.7	27.8	25.8	25	21.6
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18:00	18.6	21	20.3	21.2	20	20.4	20.4	19.3	20.7	20.1	21.3	20.8	20.8	20	22	23.2	23.2	23.8	23.3	23.3	20.8
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22:00	19.8	20.8	20	20.4	20.6	20.9	20.8	20.3	20.8	20.3	20.7	21.1	20.9	20.4	23.1	23.7	23.8	22	24.2	23	21.6
23:00	19	19	18.3	19	19.4	18.8	19.1	19.6	19.8	19.1	19.5	20.5	19.9	19.5	22.5	23.1	23.9	22.5	22.7	23	21.4
0:00	18	17.8	17.6	18.2	18.6	18.8	18.4	18.5	18.7	17.8	18.3	19.3	19.3	18.5	22.1	22.3	22.3	21.3	21.6	21.4	20.2

3Case

	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul	14-Jul	15-Jul	16-Jul
	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	Monday	Tuesday
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2:00	21.5	20.7	20.5	20.6	22	20.4	20.4	21.1	21.1	20.9	20	20	20.4	19.3	20	19.8
3:00	20.9	20.5	20.1	20.3	20.3	20.3	19.9	19.9	20.3	20.1	19.6	19.8	20.3	19.2	20.2	19.3
4:00	20.7	20.1	19.9	20.3	20.4	20	19.2	19.7	20.3	20.3	19.3	19.8	20.2	19.5	19.7	19.7
5:00	20.9	20.2	20	20.1	20.4	19	19.2	20.3	20.1	21.3	19.5	19.8	19.5	19.5	19.8	19.7
6:00	20.5	19.8	19.7	19.9	19.9	19	18	20.1	20.3	20.7	19	19.2	18.9	18.3	19.9	18.9
7:00	20.1	21.7	21.3	21.4	20.4	19.4	18.4	21.5	21.5	21.3	20.7	20.6	19.3	19	24	21.1
8:00	24.6	24.1	22.3	25.5	24.3	20.6	19.6	24.1	25.1	23.1	22.9	25.1	21.5	19.7	23.3	22.9
9:00	26.1	24.5	25.3	26.4	26.7	22.4	20.8	25.1	26.1	27.2	24	25.1	22.8	20.1	25.1	25.5
10:00	27.7	26	26.6	27.8	26.7	22.9	20.7	27.1	27.2	27.5	26.4	26.1	23.5	20.5	26.7	26.2
11:00	28.4	27.4	26.8	27.7	27.9	24.3	21.4	27.1	27.6	28.1	26.5	27	23.9	21.3	25.9	26.7
12:00	28.4	28.3	27.4	28.3	27.1	24.2	21.5	27.2	27.6	27.6	26.7	26.9	24.2	21.5	26	26.8
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22:00	24.3	24.6	24	24.2	22.7	23.6	23.1	23.7	23.8	22	24.2	23	21.6	23.9	23.7	23
23:00	23.3	23.3	23	23.3	22.2	22	22.5	23.1	23.9	22.5	22.7	23	21.4	22.3	22.1	22.1
0:00	22.4	22.2	22	22.2	21.4	20.9	22.1	22.3	22.3	21.3	21.6	21.4	20.2	21.4	20.6	22.1

	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul
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8:00	23.5	24.3	23.3	21	20.1	23.3	23.3	24	22.5	23.9	20.9	21.5	21.2	22.5	20.8
9:00	25.2	25.4	24.5	22.6	20.6	25.6	26.1	25.8	23.5	24.3	21.8	22.1	21.2	24.1	23.4
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11:00	26.6	26.9	26.3	24.2	21	26.5	26.7	26.8	25.1	26.2	23.7	25.1	21.6	26	25.9
12:00	26.6	26.5	26.1	24	21.4	26.5	26.6	26.8	25.6	26.2	24.6	24.5	21.4	26	26.2
13:00	26.6	26.6	26	24	21.4	27	26.9	27.2	25.4	26.4	24.4	24.7	21.2	26.2	26.6
14:00	27.2	26.8	26.1	24	22	27.3	26.8	27.7	25.8	26.4	25.8	26.5	21.6	26.1	27
15:00	27	27.6	26.6	23.2	21.3	27.3	27.5	27.7	23.2	26.3	24	25.7	21.2	25.4	27.2
16:00	26.2	26.8	26.1	23	21	26.9	26.9	26.7	24.2	24.7	24.4	24.9	18.5	24.2	24
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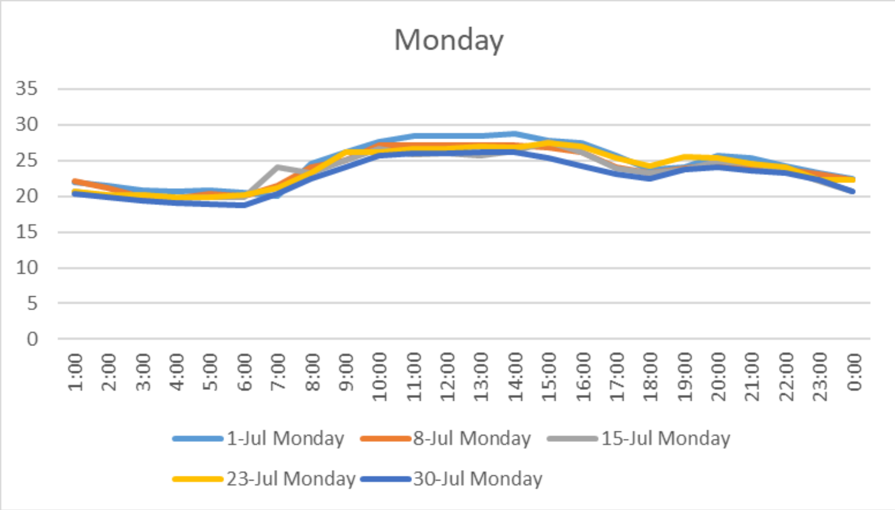
18:00	22.5	23.4	22.9	21.9	21.3	23.3	24.3	23.7	22.5	22.9	22.3	22.1	24.5	22.5	22.7
19:00	23	24.5	23.9	21.7	23	24.6	25.5	23.9	24	23.5	23.6	24.5	23	23.7	24.7
20:00	24.9	25.4	24.1	23.8	23.5	25.1	25.3	25.1	24	24.2	24	24.7	22.4	24.1	24.7
21:00	24.6	25.2	23.6	23.7	23.3	24.9	24.5	24.8	23.9	23.8	23.5	24.5	22	23.5	24.3
22:00	23.7	24.4	23	23.5	23	24.3	24.1	23.9	22.9	23.7	22.8	22.9	21.4	23.3	23.9
23:00	22.2	23.2	22.6	22.9	22.3	22.5	22.3	23.1	21.7	22.9	22.1	21.8	19.9	22.3	22.9
0:00	21	21.9	21.4	22.2	21.7	21.2	22.3	22.5	21.5	21.9	21.4	20.9	19.6	20.6	20.8

1Month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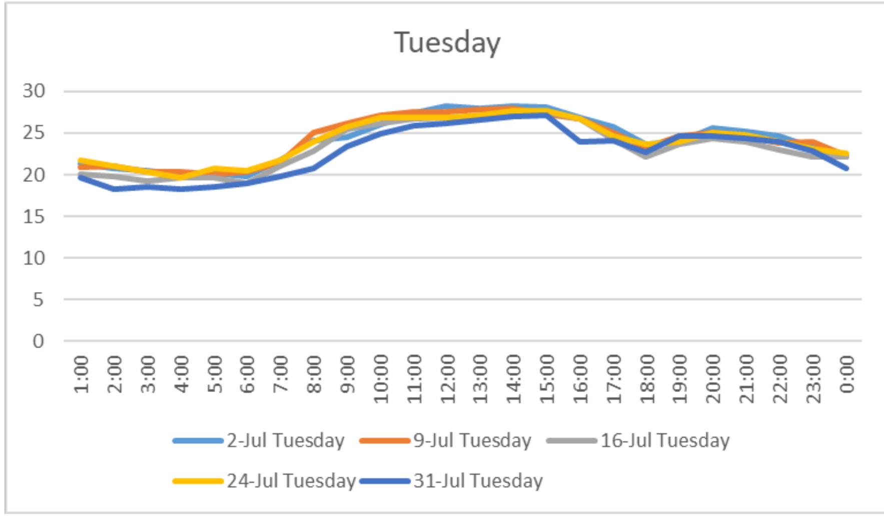
1-Jul Monday
8-Jul Monday
15-Jul Monday
23-Jul Monday
30-Jul Monday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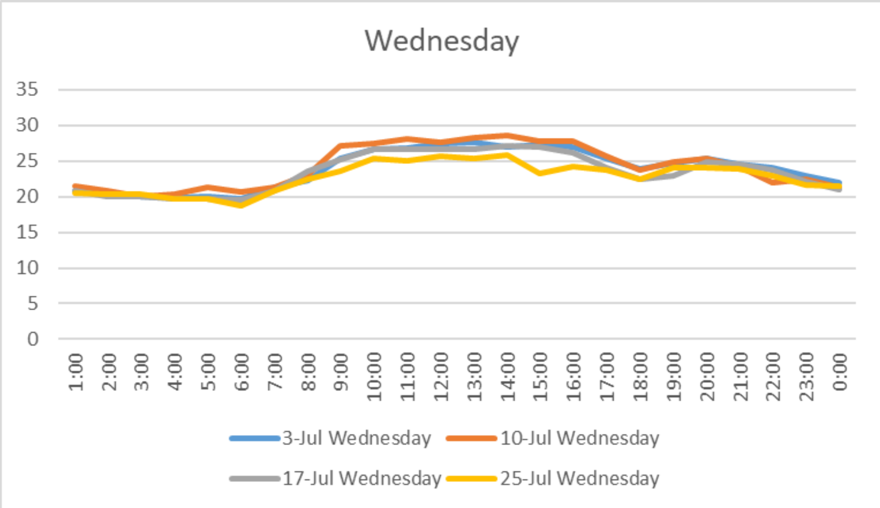
2-Jul Tuesday
9-Jul Tuesday
16-Jul Tuesday
24-Jul Tuesday
31-Jul Tuesday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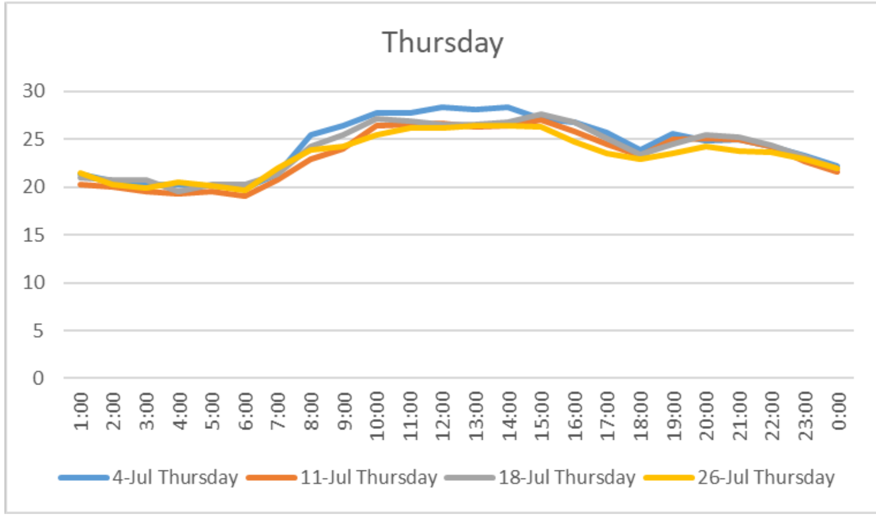
3-Jul Wednesday
10-Jul Wednesday
17-Jul Wednesday
25-Jul Wednesday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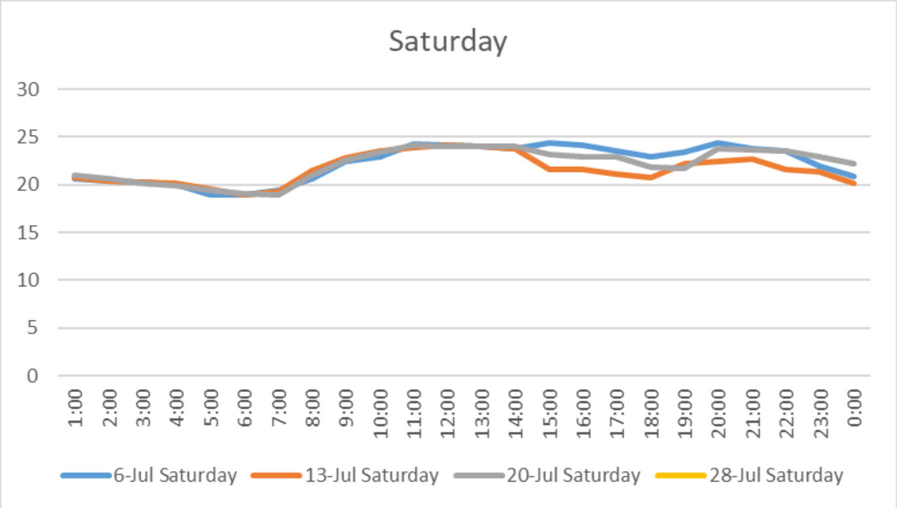
4-Jul Thursday
11-Jul Thursday
18-Jul Thursday
26-Jul Thursday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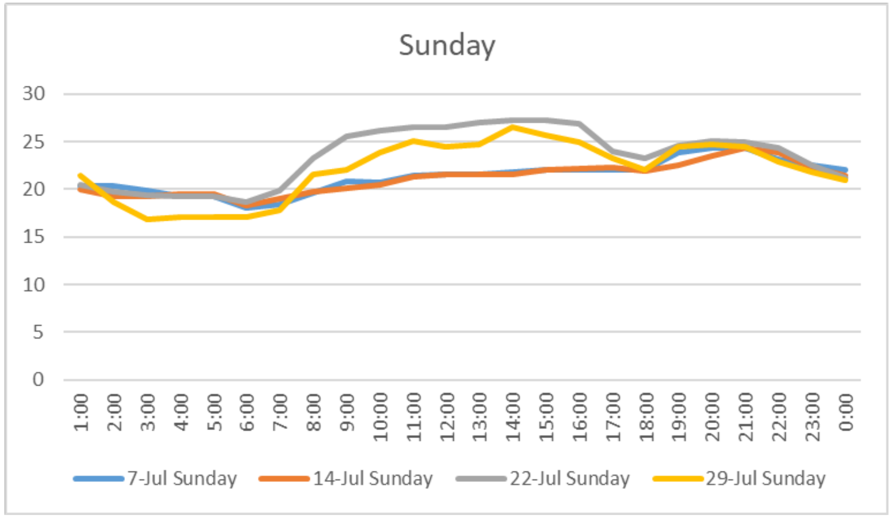
6-Jul Saturday
13-Jul Saturday
20-Jul Saturday
28-Jul Saturday

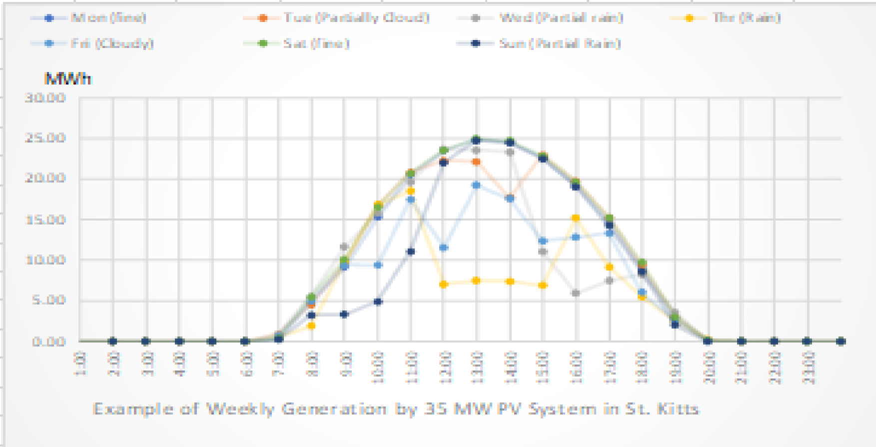

Sunday
30
25
20
15
10
5
0
1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 0:00
7-Jul Sunday
14-Jul Sunday
22-Jul Sunday
29-Jul Sunday

14. 付録 G：太陽光(35MW, 0.7MW, 0.55MW)の 1 週間分の時間ごとの出力プロファイル（想定、2019 年）

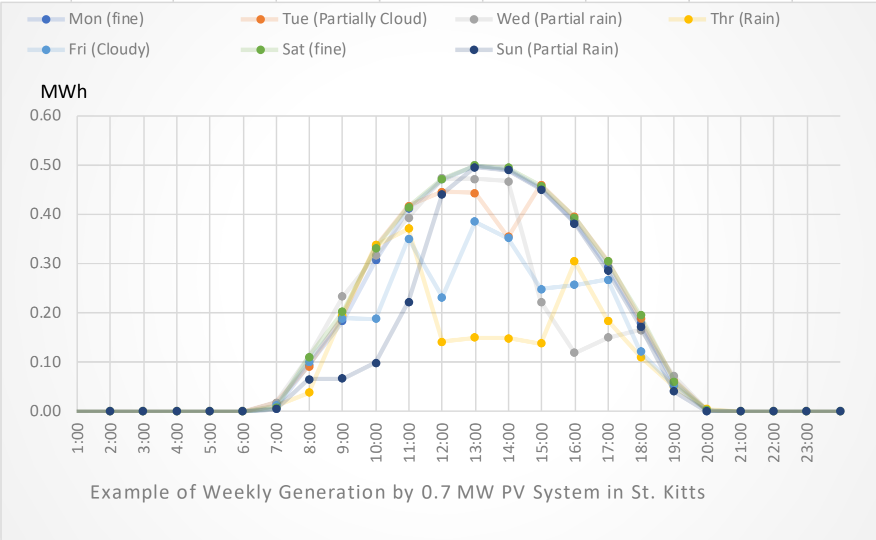
Max Irr	330	GTI	6	kWh/m2	Weekly GT	42	kWh/m2				
Total Irr	15119	PV output	4.663	kWh/kWp	35	MW		163.205	MWh/day	1,142.44	MWh/week
					0.7	0.5					

Hourly Generation MWh in an example of a week by 35 MW PV system in St. Kitts

Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)		
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
7:00	0.30	0.91	0.91	0.53	0.60	0.38	0.23		
8:00	4.68	4.61	5.52	1.89	5.06	5.52	3.25		
9:00	9.14	9.67	11.64	9.82	9.45	10.13	3.32		
10:00	15.34	16.77	15.79	16.85	9.37	16.55	4.91		
11:00	20.55	20.86	19.65	18.51	17.53	20.70	11.11		
12:00	23.50	22.29	23.65	7.10	11.56	23.58	22.06		
13:00	24.86	22.14	23.58	7.48	19.27	24.94	24.78		
14:00	24.56	17.68	23.35	7.41	17.61	24.71	24.48		
15:00	22.67	22.97	11.11	6.88	12.39	22.90	22.52		
16:00	19.27	19.72	5.97	15.19	12.85	19.65	19.04		
17:00	14.66	15.26	7.48	9.22	13.37	15.19	14.28		
18:00	8.99	9.37	8.24	5.52	6.05	9.75	8.61		
19:00	2.87	3.17	3.55	2.49	2.64	3.02	2.04		
20:00	0.08	0.15	0.15	0.23	0.15	0.15	0.00		
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
TOTAL	191.48	185.58	160.57	109.11	137.90	197.14	160.65	1,142.44	MWh
	5.47	5.30	4.59	3.12	3.94	5.63	4.59		



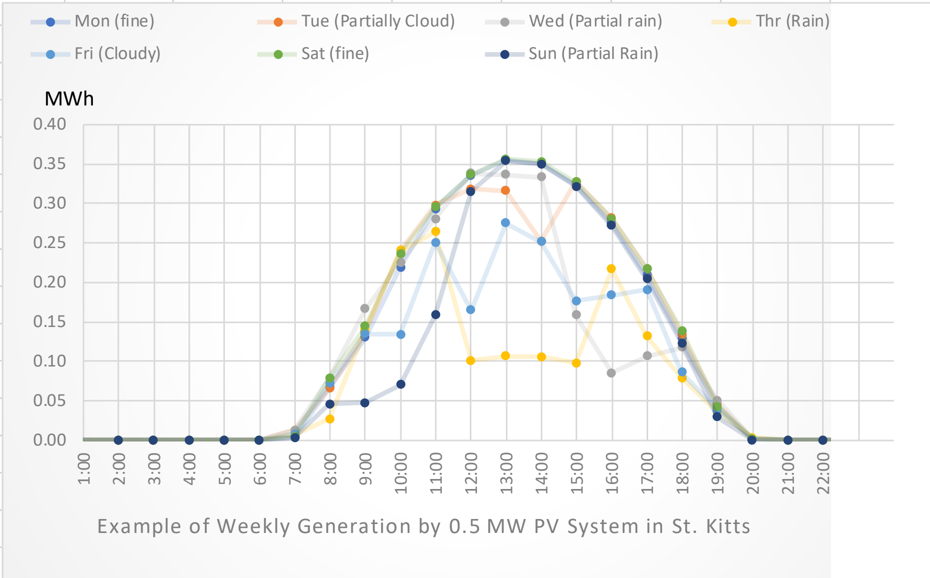
Hourly Generation MWh in an example of a week by 0.7 MW PV system in St. Kitts								
Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)	
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
7:00	0.01	0.02	0.02	0.01	0.01	0.01	0.00	
8:00	0.09	0.09	0.11	0.04	0.10	0.11	0.06	
9:00	0.18	0.19	0.23	0.20	0.19	0.20	0.07	
10:00	0.31	0.34	0.32	0.34	0.19	0.33	0.10	
11:00	0.41	0.42	0.39	0.37	0.35	0.41	0.22	
12:00	0.47	0.45	0.47	0.14	0.23	0.47	0.44	
13:00	0.50	0.44	0.47	0.15	0.39	0.50	0.50	
14:00	0.49	0.35	0.47	0.15	0.35	0.49	0.49	
15:00	0.45	0.46	0.22	0.14	0.25	0.46	0.45	
16:00	0.39	0.39	0.12	0.30	0.26	0.39	0.38	
17:00	0.29	0.31	0.15	0.18	0.27	0.30	0.29	
18:00	0.18	0.19	0.16	0.11	0.12	0.19	0.17	
19:00	0.06	0.06	0.07	0.05	0.05	0.06	0.04	
20:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
TOTAL	3.83	3.71	3.21	2.18	2.76	3.94	3.21	22.85 MWh
	0.11	0.11	0.09	0.06	0.08	0.11	0.09	



Example of Weekly Generation by 0.7 MW PV System in St. Kitts

Hourly Generation MWh in an example of a week by 0.5 MW PV system in St. Kitts

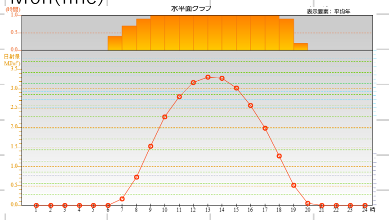
Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)		
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
7:00	0.00	0.01	0.01	0.01	0.01	0.01	0.00		
8:00	0.07	0.07	0.08	0.03	0.07	0.08	0.05		
9:00	0.13	0.14	0.17	0.14	0.13	0.14	0.05		
10:00	0.22	0.24	0.23	0.24	0.13	0.24	0.07		
11:00	0.29	0.30	0.28	0.26	0.25	0.30	0.16		
12:00	0.34	0.32	0.34	0.10	0.17	0.34	0.32		
13:00	0.36	0.32	0.34	0.11	0.28	0.36	0.35		
14:00	0.35	0.25	0.33	0.11	0.25	0.35	0.35		
15:00	0.32	0.33	0.16	0.10	0.18	0.33	0.32		
16:00	0.28	0.28	0.09	0.22	0.18	0.28	0.27		
17:00	0.21	0.22	0.11	0.13	0.19	0.22	0.20		
18:00	0.13	0.13	0.12	0.08	0.09	0.14	0.12		
19:00	0.04	0.05	0.05	0.04	0.04	0.04	0.03		
20:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
TOTAL	2.74	2.65	2.29	1.56	1.97	2.82	2.29	16.32	MWh
	0.08	0.08	0.07	0.04	0.06	0.08	0.07		



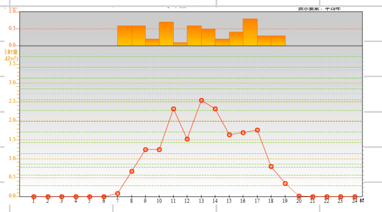
Hateruma	20-Jun	16-Jul	17-Jun	10-Jun	25-Jun	27-Jun	27-Jun
Time	Mon(fine)	Tue (Parti	Wed (Part	Thr (Rain)	Fri (Cloud	Sat (fine)	Sun (Partial Rain)
1:00	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0
7:00	4	12	12	7	8	5	3
8:00	62	61	73	25	67	73	43
9:00	121	128	154	130	125	134	44
10:00	203	222	209	223	124	219	65
11:00	272	276	260	245	232	274	147
12:00	311	295	313	94	153	312	292
13:00	329	293	312	99	255	330	328
14:00	325	234	309	98	233	327	324
15:00	300	304	147	91	164	303	298
16:00	255	261	79	201	170	260	252
17:00	194	202	99	122	177	201	189
18:00	119	124	109	73	80	129	114
19:00	38	42	47	33	35	40	27
20:00	1	2	2	3	2	2	0
21:00	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0
Max Irr	330	GTI	6	kWh/m2	Weekly G	42	kWh/m2
Total Irr	15119	PV output	4.663	kWh/kWp/day			

http://app0.infoc.nedo.go.jp/metpv/metpv.html

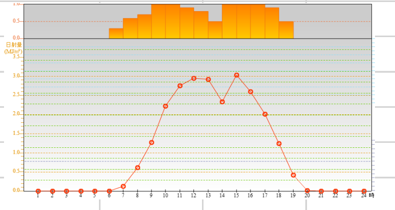
Mon(fine)



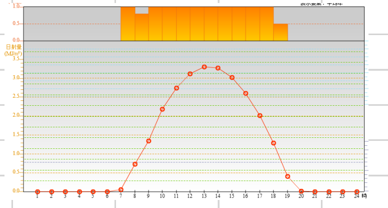
Fri (Cloudy)



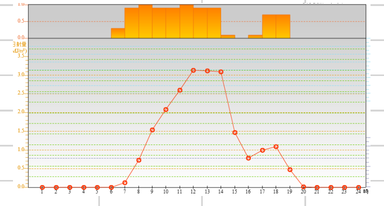
Tue (Partially Cloud)



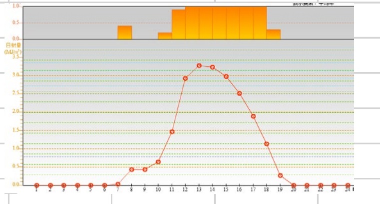
Sat (fine)



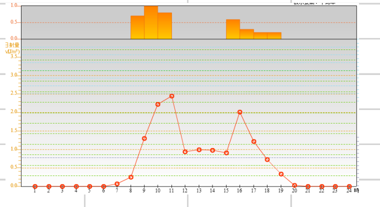
Wed (Partial rain)



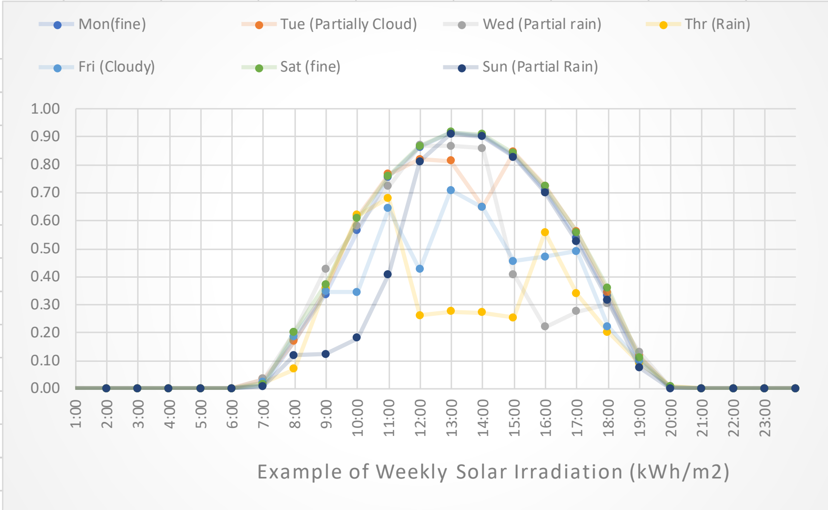
Sun (Partial Rain)

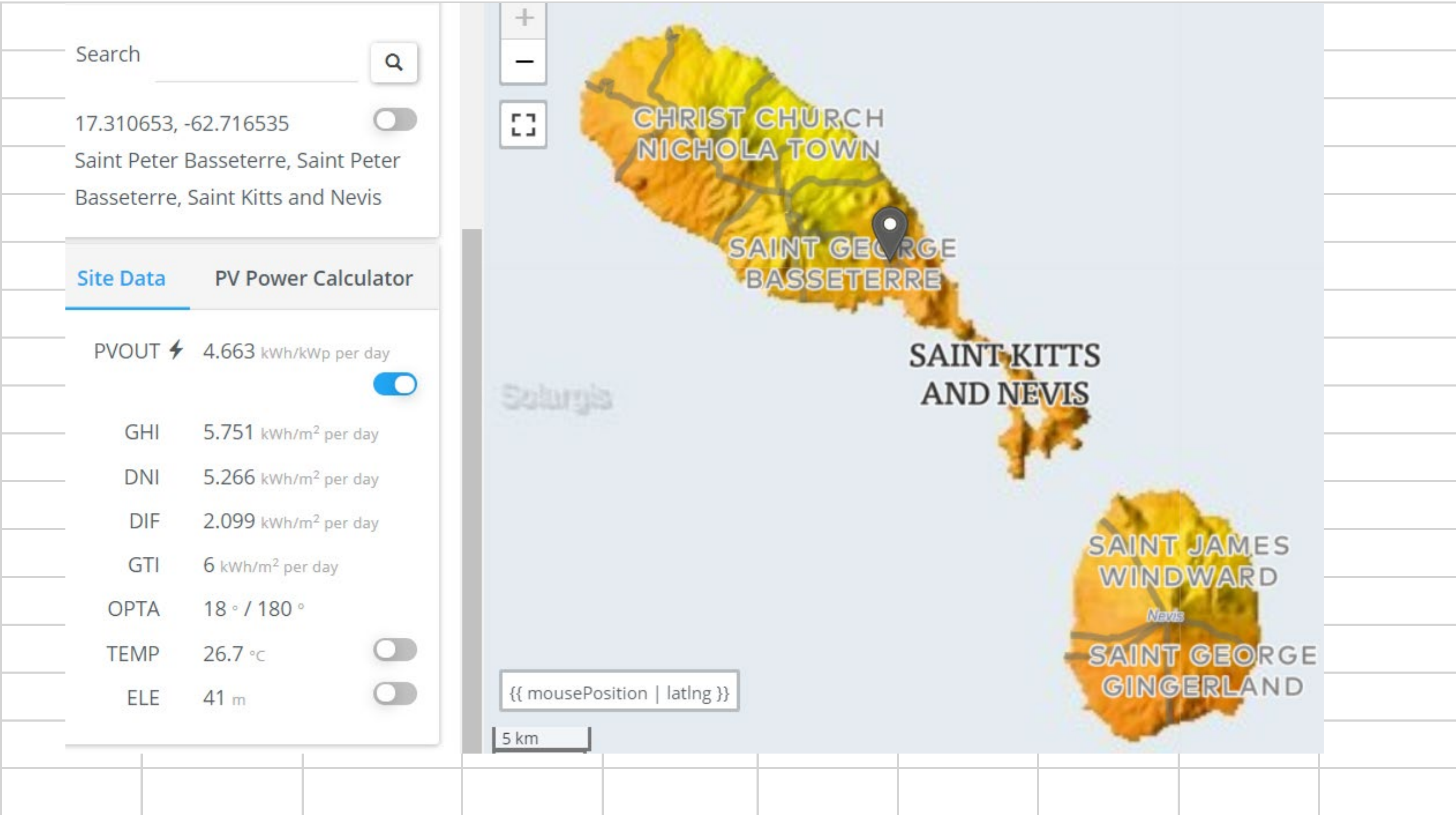


Thr (Rain)



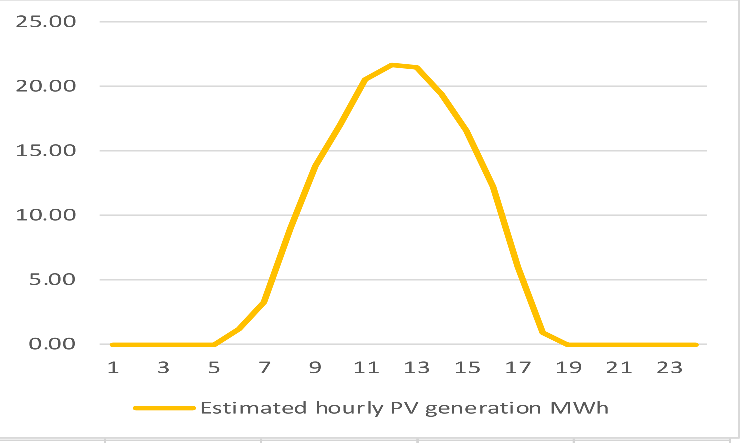
Max Irr	330	GTI	6	kWh/m2	Weekly G	42	kWh/m2	
Total Irr	15119	PV output	4.663	kWh/kWp/day				
kWh/m2								
Hateruma	20-Jun	16-Jul	17-Jun	10-Jun	25-Jun	27-Jun	27-Jun	
Time	Mon (fine)	Tue (Partially Cloud)	Wed (Partial rain)	Thr (Rain)	Fri (Cloudy)	Sat (fine)	Sun (Partial Rain)	
1:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
3:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
5:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
6:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
7:00	0.01	0.03	0.03	0.02	0.02	0.01	0.01	
8:00	0.17	0.17	0.20	0.07	0.19	0.20	0.12	
9:00	0.34	0.36	0.43	0.36	0.35	0.37	0.12	
10:00	0.56	0.62	0.58	0.62	0.34	0.61	0.18	
11:00	0.76	0.77	0.72	0.68	0.64	0.76	0.41	
12:00	0.86	0.82	0.87	0.26	0.43	0.87	0.81	
13:00	0.91	0.81	0.87	0.28	0.71	0.92	0.91	
14:00	0.90	0.65	0.86	0.27	0.65	0.91	0.90	
15:00	0.83	0.84	0.41	0.25	0.46	0.84	0.83	
16:00	0.71	0.73	0.22	0.56	0.47	0.72	0.70	
17:00	0.54	0.56	0.28	0.34	0.49	0.56	0.53	
18:00	0.33	0.34	0.30	0.20	0.22	0.36	0.32	
19:00	0.11	0.12	0.13	0.09	0.10	0.11	0.08	
20:00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	
21:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
23:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	7.04	6.82	5.90	4.01	5.07	7.25	5.91	42.00




Search
17.310653, -62.716535
Saint Peter Basseterre, Saint Peter Basseterre, Saint Kitts and Nevis
Site Data
PV Power Calculator
PVOUT 4.663 kWh/kWp per day
GHI 5.751 kWh/m2 per day
DNI 5.266 kWh/m2 per day
DIF 2.099 kWh/m2 per day
GTI 6 kWh/m2 per day
OPTA 18 ° / 180 °
TEMP 26.7 °C
ELE 41 m
CHRIST CHURCH NICHOLA TOWN
SAINT GEORGE BASSETERRE
SAINT KITTS AND NEVIS
SAINT JAMES WINDWARD
Nevis
SAINT GEORGE GINGERLAND
{{ mousePosition | latlng }}
5 km

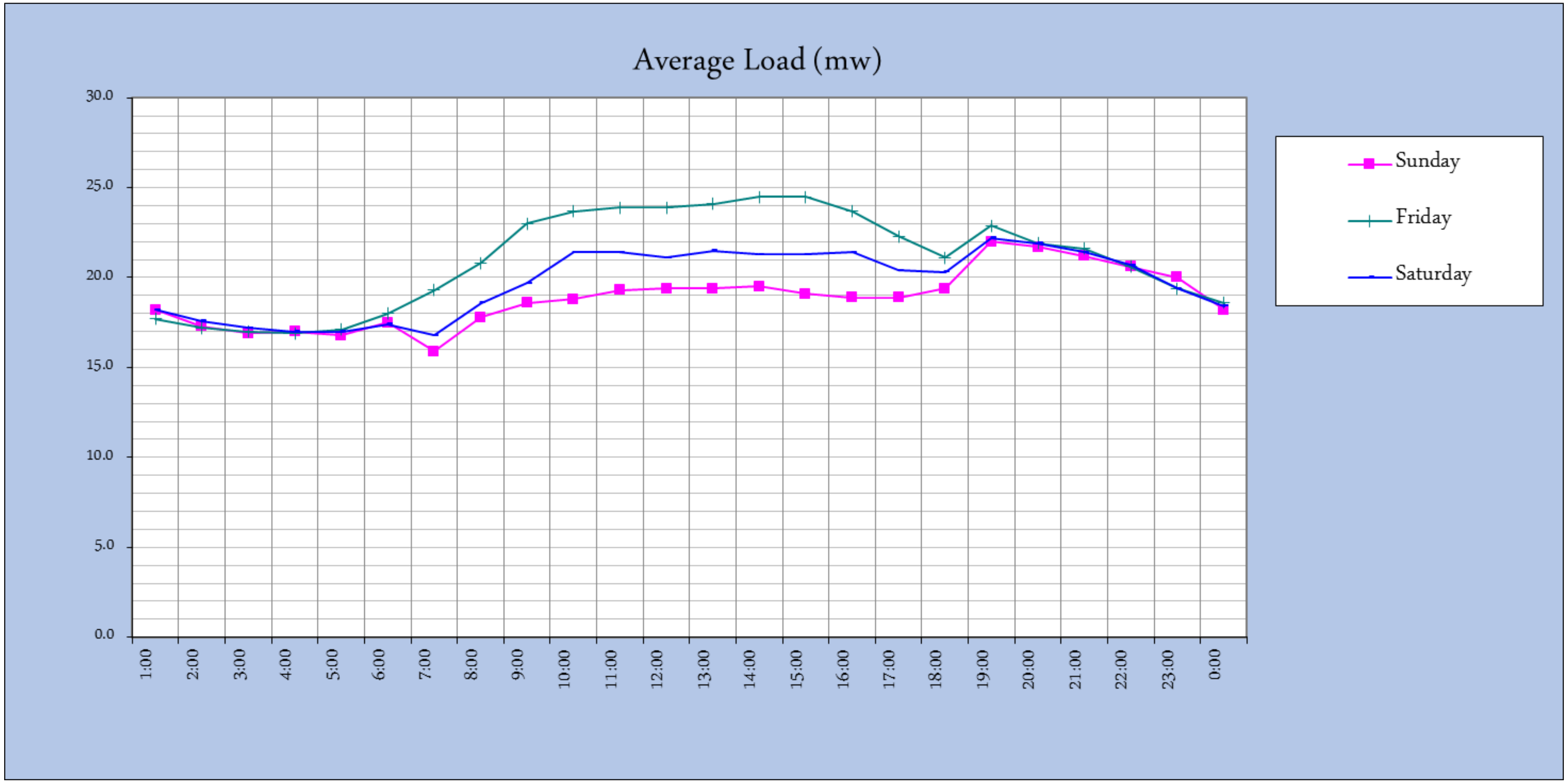
		GTI	6	kWh/m2
		PV output	4.663	kWh/kWp/day
Hourly PV generation estimation in St Kitts				
Time	Coeff. Hourly dist. Estimated	Hourly irradiation kWh/m2	Hourly PV kWh/kWp	Estimated hourly PV generation MWh
1:00	0.00	0.00	0.00	0.00
2:00	0.00	0.00	0.00	0.00
3:00	0.00	0.00	0.00	0.00
4:00	0.00	0.00	0.00	0.00
5:00	0.00	0.00	0.00	0.00
6:00	0.05	0.04	0.03	1.15
7:00	0.14	0.12	0.09	3.23
8:00	0.39	0.33	0.26	9.00
9:00	0.60	0.51	0.40	13.85
10:00	0.74	0.63	0.49	17.08
11:00	0.89	0.76	0.59	20.54
12:00	0.94	0.80	0.62	21.70
13:00	0.93	0.79	0.61	21.47
14:00	0.84	0.71	0.55	19.39
15:00	0.72	0.61	0.47	16.62
16:00	0.53	0.45	0.35	12.23
17:00	0.26	0.22	0.17	6.00
18:00	0.04	0.03	0.03	0.92
19:00	0.00	0.00	0.00	0.00
20:00	0.00	0.00	0.00	0.00
21:00	0.00	0.00	0.00	0.00
22:00	0.00	0.00	0.00	0.00
23:00	0.00	0.00	0.00	0.00
0:00	0.00	0.00	0.00	0.00
TOTAL	7.07	6.00	4.66	163.21

4.66



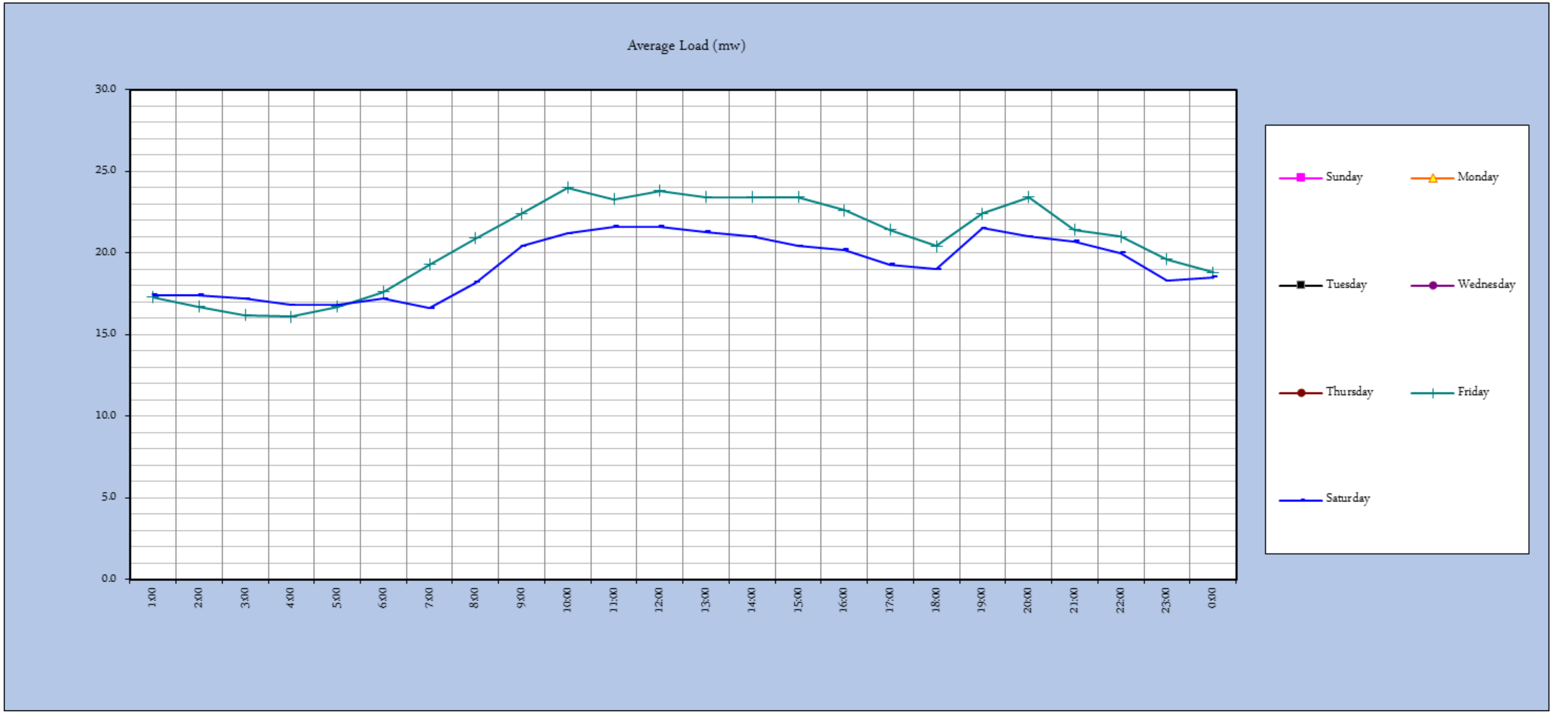
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat
1:00	18.2	17.8	17.4	17.7	17.6	17.7	18.2
2:00	17.3	17.2	16.8	17.1	16.8	17.2	17.6
3:00	16.9	16.8	16.8	16.8	16.6	17.0	17.2
4:00	17.0	16.6	16.8	16.6	16.8	16.9	17.0
5:00	16.8	17.0	16.0	16.8	16.8	17.1	17.0
6:00	17.5	17.8	16.6	18.1	18.2	18.0	17.4
7:00	15.9	17.0	18.4	19.3	20.1	19.3	16.8
8:00	17.8	19.4	20.0	20.6	21.8	20.8	18.6
9:00	18.6	21.6	21.6	22.2	21.5	23.0	19.7
10:00	18.8	22.8	23.4	23.5	23.1	23.7	21.4
11:00	19.3	23.0	23.6	23.7	23.3	23.9	21.4
12:00	19.4	23.2	24.0	23.3	23.7	23.9	21.1
13:00	19.4	22.6	23.8	23.4	24.1	24.1	21.5
14:00	19.5	23.2	24.8	24.1	24.0	24.5	21.3
15:00	19.1	22.7	24.2	24.0	23.6	24.5	21.3
16:00	18.9	21.6	23.2	23.2	22.7	23.7	21.4
17:00	18.9	20.8	21.9	22.3	22.1	22.3	20.4
18:00	19.4	18.7	21.2	20.8	21.1	21.1	20.3
19:00	22.0	20.1	23.2	23.4	23.3	22.9	22.2
20:00	21.7	20.9	22.4	23.2	22.7	21.9	21.9
21:00	21.2	20.2	21.7	21.9	22.3	21.6	21.4
22:00	20.6	19.9	20.8	20.8	21.2	20.6	20.7
23:00	20.0	19.2	19.3	19.2	19.6	19.4	19.4
0:00	18.2	18.0	18.1	18.1	18.6	18.6	18.4
DAY PEAK	19.5	23.2	24.8	24.1	24.1	24.5	21.5
NIGHT PEAK	22.0	20.9	23.2	23.4	23.3	22.9	22.2

Load


Average Load (mw)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00
Sunday
Friday
Saturday

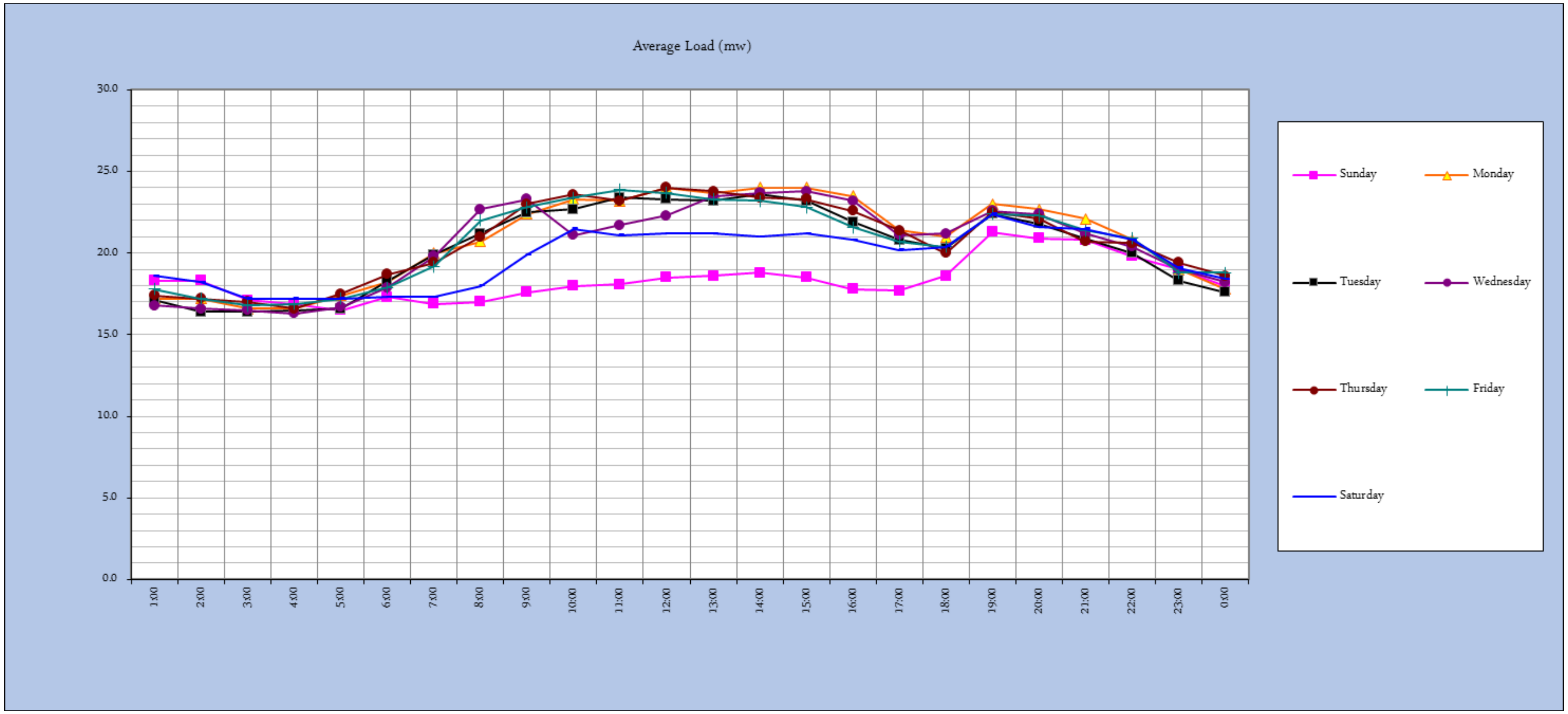
Load

		2019年3月1日				to	2019年3月2日			
	Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
	1:00						17.3	17.4	17.3	17.4
	2:00						16.7	17.4	16.7	17.4
	3:00						16.2	17.2	16.2	17.2
	4:00						16.1	16.8	16.1	16.8
	5:00						16.7	16.8	16.7	16.8
	6:00						17.6	17.2	17.2	17.6
	7:00						19.3	16.6	16.6	19.3
	8:00						20.9	18.2	18.2	20.9
	9:00						22.4	20.4	20.4	22.4
	10:00						24.0	21.2	21.2	24.0
	11:00						23.3	21.6	21.6	23.3
	12:00						23.8	21.6	21.6	23.8
	13:00						23.4	21.3	21.3	23.4
	14:00						23.4	21.0	21.0	23.4
	15:00						23.4	20.4	20.4	23.4
	16:00						22.6	20.2	20.2	22.6
	17:00						21.4	19.3	19.3	21.4
	18:00						20.4	19.0	19.0	20.4
	19:00						22.4	21.5	21.5	22.4
	20:00						23.4	21.0	21.0	23.4
	21:00						21.4	20.7	20.7	21.4
	22:00						21.0	20.0	20.0	21.0
	23:00						19.6	18.3	18.3	19.6
	0:00						18.8	18.5	18.5	18.8
DAY PEAK		0.0	0.0	0.0	0.0	0.0	24.0	21.6		
NIGHT PEAK		0.0	0.0	0.0	0.0	0.0	23.4	21.5		



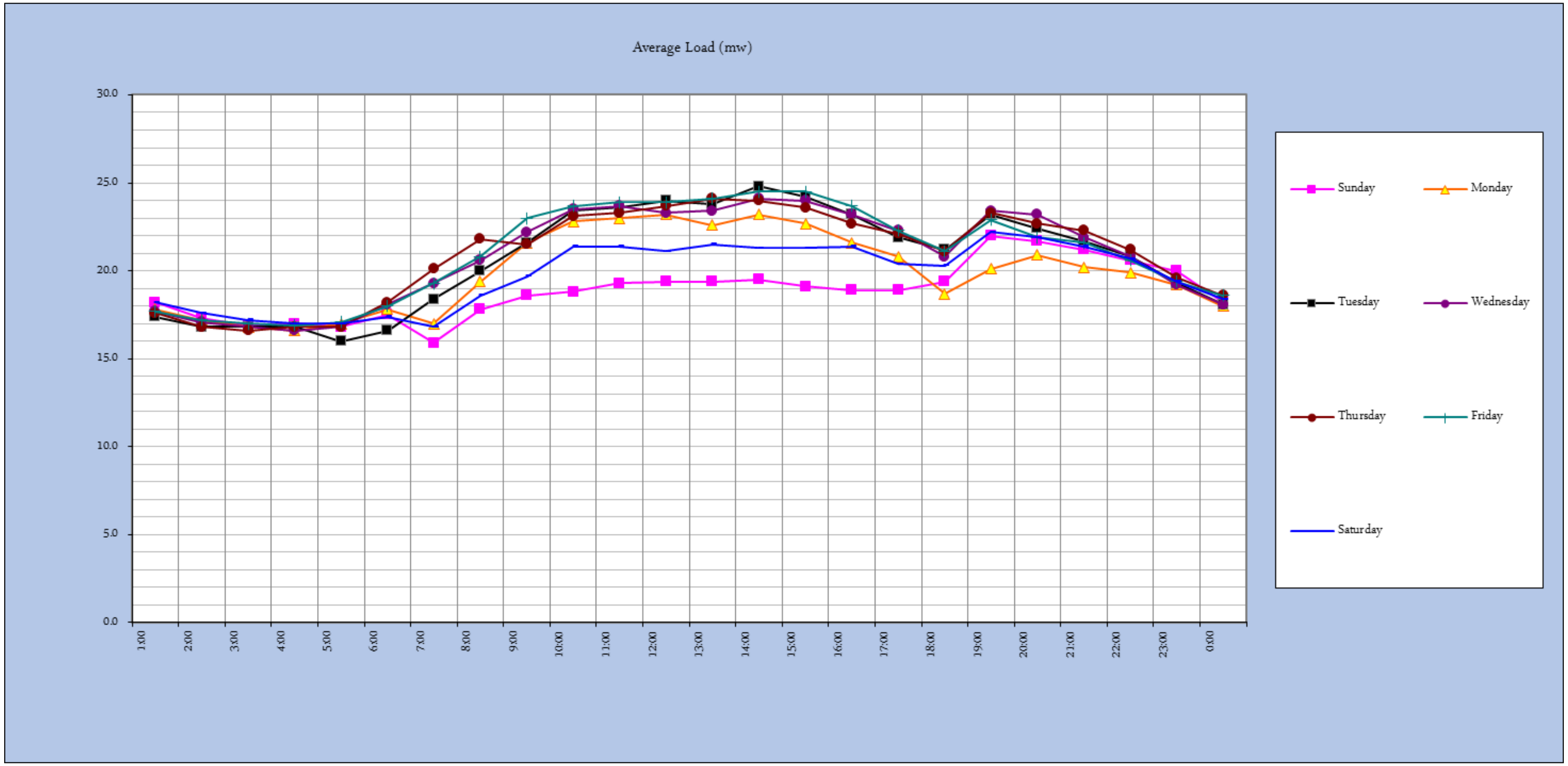
Hourly Load & Averages

		2019年3月3日			to		2019年3月9日		
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.3	17.2	17.1	16.8	17.4	17.8	18.6	16.8	18.6
2:00	18.3	17.2	16.4	16.6	17.2	17.2	18.2	16.4	18.3
3:00	17.1	16.6	16.4	16.5	17.0	16.8	17.2	16.4	17.2
4:00	16.9	16.6	16.5	16.3	16.6	16.9	17.2	16.3	17.2
5:00	16.5	17.4	16.6	16.7	17.5	17.2	17.2	16.5	17.5
6:00	17.3	18.2	18.3	17.9	18.7	17.9	17.3	17.3	18.7
7:00	16.9	20.0	19.9	19.8	19.4	19.2	17.3	16.9	20.0
8:00	17.0	20.7	21.2	22.7	21.0	22.0	18.0	17.0	22.7
9:00	17.6	22.4	22.5	23.3	23.0	22.8	19.9	17.6	23.3
10:00	18.0	23.3	22.7	21.1	23.6	23.4	21.5	18.0	23.6
11:00	18.1	23.2	23.4	21.7	23.2	23.9	21.1	18.1	23.9
12:00	18.5	24.0	23.3	22.3	24.0	23.7	21.2	18.5	24.0
13:00	18.6	23.7	23.2	23.5	23.8	23.3	21.2	18.6	23.8
14:00	18.8	24.0	23.6	23.7	23.4	23.2	21.0	18.8	24.0
15:00	18.5	24.0	23.2	23.8	23.3	22.8	21.2	18.5	24.0
16:00	17.8	23.5	21.9	23.2	22.6	21.6	20.8	17.8	23.5
17:00	17.7	21.4	20.8	21.1	21.4	20.7	20.2	17.7	21.4
18:00	18.6	21.0	20.3	21.2	20.0	20.4	20.4	18.6	21.2
19:00	21.3	23.0	22.4	22.6	22.5	22.4	22.4	21.3	23.0
20:00	20.9	22.7	21.8	22.4	22.1	22.3	21.6	20.9	22.7
21:00	20.8	22.1	20.9	21.2	20.7	21.4	21.5	20.7	22.1
22:00	19.8	20.8	20.0	20.4	20.6	20.9	20.8	19.8	20.9
23:00	19.0	19.0	18.3	19.0	19.4	18.8	19.1	18.3	19.4
0:00	18.0	17.8	17.6	18.2	18.6	18.8	18.4	17.6	18.8
DAY PEAK	18.8	24.0	23.6	23.8	24.0	23.9	21.5		
NIGHT PEAK	21.3	23.0	22.4	22.6	22.5	22.4	22.4		



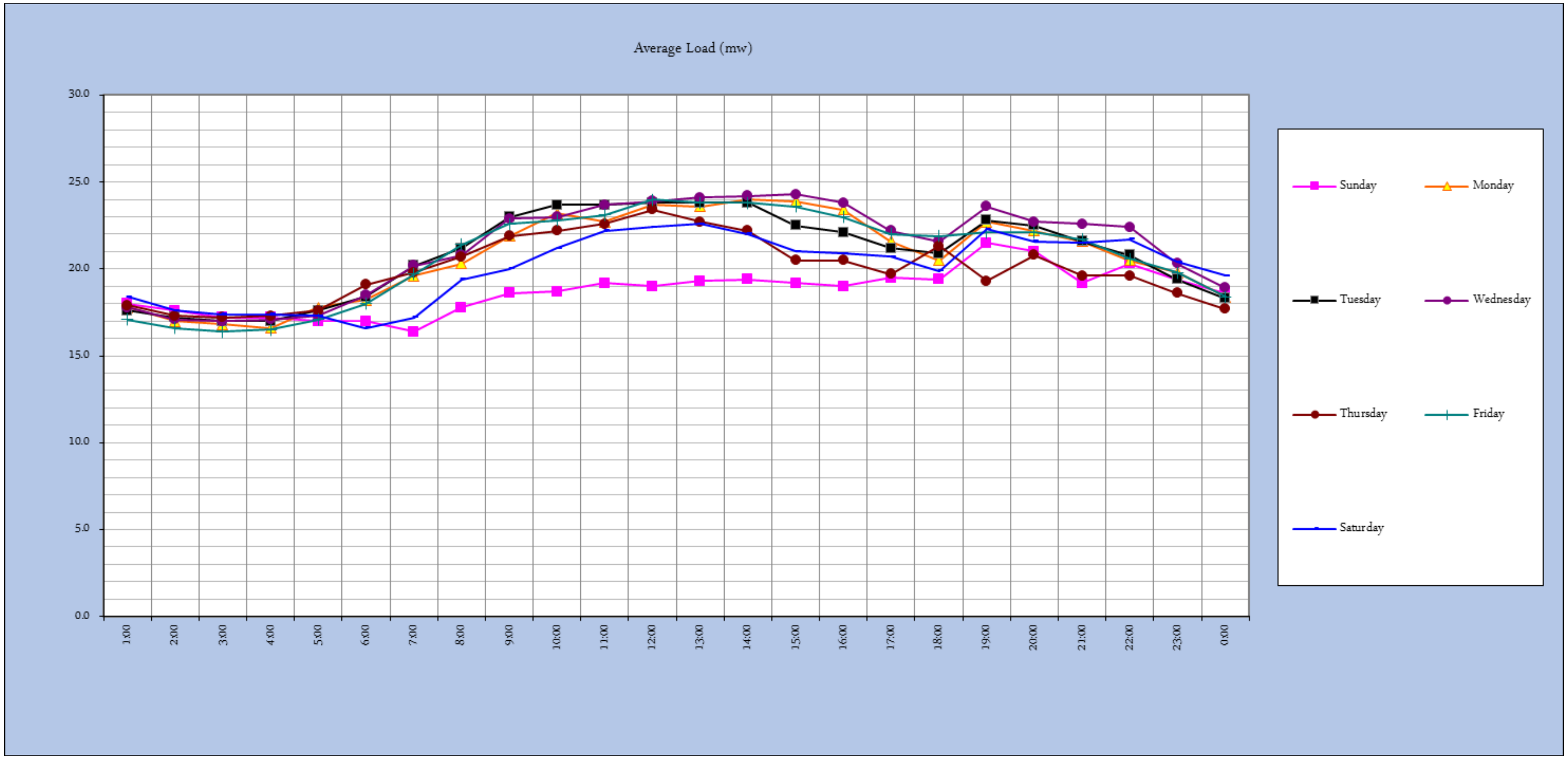
Hourly Load & Averages

		2019年3月10日			to	2019年3月16日			
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.2	17.8	17.4	17.7	17.6	17.7	18.2	17.4	18.2
2:00	17.3	17.2	16.8	17.1	16.8	17.2	17.6	16.8	17.6
3:00	16.9	16.8	16.8	16.8	16.6	17.0	17.2	16.6	17.2
4:00	17.0	16.6	16.8	16.6	16.8	16.9	17.0	16.6	17.0
5:00	16.8	17.0	16.0	16.8	16.8	17.1	17.0	16.0	17.1
6:00	17.5	17.8	16.6	18.1	18.2	18.0	17.4	16.6	18.2
7:00	15.9	17.0	18.4	19.3	20.1	19.3	16.8	15.9	20.1
8:00	17.8	19.4	20.0	20.6	21.8	20.8	18.6	17.8	21.8
9:00	18.6	21.6	21.6	22.2	21.5	23.0	19.7	18.6	23.0
10:00	18.8	22.8	23.4	23.5	23.1	23.7	21.4	18.8	23.7
11:00	19.3	23.0	23.6	23.7	23.3	23.9	21.4	19.3	23.9
12:00	19.4	23.2	24.0	23.3	23.7	23.9	21.1	19.4	24.0
13:00	19.4	22.6	23.8	23.4	24.1	24.1	21.5	19.4	24.1
14:00	19.5	23.2	24.8	24.1	24.0	24.5	21.3	19.5	24.8
15:00	19.1	22.7	24.2	24.0	23.6	24.5	21.3	19.1	24.5
16:00	18.9	21.6	23.2	23.2	22.7	23.7	21.4	18.9	23.7
17:00	18.9	20.8	21.9	22.3	22.1	22.3	20.4	18.9	22.3
18:00	19.4	18.7	21.2	20.8	21.1	21.1	20.3	18.7	21.2
19:00	22.0	20.1	23.2	23.4	23.3	22.9	22.2	20.1	23.4
20:00	21.7	20.9	22.4	23.2	22.7	21.9	21.9	20.9	23.2
21:00	21.2	20.2	21.7	21.9	22.3	21.6	21.4	20.2	22.3
22:00	20.6	19.9	20.8	20.8	21.2	20.6	20.7	19.9	21.2
23:00	20.0	19.2	19.3	19.2	19.6	19.4	19.4	19.2	20.0
0:00	18.2	18.0	18.1	18.1	18.6	18.6	18.4	18.0	18.6
DAY PEAK	19.5	23.2	24.8	24.1	24.1	24.5	21.5		
NIGHT PEAK	22.0	20.9	23.2	23.4	23.3	22.9	22.2		



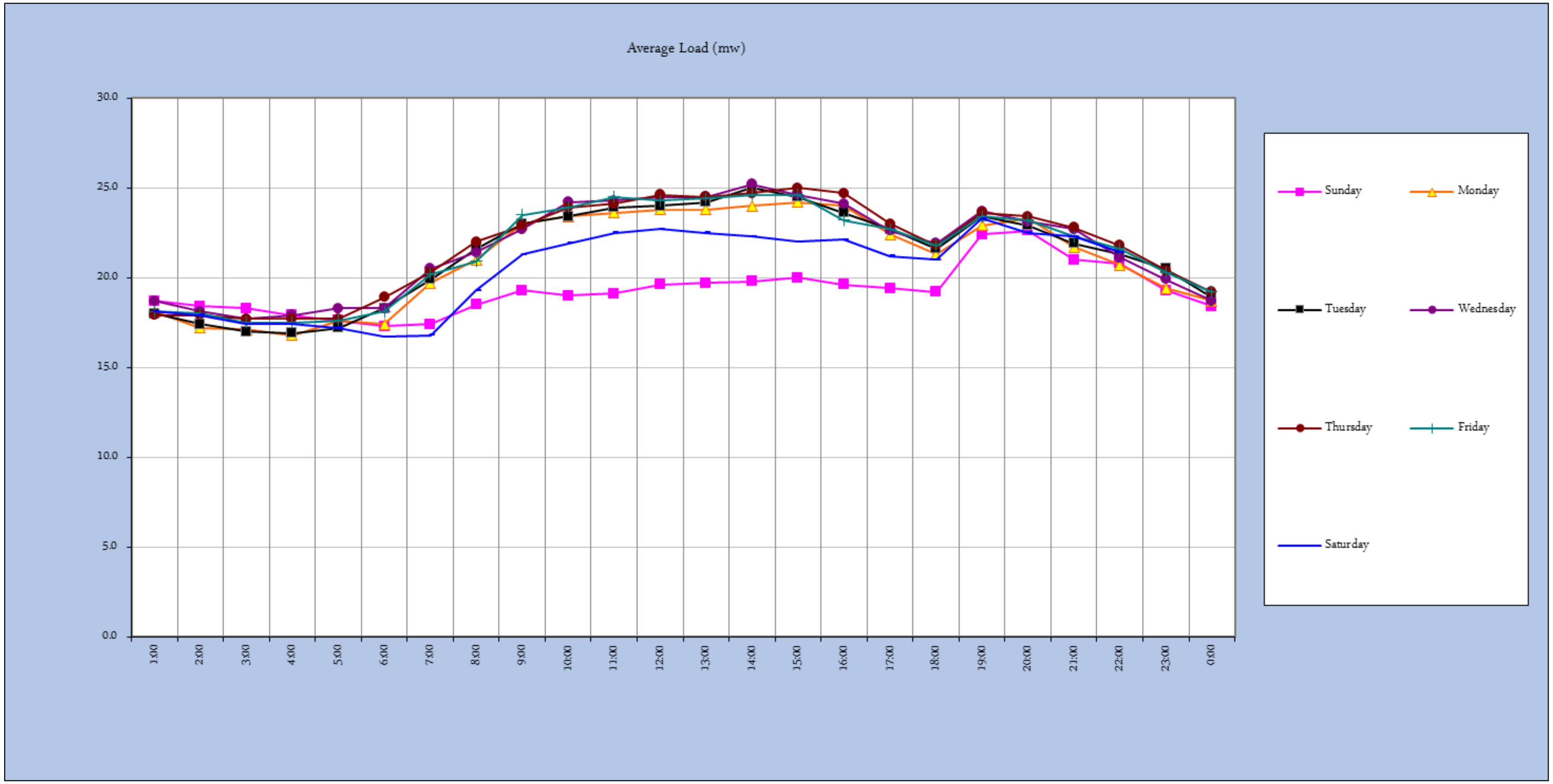
Hourly Load & Averages

		2019年3月17日			to	2019年3月23日			
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.0	17.8	17.6	17.8	17.9	17.1	18.4	17.1	18.4
2:00	17.6	17.0	17.2	17.1	17.3	16.6	17.6	16.6	17.6
3:00	17.2	16.8	17.0	17.0	17.2	16.4	17.4	16.4	17.4
4:00	17.2	16.6	17.0	17.1	17.3	16.5	17.4	16.5	17.4
5:00	17.0	17.8	17.6	17.3	17.6	17.1	17.3	17.0	17.8
6:00	17.0	18.2	18.4	18.5	19.1	18.0	16.6	16.6	19.1
7:00	16.4	19.6	20.2	20.2	19.8	19.7	17.2	16.4	20.2
8:00	17.8	20.3	21.2	20.8	20.7	21.4	19.4	17.8	21.4
9:00	18.6	21.9	23.0	22.9	21.9	22.6	20.0	18.6	23.0
10:00	18.7	23.2	23.7	23.0	22.2	22.8	21.2	18.7	23.7
11:00	19.2	22.7	23.7	23.7	22.6	23.1	22.2	19.2	23.7
12:00	19.0	23.7	23.8	23.9	23.4	24.0	22.4	19.0	24.0
13:00	19.3	23.6	23.8	24.1	22.7	23.8	22.6	19.3	24.1
14:00	19.4	24.0	23.8	24.2	22.2	23.8	22.0	19.4	24.2
15:00	19.2	23.9	22.5	24.3	20.5	23.6	21.0	19.2	24.3
16:00	19.0	23.4	22.1	23.8	20.5	23.0	20.9	19.0	23.8
17:00	19.5	21.6	21.2	22.2	19.7	22.0	20.7	19.5	22.2
18:00	19.4	20.5	20.9	21.6	21.3	21.9	19.9	19.4	21.9
19:00	21.5	22.7	22.8	23.6	19.3	22.1	22.3	19.3	23.6
20:00	21.0	22.2	22.5	22.7	20.8	22.1	21.6	20.8	22.7
21:00	19.2	21.6	21.6	22.6	19.6	21.7	21.5	19.2	22.6
22:00	20.3	20.5	20.8	22.4	19.6	20.6	21.7	19.6	22.4
23:00	19.4	19.8	19.4	20.3	18.6	19.8	20.4	18.6	20.4
0:00	18.6	18.4	18.3	18.9	17.7	18.4	19.6	17.7	19.6
DAY PEAK	17.9	24.0	23.8	24.3	23.4	24.0	22.6		
NIGHT PEAK	21.5	22.7	22.8	23.6	21.3	22.1	22.3		



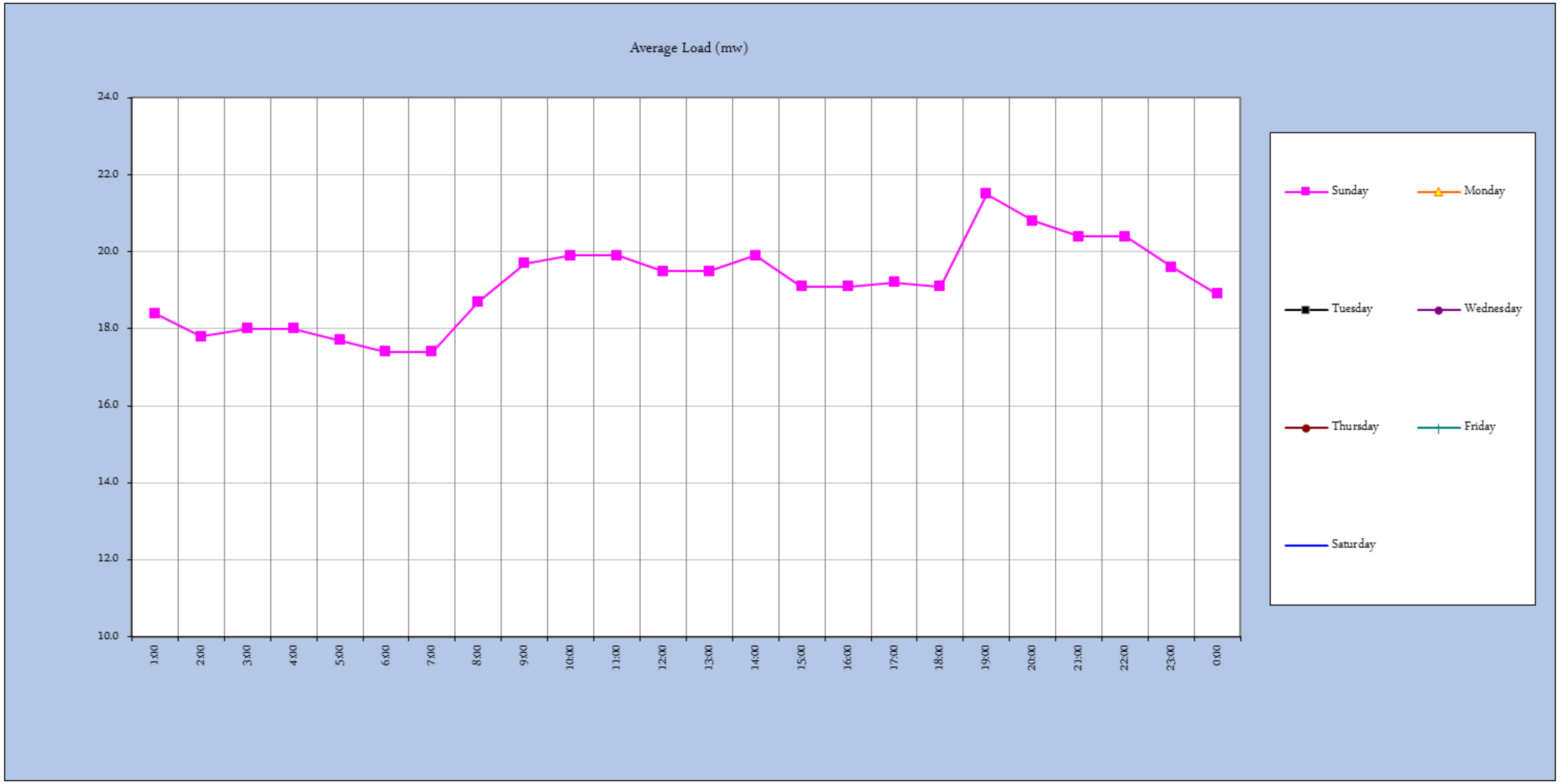
Hourly Load & Averages

			2019年2月24日		to		2019年3月30日		
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.7	18.1	18.0	18.7	17.9	18.1	18.1	17.9	18.7
2:00	18.4	17.2	17.4	18.1	17.9	18.0	17.9	17.2	18.4
3:00	18.3	17.1	17.0	17.7	17.7	17.5	17.4	17.0	18.3
4:00	17.9	16.8	16.9	17.9	17.7	17.5	17.4	16.8	17.9
5:00	17.6	17.6	17.2	18.3	17.7	17.6	17.2	17.2	18.3
6:00	17.3	17.4	18.3	18.3	18.9	18.1	16.7	16.7	18.9
7:00	17.4	19.7	19.9	20.5	20.3	20.2	16.8	16.8	20.5
8:00	18.5	21.0	21.6	21.4	22.0	20.9	19.3	18.5	22.0
9:00	19.3	23.0	23.0	22.7	22.9	23.5	21.3	19.3	23.5
10:00	19.0	23.4	23.4	24.2	23.9	23.9	21.9	19.0	24.2
11:00	19.1	23.6	23.9	24.3	24.1	24.5	22.5	19.1	24.5
12:00	19.6	23.8	24.0	24.5	24.6	24.3	22.7	19.6	24.6
13:00	19.7	23.8	24.2	24.5	24.5	24.4	22.5	19.7	24.5
14:00	19.8	24.0	25.0	25.2	24.7	24.6	22.3	19.8	25.2
15:00	20.0	24.2	24.5	24.6	25.0	24.6	22.0	20.0	25.0
16:00	19.6	24.0	23.6	24.1	24.7	23.2	22.1	19.6	24.7
17:00	19.4	22.4	22.7	22.6	23.0	22.7	21.2	19.4	23.0
18:00	19.2	21.3	21.6	21.9	21.8	21.8	21.0	19.2	21.9
19:00	22.4	22.9	23.4	23.7	23.6	23.4	23.3	22.4	23.7
20:00	22.6	23.3	22.9	23.1	23.4	23.2	22.5	22.5	23.4
21:00	21.0	21.7	21.9	22.7	22.8	22.3	22.3	21.0	22.8
22:00	20.8	20.7	21.3	21.1	21.8	21.6	21.4	20.7	21.8
23:00	19.3	19.4	20.5	19.9	20.4	20.3	20.5	19.3	20.5
0:00	18.4	18.7	18.9	18.7	19.2	19.2	19.4	18.4	19.4
DAY PEAK	20.0	24.2	25.0	25.2	25.0	24.6	22.7		
NIGHT PEAK	22.6	23.3	23.4	23.7	23.6	23.4	23.3		



Hourly Load & Averages

	2019年3月31日								
Time	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Min Load	Max Load
1:00	18.4							18.4	0.0
2:00	17.8							17.8	0.0
3:00	18.0							18.0	0.0
4:00	18.0							18.0	0.0
5:00	17.7							17.7	0.0
6:00	17.4							17.4	0.0
7:00	17.4							17.4	0.0
8:00	18.7							18.7	0.0
9:00	19.7							19.7	0.0
10:00	19.9							19.9	0.0
11:00	19.9							19.9	0.0
12:00	19.5							19.5	0.0
13:00	19.5							19.5	0.0
14:00	19.9							19.9	0.0
15:00	19.1							19.1	0.0
16:00	19.1							19.1	0.0
17:00	19.2							19.2	0.0
18:00	19.1							19.1	0.0
19:00	21.5							21.5	0.0
20:00	20.8							20.8	0.0
21:00	20.4							20.4	0.0
22:00	20.4							20.4	0.0
23:00	19.6							19.6	0.0
0:00	18.9							18.9	0.0
DAY PEAK	19.9	0.0	0.0	0.0	0.0	0.0	0.0		
NIGHT PEAK	21.5	0.0	0.0	0.0	0.0	0.0	0.0		



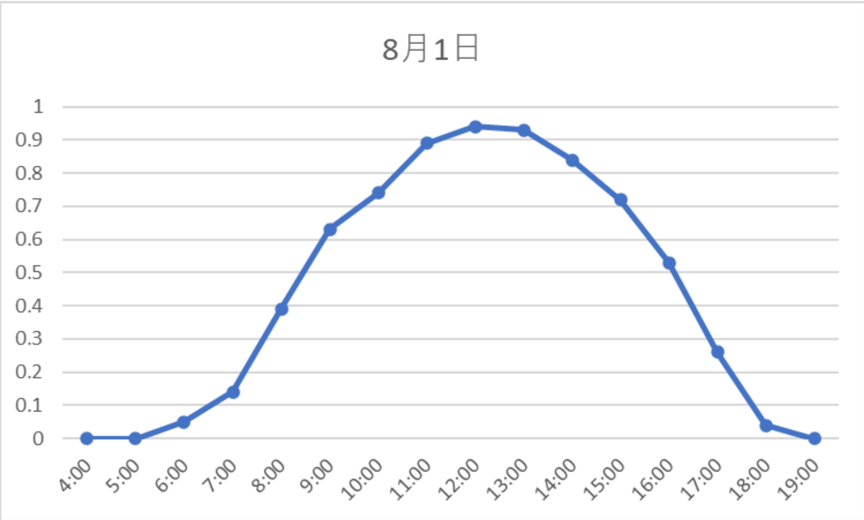
Hourly Load & Averages

	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
8月1日	0	0	0.05	0.14	0.39	0.63	0.74	0.89	0.94	0.93	0.84	0.72	0.53	0.26	0.04
8月2日	0	0	0	0.01	0.01	0.01	0.01	0.02	0.04	0.09	0.31	0.38	0.27	0.27	0.13
8月3日	0	0	0.04	0.2	0.31	0.58	0.69	0.36	0.44	0.77	0.72	0.57	0.35	0.28	0.11
8月4日	0	0	0.04	0.19	0.43	0.38	0.73	0.89	0.84	0.78	0.87	0.6	0.41	0.28	0.08
8月5日	0	0	0.06	0.18	0.38	0.55	0.7	0.85	0.94	0.97	0.86	0.73	0.5	0.3	0.1
8月6日	0	0	0.06	0.27	0.49	0.7	0.82	0.91	0.78	0.84	0.73	0.63	0.45	0.26	0.08
8月7日	0	0	0.02	0.08	0.35	0.09	0.28	0.55	0.8	0.86	0.6	0.59	0.49	0.28	0.06
8月8日	0	0	0.04	0.16	0.23	0.51	0.47	0.44	0.41	0.36	0.49	0.26	0.27	0.09	0.01
8月9日	0	0	0.01	0.07	0.1	0.15	0.27	0.22	0.22	0.41	0.44	0.2	0.16	0.06	0.03
8月10日	0	0	0	0.01	0.13	0.2	0.11	0.06	0.11	0.2	0.25	0.1	0.11	0.04	0.01
8月11日	0	0	0.03	0.2	0.3	0.51	0.44	0.58	0.64	0.65	0.65	0.53	0.25	0.29	0.06
8月12日	0	0	0.04	0.12	0.38	0.56	0.41	0.67	0.91	0.79	0.8	0.66	0.45	0.25	0.07
8月13日	0	0	0.01	0.09	0.26	0.57	0.81	0.85	0.75	0.87	0.71	0.47	0.39	0.23	0.07
8月14日	0	0	0.02	0.06	0.35	0.57	0.53	0.77	0.92	0.85	0.83	0.51	0.37	0.19	0.06
8月15日	0	0	0.04	0.22	0.35	0.56	0.54	0.55	0.8	0.78	0.66	0.66	0.43	0.22	0.07
8月16日	0	0	0.01	0.13	0.37	0.36	0.39	0.25	0.5	0.23	0.45	0.48	0.32	0.13	0.05
8月17日	0	0	0.02	0.14	0.37	0.38	0.27	0.11	0.18	0.68	0.45	0.66	0.32	0.24	0.07
8月18日	0	0	0.03	0.15	0.46	0.64	0.59	0.25	0.12	0.31	0.39	0.36	0.37	0.13	0.04
8月19日	0	0	0.01	0.05	0.11	0.08	0.54	0.49	0.69	0.23	0.17	0.2	0.18	0.19	0.04
8月20日	0	0	0.04	0.21	0.46	0.63	0.66	0.72	0.77	0.49	0.73	0.44	0.24	0.13	0.03
8月21日	0	0	0.06	0.26	0.48	0.67	0.82	0.88	0.89	0.87	0.84	0.63	0.45	0.27	0.07
8月22日	0	0	0.04	0.21	0.47	0.44	0.63	0.71	0.62	0.67	0.45	0.4	0.25	0.22	0.05
8月23日	0	0	0.02	0.19	0.31	0.61	0.82	0.89	0.95	0.86	0.75	0.53	0.39	0.17	0.05
8月24日	0	0	0.04	0.18	0.42	0.49	0.63	0.74	0.88	0.74	0.66	0.53	0.37	0.16	0.05
8月25日	0	0	0.03	0.2	0.46	0.57	0.64	0.75	0.79	0.72	0.83	0.52	0.44	0.2	0.02
8月26日	0	0	0.05	0.24	0.45	0.55	0.41	0.77	0.64	0.7	0.88	0.53	0.27	0.23	0.03
8月27日	0	0	0.04	0.21	0.34	0.44	0.63	0.82	0.81	0.61	0.79	0.61	0.43	0.21	0.04
8月28日	0	0	0.04	0.21	0.32	0.46	0.74	0.94	0.93	0.81	0.7	0.57	0.29	0.25	0.05
8月29日	0	0	0.05	0.24	0.46	0.66	0.8	0.91	0.97	0.3	0.23	0.44	0.26	0.21	0.04
8月30日	0	0	0.04	0.25	0.36	0.6	0.71	0.9	0.82	0.36	0.49	0.49	0.47	0.2	0.04
8月31日	0	0	0.04	0.23	0.37	0.54	0.76	0.81	0.75	0.91	0.79	0.61	0.4	0.16	0.03

http://k-ichikawa.blog.enjoy.jp/etc/HP/js/sunShine3/ss3H.html

沖縄、2019年8月、全天

Aug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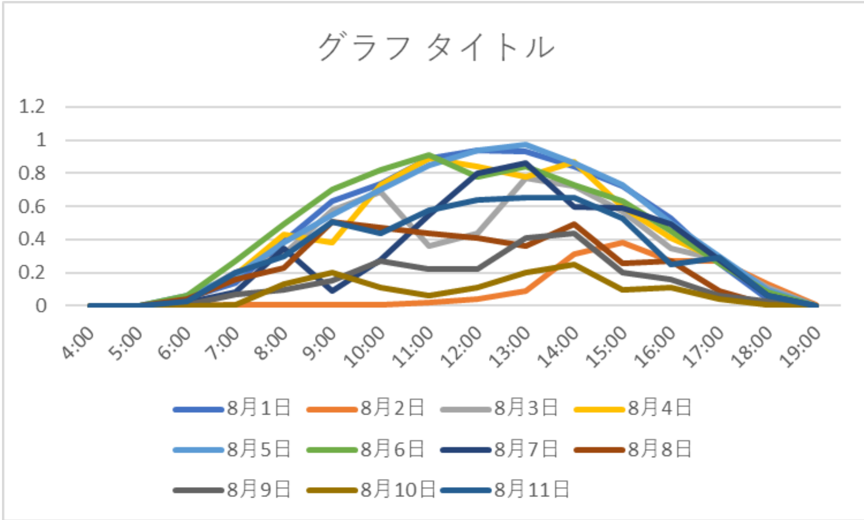
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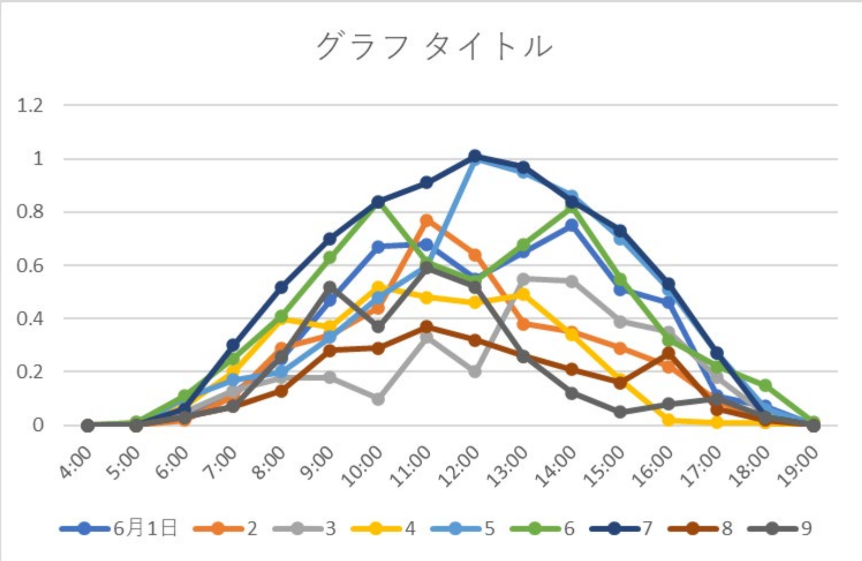
Aug

	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	
6月1日	0	0	0.04	0.12	0.25	0.47	0.67	0.68	0.55	0.65	0.75	0.51	0.46	0.11	0.07	0	5.32
2	0	0	0.02	0.11	0.29	0.34	0.44	0.77	0.64	0.38	0.35	0.29	0.22	0.09	0.01	0	3.94
3	0	0.01	0.05	0.13	0.18	0.18	0.1	0.33	0.2	0.55	0.54	0.39	0.35	0.18	0.04	0	3.22
4	0	0	0.07	0.2	0.4	0.37	0.52	0.48	0.46	0.49	0.34	0.17	0.02	0.01	0.01	0	3.54
5	0	0	0.1	0.17	0.2	0.33	0.48	0.6	1	0.95	0.86	0.7	0.51	0.27	0.06	0	6.22
6	0	0.01	0.11	0.25	0.41	0.63	0.84	0.61	0.54	0.68	0.82	0.55	0.32	0.22	0.15	0.01	6.13
7	0	0	0.06	0.3	0.52	0.7	0.84	0.91	1.01	0.97	0.84	0.73	0.53	0.27	0.03	0	7.71
8	0	0	0.03	0.07	0.13	0.28	0.29	0.37	0.32	0.26	0.21	0.16	0.27	0.06	0.02	0	2.46
9	0	0	0.03	0.07	0.26	0.52	0.37	0.59	0.52	0.26	0.12	0.05	0.08	0.1	0.03	0	3.01
10	0	0	0	0	0.02	0.16	0.58	0.29	0.39	0.22	0.42	0.23	0.13	0.06	0.02	0	2.54
11	0	0	0.01	0.04	0.11	0.09	0.07	0.29	0.36	0.54	0.24	0.16	0.23	0.08	0.02	0	2.23
12	0	0	0.06	0.18	0.46	0.73	0.88	0.9	0.66	0.64	0.64	0.51	0.44	0.27	0.09	0.01	6.46
13	0	0	0.04	0.14	0.3	0.34	0.26	0.4	0.47	0.38	0.34	0.18	0.13	0.1	0.02	0	3.1
14	0	0	0.03	0.03	0.02	0.06	0.06	0.28	0.31	0.22	0.33	0.39	0.19	0.1	0.04	0	2.04
15	0	0	0.04	0.31	0.51	0.76	0.85	0.97	1.02	0.99	0.87	0.76	0.51	0.3	0.08	0.01	7.99
16	0	0.01	0.12	0.34	0.55	0.75	0.91	0.99	1.02	0.88	0.81	0.74	0.48	0.24	0.08	0.01	7.93
17	0	0	0.05	0.19	0.19	0.36	0.35	0.37	0.24	0.15	0.14	0.09	0.11	0.08	0.07	0	2.37
18	0	0	0.02	0.14	0.3	0.46	0.26	0.23	0.23	0.11	0.34	0.02	0	0.02	0.06	0	2.19
19	0	0	0.03	0.12	0.21	0.19	0.37	0.36	0.44	0.59	0.57	0.29	0.28	0.23	0.03	0	3.72
	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	
20	0	0	0.01	0.02	0.06	0.08	0.17	0.27	0.11	0.04	0.06	0.04	0.03	0.03	0.01	0	0.94
21	0	0	0.03	0.12	0.27	0.43	0.77	0.42	0.49	0.63	0.6	0.47	0.16	0.13	0.04	0	4.55
22	0	0	0.01	0.04	0.04	0.1	0.09	0.14	0.23	0.2	0.15	0.25	0.17	0.09	0.04	0	1.55
23	0	0	0.01	0.03	0.04	0.13	0.16	0.11	0.16	0.27	0.16	0.14	0.09	0.04	0.01	0	1.35
24	0	0	0.01	0.05	0.08	0.07	0.14	0.15	0.16	0.18	0.22	0.21	0.15	0.1	0.05	0	1.58
25	0	0	0.03	0.07	0.11	0.16	0.41	0.45	0.43	0.43	0.44	0.28	0.2	0.16	0.07	0	3.23
26	0	0	0.01	0.01	0.01	0.05	0.12	0.16	0.47	0.46	0.27	0.35	0.18	0.11	0.07	0	2.27
27	0	0.01	0.07	0.15	0.41	0.68	0.56	0.85	0.83	0.65	0.34	0.21	0.13	0.11	0.04	0	5.04
28	0	0	0.03	0.24	0.48	0.54	0.51	0.62	0.78	0.96	0.73	0.43	0.33	0.15	0.03	0.01	5.81
29	0	0.01	0.09	0.22	0.31	0.57	0.88	0.71	0.76	0.73	0.79	0.74	0.53	0.34	0.14	0.01	6.82
30	0	0	0.06	0.21	0.46	0.48	0.81	0.8	0.76	0.96	0.89	0.64	0.47	0.25	0.13	0.01	6.92

Jun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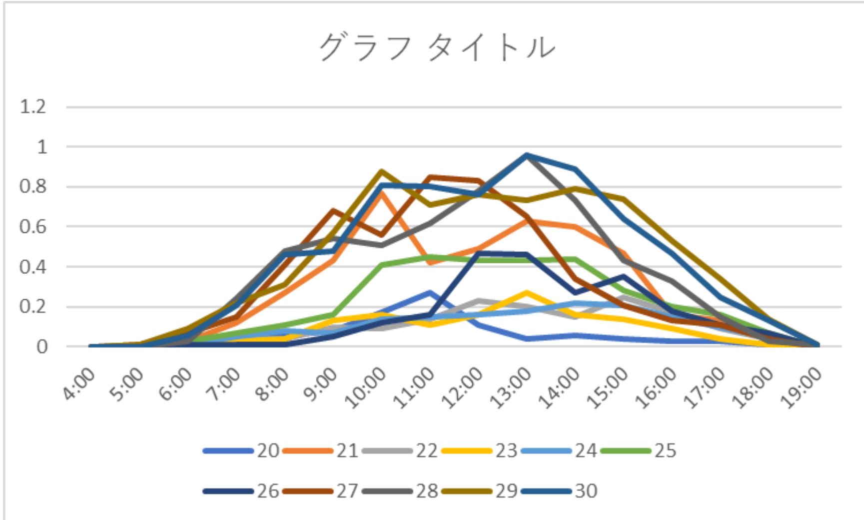
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15. 付録 H:St_Kitts_最低負荷等の別フォーマット(現地にて収集、2019 年)

2.4 Dynamic Stability Analysis

Table 2-8 Dispatch at Minimum Load

Generator	Pgen	Pmin	Pmax	Spinning Reserve	%Loading	Down Reserve
	MW	MW	MW	MW	MW	MW
Generator#1	5.80	1.22	6.13	0.00	94.60%	4.58
Generator#2	3.34	0.77	3.87	0.52	86.50%	2.58
Generator#3	3.50	0.77	3.89	0.39	89.80%	2.72
Generator#4	3.60	0.77	3.89	0.29	92.40%	2.82
Generator#8	0.00	0.73	3.66	0.00	0.00%	0.00
Generator#9	0.00	0.70	3.50	0.00	0.00%	0.00
Generator#10	0.00	0.77	3.89	0.00	0.00%	0.00
Generator#11	0.00	0.77	3.89	0.00	0.00%	0.00
Generator#12	0.00	0.77	3.89	0.00	0.00%	0.00
Generator#14	0.00	0.77	3.89	0.00	0.00%	0.00
Generator CAT1		0.41	1.65			
Generator CAT2		0.41	1.65			
Generator CAT3		0.41	1.65			
Generator CAT4		0.41	1.65			
Generator CAT5		0.41	1.65			
Generator CAT6		0.41	1.65			
sum	16.24	5.99	27.68			

Table 1.3

Existing SKELEC Generation

Ramp Capability	
kW/sec	MW/h
122.00	439.20
77.40	278.64
77.92	280.51
77.92	280.51
73.20	263.52
70.00	252.00
77.92	280.51
77.92	280.51
77.92	280.51
77.92	280.51
55.00	198.00
55.00	198.00
55.00	198.00
55.00	198.00
55.00	198.00
55.00	198.00

April 2019

Generators Fuel Eff (1).docx

Generators Fuel Efficiency (kWh/gal)

UNIT	70%	逆数
Generator#1	18.08	5.531
Generator#2	18.01	5.552
Generator#3	17.38	5.754
Generator#4	17.23	5.804
Generator#9	17.90	5.587
Generator#10	17.99	5.559
Generator#11	18.47	5.414
Generator#12	17.99	5.559
Generator#14	–	
Generator CAT1	17.50	5.715
Generator CAT2	16.00	6.248
Generator CAT3	16.00	6.248
Generator CAT4	17.50	5.715
Generator CAT5	16.00	6.248
Generator CAT6	17.50	5.715

Notes:

Pgen = amount of generation output

Spinning Reserve = Pmax - Pgen

Down Reserve = Pgen - Pmin

CAT1～CAT2のRated Capacityは2MWだが、定格1.65MWで運用中

CAT1～CAT2のPminは要調査。少なくとも25%Loadは問題無しのため。25%Loadの値を入力

CAT1～CAT2のRamp rateは不明のため、30秒で定格となるような値を想定した。

cf.https://www.jadelmas.com/en/brands-products/products-caterpillar-product-line/power-systems/electric-power/diesel-generator-sets/cm32c-inline-generator-set

CAT5, CAT6のGenerators Fuel Efficiencyは、CAT1～4をもとにした推定値

16. 付録 I：20191120St.Kitts ご報告、日本工営様の現地出張結果報告

St. Kitts 島出張 系統解析関係ご報告

2019/11/27 日本工営 新美

1．活動内容概要

・ SKELEC への系統解析関係の現状説明を実施

・ SKELEC へ追加で必要な情報をヒアリング

・ SKELEC と Site visit にて情報収集

・合同調整会議等の場で GridSim（仮称） をアピール（反応は良く、 SKELEC や MPI は協力してくださるとのこと 。 ）

2．収集情報

Bassetelle の 500kW PV は 8 月頃から運転していない。現在はシャットダウン中。 接続先のフィーダは Bayfords である。

SKELEC に設置した 1.2MW の太陽光も現在故障により稼働しておらず、保証期間の範囲であるため、全体を撤去し新たに同規模のものを設置することになっている。現在、台湾の業者からの反応を待っているところである。 34MW Laclanche 事業について、ベースは 16MW、 18MW Max で PPA を締結した。16MW を超過した分は SKELEC は電力購入料金を支払わない。 超過分はバッテリーに蓄電し、日没後に売電するよう要求している。

11.3 kV で発電し、末端で 11kV になるように送電している。電圧降下の問題はない。

Canon のフィーダの負荷は昼間 2.2 MW、夜間 3.2MW 程度である。 Wind の 5MW が入るとフィーダは限界となる。

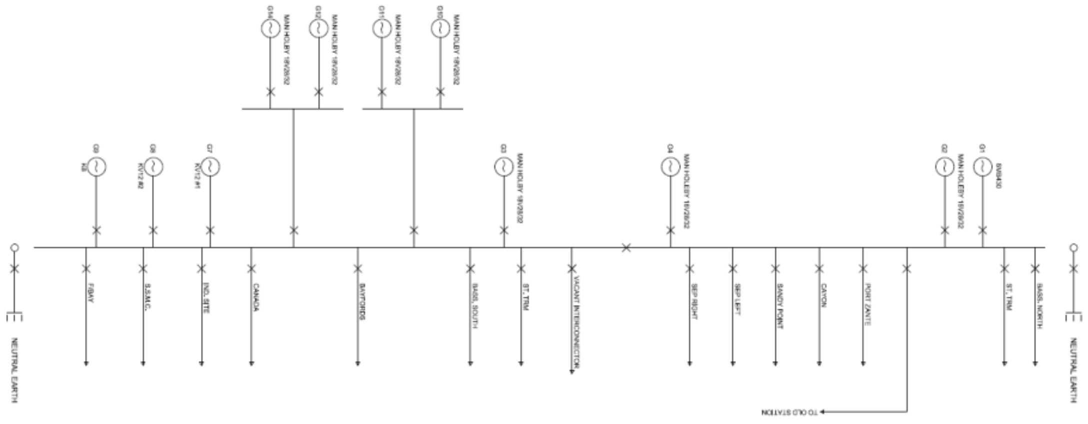
シミュレーションに必要なデータは提供する。 Heat Rate, Active power, reactive power,
cost of maintenance など提供可能。

2MW 名板容量、実際出力 1.6MW x 6 units CAT ディーゼル発電機を導入（4 基は 3 月の際に導入済で、 2 基をさらに設置）した。番号は CAT1, CAT2, ...CAT6。全て同じモデル。実際出力を抑えているのは High Speed Diesel でメーカーの推奨による。気温が熱すぎるためか。 レイドスの最新 F/S 結果はまだ正式に発行されていないため、提供できない

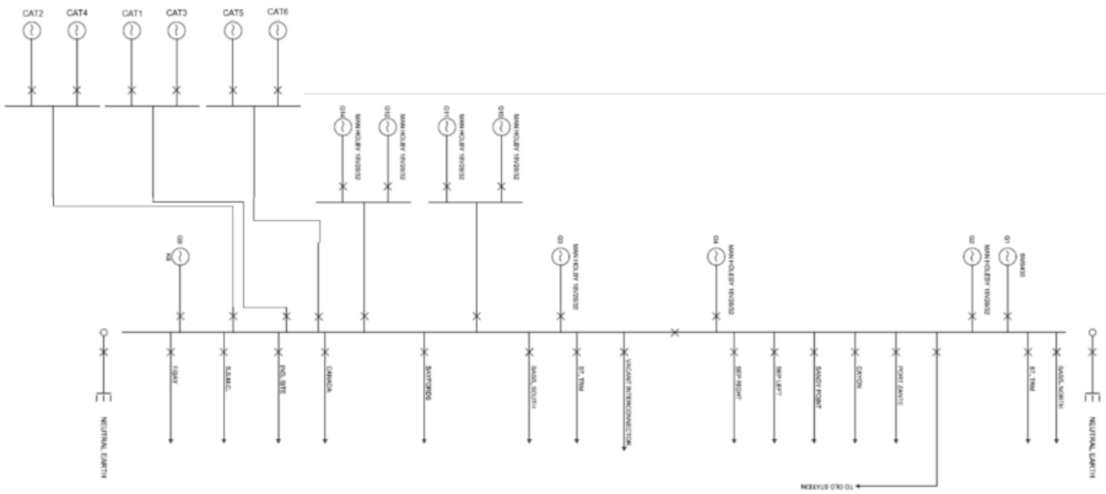
34MW Laclanche 事業におけるインバーターの仕様等はまだ機密なので提供できない

Caterpillar 製ディーゼルエンジン発電機 CAT5,6（銘板定格 2MW、実運用定格 1.6MW）
が 2 台増設されており、接続先を示す単結は次図の通りである。

変更前



変更後



 6 台の Caterpillar 製ディーゼルエンジン発電機は全て同じ仕様とのこと。CAT5 の銘板の写真:

 10 月 30 日昼間の発電状況

 各フィーダの負荷は以下の通り。

Feeder	Day Peak	Night Peak
Basseterre North	4.2	4.2
Port zone	1.5	1
Cayon	2	2.8
Sandy Point	1.4	1.8
S.E.P. (Mariott 1)		
S.E.P. (Mariott 2)		
Industrial site	5	1.6
Frigate bay	2.4	2.6
Bassetrre south	4.9	3.1
Bayfords	1.0	1.4
SSMC/Airport	0.8	0.8
CANADA	1.2	1.2

□

Lodge 開閉所は 2 重化構成のリモート制御装置、開閉器のみのシンプルな設計。その他の開閉所も同様な構成。

□ 調相装置は導入していないとのこと

３．系統解析への変更点

・発電機 CAT5,6 の追加

・発電機 G7,G8 の削除

・ 500kW PV の接続先を Bayfords フィーダに変更

・ 34MW Laclanche PV 事業の売電契約 16MW、 18MW Max に基づいたプログラム

・ノードの特異点は、データ異常であったため、他ノードを参考に調整

４．出張スケジュール

10/20 日本発

10/27	St. Kitts 着
10/28	MPI、 SKELEC、 JICA St. Lucia と打合せ
10/29	合同調整会議
10/30	SKELEC と打合せ、 Site visit
10/31	Nevis 島へ渡り関係者と打合せ
11/01	MPI と打合せ予定
11/03	St. Kitts 発
11/11	日本着

以上

17. 付録 J: 大規模送配電系統における高速潮流計算プログラムの解説

環境エネルギー技術研究所㈱

1．背景と経緯

電力系統における潮流計算手法には，送電系統向けの Newton-Raphson 法や配電系統向けの Backward/Forward 法など，多くの解法が提案されている。これらの解法の性能比較については, 過去に実施されてはいるが,「時期が古い, 大規模系統を対象としていない」などの不十分さがあり,「どの程度の系統規模まで，どれぐらい速く解けるのか」が不明確であった。

そこで，2011 年度に，大規模配電系統を対象として，Newton-Raphson 法と Backward/Forward 法の比較シミュレーションを行い, Backward/Forward 法の優位性を実証した。

しかしながら，Backward /Forward 法は弱ループ・ネットワークを取り扱える機能はあるものの，ループが多数存在する送電系統にどの程度適用可能であるかは未知数であった。

また，最適潮流計算を非線形計画問題として厳密に解くには，Newton-Raphson 法的アプローチが不可欠である。このような視点にもとづき，2012 年度に大規模送電系統を対象として，①2011 年度に開発した Newton-Raphson 法による潮流計算の大幅改造と高速化，および②近年の理論的成果と言える「線形方程式の反復法による解法」を Newton-Raphson 法に実装する試み，を行った。

①では，Jacobian 疎行列作成とその LU 分解の高速化(以降、改良 Newton-Raphson 法と称す)，②では，非対称連立一次方程式の代表的反復解法であるリスタート型 GMRES(Generalized Minimal Residual method)法を Newton 方程式に適用した Newton-GMRES 法の実装，を実現した。ここで、両者を EETRI 法と命名する。

2．大規模配電系統におけるシミュレーションの結果（2011,2012 年度）

ループの無い仮想的大規模配電系統(Radial Distribution network)を，木構造を有する有向グラフとしてランダムに発生させて，数値実験に使用した（表 1 , 2 参照)。この木の根をスラックバスとし，木の葉を負荷ノード(PQ 指定ノード)，残りは中間通過・分岐点(指定値零の PQ ノード)とする。なお、ブランチの R/X 比は[1.0,10.0]を使用し、Susceptance はすべて無視する。

結果として、改良 Newton-Raphson 法では，n=40000 のケースにおいて，2011 年度の結果より約 230 倍の高速性を達成することができた。ただし，その計算時間は Backward/Forward 法の約 4 倍であるので，Backward/Forward 法の優位性は揺るがない。

表１ 大規模配電系統での数値実験の結果（2011 年度）

ノード (n)	負荷ノード	スラック電圧	反復回数		最終誤差(PQmismatch)		実行時間(s)		速度比
			N/R	B/F	N/R	B/F	N/R	B/F	NR/BF
500	240	5.00	5	15	2.619e-6	4.592e-7	0.031	0.016	1.94
1000	483	10.00	5	18	9.683e-5	5.217e-7	0.062	0.015	4.13
2000	1012	20.00	4	7	1.274e-6	2.869e-7	0.203	0.016	12.69
5000	2510	20.00	6	23	1.985e-7	5.688e-7	1.856	0.062	29.94
10000	5125	30.00	5	9	3.392e-10	9.378e-7	6.147	0.015	409.8
20000	10387	40.00	6	17	3.201e-10	4.610e-7	29.312	0.047	623.7
30000	15920	40.00	6	16	2.474e-10	7.494e-7	65.848	0.078	844.2
40000	21142	50.00	6	20	1.756e-8	7.155e-7	116.610	0.125	932.9
50000	27346	50.00	―	25	―	9.499e-7	―	0.188	―

N/R：Newton-Raphson 法

B/F：Backward/Forward 法

表２ 大規模配電系統での数値実験の結果（2012 年度）

ノード (n)	非零要素数	フィルイン率		反復回数		最終誤差(PQmismatch)		実行時間(s)		速度比
		N_R	N_G	N_R	N_G	N_R	N_G	N_R	N_G	N_G/N_R
500	5956	1.279	1.156	5	5	2.619e-6	2.619e-6	0.016	0.031	1.94
1000	11972	1.261	1.138	6	6	2.326e-10	1.845e-8	0.016	0.047	2.94
2000	23908	1.284	1.163	4	4	1.274e-6	1.251e-6	0.015	0.031	2.07
5000	59916	1.281	1.159	6	6	1.985e-7	1.985e-7	0.062	0.140	2.26
10000	119892	1.275	1.155	5	5	3.338e-10	1.002e-8	0.093	0.234	2.52
20000	239876	1.275	1.157	6	6	2.637e-10	3.408e-8	0.249	0.562	2.26
30000	359908	1.276	1.160	6	6	2.710e-10	1.948e-8	0.358	0.874	2.44
40000	479900	1.280	1.162	6	6	1.754e-8	1.323e-6	0.500	1.233	2.47
50000	599876	1.280	1.167	6	6	5.094e-6	5.095e-6	0.656	1.575	2.40

N_R：改良 Newton-Raphson 法

N_G：Newton-GMRES 法

非零要素数：Newton 方程式のヤコビアンにおける非零要素の個数

フィルイン率：完全 LU 分解の非零要素数/上記非零要素数（改良 Newton-Raphson 法）

：不完全 LU 分解の非零要素数/上記非零要素数（Newton-GMRES 法）

ここで、Newton 法による各反復において

① 改良 Newton-Raphson 法では、まず完全 LU 分解を行い、その後に一回の求解操作を行う。

②Newton-GMRES 法では、まず不完全 LU 分解を行い，その後の求解操作において GMRES 法による収束改良を複数回行う。不完全 LU 分解は完全 LU 分解より安価であるが、後処理を要する。

３．大規模送電系統におけるシミュレーションの結果（2012 年度）

多数のループを有する仮想的大規模送電系統を，無向グラフとしてランダムに発生させて，数値実験に使用した。ここで，平均のノード次数(接続ブランチ数：degree)2.5 を

与えてランダムグラフを作成し(ノード数をn とすると, ブランチ数 m=1.25n, ループ数 m-n+1), そのノード群を以下のように分類して, 標準π型モデルの送電系統を作成した。

① 入次数(in-degree)の小さいノード順に発電ノードを割り当て，最初の発電ノードをスラック・ノード，以降を PV ノードとする。全体の発電機総数は 51 に固定する。

② 出次数(out-degree)がゼロのノードは，すべて負荷ノード(PQ 指定ノード)とし、その他のノードは，中間通過・分岐点(指定値零の PQ ノード)とする。

なお、ブランチの R/X 比は[1.0,10.0]を使用し、Susceptance は，ブランチとノードにランダムに設定した。

表３ 大規模送電系統での数値実験の結果（2012 年度）

ノード (n)	非零 要素数	フィルイン率		反復回数		最終誤差(PQmismatch)		実行時間(s)		速度比
		N_R	N_G	N_R	N_G	N_R	N_G	N_R	N_G	N_G/N_R
500	6398	3.009	1.102	5	5	4.427e-12	9.734e-8	0.031	0.047	1.516
1000	13390	4.133	1.056	5	5	1.582e-11	1.135e-7	0.078	0.078	1.000
2000	27422	6.605	1.045	4	3	1.337e-10	2.945e-6	0.109	0.094	0.862
5000	69406	12.317	1.034	4	4	1.128e-9	3.639e-8	1.029	0.343	0.333
10000	139398	22.954	1.028	4	4	4.610e-9	7.800e-8	7.972	0.842	0.106
20000	279462	40.454	1.019	4	4	2.661e-8	9.036e-7	53.274	2.106	0.040
30000	419450	59.484	1.021	4	4	5.754e-8	2.070e-6	179.541	4.212	0.023
40000	559362	75.681	0.990	4	4	1.198e-7	1.539e-5	401.264	8.986	0.022
50000	699258	82.070	0.952	5	5	3.029e-7	3.410e-7	810.835	30.779	0.038

結果として、ループの無い大規模配電系統では，Newton-GMRES 法は改良 Newton-Raphson 法よりも低速であったが、多くのループを有する大規模送電系統では，Newton-GMRES 法の方が改良 Newton-Raphson 法よりも高速となった。木構造の配電系統では、アドミッタンス行列およびそのヤコビアン行列はバンド形状の行列であり、ヤコビアン行列が効率的に完全 LU 分解できることが，改良 Newton-Raphson 法の方がより高速であった理由と言える。

４．EETRI 法の適用例

① 配電系統における分散電源最適配置問題

126 母線の配電系統での潮流計算(B/F) 159,0544 回を約 31 秒

② 配電系統における時系列依存の確率的潮流計算

126 母線の配電系統での潮流計算(B/F) 288,0000 回を約 87 秒

③ 配電系統における連続型単目的 OPF の各種メタ解法

126 母線の配電系統での潮流計算(改良 Newton-Raphson) 約 1,8200 回を約 17*秒（10-trials)

④ 配電系統における連続型・離散型多目的 OPF のメタ解法

126 母線の配電系統での潮流計算(改良 Newton-Raphson) 1,2951 回を約 12*秒 (1−trial)

⑤配電系統におけるスイッチ組合せ問題

126 母線の配電系統での潮流計算(B/F) 163,6290 回を約 29 秒