

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	2019	2020	2021	2022	2023	Remarks	Monitoring (Up to May 2023)		
								Issue	Solution	
Expert	Month	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 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12				
1. Chief Advisor/Power System (1) /Diesel/Gas-turbine Power Plant (2)	Plan						Blue highlights were inputs from Japan.			
2. Subchief Advisor/Power System (2)	Actual									
3. Renewable Energy	Plan									
4. Energy Efficiency	Actual									
5. Grid Stabilization	Plan									
6. Diesel/Gas-turbine Power Plant/Coordinator	Actual									
7. Human Resources Development/Monitoring	Plan									
8. Grid Stabilization (2)/ Power Network Asset Management/Coordinator (2)	Actual									
Equipment	Plan									
Power loggers	Actual						Handed over in September and November 2022.			
Training in Japan	Plan									
Training in Japan	Actual						Training in Japan was conducted in April 2023.			
In-country Training	Plan									
Trainings in country (RE)	Actual						4 in-country trainings were conducted.			
Trainings in country (EE)	Plan									
Trainings in country (EE)	Actual						2 in-country trainings were conducted.			
Activities	Year	2019	2020	2021	2022	2023	Responsible Organization		Achievements	Issue & Countermeasures
Sub-Activities		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 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	JET	C/P		
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 coefficient) and power system reliability (SADI/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								A total of 3 RE and grid stabilization seminars were held.	
	Actual						○	○	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						○	○		

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Inputs	Year	2019			2020			2021			2022			2023			Remarks	Monitoring (Up to May 2023)			
	Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3		4	5	6	Issue
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																				
	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																				
	Actual																			○	○
Duration / Phasing																					
Plan	Phase 1			Phase 2																	
Actual	Phase 1			Phase 2																	
Monitoring Plan																					
Monitoring	Year	2019			2020			2021			2022			2023			Remarks	Issue	Solution		
	Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3				4	5
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

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**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.

PM Form 3-1 Monitoring Sheet Summary

	<p>2. Number of public buildings with EE program including BEMS</p>	<p>2 Government facilities</p>	<p>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 as 50%.</p> <p>It features: 265 kW PV, 400 kWh LiFePo4 battery storage, Lighting control equipment, Smart metering equipment, Power conditioning equipment.</p> <p>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.</p>
	<p>3. Number of trained staffs for introduction of RE</p>	<p>6 personnel MEB:3 BL&P:3 others</p>	<p>In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12).</p>

PM Form 3-1 Monitoring Sheet Summary

			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.

PM Form 3-1 Monitoring Sheet Summary

	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	1 st RE grid stability seminar	31	4.3
Nov 2022	St. Kitts & Nevis	1 st EE workshop	12	3.8
Nov 2022	Barbados	1st EE workshop	5	3.7
Dec 2022	Jamaica	2 nd RE grid stability seminar	45	3.9
Dec 2022	Barbados	3rd RE grid stability seminar	19	3.8
Dec 2022	St. Kitts & Nevis	2 nd RE grid stability seminar	19	3.8
Jan 2022	St. Kitts & Nevis	2 nd EE workshop	11	4.4
Jan 2022	Barbados	2nd EE workshop	11	3.9
Jan 2022	St. Kitts & Nevis	3 rd RE grid stability seminar	14	3.8
Jan 2022	Barbados	4th RE grid stability seminar	13	4.1
Feb 2022	Jamaica	1 st EE workshop	3	4.5
Mar 2022	Jamaica	2 nd 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

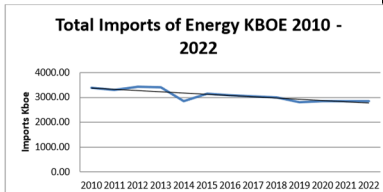
✓ N/A

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
<p>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")</p>	<ol style="list-style-type: none"> Energy self-dependency Target Value: 100% (100%RE by 2030) 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.	<ol style="list-style-type: none"> Renewable energy now makes up 3% of Barbados overall energy mix (12% of electricity production). 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. 	
<p>Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE</p>	<ol style="list-style-type: none"> 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 Number of public buildings with EE program including BEMS Target Value: 2 Government facilities. Number of trained staffs for introduction of RE Target Value: 6 personnel (MESBE:3, BLPC:3) and others 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.	<ol style="list-style-type: none"> 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. 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 as 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. 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 <ul style="list-style-type: none"> - 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) In total, number of participants (accumulated total) was 38 personnel <ul style="list-style-type: none"> - 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 	

<p>Output <u>Output 1 (to be achieved in Phase 1)</u> The basic information is confirmed for the capacity building for the introduction of RE</p>	<p>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</p>	<p>Project Report</p>		<p>1-1. Confirmed 1-2. Confirmed 1-3. Confirmed 1-4. Confirmed</p>	<p>MEWR changed to MESBE. After that, MESBE was reformed and changed to MEB</p>
<p><u>Output 2 (to be achieved in Phase 1)</u> The basic information is confirmed for the capacity building for the promotion of EE</p>	<p>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</p>	<p>Project Report</p>		<p>2-1. Confirmed 2-2. Confirmed 2-3. Confirmed 2-4. Confirmed</p>	<p>MEWR changed to MESBE. After that, MESBE was reformed and changed to MEB</p>
<p><u>Output 3 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the introduction of RE</p>	<p>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)</p>	<p>Project Report</p>		<p>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</p>	
<p><u>Output 4 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of EE</p>	<p>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)</p>	<p>Project Report</p>		<p>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</p>	

				<ul style="list-style-type: none"> - 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 <p>4-4. In total, 5 times.</p> <ul style="list-style-type: none"> - 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
<p>Output 5 (to be achieved in Phase 2) The human and institution capacity are enhanced for the promotion of power network resiliency</p>	<p>5-1. Number of trained staffs Target Value: 6 personnel (MESBE, BLPC)</p> <p>5-2. Textbooks/ manuals Target Value: For 2 programs (1 domestic training and 1 training in Japan)</p> <p>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</p> <p>5-4. Number of workshops Target Value: 2 times (Kick-off workshop and Final workshop)</p>	Project Report		<p>5-1. In total, number of participants (accumulated total) was 39 personnel (MEB: 27, BLPC: 12).</p> <p>Average (Local only): MEB: around 3 personnel BLPC: 2-4 personnel</p> <p>5-2. In total, 5 materials were prepared.</p> <ul style="list-style-type: none"> - 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 <p>5-3. In total, number of participants (accumulated total) was 82 personnel</p> <ul style="list-style-type: none"> - 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 <p>5-4. In total, 6 times</p> <ul style="list-style-type: none"> - 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
<p>Activities Activities for achieving Output 1 1-1. To verify human and institutional capacities for the introduction of RE</p>	<p>Inputs (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)</p> <p>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</p>	<p>(Barbados side) 1. Assignment of C/Ps -Project Director (P/D) -Project Manager (P/M) - Other C/P</p> <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)</p> <p>3. Recurrent costs Project Director, Project Manager and Project Administrator's salaries will be met by DET</p>	<p>Important Assumptions Most of the trained C/Ps continues commitment to the Project activities.</p> <p>Preconditions Contents of the current relevant policies on promotion of RE and EE are not largely changed.</p> <p>Issues and countermeasures</p>	
<p>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</p>				
<p>Activities for achieving Output 3 3-1. To develop microgrid concept in view of maximizing VRE introduction.</p>				

<p>3-2. To model microgrid concept in the agreed area carry out case studies using own computer simulator as part of capacity building.</p> <p>3-3. To consider the use of electric transportation in Barbados and its effects (positive and negative) on the grid and economy.</p> <p>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.</p> <p>3-5. To prepare the necessary training plan for doing the above Activities '3-1' through '3-4'</p> <p>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'</p> <p>3-7. To review the training plan through monitoring of the training conducted in Activity '3-6'</p> <p>3-8. To provide advice on realization of the RE projects</p> <p>3-9. To provide recommendations on design of the policy/ legal system proposed in Activity '3-4'</p> <p>3-10. To share the project output with other recipient countries</p>	<p>3. Training/Workshop in each recipient country -Training for project counterparts in each recipient country</p> <p>4. Equipment - Power loggers</p>		
<p><u>Activities for achieving Output 4</u></p> <p>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.</p> <p>4-2. To consider and propose the EE facilities necessary for achieving the EE goals</p> <p>4-3. To consider and propose necessary technologies for achieving EE goals, including building energy management system (BEMS) for public sector, etc.</p> <p>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</p> <p>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</p> <p>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'.</p> <p>4-7. To prepare the necessary training plan for doing the above Activities '4-1' through '4-6'</p> <p>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'</p> <p>4-9. To review the training plan through monitoring of the training conducted in Activity '4-8'</p> <p>4-10. To provide advice on realization of the EE projects</p> <p>4-11. To provide recommendation on design of the policy/ legal system proposed in Activity '4-6'</p> <p>4-12. To share the project output with other recipient countries</p>			
<p><u>Activities for achieving Output 5</u></p> <p>5-1. To demonstrate the way to enhance resiliency of the power infrastructure using network asset management system.</p>			

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)

Monitoring (Up to May 2023)

Inputs	Year	2019		2020		2021		2022		2023	Remarks	Monitoring (Up to May 2023)		
	Month	J	F	M	A	M	J	J	A	S		Issue	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 conducted.			
	Actual													
Activities	Year	2019		2020		2021		2022		2023	Responsible Organization		Achievements	Issue & Countermeasures
Sub-Activities	Month	J	F	M	A	M	J	J	A	S	JET	C/P		
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										○	○		DET was reformed to MEWR, MEWR was reformed to MESBE and MESBE was reformed to MEB.
	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 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										○	○		DET was reformed to MEWR, MEWR was reformed to MESBE and MESBE was reformed to MEB.
	Actual										○	○		
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										○	○	A total of 4 RE and grid stabilization seminars were held.	
	Actual										○	○		
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										○	○	A total of 39 people (accumulated total) participated.	
	Actual										○	○		
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										○	○		

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

PM Form 3-1 Monitoring Sheet Summary

<p>Output 3: (to be achieved in Phase 2)</p> <p>The human and institution capacity are enhanced for the introduction of RE</p>	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
<p>Output 4: (to be achieved in Phase 2)</p> <p>The human and institution capacity are enhanced for the promotion of EE</p>	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)	5-1. Number of trained staffs	10 personnel	In total, number of participants (accumulated total) was 66 personnel
The human and institution capacity are enhanced for the promotion of Power Network Resiliency	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	1 st 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	1 st RE grid stability seminar	31	4.3
Nov 2022	St. Kitts & Nevis	1st EE workshop	12	3.8
Nov 2022	Barbados	1 st EE workshop	5	3.7
Dec 2022	Jamaica	2 nd RE grid stability seminar	45	3.9
Dec 2022	Barbados	3 rd 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	2 nd EE workshop	11	3.9
Jan 2022	St. Kitts & Nevis	3rd RE grid stability seminar	14	3.8
Jan 2022	Barbados	4 th RE grid stability seminar	13	4.1
Feb 2022	Jamaica	1 st EE workshop	3	4.5
Mar 2022	Jamaica	2 nd 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),****Version : 6****SKELEC (St. Kitts Electricity Company Ltd.), NEVLEC (Nevis Electricity Company Ltd.)****Date: 24th May 2023****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**

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")	<ol style="list-style-type: none"> Energy self-dependency Target Value: 100% RE in Power Generation by 2030 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.	<ol style="list-style-type: none"> Approximately 2 percent Unchanged 	
Project Purpose Human and institutional capacities are enhanced for the introduction of RE and promotion of EE	<ol style="list-style-type: none"> 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) Number of public buildings with EE program including BEMS Target Value: Proposal by JET will be prepared for the BEMS introduction Number of trained staffs for introduction of RE Target Value: 10 personnel 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.	<ol style="list-style-type: none"> 10MW geothermal is in procurement process. One. The Alexandra Hospital was upgraded to be more energy efficient. 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 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	<ol style="list-style-type: none"> 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		<ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 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		<ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 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		<ol style="list-style-type: none"> 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 	

	<p><i>Final workshop: 10 personnel</i></p> <p>3-4. Number of workshops Target Value: 2 times <i>(Kick-off workshop and Final workshop)</i></p>			<p>- 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</p> <p>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</p>	
<p><u>Output 4 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of EE</p>	<p>4-1. Number of trained staffs Target Value: 10 personnel</p> <p>4-2. Textbooks/ manuals Target Value: 3 programs <i>(2 domestic trainings and 1 training in Japan)</i></p> <p>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</p> <p>4-4. Number of workshops Target Value: 2 times <i>(Kick-off workshop and Final workshop)</i></p>	Project Report		<p>4-1. In total, number of participants (accumulated total) was 62 personnel</p> <p>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.</p> <p>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</p> <p>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</p>	
<p><u>Output 5 (to be achieved in Phase 2)</u> The human and institution capacity are enhanced for the promotion of Power Network Resiliency</p>	<p>5-1. Number of trained staffs Target Value: 10 personnel</p> <p>5-2. Textbooks/ manuals Target Value: 2 programs <i>(1 domestic trainings and 1 training in Japan)</i></p> <p>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</p> <p>5-4. Number of workshops Target Value: 2 times <i>(Kick-off workshop and Final workshop)</i></p>	Project Report		<p>5-1. In total, number of participants (accumulated total) was 66 personnel</p> <p>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</p> <p>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</p> <p>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</p>	

<p>Activities Activities for achieving Output 1 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 (CO₂ 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</p>	Inputs		Important Assumption	<p>Most of the trained C/Ps continues commitment to the Project activities.</p> <p style="text-align: center;">Preconditions</p> <p>Contents of the current relevant policies on promotion of RE and EE are not largely changed.</p> <p>Issues and countermeasures</p>			
<p>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 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</p>	<p>(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 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)</p>	<p>(Saint Christopher and Nevis side) 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</p>	Preconditions				
<p>Activities for achieving Output 3 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</p>							
<p>Activities for achieving Output 4 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</p>							
<p>Activities for achieving Output 5 5-1. To demonstrate the way to enhance resiliency by use of power network asset management system.</p>							



Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Project Outline and Result of Activities



Photographs:
Wind Farm in Jamaica / EE Testing Laboratory in Jamaica
Solar PV System in St. Christopher 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: tsuji-tm@n-koei.jp)

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



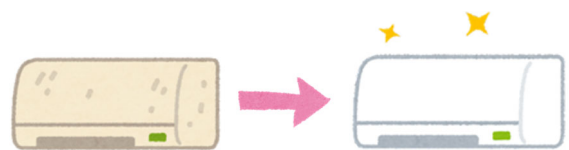
Energy Efficiency (EE)

[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.

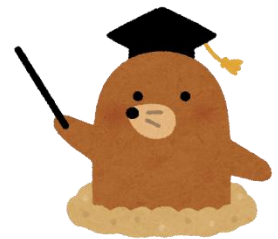
Tips for Saving Energy at Home



What is happening in the world?

- Carbon dioxide (CO₂), methane (CH₄), 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



CO₂ 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.



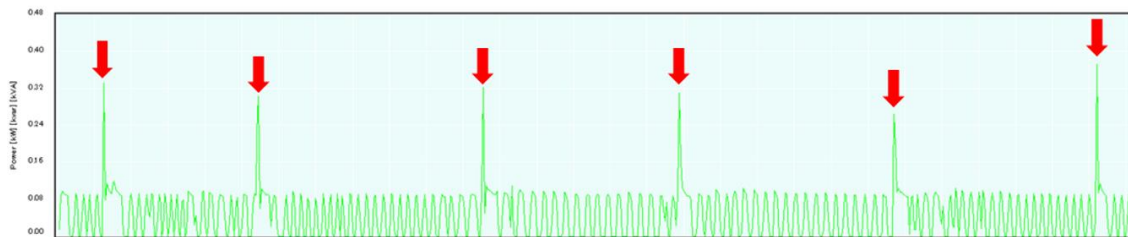
Let's stop overstuffing and don't keep the door open too long.



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.

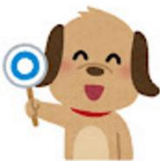
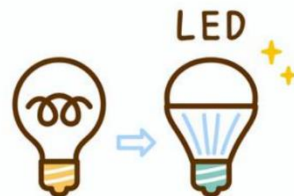


Tip 2: Good lighting Use



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





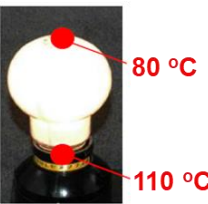
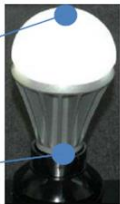
LED light bulbs vary by product in how it spreads the light, so choose a bulb that best suits the lighting fixture and the space.

		
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.

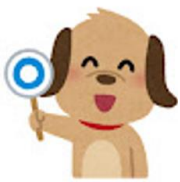
Incandescent Lamp (810 lm, 54W)	LED lamp (810 lm, 9W)
30 minutes after lighting	
 <p>80 °C (top)</p> <p>110 °C (bottom)</p>	 <p>26 °C (top)</p> <p>55 °C (bottom)</p>

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.



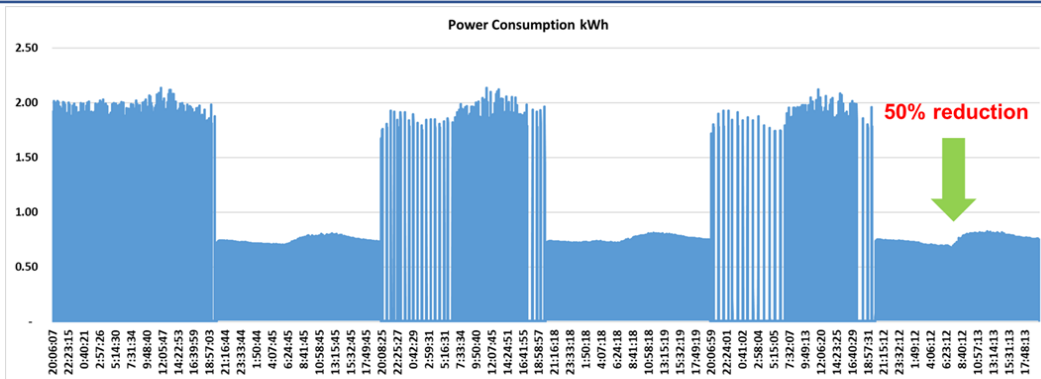
A fan will help circulate cool air.



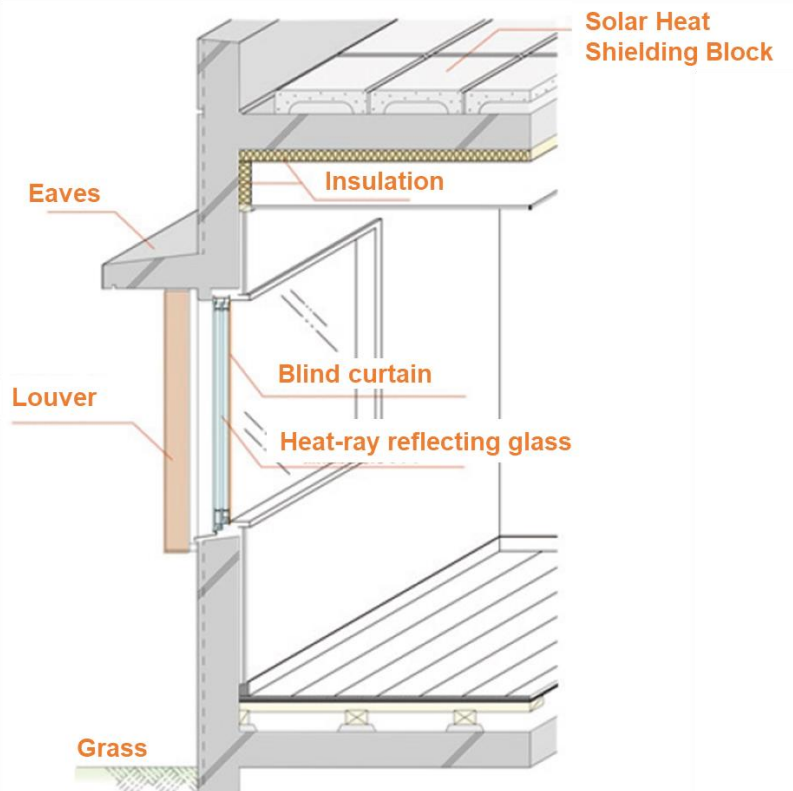
Raising the temperature setting of AC by 1°C saves about 10% energy.



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

1. About The MicroGrid Designer	3
2. Module Structure and Procedures of Use of <i>The MicroGrid Designer</i>	5
2.1. How to input and output	5
2.2. Procedures of executions of <i>The MicroGrid Designer</i>	5
2.3. Sequential use of modules of economic load dispatch and power flow analysis	5
3. Formulation and Solution of Economic Load Dispatch	7
3.1. Formulation and solution of Economic Load Disptach	7
3.2. The processing of the Economic Load Dispatch and Economic Dispatching Control	8
3.3. Formulation of the ELD as a constrained optimization problem with an objective function ..	9
3.4. Generator start up priority determination (maximum load point unit price)	11
3.5. Calculation of environmental emissions	12
3.6. Decision of EDC command by using load forecast ing	12
3.7. Economic Dispatching Control by the Equal Lambda method	14
3.8. Scheduled output and control mode used for EDC computations	17
3.9. Flow chart of Economic dispatching control considering output constraints of generator ...	20
3.10. Input and Output Data Forms and Application of ELD to 15-generator system	21
3.11. Interface of the Multi Stage Economic Load Dispatch for Data Input, Calculation and Result Output	28
4. Input and Output Form for Single and Multi Power Flow Analysis	30
4.1. Solution method of power flow analysis	30
4.2. Per-Unit System in power flow analysis	31
4.3. Network representation in power flow analysis	32
4.4. Input and output form of the power flow analysis module	33
4.5. Application of power flow analysis to A microgrid with Standard Structures	35
4.6. Evaluations of power loss in the grid operation	42
4.7. Interface of multi Stage Power Flow Analysis for Data Input, Calculation and Result Output 44	
5. Application of Power Flow Analysis to The IEEE 30 Node Power System	46
5.1. Single line diagram of the IEEE 30 node Power System	46
5.2. Obtained Results for Nodes by Single Stage Power Flow Analysis	49
5.3. Obtained Voltage profile and active and Reactive Power at nodes	50
5.4. Obtained Results for Branches by Single Stage Power Flow Analysis	51
5.5. Obtained Active /Reactive Power Flow on Branches by Power Flow Analysis	52

5.6.	Interface of Single Stage Power Flow Analysis for Data input, Calculation and Result output	54
5.7.	Extension of power flow analysis to long term power flow analysis	55
6.	Appendix-A Formulations and Solution of Power Flow Analysis.....	57
6.1.	Components of Power system.....	57
6.2.	Power flow equation	59
6.3.	Classification of Nodes into Three Types.....	62
6.4.	Load Flow Solution by Newton–Raphson Method	64
6.5.	Extension of the Newton Method to Simultaneous Nonlinear Equations	67
6.6.	Reference	73
7.	Appendix-B Terminologies for The <i>MicroGrid Designer</i>	74
7.1.	Power system network model	74
7.2.	Linear relation of power system network	75
7.3.	Known and Unknown Quantities in power flow analysis.....	76
7.4.	Active and reactive power flow equation	78
7.5.	Revised Newton-Raphson Method	78
7.6.	LU factorization, forward and back substitution	79
7.7.	Power System Operation and Control.....	79
7.8.	Economic Load Dispatch.....	81

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 regional 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 *the 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.

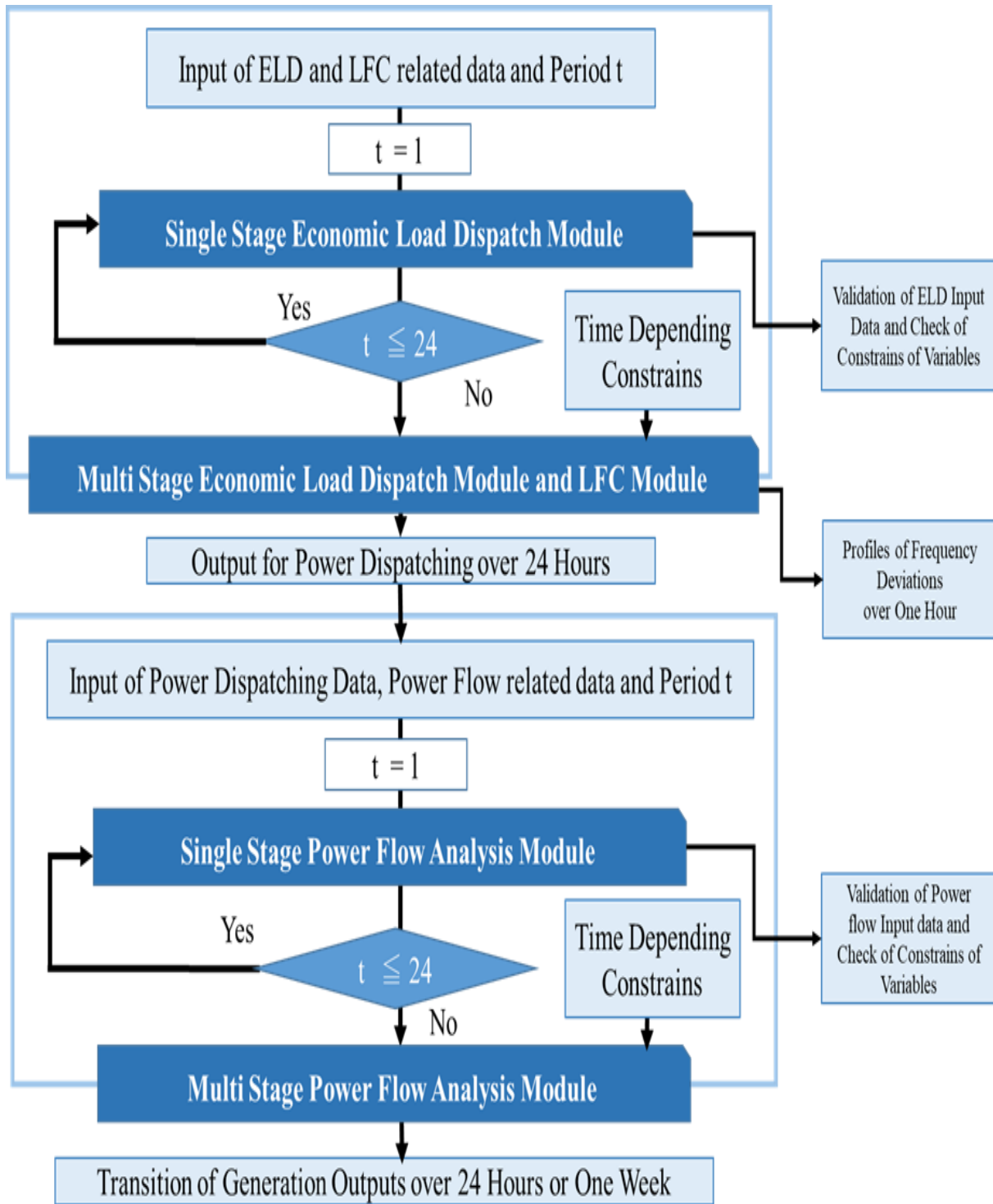


Figure 2.1 Sequential use of modules of economic load dispatch and load plow analysis

(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 DISPATCH

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.

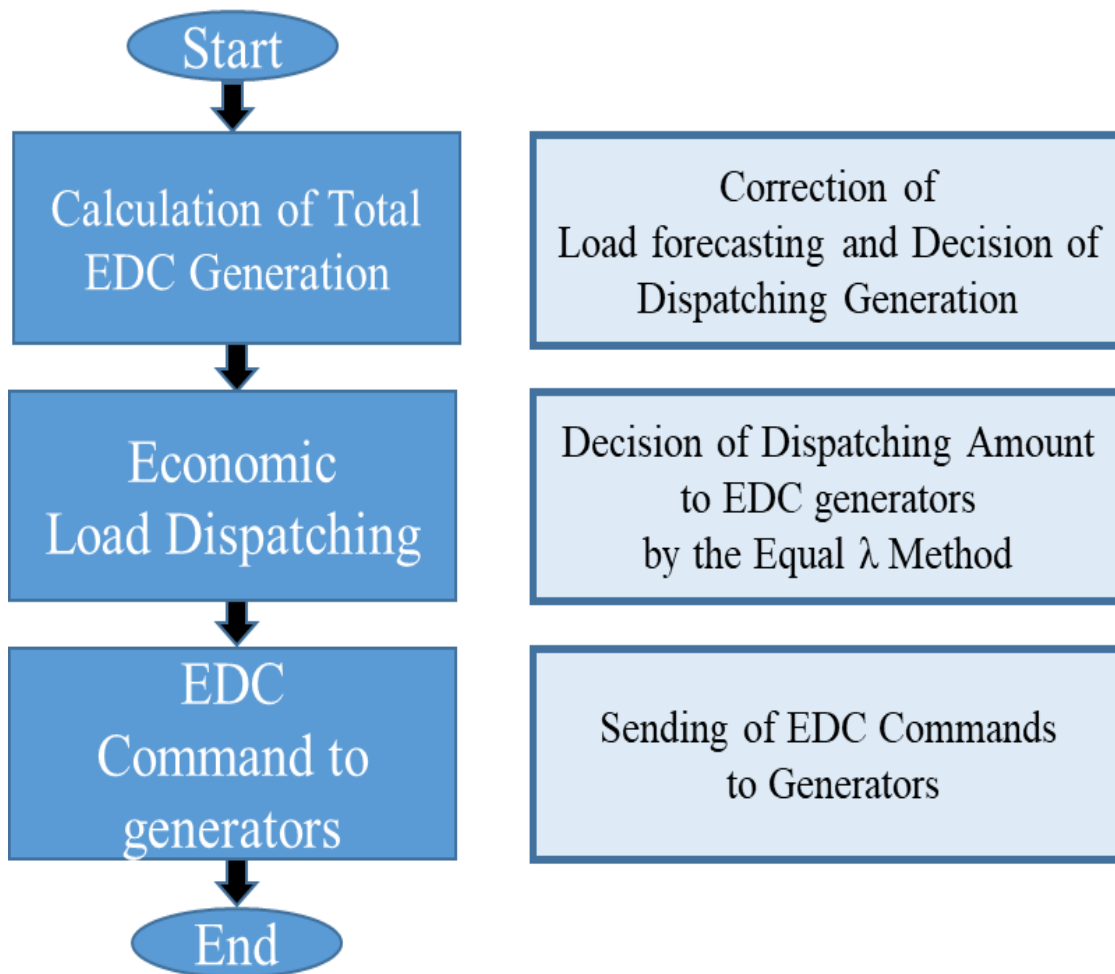


Figure 3.1 Processing of EDC computation module

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. $f(P_i)$ 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.

Generator maximum power generation unit price:

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 should 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 (kW)	Output upper limit (a) (kW)	Generator Turn/Off State (Tuen - 1, Off - 0)														
			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 CO₂ 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,

$$\text{CO}_2 \text{ emissions} = \text{fuel consumption (GJ)} \cdot \text{carbon coefficient (tC / GJ)} \quad (\text{tC})$$

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 FORECAST ING

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

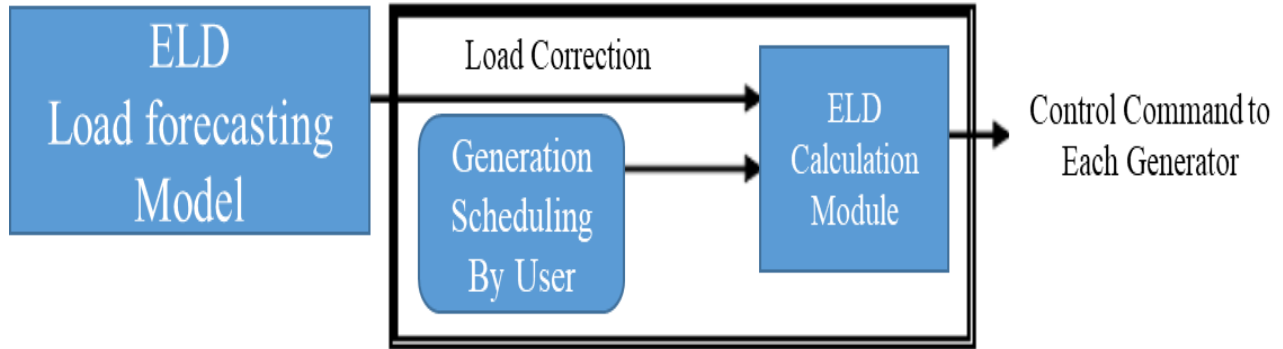


Figure 3.2 Block diagram of ELD standard model

This dispatching must be satisfied with the following load and generation balance equation.

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

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

Where

P_L : Generation for ELD

L_C : 5-minutes ahead forecasted load

P_S : Sum of generation for scheduled operation

P_C : Sum of generation for base loads

P_0 : 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)

$f_i(P_i)$: Fuel consumption function for i-th generator

P_i : Output of i-th generator

n : Number of generators

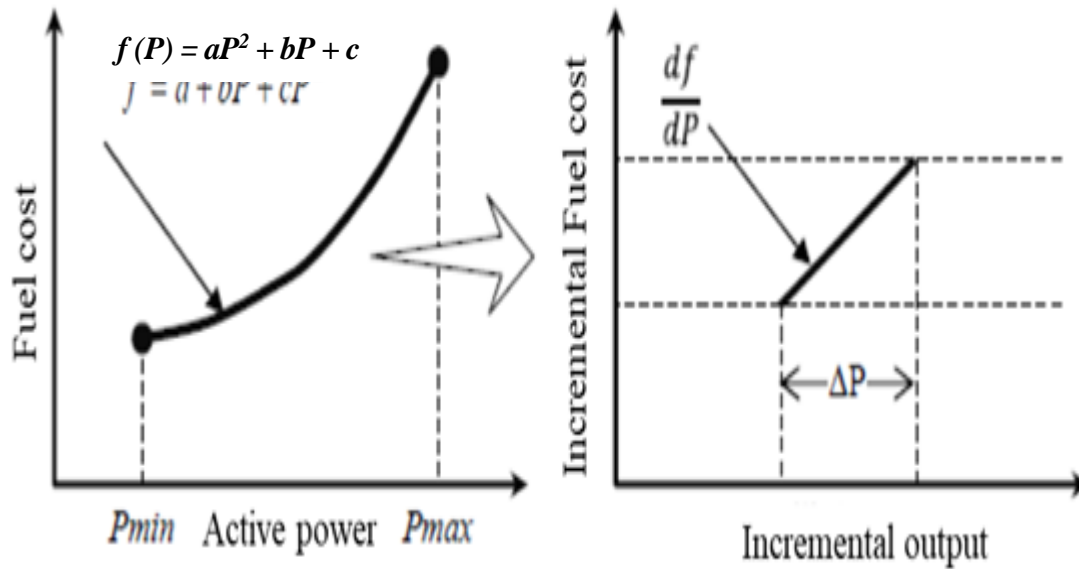


Figure 3.3 Fuel consumption function and incremental output

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 $\lambda_1 = 2.5$, generator outputs, $P_{1\lambda_1}$ and $P_{2\lambda_1}$ are decided as in the figure and when loads increased and $\lambda_2 = 2.6$, generator outputs, $P_{1\lambda_2}$ and $P_{2\lambda_2}$ are also decided in the same way.

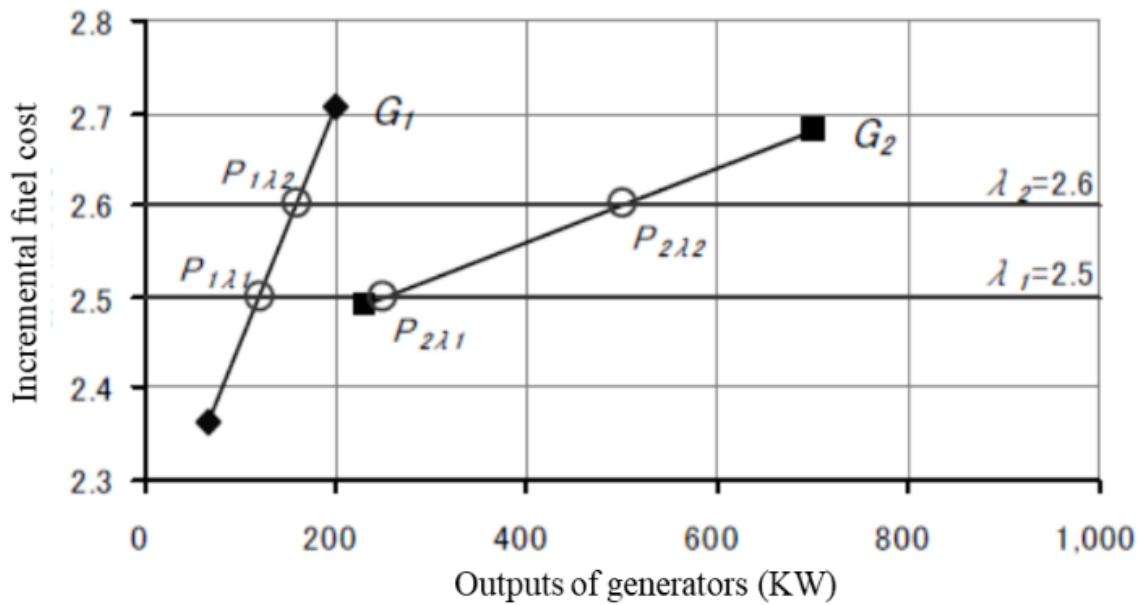


Figure 3.4 Relation of output of generators and Lagrange Multiplier

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} (Table 3.3), 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 <ul style="list-style-type: none"> • Upper limit of scheduled generation output • Current EDC command + output change speed \times 5 minutes
Lower limits of generator outputs	Select the larger value from <ul style="list-style-type: none"> • Lower limit of scheduled generation output • Current EDC command + output change speed \times 5 minutes

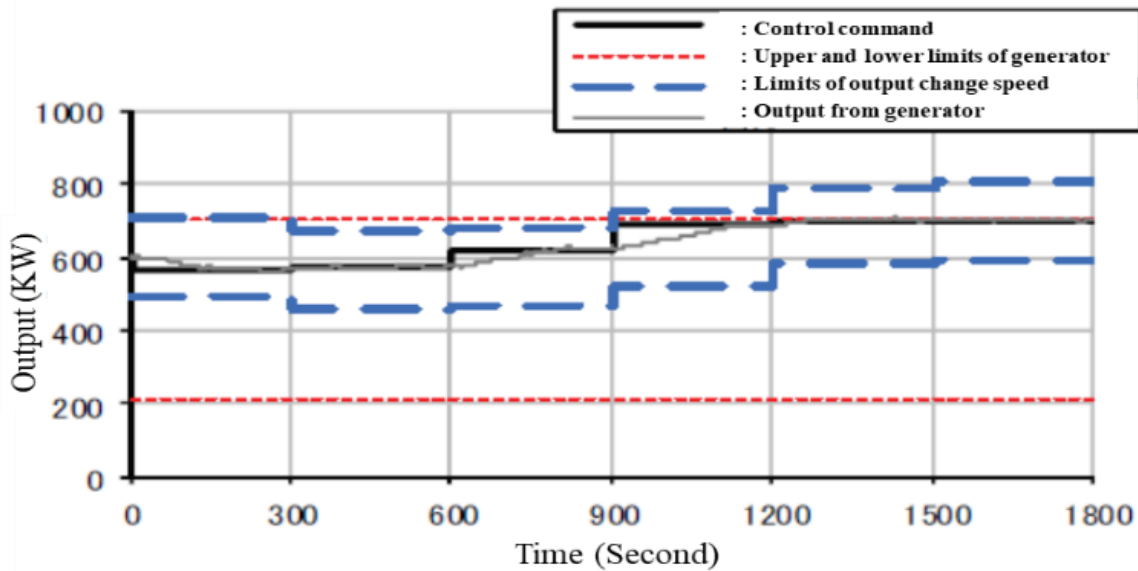


Figure 3.5 Output constraints of generators

3.9. FLOW CHART OF ECONOMIC DISPATCHING CONTROL CONSIDERING OUTPUT CONSTRAINTS OF GENERATOR

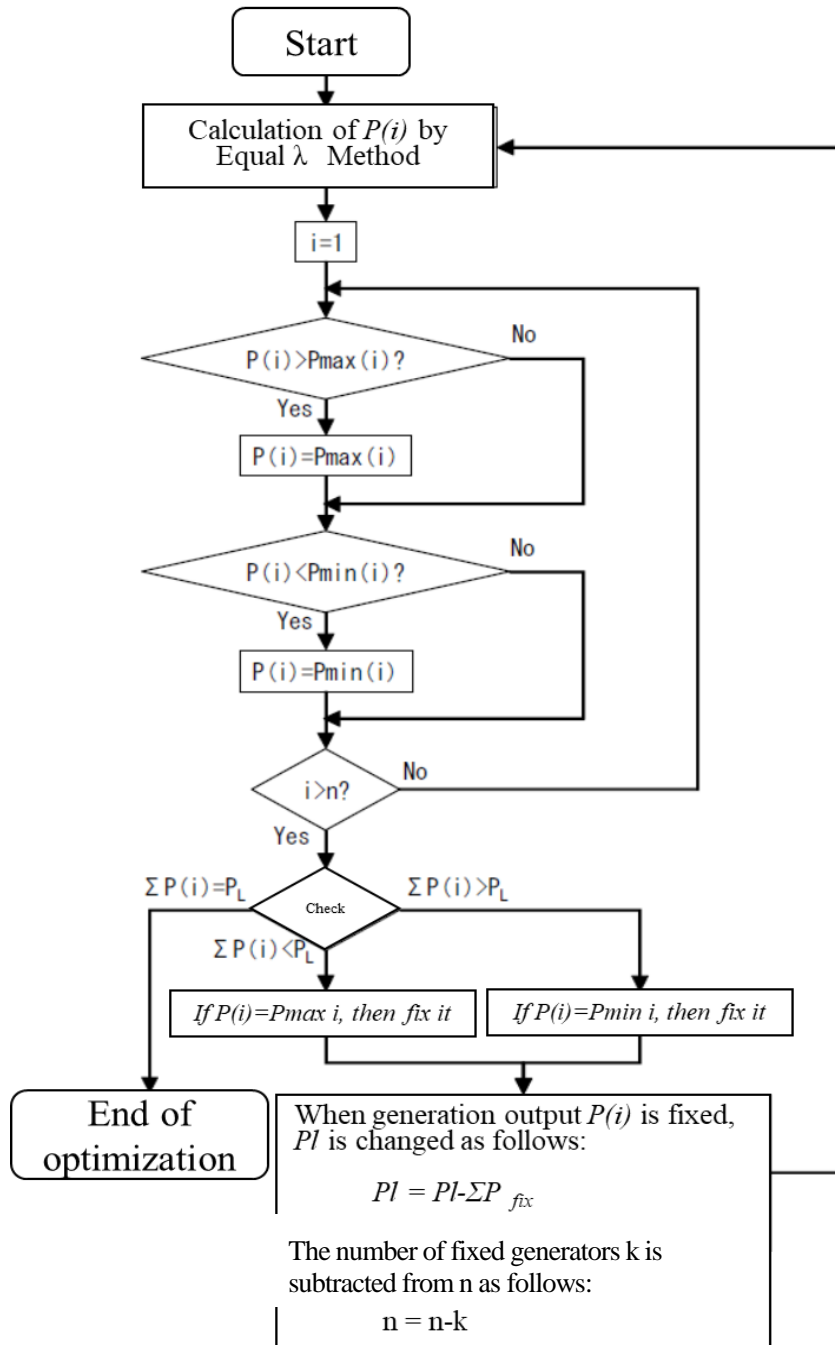


Figure 3.6 Economic dispatching control considering output constraints of generator

Reference

- 1) Standard analysis models for Economic Dispatching Control and Load Frequency Control,
The Institute of Electrical Engineers of Japan, IEEJ Technical Report 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 Single 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 Single 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: CO₂ 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.

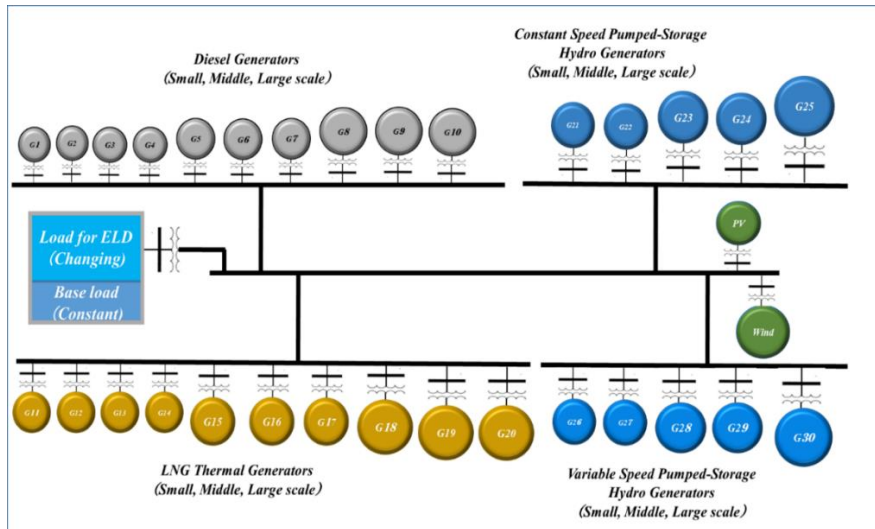


Figure 3.7 Structure and components of ELD test system

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 depicted 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 depicted by using Excel functions as shown in Figure3.9.

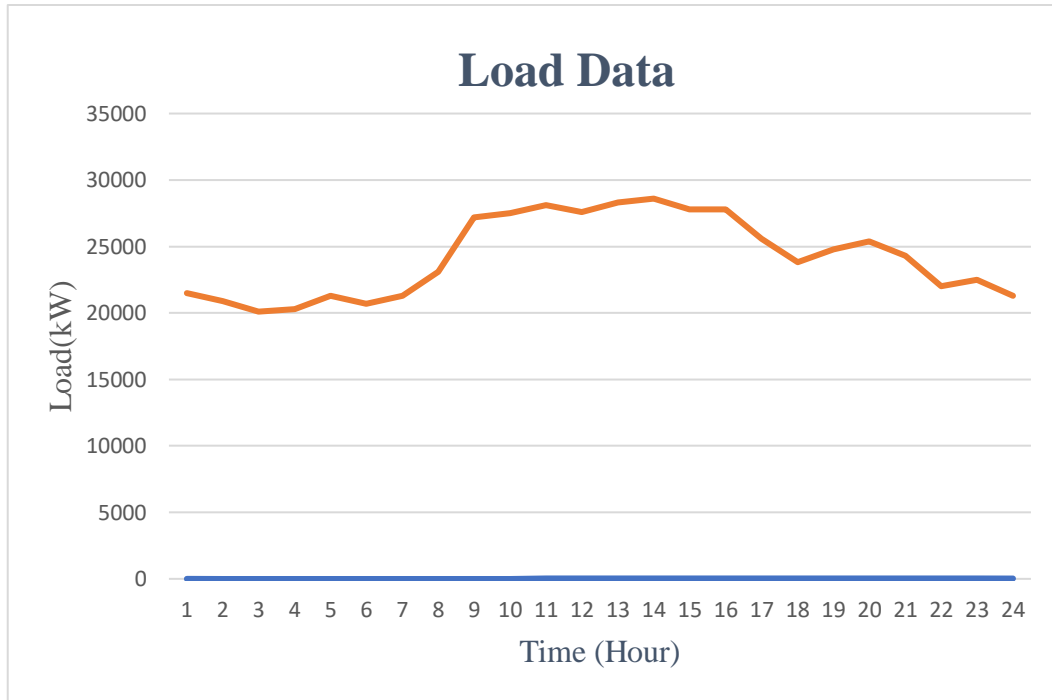


Figure 3.8 Change of demand over 24 hours (Example)

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

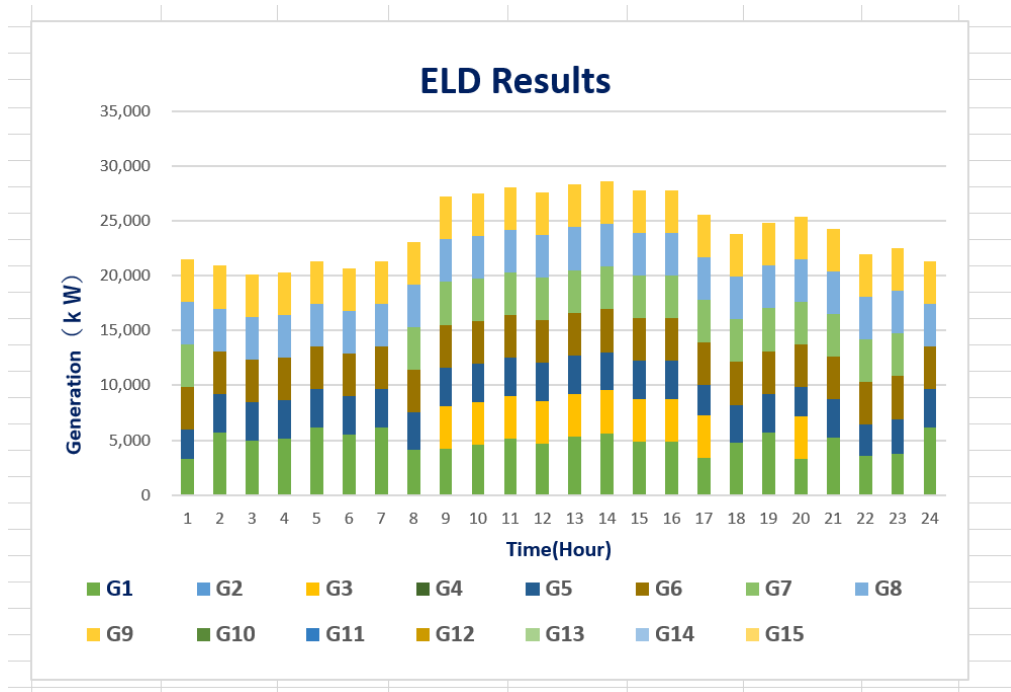


Figure 3.9 Outputs of 30 generators decided by the economic load dispatching

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 Figurer3.10 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.

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:

- V_{base} : The base voltage quantity
- S_{base} : 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.

V_{base} : 1~132 kV

S_{base} : 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 MVA_r 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 [MVA_r] 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.

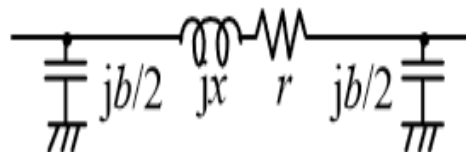


Figure 4.1 π -shaped equivalent circuit

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

V_{base} [kV] and S_{base} [MVA] 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 angle θ (generally is specified around 0.0 degree)
- Node admittance $Y/2$
- Generator active power for scheduled operation P_g
- Generator reactive power for scheduled operation Q_g
- Active power required by load P_l
- Reactive power required by load Q_l

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.

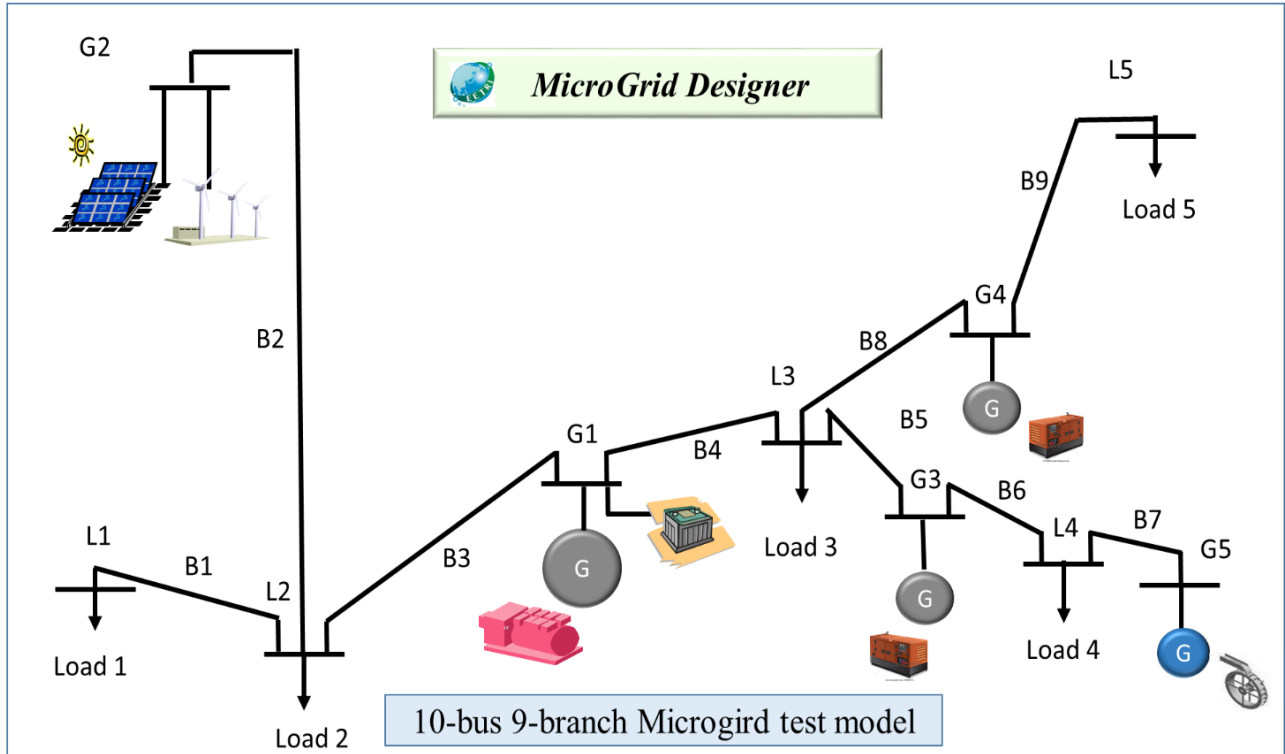


Figure 4.2 Micro Grid with standard structure and components.

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 P_g (p.u.)
- Column 8 Generator reactive power for scheduled operation Q_g (p.u.)
- Column 9 Active power required by load P_l (p.u.)
- Column 10 Reactive power required by load Q_l (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									
Comment	Node ID	Type	Specify V	Specified θ	Node admittance	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 branche 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

Generator 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	
Stage	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

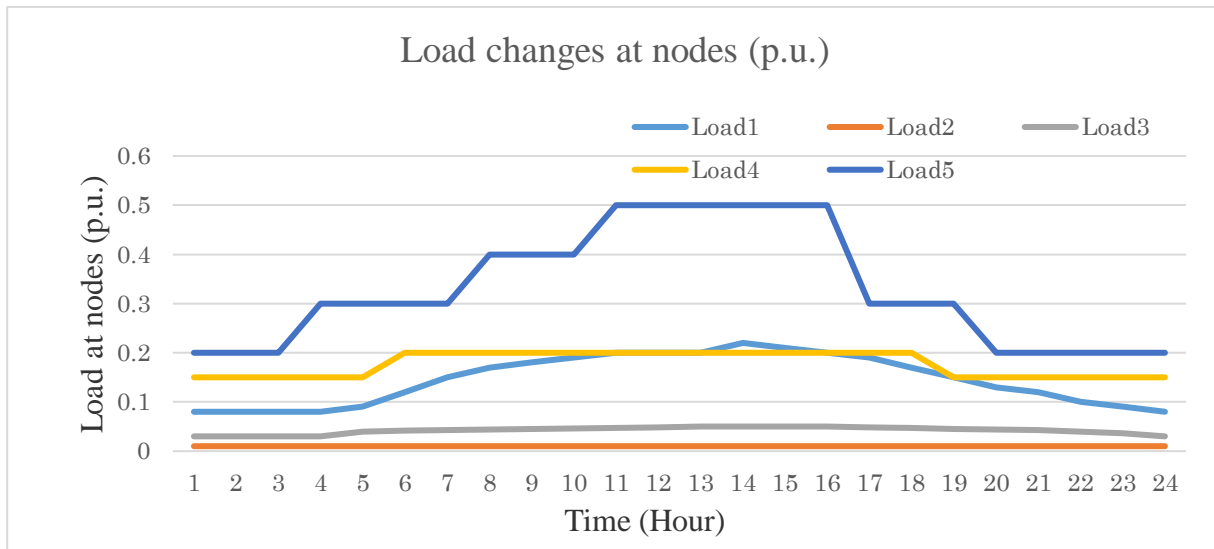


Figure 4.3 Load changes at nodes over 24 hours

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

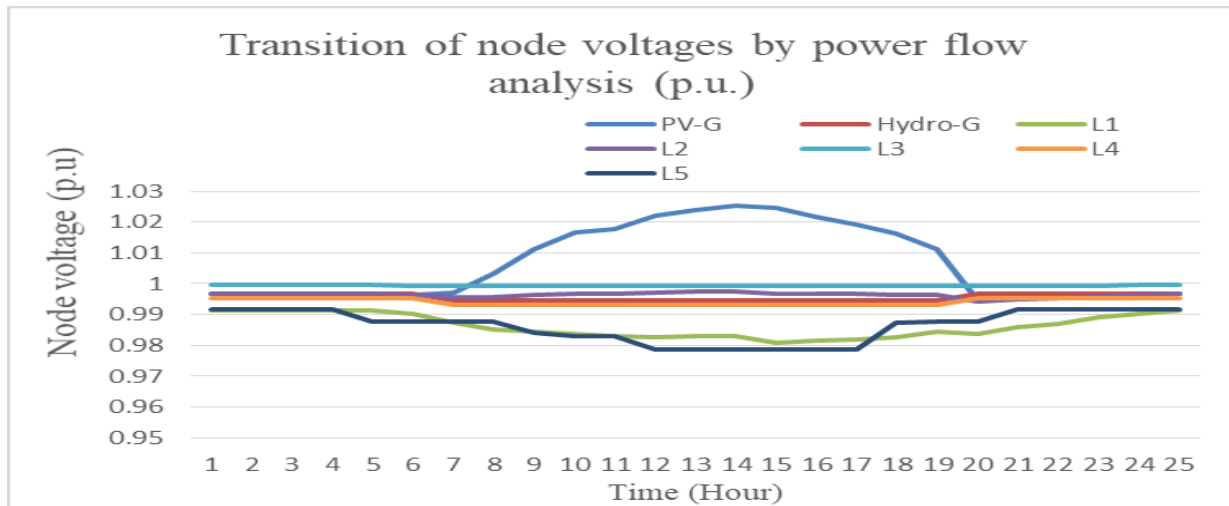


Figure 4.4 Transition of voltage at nodes over 24 hours by the multi stage power flow analysis

Table 4.7 Transition of output of generators over 24 hours by the multi stage power flow analysis

Node pow Stage	G1		PV1		G3		G4		WP1	
	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

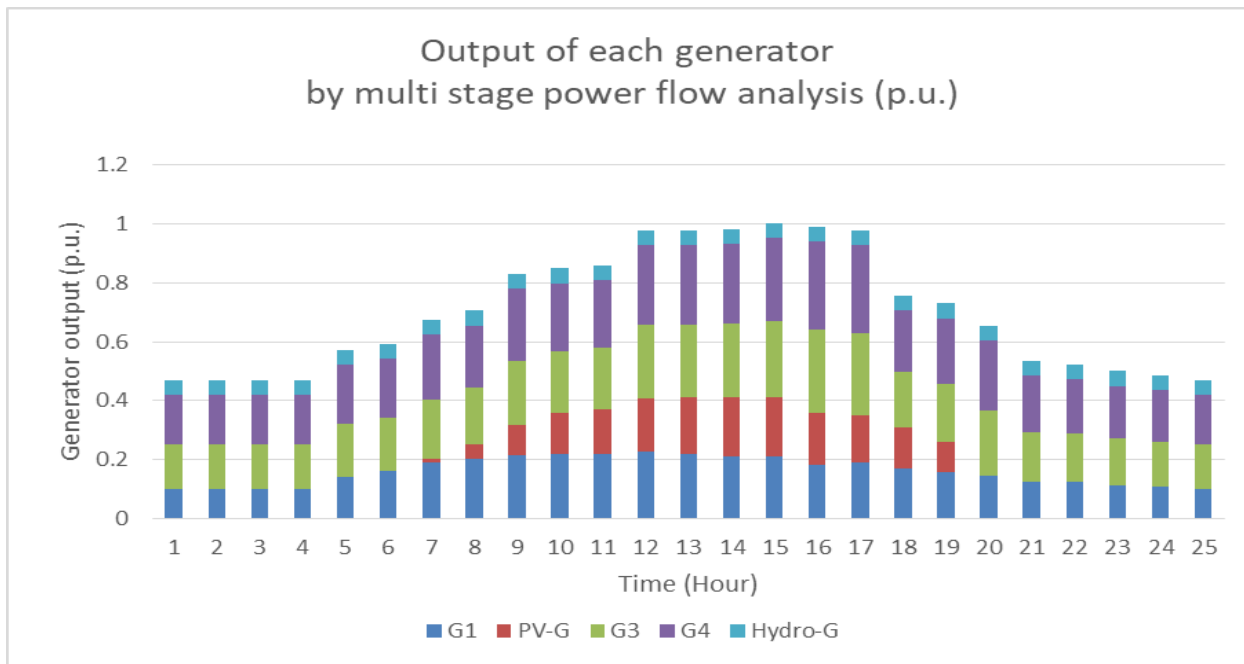


Figure 4.5 Transition of generator outputs over 24 hours by the multi stage power flow analysis

Table 4.8 Transition of branch power flows over 24 hours by the multi stage power flow analysis

Lone flow Stage	1		2		3		4		5		6		7		8		9	
	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

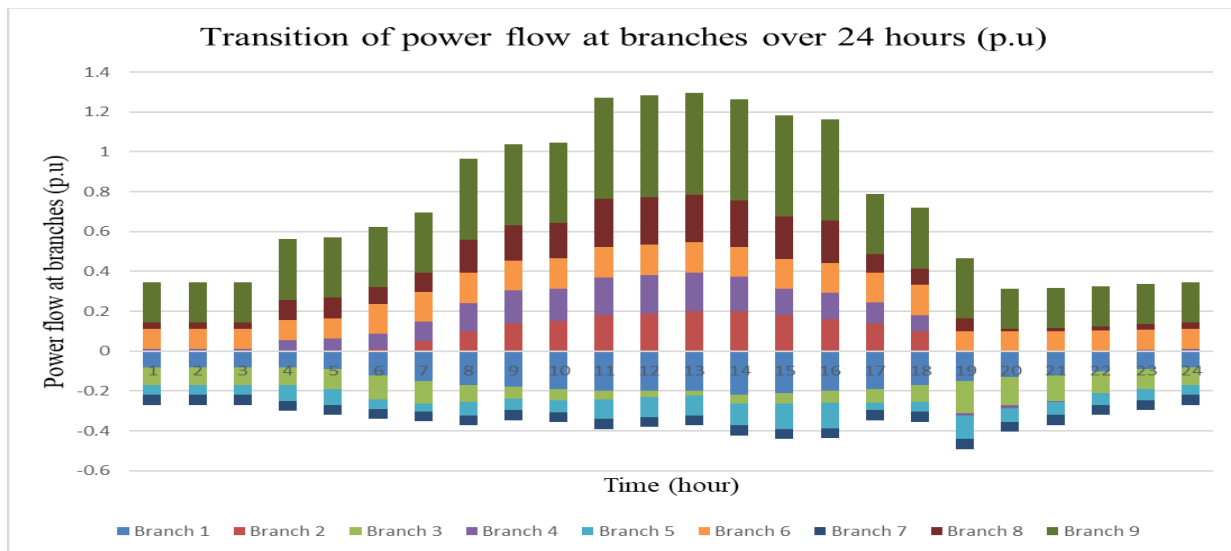


Figure 4.6 Transition of power flow at branches over 24 hours by the multi stage power flow analysis

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 angle 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.

Title: **10 nodes microgrid, Case-1** Cell(B1) is used as a title of graphs

Multi stage power flow

Step

- 1) Set data in Sheets: Node_set, Branch_set, Gen24H, PV24H, WP24H, BA24H, SC · SH24H, and Load24H
Node and branch stays the same during all stages.
Elements in Gen, PV, WP, BA, SC · SH, and Load are in order of appearance in Node_set.
- 2) Return in this Start sheet.
- 3) Click "Calculation start".
- 4) Click "Jump to PLOT-sheet", and get graphs after element selecton

Stages Stage 1 to Stage 24 are caulcuated

Specification

Maximum iteration	20
Convergence criterion (pu)	0.0001

Explanation

- 1) Newton-Raphson method is applied as the solver.
- 2) Convergence criterion is applied to the amplitude of node voltage.
- 3) Line admittance is Y/2 in branch data, not Y.
- 4) "PWF_eetri1.exe" is called in this program






Figure 4.7 Interface of the Multistage Power Flow Analysis for data input, calculation and results output

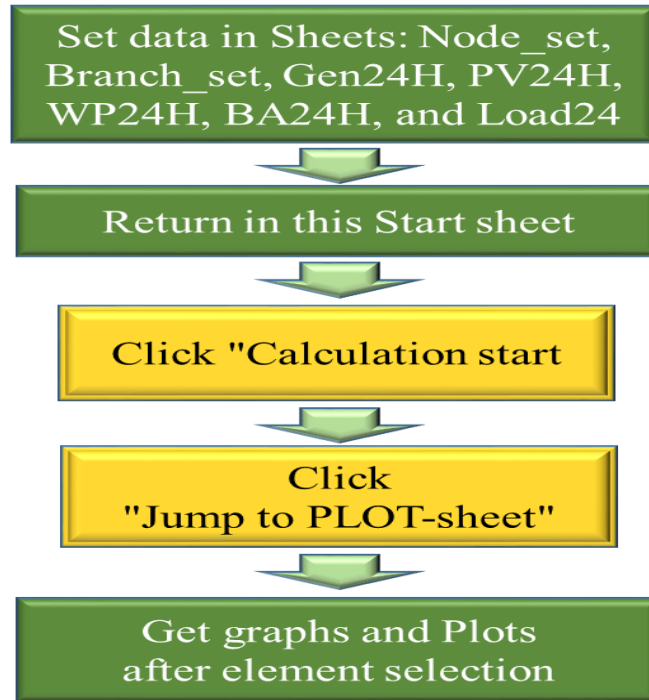


Figure 4.8 Procedure of calculations by utilizing the interface of the Multi Stage Power Flow Analysis

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

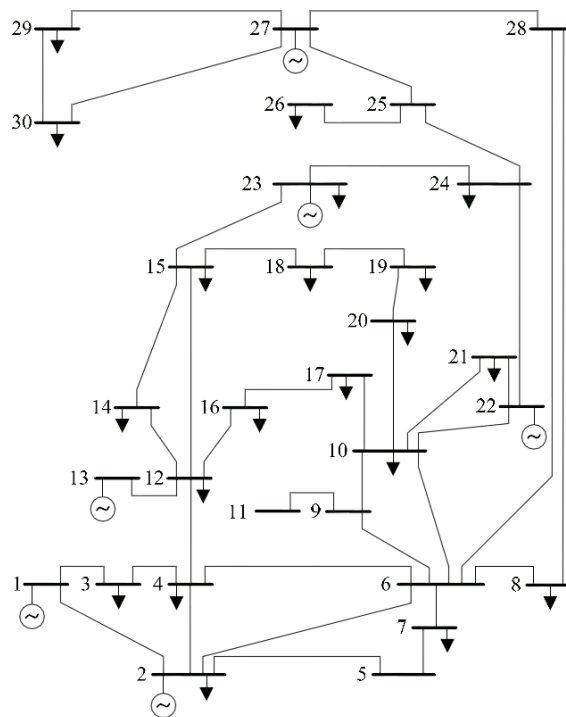


Figure 5.1 Single line diagram of the IEEE 30 node Power System (Example)

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

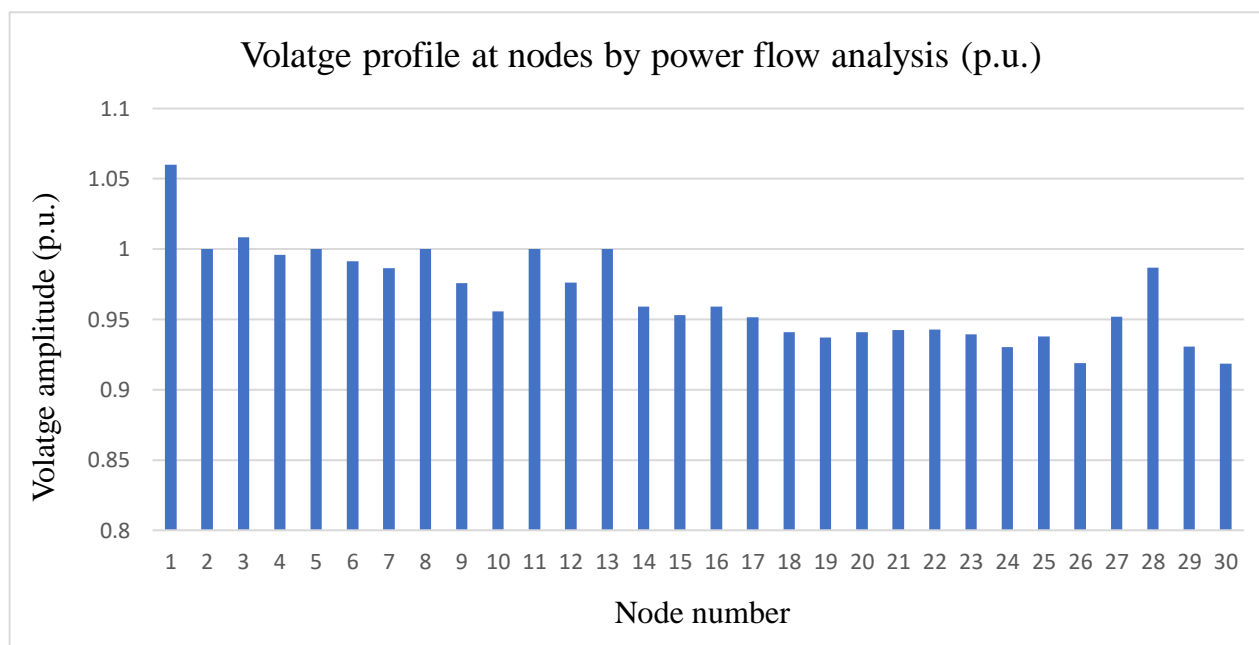


Figure 5.2 Voltage profile at nodes obtained by power flow analysis

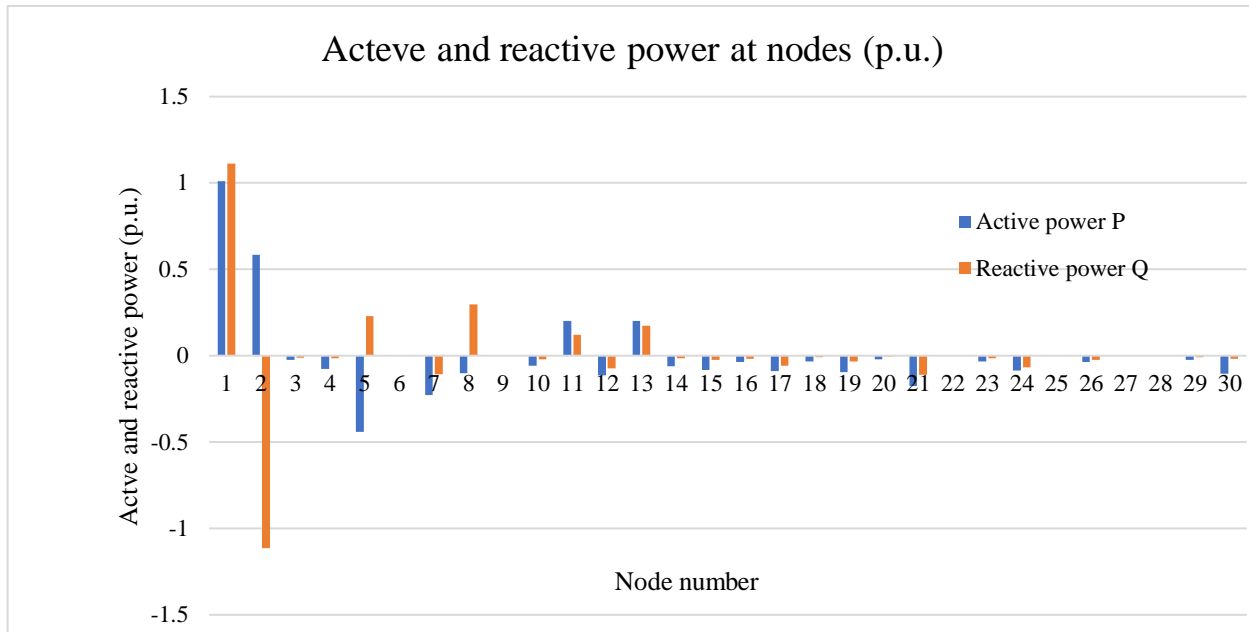


Figure 5.3 Active and reactive power at nodes obtained by power flow analysis

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.

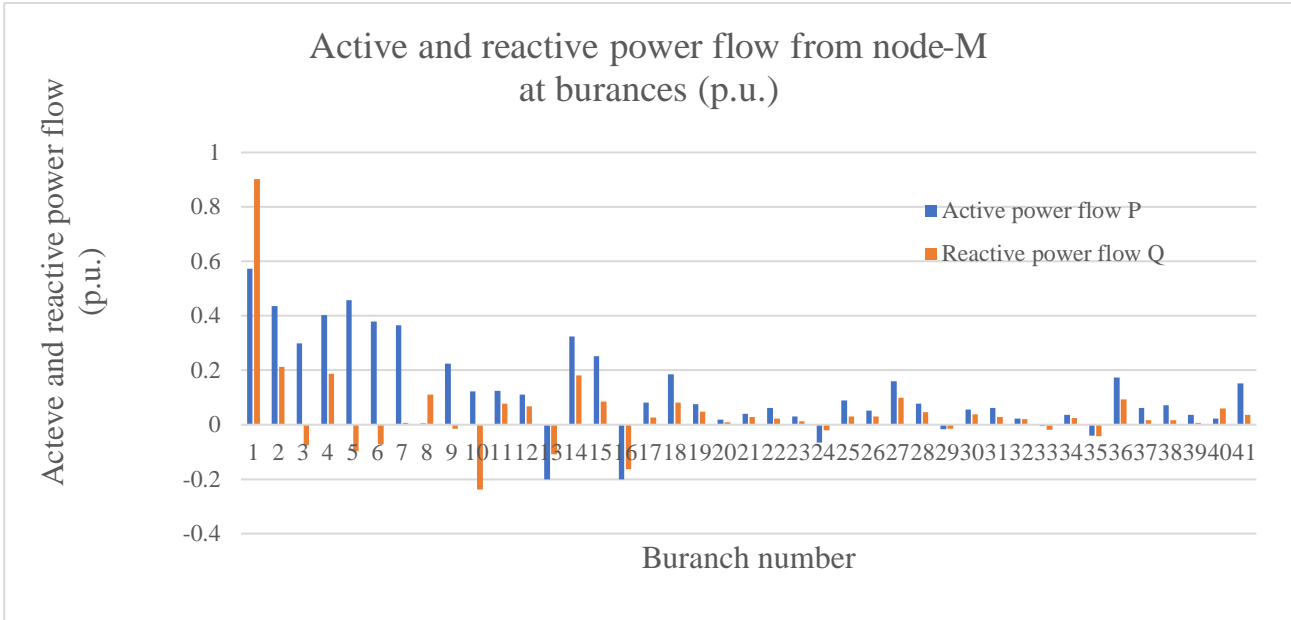


Figure 5.4 Active and reactive power flow at branches obtained by power flow analysis

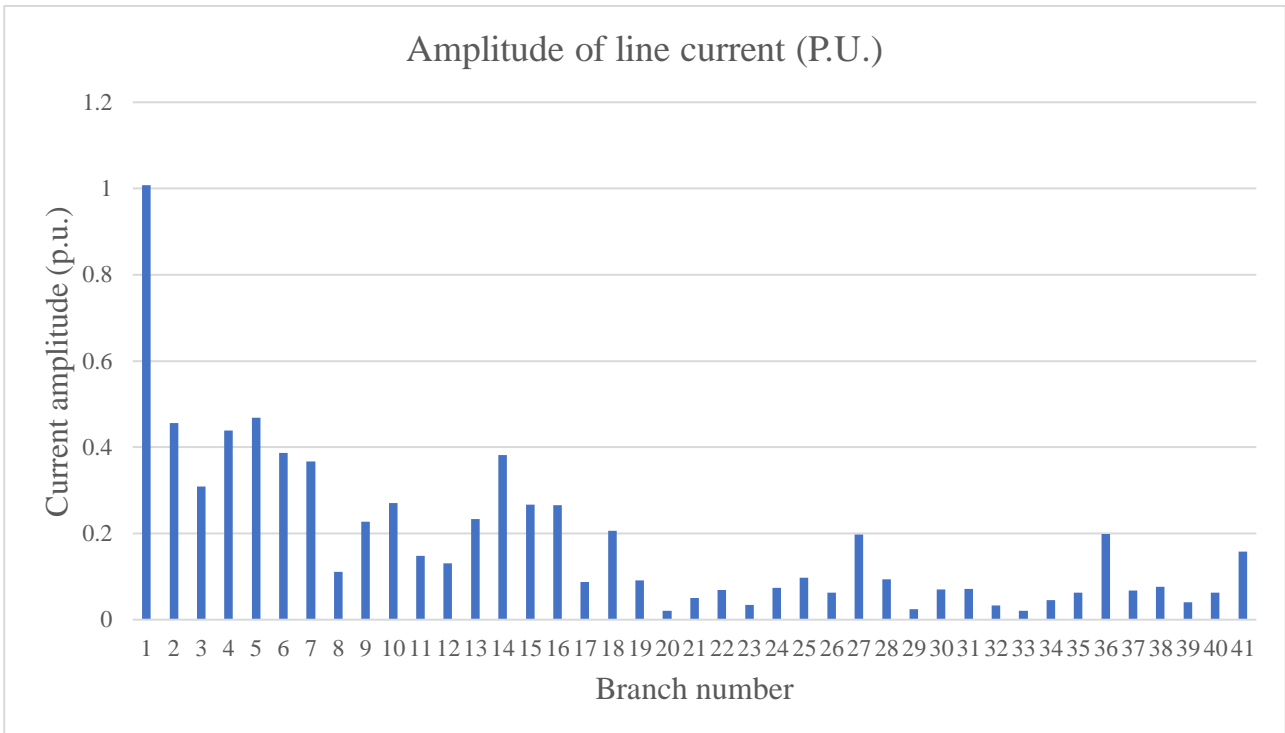


Figure 5.5 Amplitude of line current obtained by power flow analysis

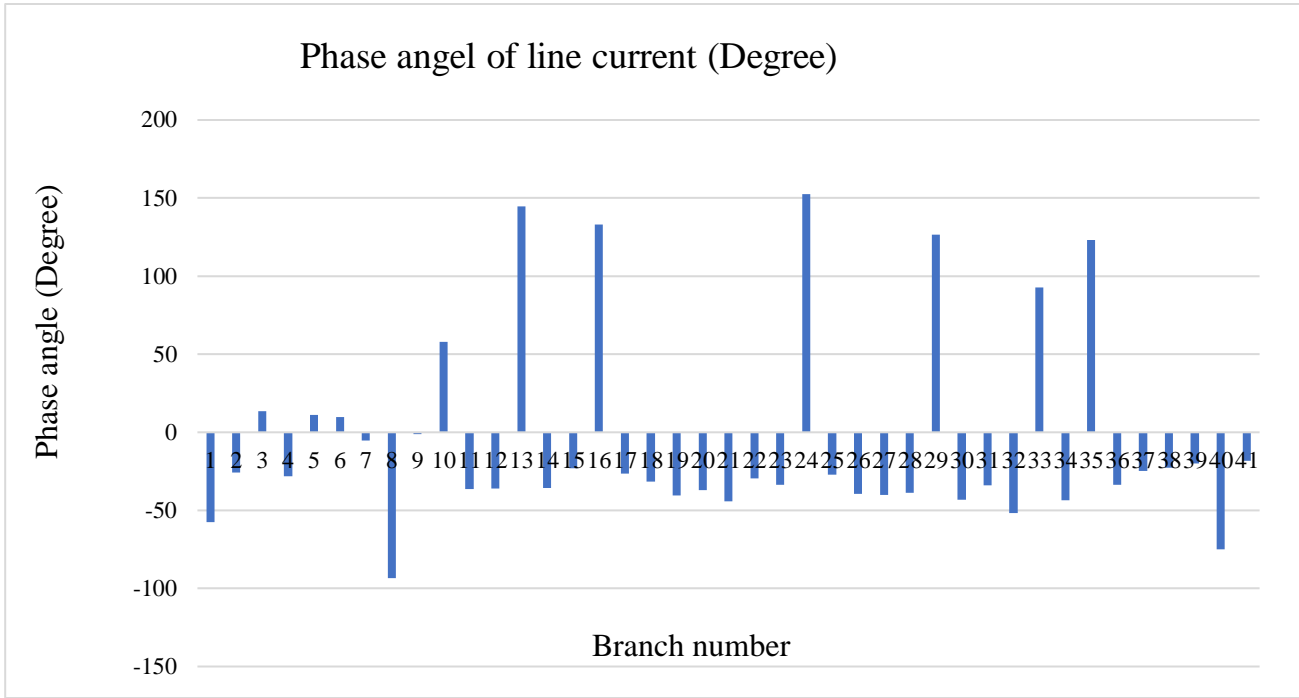


Figure 5.6 Phase angel of line current at branches obtained by power flow analysis

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.

Power Flow Calculation

Step

- Set node data and branch data
- Click "Calculation" button
- Node max 800, Branch max 850

Specification

Maximum iteration	20
Convergence criterion (pu)	0.0001

Explanation

- 1) Capacity base is not shown here, it is assumed by user.
- 2) Newton-Raphson method is applied as the solver.
- 3) Convergence criterion is applied to the amplitude of node voltage.
- 4) Line admittance is Y/2 in branch data, not Y.

Jump to NodeData input

Jump to BranchData input

Calculation

Figure 5.7 Interface of the single stage power flow analysis for data input, calculation and results output

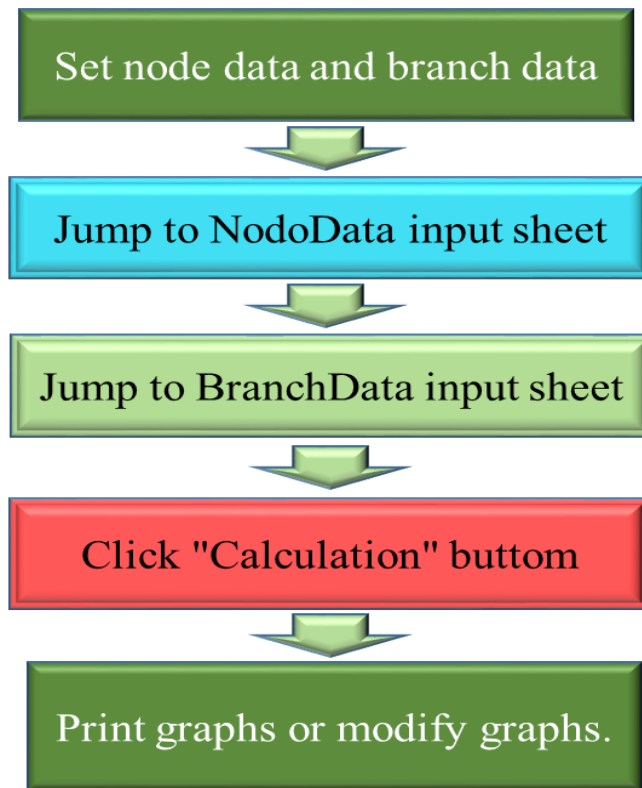


Figure 5.8 Procedure of Calculations by utilizing the interface of Power Flow Analysis

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 repetitively with multi stage 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.

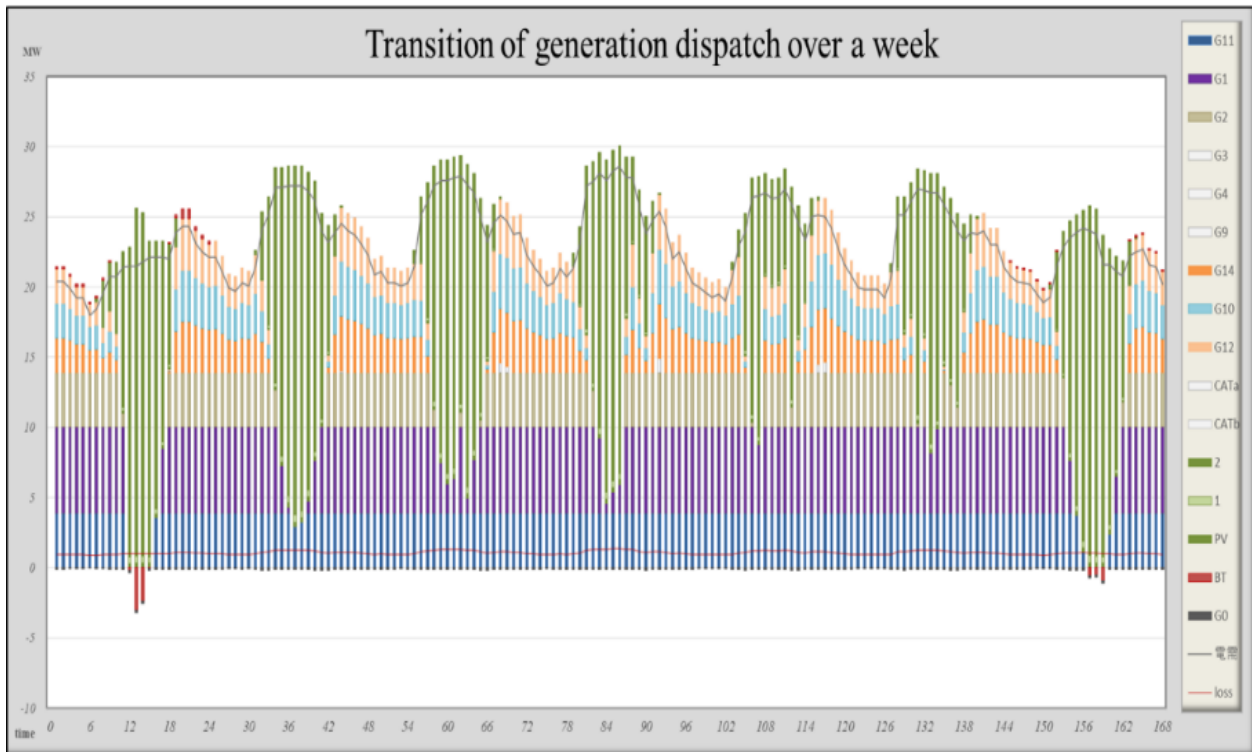


Figure 5.9 Image of transition of Generation dispatch by the extended power flow analysis

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.

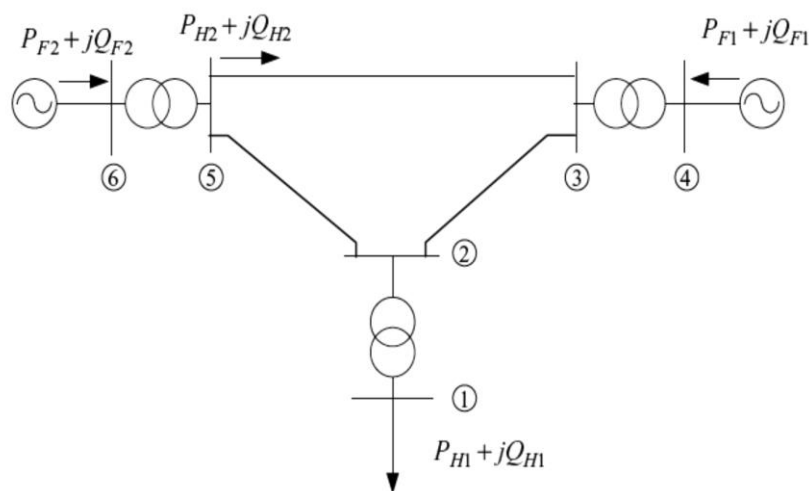


Figure 6.1 Components of Power system

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 $n \times n$ 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.

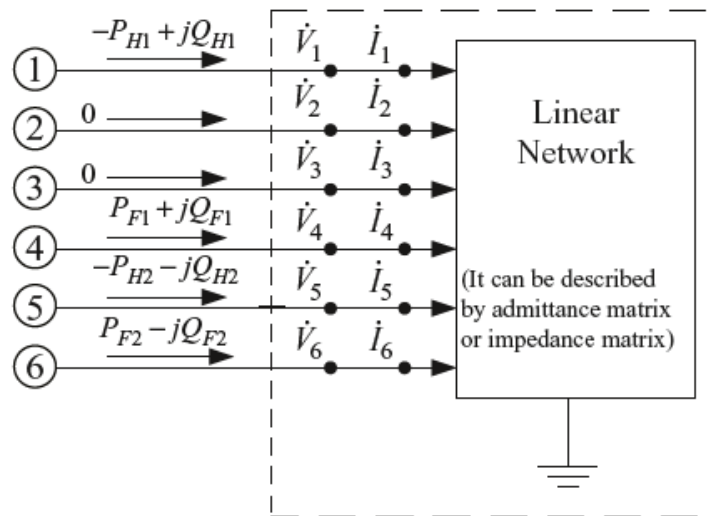


Figure 6.2 linear network of power system

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

$$\bar{I}_i = \sum_{j=1}^n Y_{ij} \bar{V}_j \quad (i = 1, 2, \dots, n)$$

where \bar{I}_i and \bar{V}_j are the injected current at node i and voltage at node j , respectively, Y_{ij} 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

$$\bar{I}_i = \frac{P_i - jQ_i}{\hat{V}_i} \quad (i = 1, 2, \dots, n)$$

where P_i , Q_i are the injected active and reactive power at node i , respectively.

If node i is a load node, then P_i and Q_i should take negative values.

In the above equation, \hat{V}_i is the conjugate of the voltage vector at node i . Substituting this relation, we have,

$$\frac{P_i - jQ_i}{\hat{V}_i} = \sum_{j=1}^n Y_{ij} \bar{V}_j \quad (i = 1, 2, \dots, n)$$

Or

$$\frac{P_i + jQ_i}{\dot{V}_i} = \sum_{j=1}^n \hat{Y}_{ij} \hat{V}_j \quad (i = 1, 2, \dots, n)$$

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 $4n$. 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;

$$P_i + jQ_i = \dot{V}_i \sum_{j \in i} \hat{Y}_{ij} \hat{V}_j \quad (i = 1, 2, \dots, n)$$

Where $j \in i$ 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 V_i , θ_i 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

$$P_i + jQ_i = V_i e^{j\theta_i} \sum_{j \in i} (G_{ij} - jB_{ij}) V_j e^{-j\theta_j} \quad (i = 1, 2, \dots, n)$$

Combining the exponential items of above equation and using the exponential relationship

$$P_i + jQ_i = V_i \sum_{j \in i} V_j (G_{ij} - jB_{ij}) (\cos \theta_{ij} + j \sin \theta_{ij}) \quad (i = 1, 2, \dots, n)$$

Where $\theta_{ij} = \theta_i - \theta_j$ is the voltage phase angle difference between node i and j .

Dividing above equations into real and imaginary parts,

$$\left. \begin{aligned} P_i &= V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ Q_i &= V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \end{aligned} \right\} \quad (i = 1, 2, \dots, n)$$

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,

$$\dot{V}_i = e_i + jf_i \quad e_i = V_i \cos \theta_i \quad f_i = V_i \sin \theta_i$$

We can obtain the following from;

$$\left. \begin{aligned} P_i &= e_i \sum_{j \in i} (G_{ij}e_j - B_{ij}f_j) + f_i \sum_{j \in i} (G_{ij}f_j + B_{ij}e_j) \\ Q_i &= f_i \sum_{j \in i} (G_{ij}e_j - B_{ij}f_j) - e_i \sum_{j \in i} (G_{ij}f_j + B_{ij}e_j) \end{aligned} \right\} (i = 1, 2, \dots, n)$$

Let

$$\left. \begin{aligned} \sum_{j \in i} (G_{ij}e_j - B_{ij}f_j) &= a_i \\ \sum_{j \in i} (G_{ij}f_j + B_{ij}e_j) &= b_i \end{aligned} \right\}$$

$$\left. \begin{aligned} P_i &= e_i a_i + f_i b_i \\ Q_i &= f_i a_i - e_i b_i \end{aligned} \right\} (i = 1, 2, \dots, n)$$

Obviously, a_i and b_i 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.

$$\left. \begin{aligned} \Delta P_i &= P_{is} - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \\ \Delta Q_i &= Q_{is} - V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \end{aligned} \right\} (i = 1, 2, \dots, n)$$

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 $4n$.

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 ($V; \delta$) 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 γ 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 γ 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 P_i , Q_i ($i=1; 2; \dots; n$), find voltage vector V_i , δ_i or e_i , f_i ($i=1; 2; \dots; n$), such that the Amplitudes of the power errors ΔP_i , ΔQ_i ,

($i=1; 2; \dots; n$) in equations are less than 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 $\Delta x(0)$ is a modification value of $x(0)$ and the following equation holds.

When $\Delta x(0)$ is known, the solution x can be calculated by expanding this function in a Taylor series expansion about point $x(0)$ yields:

$$f(x^{(0)} - \Delta x^{(0)}) = f(x^{(0)}) - f'(x^{(0)})\Delta x^{(0)} + f''(x^{(0)})\frac{(\Delta x^{(0)})^2}{2!} - \dots + (-1)^n f^{(n)}(x^{(0)})\frac{(\Delta x^{(0)})^n}{n!} + \dots = 0$$

Then, $f'(x(0)), \dots, f^{(n)}(x(0))$ 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 $\Delta x(0)$ and can be easily solved and using $\Delta x(0)$ 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 $\Delta x^{(t)}$ is 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.

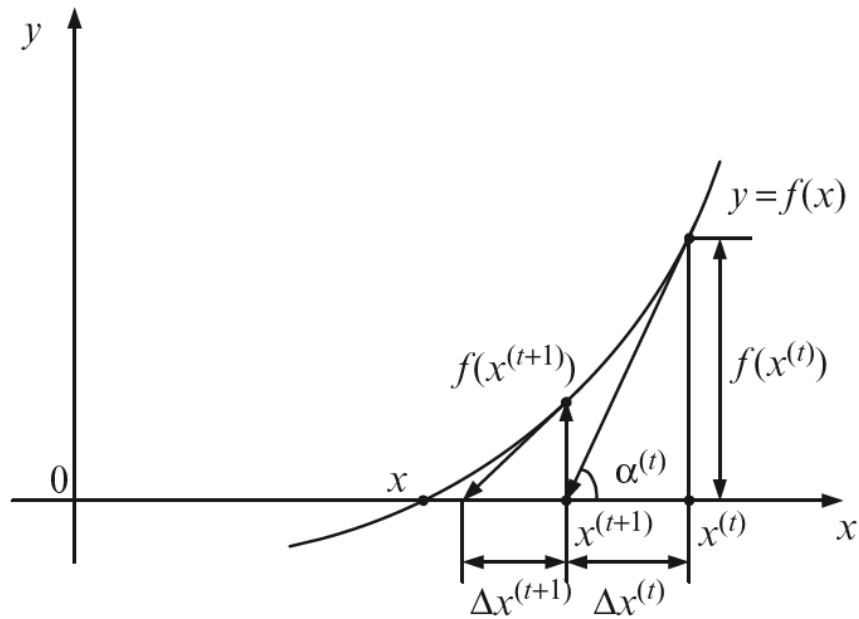


Figure 6.3 Iterative Solution by the Newton–Raphson Method

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 x_1, x_2, \dots, x_n as shown the equation left. Specify the initial guess values of all variables $x_n(1)$ 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.

$$\left. \begin{array}{l} x_1^{(1)} = x_1^{(0)} - \Delta x_1^{(0)} \\ x_2^{(1)} = x_2^{(0)} - \Delta x_2^{(0)} \\ \vdots \quad \quad \quad \vdots \\ x_n^{(1)} = x_n^{(0)} - \Delta x_n^{(0)} \end{array} \right\}$$

$$\left. \begin{array}{l} f_1(x_1^{(0)} - \Delta x_1^{(0)}, x_2^{(0)} - \Delta x_2^{(0)}, \dots, x_n^{(0)} - \Delta x_n^{(0)}) = 0 \\ f_2(x_1^{(0)} - \Delta x_1^{(0)}, x_2^{(0)} - \Delta x_2^{(0)}, \dots, x_n^{(0)} - \Delta x_n^{(0)}) = 0 \\ \vdots \\ f_n(x_1^{(0)} - \Delta x_1^{(0)}, x_2^{(0)} - \Delta x_2^{(0)}, \dots, x_n^{(0)} - \Delta x_n^{(0)}) = 0 \end{array} \right\}$$

Expanding the above n equations via the multivariate Taylor series and neglecting the higher order terms, we have the following equations

$$\left. \begin{array}{l} f_1(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}) - \left[\frac{\partial f_1}{\partial x_1} \Big|_0 \Delta x_1^{(0)} + \frac{\partial f_1}{\partial x_2} \Big|_0 \Delta x_2^{(0)} + \dots + \frac{\partial f_1}{\partial x_n} \Big|_0 \Delta x_n^{(0)} \right] = 0 \\ f_2(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}) - \left[\frac{\partial f_2}{\partial x_1} \Big|_0 \Delta x_1^{(0)} + \frac{\partial f_2}{\partial x_2} \Big|_0 \Delta x_2^{(0)} + \dots + \frac{\partial f_2}{\partial x_n} \Big|_0 \Delta x_n^{(0)} \right] = 0 \\ \vdots \\ f_n(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}) - \left[\frac{\partial f_n}{\partial x_1} \Big|_0 \Delta x_1^{(0)} + \frac{\partial f_n}{\partial x_2} \Big|_0 \Delta x_2^{(0)} + \dots + \frac{\partial f_n}{\partial x_n} \Big|_0 \Delta x_n^{(0)} \right] = 0 \end{array} \right\}$$

The above equation in matrix form is shown as follows.

$$\begin{bmatrix} f_1(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}) \\ f_2(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}) \\ \vdots \\ f_n(x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} \Big|_0 & \frac{\partial f_1}{\partial x_2} \Big|_0 & \dots & \frac{\partial f_1}{\partial x_n} \Big|_0 \\ \frac{\partial f_2}{\partial x_1} \Big|_0 & \frac{\partial f_2}{\partial x_2} \Big|_0 & \dots & \frac{\partial f_2}{\partial x_n} \Big|_0 \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} \Big|_0 & \frac{\partial f_n}{\partial x_2} \Big|_0 & \dots & \frac{\partial f_n}{\partial x_n} \Big|_0 \end{bmatrix} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix}$$

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,

$$\left. \begin{array}{l} x_1^{(1)} = x_1^{(0)} - \Delta x_1^{(0)} \\ x_2^{(1)} = x_2^{(0)} - \Delta x_2^{(0)} \\ \vdots \quad \quad \quad \vdots \\ x_n^{(1)} = x_n^{(0)} - \Delta x_n^{(0)} \end{array} \right\}$$

$x_n(1)$ 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,

$$\begin{bmatrix} f_1(x_1^{(t)}, x_2^{(t)}, \dots, x_n^{(t)}) \\ f_2(x_1^{(t)}, x_2^{(t)}, \dots, x_n^{(t)}) \\ \vdots \quad \quad \quad \vdots \\ f_n(x_1^{(t)}, x_2^{(t)}, \dots, x_n^{(t)}) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} \Big|_t & \frac{\partial f_1}{\partial x_2} \Big|_t & \dots & \frac{\partial f_1}{\partial x_n} \Big|_t \\ \frac{\partial f_2}{\partial x_1} \Big|_t & \frac{\partial f_2}{\partial x_2} \Big|_t & \dots & \frac{\partial f_2}{\partial x_n} \Big|_t \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} \Big|_t & \frac{\partial f_n}{\partial x_2} \Big|_t & \dots & \frac{\partial f_n}{\partial x_n} \Big|_t \end{bmatrix} \begin{bmatrix} \Delta x_1^{(t)} \\ \Delta x_2^{(t)} \\ \vdots \\ \Delta x_n^{(t)} \end{bmatrix}$$

The above equations are expressed in matrix form.

$$\mathbf{F}(\mathbf{X}^{(t)}) = \mathbf{J}^{(t)} \Delta \mathbf{X}^{(t)}$$

Where,

$$\mathbf{F}(\mathbf{X}^{(t)}) = \begin{bmatrix} f_1(x_1^{(t)}, x_2^{(t)}, \dots, x_n^{(t)}) \\ f_2(x_1^{(t)}, x_2^{(t)}, \dots, x_n^{(t)}) \\ \vdots \\ f_n(x_1^{(t)}, x_2^{(t)}, \dots, x_n^{(t)}) \end{bmatrix} \quad \mathbf{J}^{(t)} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} |_t & \frac{\partial f_1}{\partial x_2} |_t & \dots & \frac{\partial f_1}{\partial x_n} |_t \\ \frac{\partial f_2}{\partial x_1} |_t & \frac{\partial f_2}{\partial x_2} |_t & \dots & \frac{\partial f_2}{\partial x_n} |_t \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} |_t & \frac{\partial f_n}{\partial x_2} |_t & \dots & \frac{\partial f_n}{\partial x_n} |_t \end{bmatrix} \quad \Delta \mathbf{X}^{(t)} = \begin{bmatrix} \Delta x_1^{(t)} \\ \Delta x_2^{(t)} \\ \vdots \\ \Delta x_n^{(t)} \end{bmatrix}$$

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.

$$\mathbf{X}^{(t+1)} = \mathbf{X}^{(t)} - \Delta \mathbf{X}^{(t)}$$

$$\|\mathbf{F}(\mathbf{X}^{(t)})\| < \varepsilon_2$$

$$\|\Delta \mathbf{X}^{(t)}\| < \varepsilon_1$$

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.

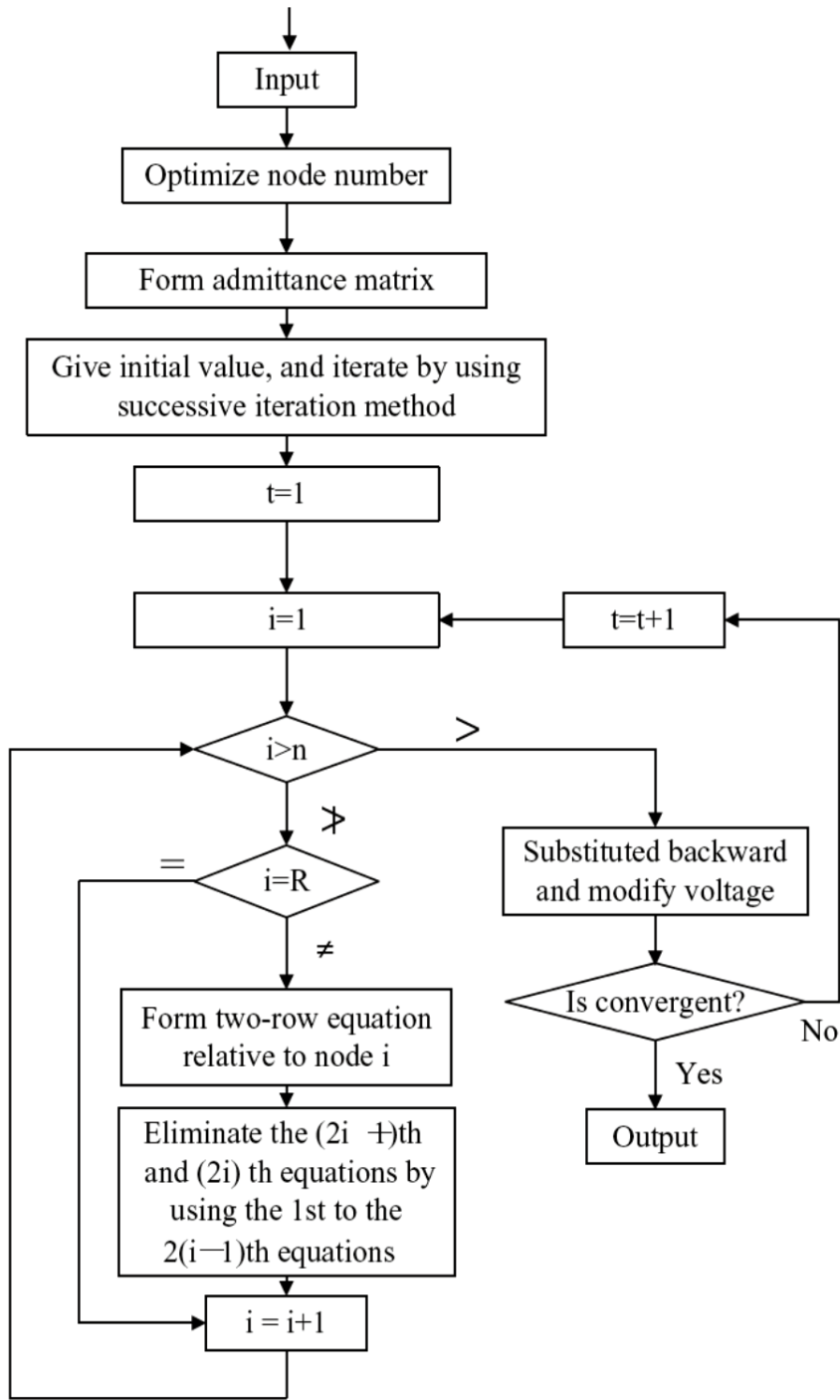
Its solution usually cannot avoid some iteration process.

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.

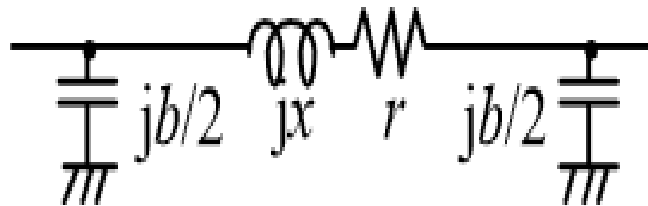


Figure7.1 π -shaped equivalent circuit

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.

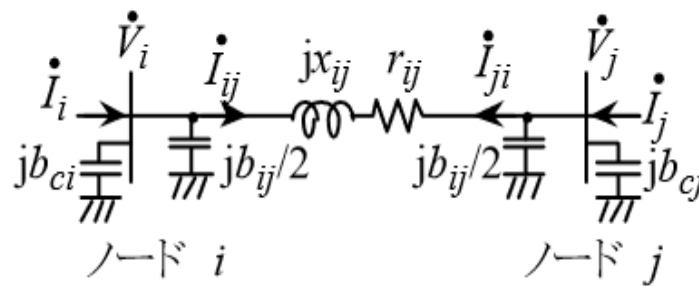


Figure 7.2 Equivalent expression of π -shaped equivalent circuit

7.2. LINEAR RELATION OF POWER SYSTEM NETWORK

Furthermore, if we write this for all (1 to n) i , it becomes as follows.

$$\dot{\mathbf{I}} = \dot{\mathbf{Y}}\dot{\mathbf{V}}$$

Where,

$$\dot{\mathbf{I}} = \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_n \end{bmatrix}, \quad \dot{\mathbf{V}} = \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \vdots \\ \dot{V}_n \end{bmatrix}, \quad \dot{\mathbf{Y}} = \{Y_{ij}\}$$

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,

$$P_i + jQ_i = \dot{V}_i \sum_{j=1}^n \bar{Y}_{ij} \bar{V}_j$$

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

$$\dot{I}_{ij} = j \frac{b_{ij}}{2} \dot{V}_i + \frac{\dot{V}_i - \dot{V}_j}{r_{ij} + jx_{ij}}$$

Taking into consideration the admittance parts located at both ends in a π -type equivalent circuit, the power flow $P_{ij} + jQ_{ij}$ flowing out from node i toward node j is,

$$P_{ij} + jQ_{ij} = \dot{V}_i \bar{\dot{I}}_{ij} = \dot{V}_i \left(-j \frac{b_{ij}}{2} \bar{V}_i + \frac{\bar{V}_i - \bar{V}_j}{r_{ij} - jx_{ij}} \right)$$

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,

$$\mathbf{p} = \mathbf{f}(\mathbf{v})$$

Where P_i and Q_i can be expressed as

$$f_{P_i}(\mathbf{v}) = V_i \sum_{j=1}^n V_j \left\{ G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right\}$$
$$f_{Q_i}(\mathbf{v}) = V_i \sum_{j=1}^n V_j \left\{ G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right\}$$

and the vector \mathbf{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:

$$\mathbf{v} \leftarrow \mathbf{v} + \left(\frac{\partial \mathbf{f}}{\partial \mathbf{v}} \right)^{-1} (\mathbf{p} - \mathbf{f}(\mathbf{v}))$$

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 $A\mathbf{x} = \mathbf{b}$, the matrix A can be decomposed to $A = LU$, where

$$\mathbf{L} = \begin{bmatrix} l_{1,1} & 0 & \cdots & 0 \\ l_{2,1} & l_{2,2} & \ddots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ l_{n,1} & \cdots & l_{n,n-1} & l_{n,n} \end{bmatrix}, \quad \mathbf{U} = \begin{bmatrix} 1 & u_{1,2} & \cdots & u_{1,n} \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & u_{n-1,n} \\ 0 & \cdots & 0 & 1 \end{bmatrix}$$

With these lower triangular matrix or upper triangular matrix, we have

$$\mathbf{L}\mathbf{y} = \mathbf{b}$$

$$\mathbf{U}\mathbf{x} = \mathbf{y}$$

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 distributed among the generation units in operation, by minimizing the selected cost criterion, and subjecting 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; FC_i is the power generation cost function of the i th 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 P_i is the power of the i th generating unit; a_i , b_i , c_i are the fuel cost coefficients of the i th generating unit.

Technical Cooperation to Promote Energy
Efficiency in Caribbean Countries
Commissioned work for grid stabilization
simulation
Final Report

October 31, 2022

Energy and Environment Technology Research Institute.

Table of Contents

Preface	1
Implementation Items and Results	1
1.1. Fundamentals of Power System Analysis.....	1
1.2. A close examination of the collection on St. Kitts Island	1
1.3. Determination of Grid attributes on St. Kitts Island.....	1
1.4. Confirmation of the grid plan for St. Kitts Island	2
1.5. Simulation of Grid analysis on St. Kitts Island	2
Creation of fuel curves and ELD determination for generators on St. Kitts Island 3	
1.6. Generator fuel cost curves and related data.....	3
1.7. Load data	4
1.8. Economic Load Distribution (ELD) Simulation Results	5
1.9. Conclusion	6
Tidal current analysis simulation at St. Kitts Island.....	7
1.10. Objective	7
1.11. Simulation case.....	7
1.12. Data	7
1.13. Tidal current calculation results	1
1.14. Summary of Simulation Result.....	11
1.15. Conclusion	11
Determination of battery storage capacity on St. Kitts Island Simulation	12
1.16. Objective.....	12
1.17. Simulation data	12
1.18. Simulation Procedure	13
1.19. Simulation Results	14
1.20. Result.....	21
Conclusion.....	22
Description of the Grid Analysis Simulation Tool (Supplement)	23
Appendix A: CARICOM Grid Stabilization Simulation Report (Interim), July 2019	

Appendix B: Microgrid Analysis Formulation and Solution Method (meeting materials).....	40
Appendix C: Fast Solutions for Large-Scale Distribution System Tidal Flow Calculations.....	66
Appendix D: CATAPLLER Generator Data (collected locally, 2019).....	86
Appendix E: Wire Attributes (collected locally, 2019)	89
Appendix F: hourly loads_1 week x 3 cases in 2019 (collected locally, 2019)	90
Appendix G: Hourly output profiles for solar (35 MW, 0.7 MW, 0.55 MW) for one week (assumed, 2019)	94
Appendix H: Separate Formats for St_Kitts_Minimum Load, etc. (collected locally, 2019).....	119
Appendix I: Report on 27th Nov 2019, St. Kitts, Report on the results of the field trip by Nippon Koei Co.....	120
Appendix J: Description of Fast Tidal Current Calculation Programs for Large Transmission and Distribution Systems	123

Preface

Caribbean islands face many challenges in the energy sector, despite the large amount of readily available renewable energy resources, including solar power, wind power, geothermal, and biomass. Small island developing countries such as St. Kitts and Nevis receive subsidies, but economically this is not seen as a long-term solution.

A long-term, much larger economic solution would be to diversify the energy mix by introducing renewable energy technologies, thereby reducing dependence on imported fossil fuel, and ensuring long-term energy security, a top priority for Caribbean governments.

The objective here is to analyze the energy sector on St. Kitts and demonstrate how energy security can be achieved by installing large-scale solar PV as a renewable energy technology to cover base load.

We collected data on renewable energy, electricity demand, and the electricity system on St. Kitts and used these data to perform a system stabilization simulation using *Micro Grid Designer*, a tool that supports power system analysis. The results of the analysis are reported.

Implementation Items and Results

1.1. Fundamentals of Power System Analysis

Lectured on the basics of power system analysis since it was assumed that Micro Grid Designer would be used as the software for power system analysis, materials explaining the contents of the work were prepared and discussed by the members of the project, including the basics of power system analysis. The project members discussed the work, including the basics of power system analysis.

1.2. A close examination of the collection on St. Kitts Island

The information on power plants and generators, grid structure and attributes, and load and renewable energy (solar and wind) information for St. Kitts Island collected during the first mission was reviewed to identify data that could be used in the grid analysis, and the previously conducted grid planning report for “St. Kitts Island, Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept. 2014 by leidos”, which was collected simultaneously, was also reviewed as the main reference material.

1.3. Determination of Grid attributes on St. Kitts Island

Since the system information on St. Kitts Island collected during the first mission did not contain much practical and numerical data that could be used immediately, we proposed to utilize the data for PSS/E

for this project as well, since the tidal current calculations were conducted using PSS/E, which was mentioned in the reference material. PSS/E is an expensive system analysis tool developed by Siemens. As a result, data for PSS/E was collected during the second mission, and it could be converted into data for Micro Grid Designer.

1.4. Confirmation of the grid plan for St. Kitts Island

Information on power plants and generators, system configuration and attributes, and load and renewable energy (PV) information on St. Kitts Island were to reconfirm and collect during third mission. The data for the grid analysis (multistage economic load distribution and tidal current calculation) using Micro Grid Designer was created from these data, six generators were added to confirm the planned installation of 35 MW of large-scale PV with batteries. The location information and line types of underground cables and aboveground transmission lines were collected, and weekly and load curve data were also finalized.

1.5. Simulation of Grid analysis on St. Kitts Island

After the above process, the optimal battery capacity in the St. Kitts Island and power system was determined and the multi-stage economic load dispatch and tidal current calculations were performed using Micro Grid Designer.

Creation of fuel curves and ELD determination for generators on St. Kitts Island

1.6. Generator fuel cost curves and related data

Generator fuel cost curves were made from the following measured provided data. (Table 3-1) The corresponding generator numbers for the generator curves are as follows

- Generator #1
- Generator #2
- Generator #3
- Generator #4
- Generator #9
- Generator #10
- Generator #11
- Generator #12

Table 3-1 Generators and Fuel Efficiency

UNIT	Fuel Efficiency									
	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	-	-	-	-	-	-	-	-	-	-

Source: Prepared by EETRI

The fuel cost curves, corresponding bus bar numbers, and generator numbers for simulation are shown below. Note that the coefficients at bus bar numbers 49-55 are tentatively taken as the average of the coefficients for the eight known generators.

Table 3-2 Generators and Fuel Cost Factors

Unit	Line No.	Generator No.	Fuel Cost Curve	a (Sec ond)	b (Sec ond)	c (Cons tant)
Generator #1	40	1	$y = 0.0336x^2 + 0.0436x + 17.72$	0.03360	0.04360	17.72000
Generator #2	41	2	$y = 0.0197x^2 + 0.0344x + 0.0065$	0.01970	0.03440	0.00650
Generator #3	42	3	$y = 0.0043x^2 + 0.0395x + 0.0098$	0.00430	0.03950	0.00980
Generator #4	43	4	$y = 0.0035x^2 + 0.0503x + 0.0031$	0.00350	0.05030	0.00310
Generator #9	45	5	$y = 0.0247x^2 + 0.0173x + 0.0156$	0.02470	0.01730	0.01560
Generator #10	46	6	$y = 0.001x^2 + 0.0483x + 0.0047$	0.00100	0.04830	0.00470
Generator #11	47	7	$y = 0.0037x^2 + 0.0443x + 0.0061$	0.00370	0.04430	0.00610
Generator #12	48	8	$y = 0.0052x^2 + 0.0441x + 0.0057$	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

Source: Prepared by EETRI

The following data provided was used for the generator output upper and lower limits; the data for CAT1 through CAT6 are the same, so they were placed in the bus bar numbers 49 through 55.

Table 3-3 Generator output upper and lower limits

Generator	Pgen MW	Pmin MW	Pmax MW	Spinning		Down		Ramp Capability	
				Reserve MW	%Loading MW	Reserve MW		kW/sec	MW/h
				Generator#1	5.80	1.22	6.13	0.00	94.60%
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						

Source: Prepared by EETRI

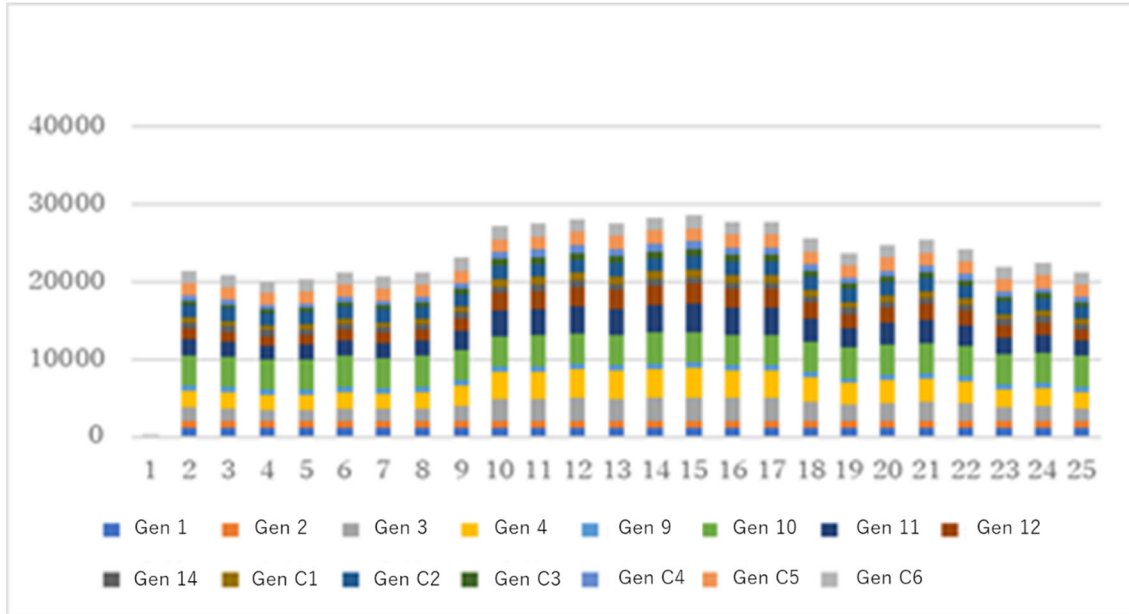
1.7. Load data

The load data for the simulation was extracted based on the load data received (20200918_hourly loads_1 week x 4 cases rev1.xlsx).

1.8. Economic Load Distribution (ELD) Simulation Results

An example of simulation results is shown from Figure 3-1, 3-2, 3-3 and 3-4.

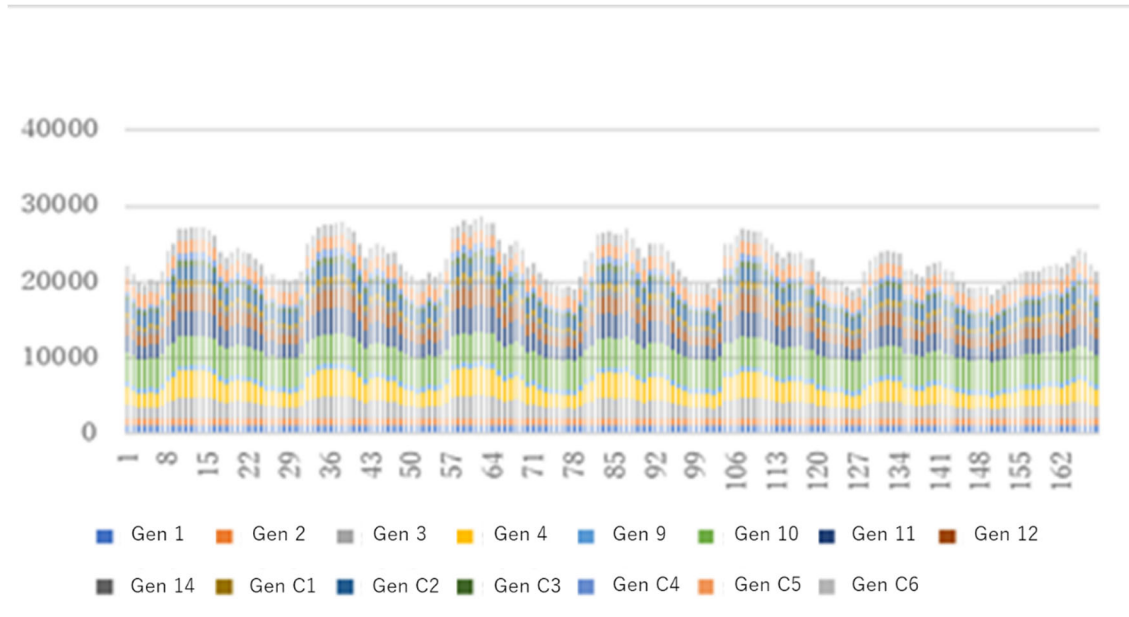
<Example 1: 10 July 2019 (24 hours load per day)>



Source: Prepared by EETRI

Figure 3-1 Simulation results (Example 1)

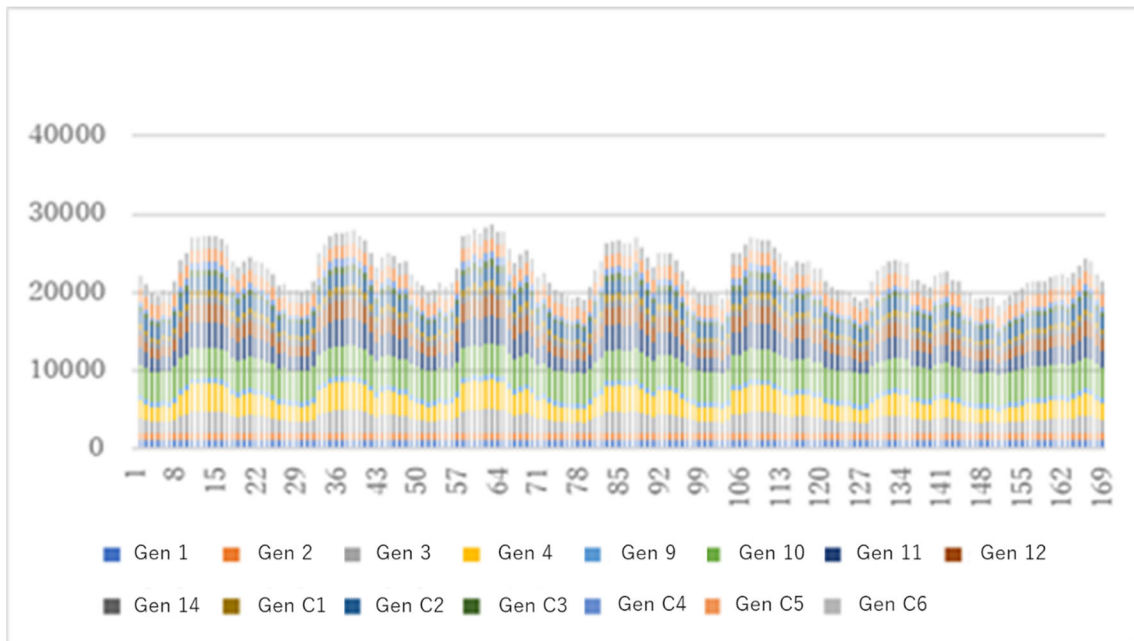
<Example 2: 8 July to 14 July 2019_One month 168 hours data (no speed response constraints)>



Source: Prepared by EETRI

Figure 3-2 Simulation results (Example 2)

<Example 3: 8 July to 14 July 2019_One month 168 hours data (The speed response constraint assumes 20% of rating, i.e., minimum load to full load is calculated to be 5 hours.)>



Source: Prepared by EETRI

Figure 3-3 Simulation results (Example 3)

1.9. Conclusion

These verifications led to the conclusion that there were no problems with the ELD calculations.

Tidal current analysis simulation at St. Kitts Island

1.10. Objective

Based on the converted data from PSS/E, a schematic system configuration chart of St. Kitts Island was made, tidal current calculations were performed by MicroGrid Designer, and the results were examined.

The data for PSS/E is characterized by a loopless distribution system with 12 feeders coming out of one power plant, with a small solar PV at each feeder end and one large wind turbine (5.4 MW) in the middle of one feeder.

The reference material does not include details of the tidal current calculation results, so no comparison can be made. However, since the tidal current calculation results by Micro Grid Designer appear to be sufficiently valid, it is clarified that the data for PSS/E in the field can be utilized. However, since this data was created more than 6 years ago, it is necessary to keep in mind that the system will be updated in the future.

The converted and organized tidal current calculation data is shown. Tidal current calculation simulations using this data will be performed and the results evaluated.

1.11. Simulation case

(1) Case 0: No PV and BAT (battery)

The output sharing of the generators was assumed to be the distribution of the total load by the capacity ratio of the generators.

(2) Case1: PV and BAT (battery)

PV output was set at 35 MW. Other generator output was calculated using the results of the tidal current calculations for Case 0. The BAT (battery) node was assumed to be slack, and the required battery capacity (kW) was calculated under these conditions.

(3) Case 2: PV and BAT (battery)

In Case 1, other generator output is set to 20% of Case 0.

(4) Case3: V and BAT (battery)

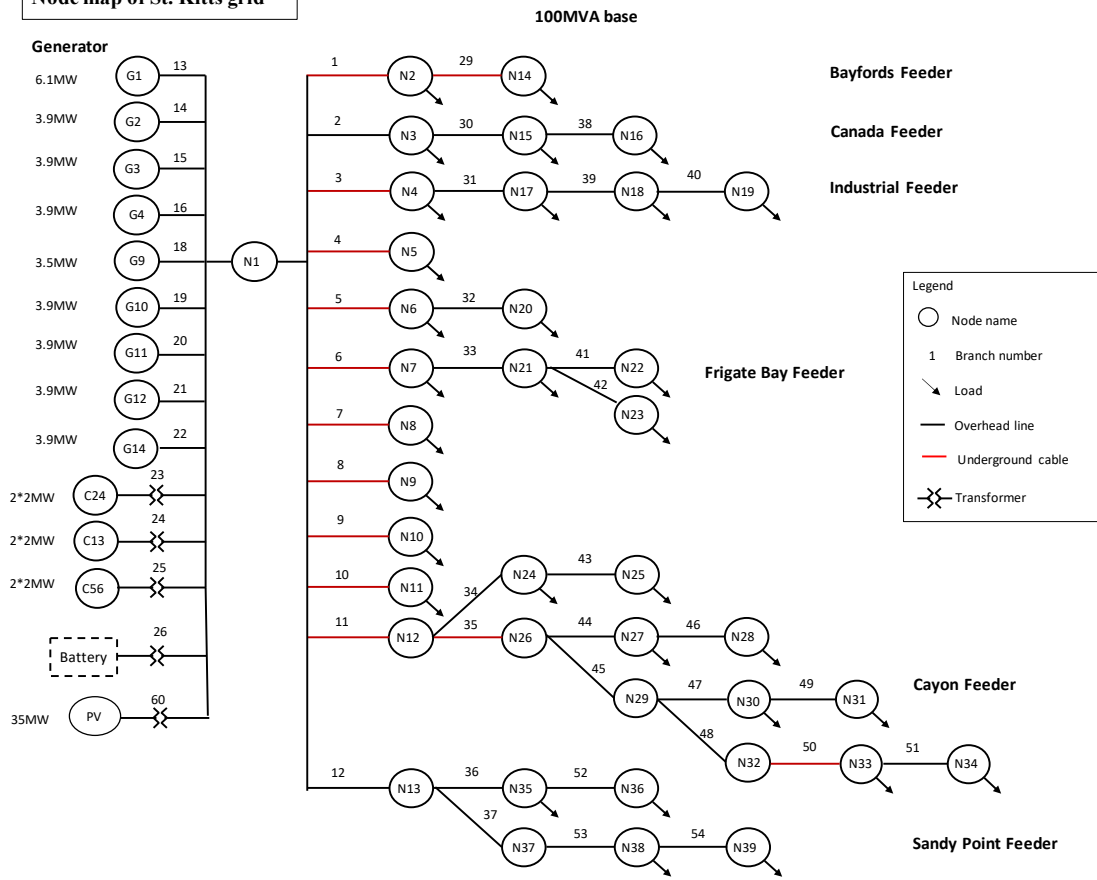
In Case 2, PV output was set to 0%.

1.12. Data

(1) System configuration

Figure 4-1 shows the system diagram read from the PSS/E data.

Node map of St. Kitts grid



Source: Prepared by EETRI based on PSS/E data

Figure 4-1 Schematic diagram

(2) Generator

Table 4-1 shows generator data obtained from Generator information.xlsx.

Table 4-1 Generator Data

Node name	Unit	Engine model	Year installed	Generator Model	Rated Power	Voltage Rate (Provided by Nippon Koei)	Basis
G1	G1	Mirlees Blackstone MB430	1999	Leroy Sommer LSA60 B105-14P	6.1 MW	11kV	Nameplate photograph
G2	G2	MAN 18V28/32S	2009	Hyundai	3.9 MW	11kV	Single line diagram
G3	G3	MAN 18V28/32S	2008	AVK	3.9 MW	11kV	Nameplate photograph
G4	G4	MAN 18V28/32S	2007	AVK	3.9 MW	11kV	Nameplate photograph
G9	G9	Mirlees Blackstone K8	1987	Brush	3.5 MW	11kV	Single line diagram
G10	G10	MAN 18V28/32S	2010	AVK	3.9 MW	11kV	Nameplate photograph
G11	G11	MAN 18V28/32S	2010	AVK	3.9 MW	11kV	Nameplate photograph
G12	G12	MAN 18V28/32S	2011	AVK	3.9 MW	11kV	Nameplate photograph
G-14	G-14	MAN 18V28/32S	2011	AVK	3.9 MW	11kV	Nameplate photograph
C13	Mobile set 1	Caterpillar 3516	2017	Caterpillar	2.0 MW	480V	Nameplate photos and catalogs
	Mobile set 3	Caterpillar 3516	2018	Caterpillar	2.0 MW	480V	Nameplate photos and catalogs
C24	Mobile set 2	Caterpillar 3516	2017	Caterpillar	2.0 MW	480V	Nameplate photos and catalogs
	Mobile set 4	Caterpillar 3516	2018	Caterpillar	2.0 MW	480V	Nameplate photos and catalogs
C56	Mobile set 5	Caterpillar 3516	2019	Caterpillar	2.0 MW	480V	Nameplate photos and catalogs
	Mobile set 6	Caterpillar 3516	2019	Caterpillar	2.0 MW	480V	Nameplate photos and catalogs

Source: Prepared by EETRI

(3) Distribution lines

Table 4-2 shows the distribution line data read from the PSS/E data.

Table 4-2 Distribution line data

Branch ID	Sending node	Receiving node	No. of circuits	Resistance R (p.u.)	Reactance X (p.u.)	Admittance Y/2 (p.u.)
1	N1	N2	1	0.9024	0.8624	0
2	N1	N3	1	0.3319	0.4143	0
3	N1	N4	1	0.0887	0.0815	0
4	N1	N5	1	0.0919	0.0844	0
5	N1	N6	1	0.3422	0.3873	0
6	N1	N7	1	0.1229	0.1129	0
7	N1	N8	1	0.1873	0.1721	0
8	N1	N9	1	3.1699	1.4664	0
9	N1	N10	1	1.1316	1.0392	0
10	N1	N11	1	0.3079	0.2827	0
11	N1	N12	1	0.4534	0.4164	0
12	N1	N13	1	0.6357	0.5838	0
13	N1	G1	1	0	0.001	0
14	N1	G2	1	0	0.001	0
15	N1	G3	1	0	0.001	0
16	N1	G4	1	0	0.001	0
18	N1	G9	1	0	0.001	0
19	N1	G10	1	0	0.001	0
20	N1	G11	1	0	0.001	0
21	N1	G12	1	0	0.001	0
22	N1	G-14	1	0	0.001	0
23	N1	C24	1	0	0.6	0
24	N1	C13	1	0	0.6	0
25	N1	C56	1	0	0.6	0
26	N1	BAT	1	0	0.6	0
29	N2	N14	1	1.2189	1.1748	0
30	N3	N15	1	0.5531	0.4264	0
31	N4	N17	1	0.1394	0.1281	0
32	N6	N20	1	0.7286	1.1558	0
33	N7	N21	1	0.1476	0.1356	0
34	N12	N24	1	2.479	1.1468	0

Branch ID	Sending node	Receiving node	No. of circuits	Resistance R (p.u.)	Reactance X (p.u.)	Admittance Y/2 (p.u.)
35	N12	N26	1	0.3476	0.3192	0
36	N13	N35	1	3.0158	2.3139	0
37	N13	N37	1	0.9404	0.8325	0
38	N15	N16	1	1.2419	1.0997	0
39	N17	N18	1	0.09	0.8262	0
40	N18	N19	1	0.0669	0.0615	0
41	N21	N22	1	0.1776	0.1632	0
42	N21	N23	1	0.1956	0.1797	0
43	N24	N25	1	3.3119	1.5322	0
44	N26	N27	1	0.9501	0.4395	0
45	N26	N29	1	1.7516	2.7785	0
46	N27	N28	1	4.0389	1.8684	0
47	N29	N30	1	1.1891	1.8862	0
48	N29	N32	1	3.6489	1.6882	0
49	N30	N31	1	2.548	1.1788	0
50	N32	N33	1	1.9684	0.9106	0
51	N33	N34	1	4.0223	1.8608	0
52	N35	N36	1	5.0793	2.3498	0
53	N37	N38	1	1.2729	0.5889	0
54	N38	N39	1	3.7738	1.7458	0

Source: Prepared by EETRI

- Branches 24, 25, and 26 are step-up transformers for Caterpillar generators. 2 units total $2 \times 2\text{MW}/0.8 = 5\text{MVA}$, so transformer is assumed to be 5MVA, 3%Z. On a 100MVA basis, $0.03 \times 100/5 = 0.6\text{pu}$.
- The Battery in Branch 26 shall not be present. Its transformer shall be 5MVA, 3%Z.
- The ground capacitance Y is zero in all the branches.
- Branch 29 $R=1.2189\text{pu}$, $X=1.1748\text{pu}$ This is $R=1.2189 \times (11\text{kV}^2)/100\text{M}=1.47\Omega$, 3.77mH. If we consider $L \approx 1\text{mH}$ of the line, this distribution line would be 3.77km. We consider this a reasonable place to start.
- Branch 30 $R=0.5531\text{pu}$, $X=0.4264\text{pu}$ This corresponds to approximately 1.7 km.

(4) Node data and load PQ

Node data and load PQs are shown in **Table 4-3**. The total load is 15.711 MW, and 10.136 Mvar.

Table 4-3 Node Data and Load PQ (100MVAbase)

Node ID	Node type (PQ=0, PV=1, Slack=2)	Pg. (p.u.)	Qg. (p.u.)	Pl. (p.u.)	Ql. (p.u.)
N1	0	0	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

Node ID	Node type (PQ=0, PV=1, Slack=2)	Pg. (p.u.)	Qg. (p.u.)	Pl (p.u.)	Ql. (p.u.)
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
Group of Ten	1	0.0125	0	0	0
G11	1	0.0125	0	0	0
G12	1	0.0125	0	0	0
G-14	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
			Total	0.15711	0.10136

Source: Prepared by EETRI

1.13. Tidal current calculation results

(1) Case 0: No PV

Generator output sharing allocates the total load to the generator capacity ratio.

The data in **Table 4-3** illustrate this case.

1) Convergence conditions, etc.

Summary of calculation conditions are shown in **Table 4-4**.

- Convergence condition 0.0001pu
- Convergence 3 times
- 0.00539 pu (= 0.539 MW) loss for the entire circuit

Table 4-4 Calculation Basic Conditions (1)

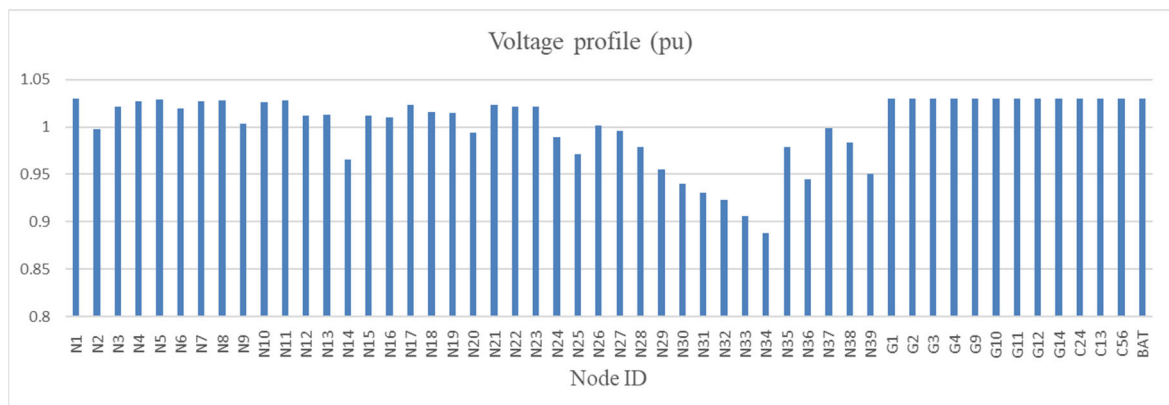
Nodes		52
Branch:		51
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

Source: Prepared by EETRI

2) Voltage profile

The voltage profile is shown in **Figure 4-2**.

The voltage at the N34 node at the end of the line is below 0.9 pu. Countermeasures are needed.

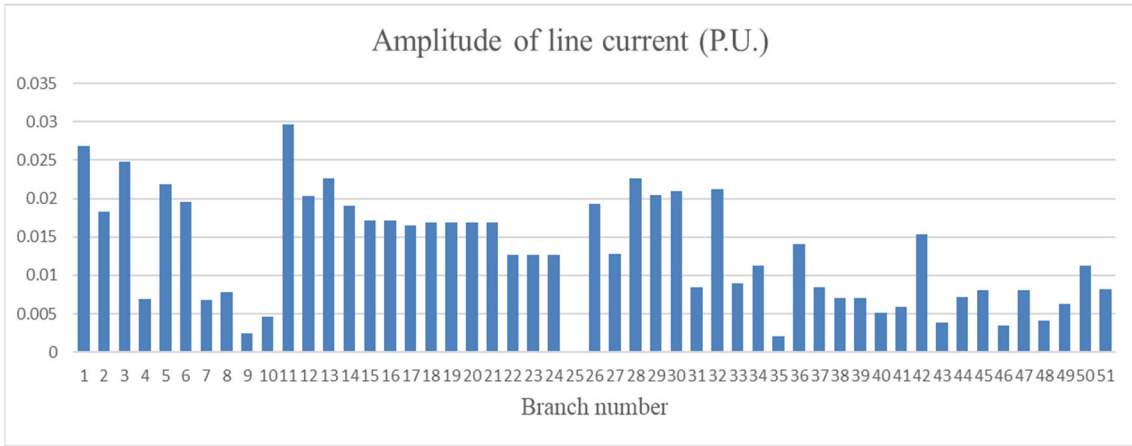


Source: Prepared by EETRI

Figure 4-2 Voltage profile

3) Line current

Line currents are shown in **Figure 4-3**.



Source: Prepared by EETRI

Figure 4-3 Line current

4) Generator output

Generator output is shown in **Table 4-5**.

Table 4-5 Generator Output (100MVA base)

Generator No.	Node type (PQ=0, PV=1, Slack=2)	Voltage designation V	Designation: P(p.u.)	Designation: Q(p.u.)	P(p.u.) result	Q(p.u.) result	Article
G1	1	1.03	0.02	0	0.02	0.01194	
G2	2	1.03	0.013	0	0.01549	0.01194	slack
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	
G-14	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	
				Total	0.16249	0.10767	

Source: Prepared by EETRI

(2) Case 1: With PV and Batteries

PV output is assumed to be 35 MW. Found the required battery capacity when the generator output is the same as the tidal flow calculation results for Case 0.

1) Node data addition and modification

Table 4-6 shows the generator, battery, and PV data, including additions and modifications, among the node data. The additions and changes are as follows.

- PV (photovoltaic) node "PV" was added. The output was set to 35 MW (0.35 p.u.: based on 100 MVA).
- The G2 node was designated as PV and the output was set to 1.549 MW (0.0549 p.u.: based on 100 MVA) based on the tidal flow calculation results for Case 0.
- The storage node "BAT" is designated as a slack node.

Table 4-6 Node data (Generator, battery, and PV data)

Comments	Node data Input Form for Single Stage Power Flow Analysis								
	Node ID (Up to 4 characters)	Node type PQ=0, PV=1, Slack=2	Amplitude of V (p.u.)	Phase angle of V (Degree)	Node Admittance (p.u.)	Pg (p.u.)	Qg (p.u.)	Pl (p.u.)	Ql (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			

Source: Prepared by EETRI

2) Branch data addition

- A transformer between PV (solar) node "PV" and node "N1" was added as branch number 60. (See **Table 4-7**).
- Assume transformer is 40MVA, 3%Z. On a 100MVA basis, $0.03 * 100 / 40 = 0.075$ p.u.

Table 4-7 Branch data (for additions)

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 characters)	(Up to 4 characters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
	60	N1	PV		0	0.075		

Source: Prepared by EETRI

3) Simulation Results

(i) Convergence conditions, etc.

- Convergence condition 0.0001p.u.
- Convergence 3 times
- 0.00539 p.u. (= 0.539 MW) loss for the entire circuit

Table 4-8 Calculation Basic Conditions (2)

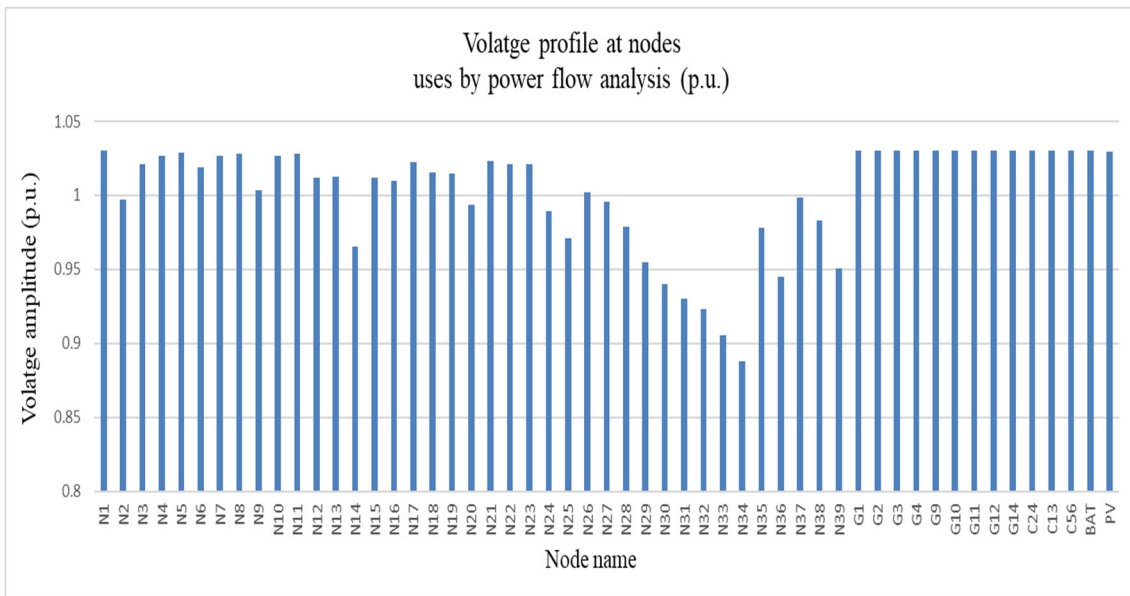
Nodes		53
Branch:		52
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

Source: Prepared by EETRI

(ii) Voltage Result

Voltage results are shown in **Figure 4-4**.

The PV terminal voltage (PV node) is 1.03 p.u., a value like other generators, so there is no problem. The voltage at the terminal N34 node is below 0.9 p.u. Same as case 0 and, countermeasures are needed.



Source: Prepared by EETRI

Figure 4-4 Voltage Results

(iii) Generator and PV output, battery charge/discharge results

The results for generator output, PV output, and battery charge/discharge are shown in **Table 4-9**. Most of the 0.35 p.u. (35 MW) of PV output is charged to batteries.

The generator is discharging reactive power and is running in slow phase. However, all of them are within their capacities and there is no problem.

Table 4-9 Generator and PV output, battery charge/discharge results

(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

Source: Prepared by EETRI

(iv) Line current

Almost same as Case 0.

(v) Required battery capacity

As a result of specifying the battery node "BAT" as slack, **Table 4-9** shows that a P output of -0.35 p.u. (charge) and a Q output of 0.035 p.u. (discharge) are required. Therefore, other generator outputs are the same as in Case 0, the required battery capacity is 0.3517 p.u. (35.17 MVA).

(3) Case 2: With PV and Batteries, Generator output 20%.

The PV output is assumed to be 35 MW, and the required battery capacity is obtained when the generator output is 20% of Case 1. Compared to the total load of 15.711 MW, the PV output of 35 MW is large, and considering charging and discharging, the case of 0% generator output has the lowest required battery capacity, but considering voltage and frequency maintenance, 20% generator output is used.

1) Node data addition and modification

In Case 1, all generator outputs are set to 20%. **Table 4-10** shows the generator, battery, and PV data, including additions and modifications, among the node data.

Table 4-10 Node data (generator, battery, and PV data)

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	0	
G2	1	1.03	0	0.003098	0	0	0	0	
G3	1	1.03	0	0.0026	0	0	0	0	
G4	1	1.03	0	0.0026	0	0	0	0	
G9	1	1.03	0	0.0024	0	0	0	0	
G10	1	1.03	0	0.0025	0	0	0	0	
G11	1	1.03	0	0.0025	0	0	0	0	
G12	1	1.03	0	0.0025	0	0	0	0	
G14	1	1.03	0	0.0025	0	0	0	0	
C24	1	1.03	0	0.0026	0	0	0	0	
C13	1	1.03	0	0.0026	0	0	0	0	
C56	1	1.03	0	0.0026	0	0	0	0	
BAT	2	1.03	0		0	0	0	0	
PV	0	1	0	0.35					

Source: Prepared by EETRI

2) Branch data

No change from Case 1.

3) Simulation results

(i) Convergence conditions, etc.

- Convergence condition 0.0001p.u.
- Convergence 3 times
- 0.00539 p.u. (= 0.539 MW) loss for the entire circuit

Table 4-11 Calculation Basic Conditions (3)

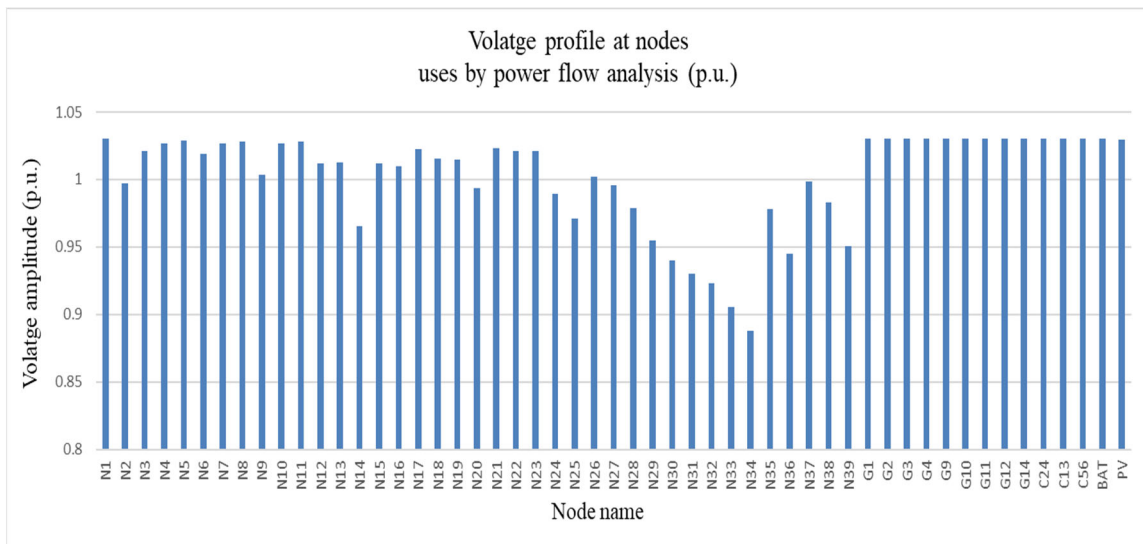
Nodes		53
Branch:		52
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

Source: Prepared by EETRI

(ii) Voltage Result

Voltage results are shown in **Figure 4-5**.

The PV terminal voltage is 1.03 p.u., a value like other generators, so there is no problem. The voltage at the terminal N34 node is below 0.9 p.u. as in Case 0. Countermeasures are required.



Source: Prepared by EETRI

Figure 4-5 Voltage results

(iii) Generator and PV output, battery charge/discharge results

The results for generator output, PV output, and battery charge/discharge are shown in **Table 4-**

12. 0.22 p.u. (22 MW) of the PV output of 0.35 p.u. (35 MW) is charged to batteries. The generator is discharging reactive power and is running in slow phase. However, all of them are within their capacities and there is no problem.

Table 4-12 Generator and PV output, battery charge/discharge results

Output Form of Obtained Results for Nodes by Singel Stage Power Flow Anlysis											
Node ID	Node type	Specified voltage	Obtaained 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	

Source: Prepared by EETRI

(iv) Line current

Almost same as Case 0

(v) Required battery capacity

The slack designation of the battery node "BAT" results in the need for a P output of -0.22 p.u. (charging) and a Q output of 0.014 p.u. (discharging). Therefore, if the other generator output is 20% of Case 0, the required battery capacity is 0.22 p.u. (22.04 MVA).

(4) Case 3: PV output 0%, With batteries, Generator output 20%

Found the required battery capacity when the generator output is the same as in Case 2 (20% generator output) and the PV output is 0 MW. In Case 2, consider the case where the PV output is 0% due to weather changes, etc.

1) Node data change

In Case 2, the PV output is set to 0 MW. **Table 4-13** shows the generator, battery, and PV data, including additions and modifications, among the node data.

Table 4-13 Node data (generator, battery, and PV data)

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			

Source: Prepared by EETRI

2) Branch data

The results are the same as in Case 1 and Case 2.

3) Simulation Results

(i) Convergence conditions, etc.

- Convergence condition 0.0001p.u.
- Convergence 3 times
- 0.00539 p.u. (= 0.539 MW) loss for the entire circuit

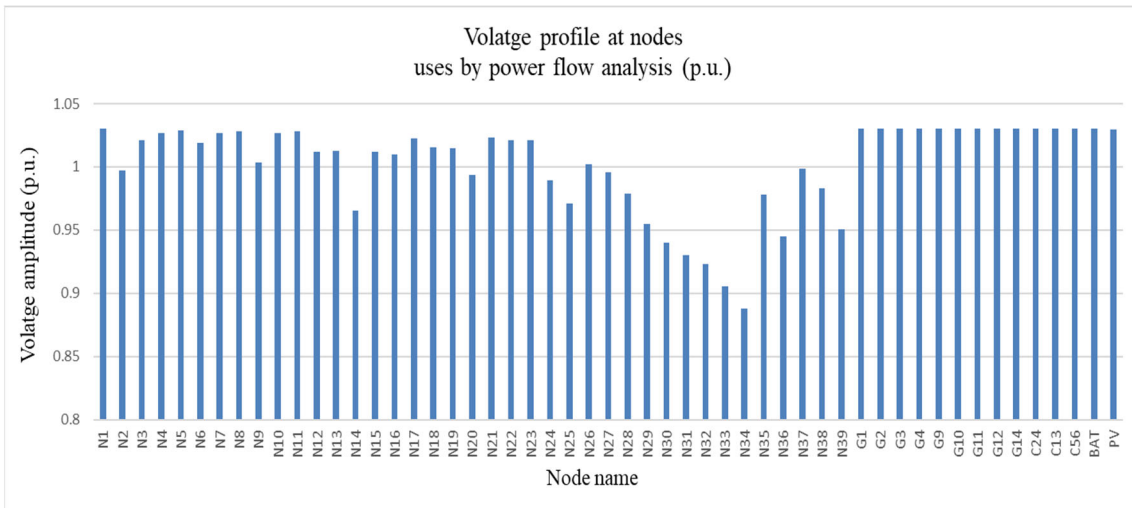
Table 4-14 Calculation Basic Conditions (4)

Nodes		53
Branch:		52
Branch with Tap		0
Iteration:		3
Loss (pu):		0.00539

Source: Prepared by EETRI

(ii) Voltage Result

Voltage results are shown in **Figure 4-6**. The PV terminal voltage is 1.03 p.u., a value like other generators, so there is no problem. The voltage at the N34 node at the end of the line is less than 0.9 p.u. is the same as in case 0. Countermeasures are needed.



Source: Prepared by EETRI

Figure 4-6 Voltage Results

(iii) Generator and PV output, battery charge/discharge results

The results for generator output, PV output, and battery charge/discharge are shown in **Table 4-15**. The battery has discharged approximately 0.13 p.u. (13 MW). The generator is discharging reactive power and is running in slow phase. However, all of them are within their capacities and there is no problem.

Table 4-15 Generator and PV output, battery charge/discharge results

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	

Source: Prepared by EETRI

(iv) Line current

Almost same as Case 0.

(v) Required battery capacity

The results show that a P output of -0.13 p.u. (discharge) and a Q output of 0.0048 p.u. (discharge) are required. Therefore, the required battery capacity is 0.13 p.u. (13 MVA).

1.14. Summary of Simulation Result

The calculation results of Case 1, 2, and 3 were compared based on the results of Case 0. In all cases, the required battery capacity was examined for Case 0 and other cases where the generator output (power generation output excluding PV) is the same as the total load and the maximum PV output is 35 MW.

(1) Case 1

Assuming other generator output to be the same as Case 0 (total load), the required battery capacity was P: 0.35 p.u. and Q: 0.035 p.u. (P: 35MW, Q: 3.5MVar, 35.17MVA)

(2) Case 2

Assuming other generator output as 20% of Case 0 (total load), the required battery capacity was P: 0.22 p.u. and Q: 0.014 p.u. (P: 22MW, Q: 1.4MVar, 22.04MVA)

(3) Case 3

Assuming 0% PV output in Case 2, the required battery capacity was P: 0.13 p.u. and Q: 0.0048 p.u. (P: 13MW, Q: 0.048MVar, 13MVA)

Compared to the total load of 15.711 MW, the PV output of 35 MW is large, and the generator output of 0% is the lowest required battery capacity when considering charging and discharging, but considering voltage and frequency maintenance, a generator output of 20% was chosen.

Therefore, assuming a generator output of 20%, the required battery capacity from Case 2 and Case 3 is approximately 22 MVA.

1.15. Conclusion

Assuming a total load of 15.711 MW, a maximum PV output of 35 MW, voltage and frequency maintenance of other generator output, and 20% of total load, the required battery capacity would be approximately 22 MVA.

Determination of battery storage capacity on St. Kitts Island

Simulation

The tidal current calculations in **Chapter 3** confirmed that there are no grid stability problems with the installation of 35 MW of PV. In addition, the required battery capacity (MW) was calculated in **Chapter 4**. In this chapter, EETRI conducted a simulation to determine the battery capacity on St. Kitts Island. The assumed PV capacity was 35 MW, the same as in the tidal flow calculation. In this section, a 24-hours battery charge/discharge simulation is performed to calculate the required battery capacity (MWh).

1.16. Objective.

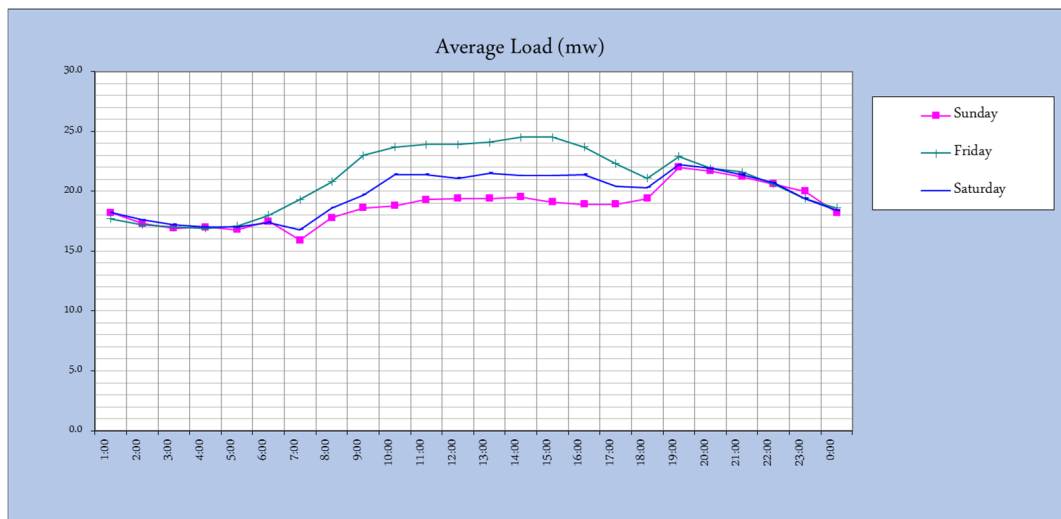
The 24-hour load curve for St. Kitts Island and the PV curve are used to calculate the required battery capacity (MWh).

1.17. Simulation data

(1) Daily Load Data

Of the daily load data obtained, it was decided to use data from Sundays when demand was low. The data is shown in **Figure 5-1**. The reason for this is that when demand is low, recharge/discharge is low, so the required battery capacity is large.

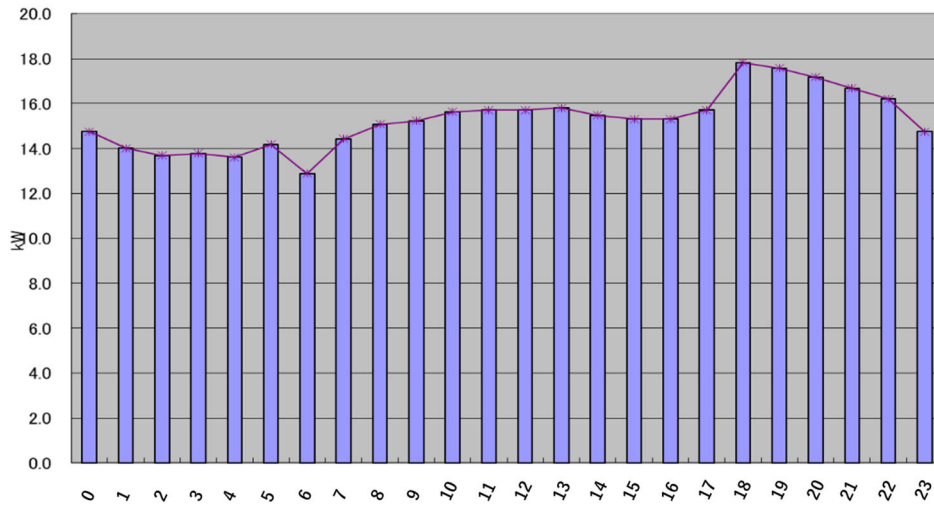
In addition, to maintain consistency with the tidal flow calculation results, the daytime peak demand was adjusted to 15.7 MW. The same ratio was also adjusted for all hours of the day.



Source: Prepared by EETRI based on obtained data

Figure 5-1 Daily load curve

Figure 5-2 shows the daily load curve created for the simulation.

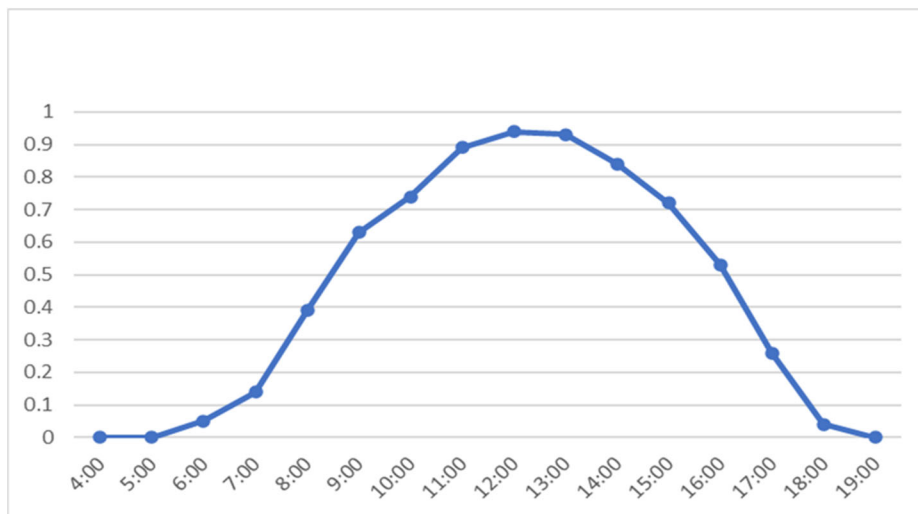


Source: Prepared by EETRI based on obtained data

Figure 5-2 Daily load curve for simulation

(2) PV Data

From the available PV data, EETRI used the data from 1st August, which was close to clear skies. In addition, the maximum PV output was adjusted to 35 MW to be consistent with the tidal current calculation results (see **Figure 5-3**).



Source: Prepared by EETRI based on obtained data

Figure 5-3 PV curve

1.18. Simulation Procedure

Battery charge/discharge simulations were performed using the daily load and PV data created. The battery charge/discharge situation also depends on the generator output (power generation equipment other than PV), so the following case was performed.

However, the generator output was assumed to be the minimum output when PV output exceeds demand. The minimum output was set to 3.2 MW to be consistent with the tidal flow calculation results.

(1) Consideration for maximum PV output

- Case 1: Generator output 15MW
- Case 2: Generator output 8MW
- Case 3: Generator output 5MW
- Case 4: Generator output 3.2MW

(2) Examination of the case of PV output 0

The following simulations were performed using the battery capacities determined in "(1) Examination of the case of maximum PV output".

- Case 5: Generator output 15MW
- Case 6: Generator output 10MW
- Case 7: Generator output 8MW

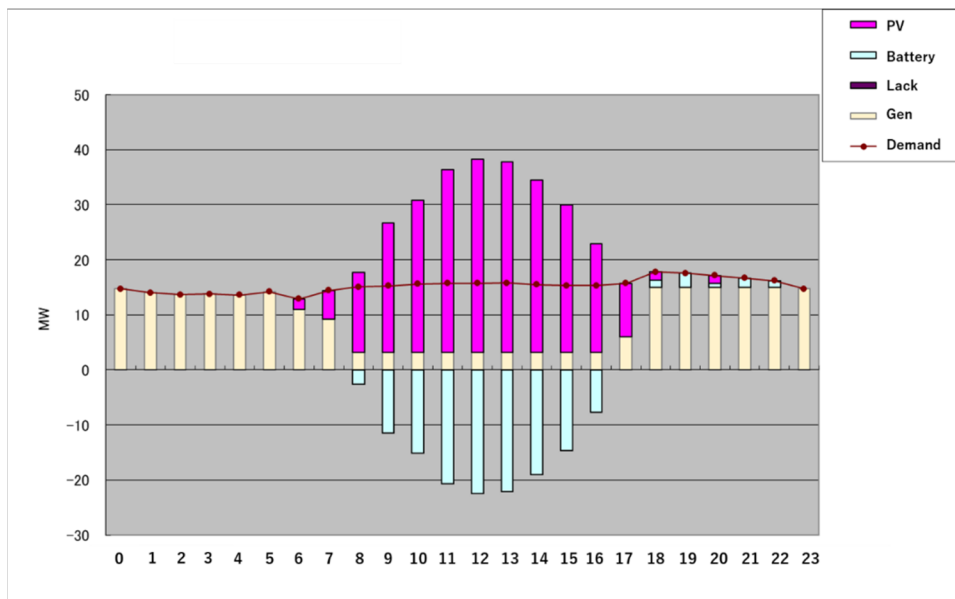
1.19. Simulation Results

(1) Consideration for the case of maximum PV output

1) Case 1: Generator output 15MW

(i) Charge and discharge results

Charge and discharge results are shown in **Figure 5-4**. The maximum battery charge was approximately 22 MW. This result was the same as the tidal flow calculation result.

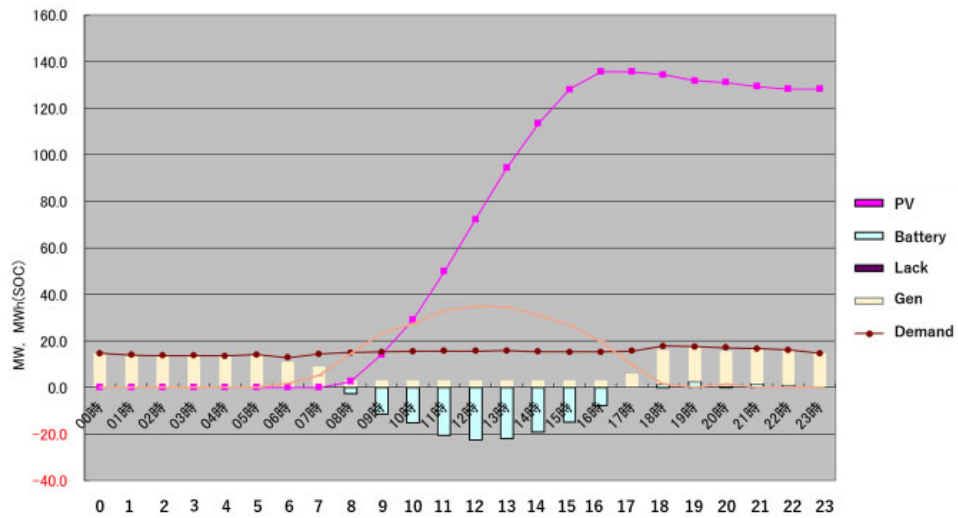


Source: Prepared by EETRI

Figure 5-4 Case 1 charging/discharging results

(ii) SOC Results

The SOC results are shown in **Figure 5-5**. The maximum SOC was 136 MWh. This indicates that the required battery capacity is 136 MWh. In addition, the final SOC is considerably larger than the initial SOC. This indicates that the generator output of 15 MW is excessive in clear weather.



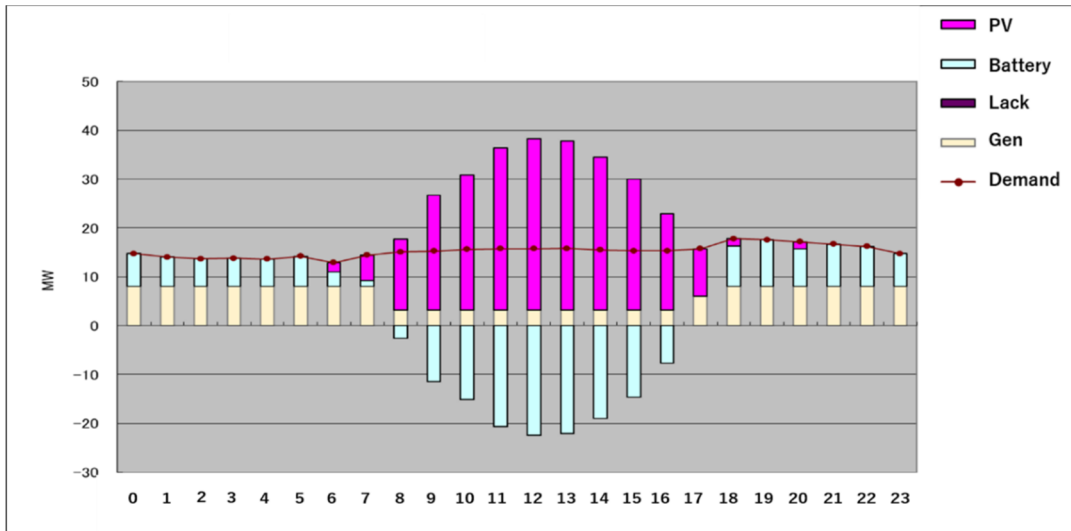
Source: Prepared by EETRI

Figure 5-5 Case 1 SOC results

2) Case 2: Generator output 8MW

(i) Charge and discharge results

Charge and discharge results are shown in **Figure 5-6**. As in Case 1, the maximum battery charge was approximately 22 MW.

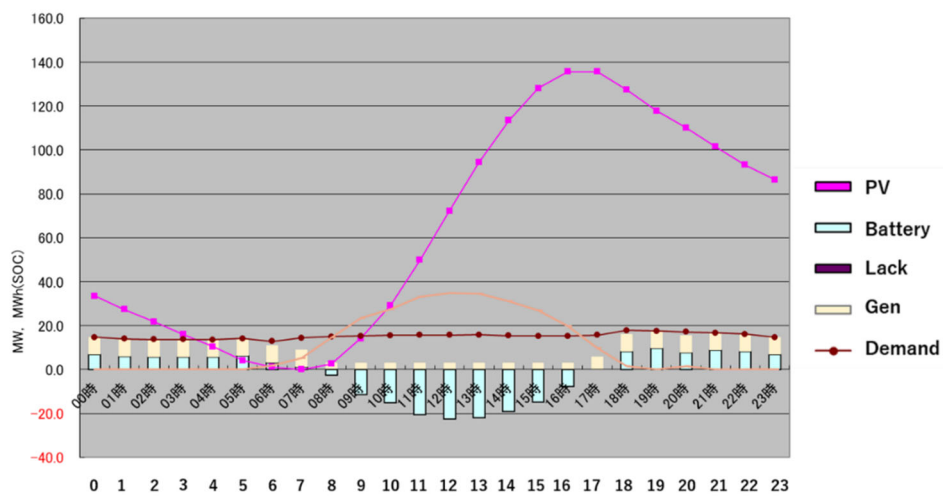


Source: Prepared by EETRI

Figure 5-6 Case 2 charging/discharging results

(ii) SOC Results

SOC results are shown in **Figure 5-7**. The maximum SOC was 136 MWh. This case also indicates that the required battery capacity is 136 MWh. The difference between the initial SOC and the final SOC has decreased compared to Case 1, but the final SOC is larger. This indicates that the generator output of 8 MW is slightly excessive in clear weather.



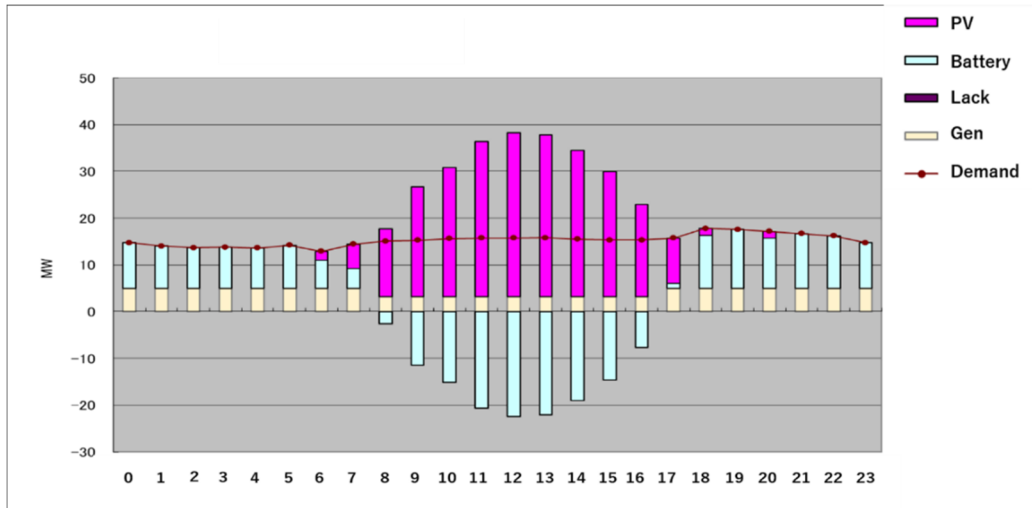
Source: Prepared by EETRI

Figure 5-7 Case 2 SOC results

3) Case 3: Generator output 5MW

(i) Charge and discharge results

Charge and discharge results are shown in **Figure 5-8**. As in Case 1 and Case 2, the maximum battery charge was approximately 22 MW.

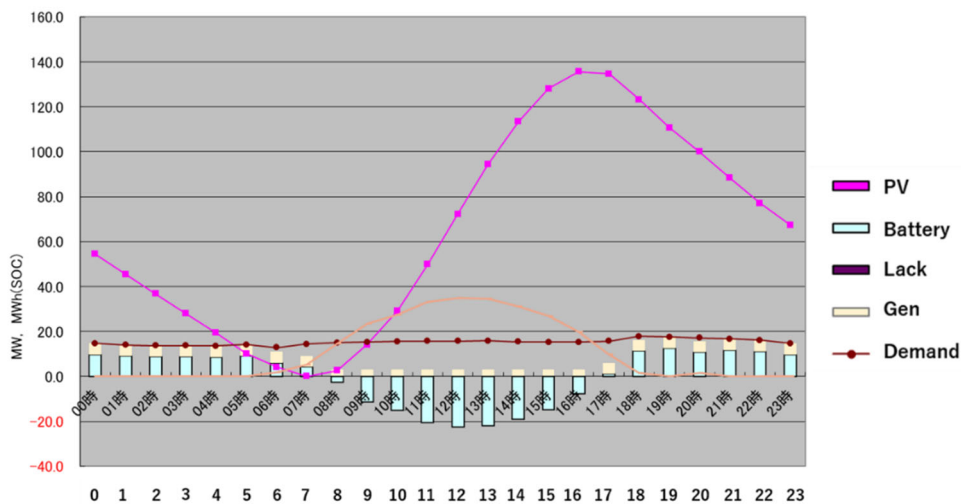


Source: Prepared by EETRI

Figure 5-8 Case 3 charging/discharging results

(ii) SOC Results

SOC results are shown in **Figure 5-9**. The maximum SOC was 136 MWh. This case also indicates that the required battery capacity is 136 MWh. In addition, the initial and final SOC were close to each other. This indicates that the generator output of 5 MW is almost adequate in clear weather.



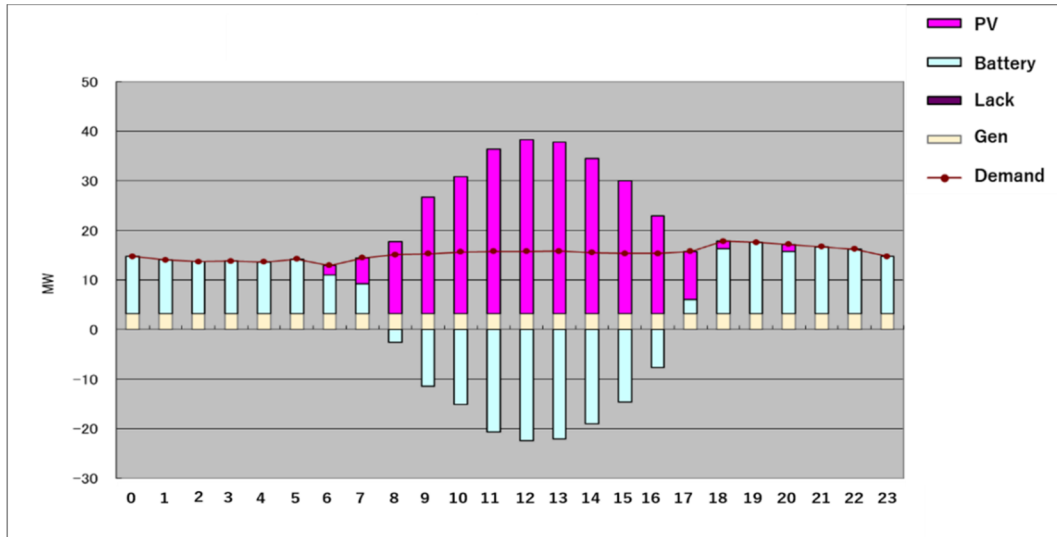
Source: Prepared by EETRI

Figure 5-9 Case 3 SOC results

4) Case 4: Generator output 3.2MW

(i) Charge and discharge results

Charge and discharge results are shown in **Figure 5-10**. As in Case 1, Case 2, and Case 3, the maximum battery charge was approximately 22 MW.

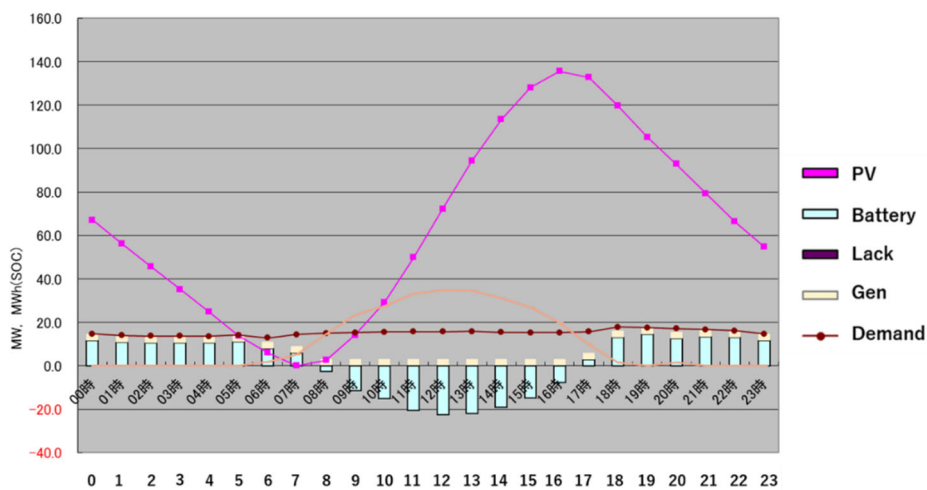


Source: Prepared by EETRI

Figure 5-10 Case 4 charging/discharging results

(ii) SOC Results

SOC results are shown in **Figure 5-11**. The maximum SOC was 136 MWh. This case also indicates that the required battery capacity is 136 MWh. In addition, the final SOC was slightly smaller than the initial SOC. This indicates that the generator output of 3.2 is slightly smaller in clear weather.



Source: Prepared by EETRI

Figure 5-11 Case 4 SOC results

(2) Examination of the case of PV output 0

The maximum battery capacity was considered as 136 MWh.

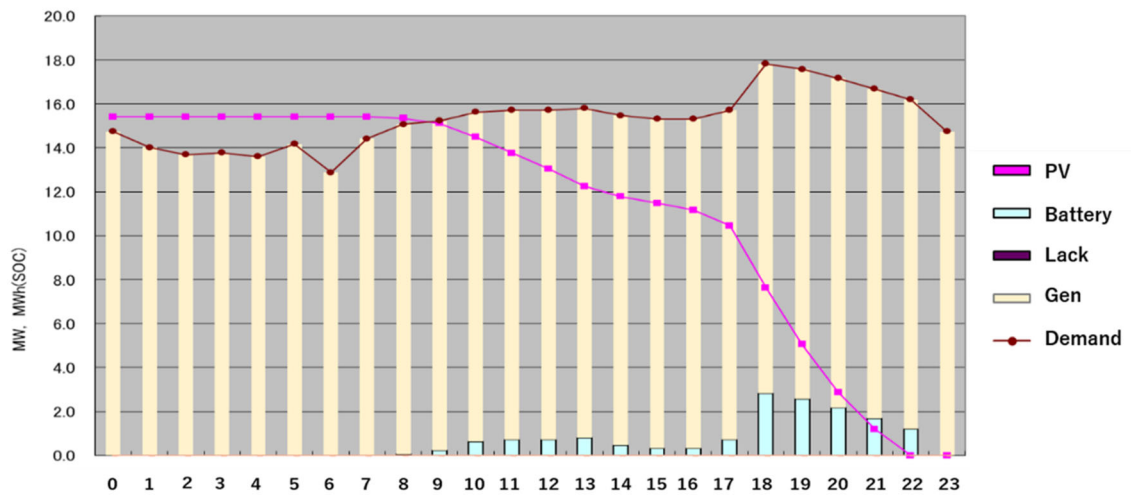
1) Case 5: Generator output 15MW

SOC results are shown in **Figure 5-12**. The initial SOC was 15.4 MWh. If the initial SOC is 15.4 MWh or higher, it can be supplied.

Figure 5-13 shows the case where the initial SOC (the value at 23:00 the previous day) is 136 MWh, the maximum battery capacity. Since the final SOC is 120.6 kWh, the daily discharge is 15.4 MWh.

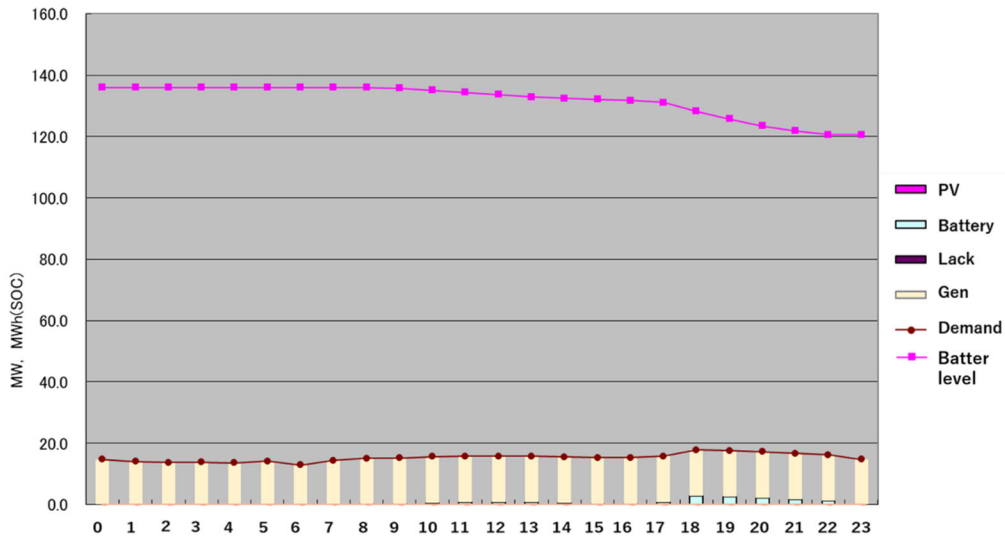
Therefore, if the initial SOC is set to 136MW and the generator output is set to 15MW, this indicates that the PV system can supply power for approximately 8.8 days even if the PV output is zero. This is calculated by,

$$136 \text{ [kWh]} \div 15.4 \text{ [kWh/day]} = 8.8 \text{ [days]}$$



Source: Prepared by EETRI

Figure 5-12 Case 5 SOC Result 1

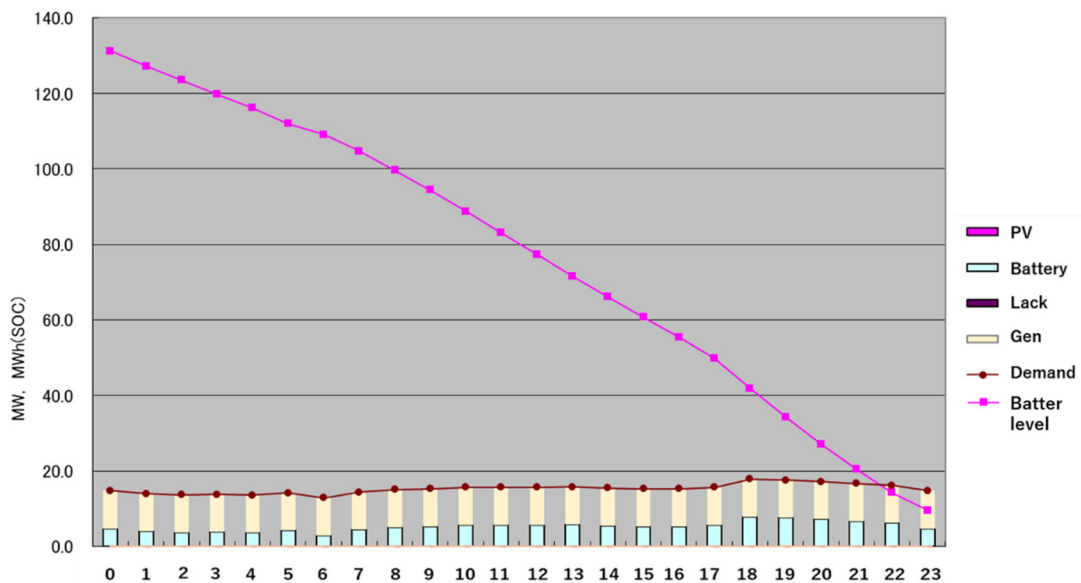


Source: Prepared by EETRI

Figure 5-13 Case 5 SOC Result 2

2) Case 6: Generator output 10MW

SOC results are shown in **Figure 5-14**. The initial SOC (value at 23:00 the previous day) was set at 136 MWh, the maximum battery capacity. There was no supply shortage, but the final SOC was close to 0.

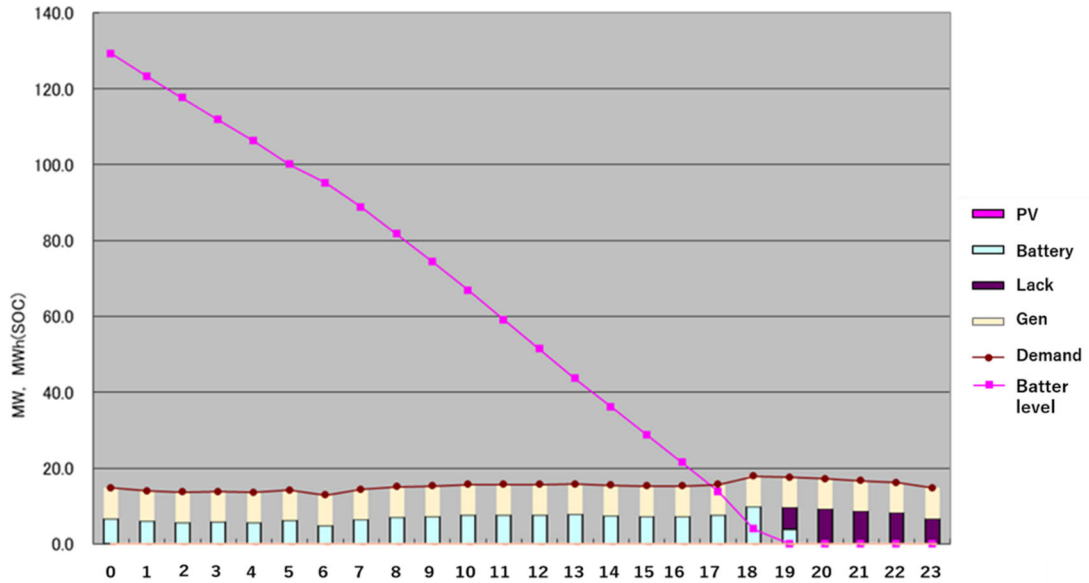


Source: Prepared by EETRI

Figure 5-14 Case 6 SOC results

3) Case 7: Generator output 8MW

SOC results are shown in **Figure 5-15**. The initial SOC (value at 23:00 the previous day) is set to 136 MWh, the maximum battery capacity. The supply becomes insufficient after 19:00, so the generator output must be increased after 19:00 (the figure shows the case where the generator output is not increased).



Source: Prepared by EETRI

Figure 5-15 Case 7 SOC results

1.20. Result

The PV data was also based on the data obtained and was adjusted for a maximum PV output of 35 MW to be consistent with the results of the tidal flow calculations. The PV data was also adjusted so that the maximum PV output was 35 MW to be consistent with the tidal flow calculation results. Using these data, EETRI calculated the required battery capacity by battery charge/discharge simulation. Simulations were performed for cases with generator outputs (other than PV) of 15 MW, 8 MW, 5 MW, and 3.2 MW. As a result, the required battery capacity was calculated to be 22 MW and 136 MWh in all cases. The required battery capacity of 22 MW is consistent with the tidal flow calculation results.

In the case of zero PV output, it was shown that batteries can supply power for more than one day when the generator output is 10 MW or more. Even if the generator output is less than 10 MW, the battery can supply enough power by increasing the generator output in the middle of the day.

Conclusion.

In CARICOM countries, diversifying the energy mix by introducing renewable energy as a long-term, major economic solution can reduce dependence on imported fossil fuels and ensure long-term energy security.

Here EETRI analyze the energy sector on St. Kitts and demonstrate how energy security can be achieved by installing large-scale PV as a renewable energy technology to cover base load.

We collected data on renewable energy, electricity demand and power systems on St. Kitts and used these data to perform a grid system stabilization simulation using Micro Grid Designer, a tool to assist in the analysis of power systems.

In conclusion, battery charge/discharge simulations were performed on St. Kitts Island using a daily load curve with a peak daytime load of 15.7 MW and a PV curve with a maximum output of 35 MW, and the required battery capacity was calculated to be 22 MW and 136 MWh.

The required battery capacity of 22 MW is consistent with the tidal current calculation results. In addition, the tidal current calculations confirmed that even with 35 MW of PV installed, there is no heavy tidal current in the grid, and the voltage distribution is within the appropriate values.

However, since the voltage at the terminal N34 node drops below 0.9 p.u., it became clear that measures such as the installation of voltage regulating equipment were necessary. In fact, it is necessary to measure and confirm whether voltage drops are occurring.

On the other hand, it was verified that the planned large-scale photovoltaic installation will contribute significantly to the stable supply of electricity, lower generation costs, and improve the environmental impact of the region.

Description of the Grid Analysis Simulation Tool (Supplement)

The power system simulator *Micro Grid Designer* is a numerical analysis tool for power transmission and distribution systems developed (and partially under development) by the Energy and Environment Technology Research Institute (EETRI) for power system engineers and practitioners.

Its main application is to determine the generator output that minimizes fuel cost by optimizing the supply-demand balance for the entire planning time, given a group of generators and their load for the planning period in the target power system, and to verify the operational stability of frequency and voltage by continuing to perform time-of-day tidal flow calculations for the system. The system is then used to verify the operational stability of frequency and voltage by performing time-of-day tidal flow calculations. As a generator group, renewable energy and batteries can also be considered.

In the power system field, many analyses software have been developed, but with the recent development of smart grid technology and the expansion of renewable energy, there is a need to develop simplified tools that can be used by non-specialized engineers as well as more sophisticated system analysis for power distribution systems. The development of such tools has been a major challenge in recent years.

The power system simulator *Micro Grid Designer* has been developed based on the following concept

- (1) The system analysis tool will contribute to more advanced power supply-demand balance analysis and frequency and voltage fluctuation analysis, mainly for small- and medium-scale power distribution systems such as microgrids.
- (2) The Excel-based input/output and arithmetic operation interface gives the software user-friendly functions and makes it easy to use for non-specialized engineers.

The power supply-demand balance analysis is treated as an optimization problem that incorporates real operational conditions and uses generally known efficient solution methods.

Micro Grid Designer performs economic load dispatch (ELD) and tidal flow calculations (power flow) in multiple cross sections. In this software, EETRI named the multi-stage economic load distribution (Multistage ELD) and the multi-stage tidal flow calculation (Multistage Power flow). In multistage economic load dispatch, given a group of generators and the total load for the planning period in the target power system, the effective power output of the group of generators that minimizes the fuel cost is determined by optimizing the supply-demand balance for the entire planning time.

In the multistage tidal current calculation, the effective power output of a group of generators

determined by the multistage economic load dispatch is used to sequentially perform time-of-day tidal current calculations to calculate the bus line voltage and branch tidal currents.

Renewable energy sources (RES) and batteries can also be considered as a group of generators. Batteries absorb the supply-demand imbalance of the entire grid by adjusting the amount of recharge and discharge.

Micro Grid Designer is a tool with the ability to perform multi-stage economic load dispatch and multi-stage tidal flow calculations in sequence, as described above, but when applied to a single cross-section, it can also be used to perform commonly used economic load dispatch and tidal flow calculations independently.

The above is an overview of the power system simulator MicroGrid Designer. The details are described in detail in the ELD, LFC, and power flow analysis formulations and solutions in the English report.

Other Appendices and References

See the Appendix for references to the work to be performed in the tasks described here.

- (1) Interim Report April 27, 2020 (Appendix A)
- (2) Explanatory materials for the formulation and solution of power system analysis (Appendix B, Appendix C, and Appendix J)

These appendixes are explanatory materials for meetings.

- (3) A close examination of the material collected on St. Kitts Island (Appendix D)
Information on power plants and generators, grid structure and attributes, and load and renewable energy status on St. Kitts Island collected during the first phase of the project.
- (4) Determination of Grid attributes on St. Kitts Island (Appendix E)
Data for PSS/E collected during the second round of travel and converted for Micro Grid Designer.
- (5) Follow-up tidal current calculations on St. Kitts Island (results only shown in Appendix A)
Results of 5 cases of tidal current calculations (single period) by MicroGrid Designer calculated based on the converted data from PSS/E
- (6) Confirmation of the grid plan for St. Kitts Island (Appendix F, Appendix G, Appendix H, Appendix I)
Information on power plants and generators, grid structure and attributes, and load and renewable energy (PV) information on St. Kitts Island collected during Tier III.

Appendix A: CARICOM Grid Stabilization Simulation Report (Interim), July 2019

Prepared by Energy and Environment Technology Research Institute

1. Outline of work to be performed

The following table of contents, categorized below, describes what was implemented in FY 2019.

- Implementation items and progress in this fiscal year's work
- Description of Grid Analysis Simulation Tool
- Tentative results of Grid analysis simulations
- Deliverables and Reports
- Issues for the future (FY2020 and beyond)

2. Implementation items and progress in 2019 work

1) Fundamentals of power system analysis

The following table summarizes the content and progress regarding the previously planned items and items added in the middle of the fiscal year 2019 work.

Lecture on the Basics of Electric Power System Analysis Since it was assumed that *Micro Grid Designer* (tentative name), a tool under development, would be used as the software for power system analysis, lecture materials were prepared explaining the contents of the work and the basics of power system analysis were discussed among the members of the project. The members of the project discussed the work with the basic issues of power system analysis at the meeting. (Jul 2019)

2) Scrutiny of collected materials on St. Kitts Island

The information on power plants and generators, grid structure and attributes, and load and renewable energy (PV and wind) information for St. Kitts Island collected during the first mission was reviewed to identify data that could be used in the grid analysis.

In addition, a system planning report for St. Kitts Island, "Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept. 2014 by leidos" (hereinafter referred to as the "Reference Material"), which was collected at the same mission, was reviewed as the main reference material.

3) Determination of Grid attributes on St. Kitts Island

Since the system information on St. Kitts Island collected during the first mission did not contain much practical numerical data that could be used immediately, EETRI proposed to utilize the data for PSS/E for this project as well, since the tidal current calculations were conducted using PSS/E, which was

mentioned in the reference material. PSS/E is an expensive system analysis tool developed by Siemens. As a result, data for PSS/E was collected during the second crossing, which could be converted into data for *Micro Grid Designer*.

4) A follow-up trial of tidal current calculations on St. Kitts Island

Based on the converted data from PSS/E, a schematic system configuration diagram of St. Kitts Island was created, and five cases of tidal current calculations (single period) (see below) were performed by *Micro Grid Designer*, and the results were examined.

The data for PSS/E is characterized by a loopless distribution system with 12 feeders coming out of one power plant, with a small solar PV at each feeder end and one large wind turbine (5.4 MW) in the middle of one feeder.

The reference material does not include details of the tidal current calculation results, so no comparison can be made. However, since the tidal current calculation results by *Micro Grid Designer* appear to be sufficiently valid, it is clarified that the data for PSS/E in the field can be utilized. However, since this data was created more than 6 years ago, it is necessary to keep in mind that the system will be updated in the future.

The five cases in which tidal current calculations (single section) were performed are shown below.

Case 0: Direct use of PSS/E conversion data (Figure 1)

Case 1: No Renewable Energy Pattern: Case with PV and Wind output set to 0

Case 2: Base conditions (Figure 2)

- PV 500 kW (SKELEC site) connected to Bus 4
- PV 700 kW (airport) connected to Bus 1 as with other thermal units
- Set PV and Wind output to 0 except for the above two locations

Case3: Base condition

- PV 500kW (SKELEC site) connected to Bus 3 (Canada_1219)
- PV 700 kW (airport) connected to Bus 1 like any other thermal power unit
- Set PV and Wind output to 0 except for the above two locations

Case4: Existing Plan Reflection00 (Figure 3)

- Add to Base Condition I and connect 35 MW of PV to Bus 1
- Battery (BESS) 34MWh/5.6MW connected to Bus 1 as well
- Set PV and Wind outputs other than the above to 0

5) Confirmation of the grid plan for St. Kitts Island

The data for the grid analysis (multistage economic load dispatch and multistage tidal current calculation) using *Micro Grid Designer* was prepared from the information on power plants and

generators, grid structure and grid attributes, and load and renewable energy (PV) information on St. Kitts Island during the third round of the trip.

The data for the grid analysis (multistage economic load dispatch and multistage tidal current calculation) using MicroGrid Designer was created, and although it is an assumption, six generators were added to confirm the planned installation of 35 MW of large-scale PV with batteries, the location information and line types of underground cables and aboveground transmission lines were collected (Figure 4), and weekly and load curve data were finalized.

(6) Grid analysis simulation on St. Kitts Island

After the above process, the preparation for the final grid analysis in this year's work was completed, and the optimal battery capacity in the St. Kitts Island and power system was determined and the multi-level economic load dispatch and multi-tidal current calculations were performed using *Micro Grid Designer* to develop the optimal dispatch and scheduling plan for the generator group and the batteries based on a weekly supply and demand scenario.

The optimal dispatch scheduling plan for generators and batteries was developed based on a weekly supply-demand scenario, and voltage stability was verified.

The details are described in the "Tentative Results of the Grid Analysis Simulation" below. These results demonstrate that *Micro Grid Designer* is a tool that can contribute to grid supply-demand planning and voltage stability evaluation.

3. Description of the simulation tool for Grid analysis

The power system simulator *Micro Grid Designer* is a numerical analysis tool for power transmission and distribution systems developed (and partially under development) by the Institute for Sustainable Energy Technologies for power system engineers and practitioners. Its main application is to determine the generator output that minimizes fuel cost by optimizing the supply-demand balance for the entire planning time, given a group of generators and their load for the planning time period in the target power system, and to verify the operational stability of frequency and voltage by continuing to perform time-of-day tidal flow calculations for the system. The system is then used to verify the operational stability of frequency and voltage by performing time-of-day tidal flow calculations. As a generator group, renewable energy and batteries can also be considered.

In the power system field, many analyses software have been developed, but with the recent development of smart grid technology and the expansion of renewable energy, there is a need to develop simplified tools that can be used by non-specialized engineers as well as more sophisticated system analysis for power distribution systems. The development of such tools has been a major challenge in recent years.

The power system simulator MicroGrid Designer has been developed based on the following concept
(1) The system analysis tool will contribute to more advanced power supply-demand balance analysis

and frequency and voltage fluctuation analysis, mainly for small- and medium-scale power distribution systems such as microgrids.

- (2) The Excel-based input/output and arithmetic operation interface gives the software user-friendly functions and makes it easy to use for non-specialized engineers.

The power supply-demand balance analysis is treated as an optimization problem that incorporates real operational conditions and uses generally known efficient solution methods.

Micro Grid Designer performs economic load dispatch (ELD) and tidal flow calculations (power flow) in multiple cross sections.

In *Micro Grid Designer*, EETRI named the multi-stage economic load distribution (Multistage ELD) and the multi-stage tidal flow calculation (Multistage Power flow).

In multistage economic load dispatch, given a group of generators and the total load for the planning period in the target power system, the effective power output of the group of generators that minimizes the fuel cost is determined by optimizing the supply-demand balance for the entire planning time.

In the multistage tidal current calculation, the effective power output of a group of generators determined by the multistage economic load dispatch is used to sequentially perform time-of-day tidal current calculations to calculate the bus line voltage and branch tidal currents.

Renewable energy sources (RES) and batteries can also be considered as a group of generators. Batteries absorb the supply-demand imbalance of the entire grid by adjusting the amount of recharge and discharge.

Micro Grid Designer is a tool with the ability to perform multi-stage economic load dispatch and multi-stage tidal flow calculations in sequence, as described above, but when applied to a single cross-section, it can also be used to perform commonly used economic load dispatch and tidal flow calculations independently.

The above is an overview of the power system simulator MicroGrid Designer. For more details, please refer to the ELD, LFC, and power flow analysis formulations and solutions in Chapters 3, 4, and 5 of the English report.

3. Tentative results of Grid analysis simulation

The following are two categories of the specifics of the (planned) items and progress in the FY2019 work and the simulation of the system analysis on St. Kitts Island, as described above.

- Determination of optimal battery capacity
- *Micro Grid Designer* for simulation of system analysis

1) Determination of optimal battery capacity

In the introduction of 35 MW of large-scale PV power generation, it is essential to take measures to deal with surplus power, and for this purpose, large-capacity batteries are usually installed in

conjunction with PV power generation. EETRI is currently developing a prototype of a tool (Figure 5) to equalize the electricity demand considering PV and batteries and have calculated the minimum required capacity of batteries without considering the margin ratio and SOC, the values of which are unknown, as shown below.

Based on the typical daily load pattern and solar output on St. Kitts Island, EETRI estimated the battery and minimum required capacity for each of the following three scenarios, varying the maximum hourly output of batteries. Here, the maximum solar output is assumed to be 35 MW, which is larger than the maximum load of 28.8 MW.

- 1) Scenario A (at maximum load): Maximum load 28.8MW
- 2) Scenario B (medium load): Maximum load 20.0MW
- 3) Scenario C (with small load): Maximum load 10.0MW

Note that scenarios in which the solar output is less than the load are excluded because there is no place for batteries.

The results, which are based on assumptions, are as follows.

- 1) Scenario A (at maximum load): minimum required capacity 19.943MWh
- 2) Scenario B (medium load): Minimum required capacity 75.548MWh
- 3) Scenario C (with small load): Minimum required capacity 159.785MWh

Tentative conclusions from the estimation results are as follows.

- (i) The battery capacity to accommodate all scenarios A, B, and C is too excessive.
- (ii) The battery capacity available for Scenarios B and C is also too excessive.
- (iii) Therefore, it is better to determine the battery capacity according to Scenario A. However, the battery capacity according to this scenario cannot handle Scenarios B and C. Therefore, in a situation where Scenarios B and C occur, it is necessary to respond by implementing solar output suppression.
- (iv) The optimal battery and minimum required capacity determined in Scenario A is approximately 20 MWh, and this optimal capacity is determined so that no excess power is generated at the maximum battery recharge/discharge rate of 8 MW.

Since the tool shown above is for simplified estimation of battery capacity, *Micro Grid Designer's* multi-stage economic load dispatch can also be used to determine the optimal battery and minimum required capacity daily (Figure 6). The results demonstrate that for Scenario A, the maximum battery recharge/discharge is 5.386 MW, and the minimum battery capacity is 14.840 MWh, demonstrating

that MicroGrid Designer's multi-stage economic load dispatch gives less minimum battery capacity. However, this is a result based on various assumptions, and recalculation is necessary to set conditions based on actual operation.

2) Systematic analysis simulation with *Micro Grid Designer*

(i) Multi-stage economic load distribution with *Micro Grid Designer*

Optimal dispatch and scheduling plans (on an hourly basis) for generator groups and batteries based on weekly supply and demand scenarios were developed for the following three cases.

In the three cases studied (Figure 9), one week of the representative month; the load profiles are different.

- case-1: 3/3/2019 3/9/2019 (1 week)
- case-2: 4/7/2019 4/13/2019 (1 week)
- case-3: 7/7/2019 7/13/2019 (1 week) Maximum load month

Here, PV power generation and surplus power measures are described as the common grid conditions used in the above three cases.

- Three PV units (35MW, 0.7MW, 0.5MW)

A representative one-week weather-controlled pattern was used as these power generation scenarios (Figure 8). The maximum output of large photovoltaic generation (rated at 35 MW) is limited to an effective value of 25 MW.

- Surplus Power Measures

As a countermeasure for excess power from solar power generation, "a regulating slack was installed to absorb the supply-demand imbalance with batteries, and excess power was channeled to the outside through this regulating slack" (Figure 7). However, since the maximum output of large solar power generation was limited to 25 MW, only a small amount of outflow from the adjustment slack was observed in all three cases studied.

In addition, the recharging of batteries was restricted to daylight hours and the maximum output (maximum recharge/discharge) was limited to 5 MW with reference to the determination of the optimal battery capacity. This results in a maximum estimate of the minimum required capacity of the batteries of maximum charge (5MW) *7h = 35MWh. However, the actual (optimal) minimum required capacity based on the simulation results was

- case-1: maximum output 5.00 MW, minimum required capacity 18.16 MWh
- case-2: maximum output 3.97 MW, minimum required capacity 10.28 MWh
- case-3: maximum output 3.02 MW, minimum required capacity 5.65 MWh

These results provide a basis for determining that the minimum required capacity of storage batteries in the three cases studied is approximately 18 MWh.

- Multi-stage tidal current calculation by *Micro Grid Designer*

Using the effective power output of generators and batteries obtained from the above multi-stage economic load dispatch results, multi-stage tidal current calculations were conducted for one week (168 sections per hour) for the three cases studied.

As shown in the table below, voltage stability was verified using the maximum and minimum voltage values obtained, and it was confirmed that, although there were some deviations, the values were generally within the specified range (0.95 to 1.05 p.u.).

However, the voltage values shown in this table were calculated based on data that does not reflect the system attributes (impedance, etc.) considering the recent system renewal on St. Kitts Island, so they are not accurate.

The voltage value and effective power loss from the multistage tidal flow calculation are voltage value min [p.u.] voltage value max [p.u.] effective power loss [%].

- case-1 : 0.96087 1.06998 4.699 See Figure 10.
- case-2 : 0.95743 1.07247 4.655 See Figure 11.
- case-3 : 0.92619 1.05684 4.591 See Figure 12.

4. Deliverables and reports

The deliverables and reports corresponding to the "Items Implemented and Progress Made in the Current Year's Work" are as follows.

(1) Formulation and solution of power system analysis

Lecture material for lectures (Chapter 4 of the English report)

(2) Examination of collected materials on St. Kitts Island

The Renewable Infusion Study, St. Kitts Electricity Company Limited, Sept. 2014 by leidos, a grid planning report with information on power plants and generators, grid structure and grid attributes, and load and renewable energy (solar and wind) information for St. Kitts Island collected during the first round of trips. Limited, Sept. 2014 by leidos".

(3) Determination of Grid attributes on St. Kitts Island

Data for PSS/E collected during the second round of travel and converted for *Micro Grid Designer*.

(4) A follow-up study of tidal current calculations on St. Kitts Island

Results of five cases of tidal current calculations (single period) by *Micro Grid Designer*,

calculated based on the converted data from PSS/E (shown in the chart below).

(5) Confirmation of grid plan for St. Kitts Island

Information on power plants and generators, grid structure and attributes, and load and renewable energy (PV) information on St. Kitts Island collected during Tier III.

(6) Grid analysis simulation on St. Kitts Island

The results of the tidal current calculations performed by *Micro Grid Designer* on the St. Kitts Island power system are summarized in the English report. The multi-stage tidal current calculations are illustrated in the figure at the end of this report.

5. Issues for the future (FY2020 and beyond), etc.

In FY2020, EETRI will conduct grid analysis simulations using *Micro Grid Designer* based on the grid information collected on St. Kitts Island, demonstrate the validity of the application, make generator dispatch scheduling for grid planning, and analyze frequency and voltage variations to verify operational stability. The operational stability is verified by analyzing the frequency and voltage fluctuations.

One important base material that has been effective is data for PSS/E. In the past on-site data collection, it was possible to collect information on generator configuration, RE installation plans, load information, etc., but it became clear that it was difficult to collect practical grid attributes, such as impedance. Therefore, to expand the project to other islands in the future, there are still issues to be solved, such as how to collect practical grid attributes, whether data for PSS/E or equivalent data exist, and whether cooperation from local counterparts in preparing grid maps with the latest numerical information can be obtained.

Below is an image of the inputs and outputs of the microgrid analysis tool that will be created. This analysis tool will be completed by late FY2021.

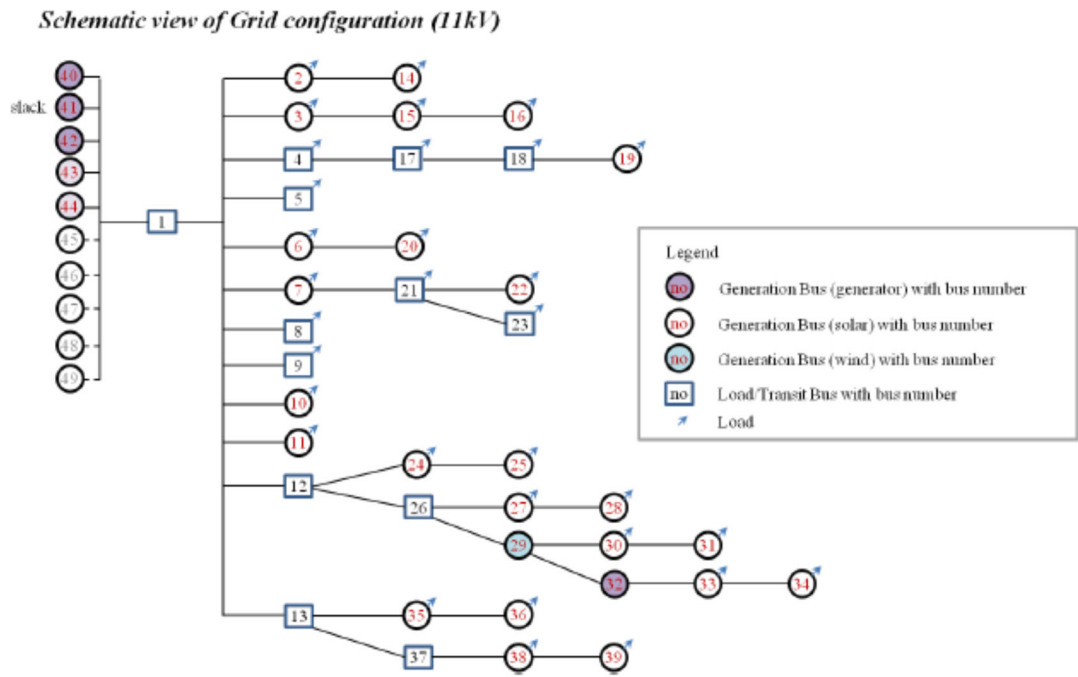


Figure 1: Schematic system diagram for single period tidal current calculation (case-0)

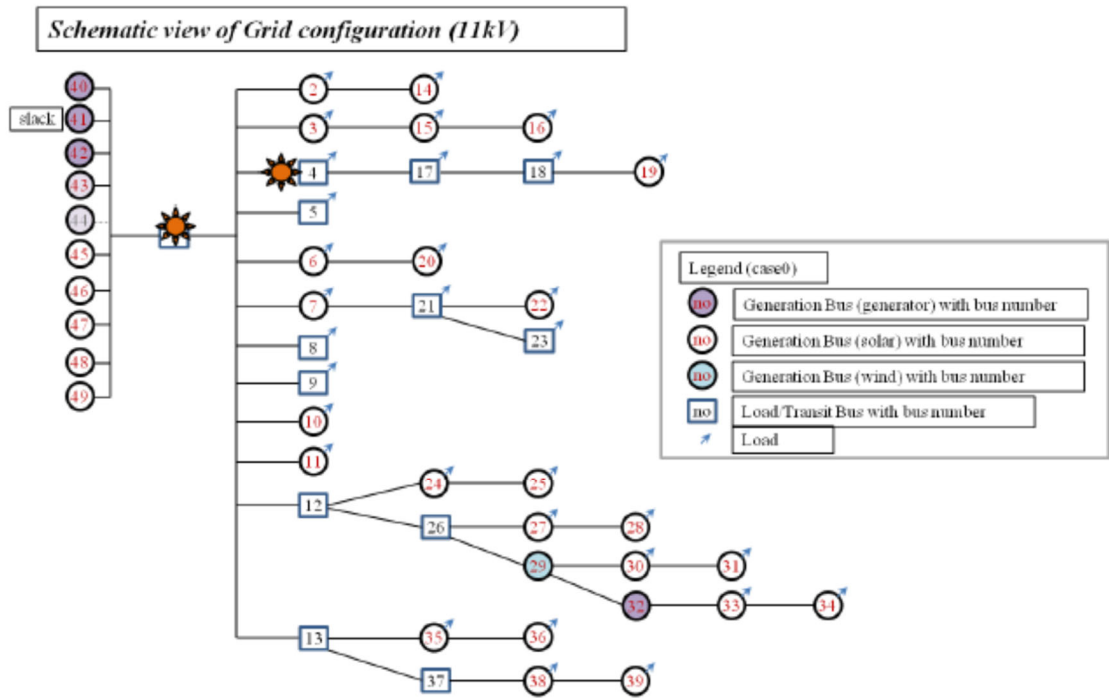
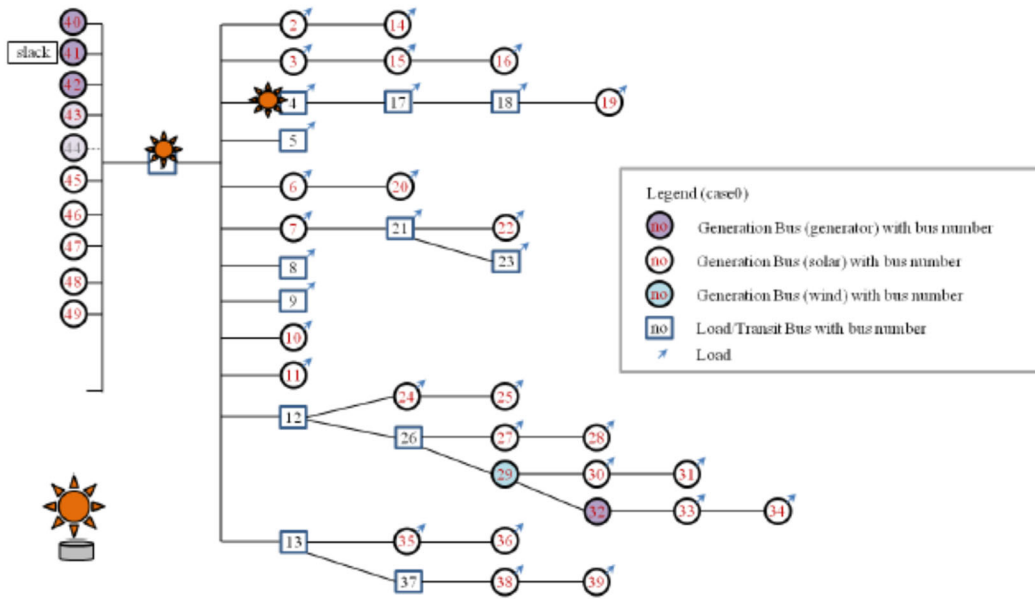


Figure 2: Schematic system diagram for single period tidal current calculation (case-2)

Schematic view of Grid configuration (11kV)



PVBT: PV + BT

Figure 3: Schematic system diagram for single period tidal current calculation (case-4)

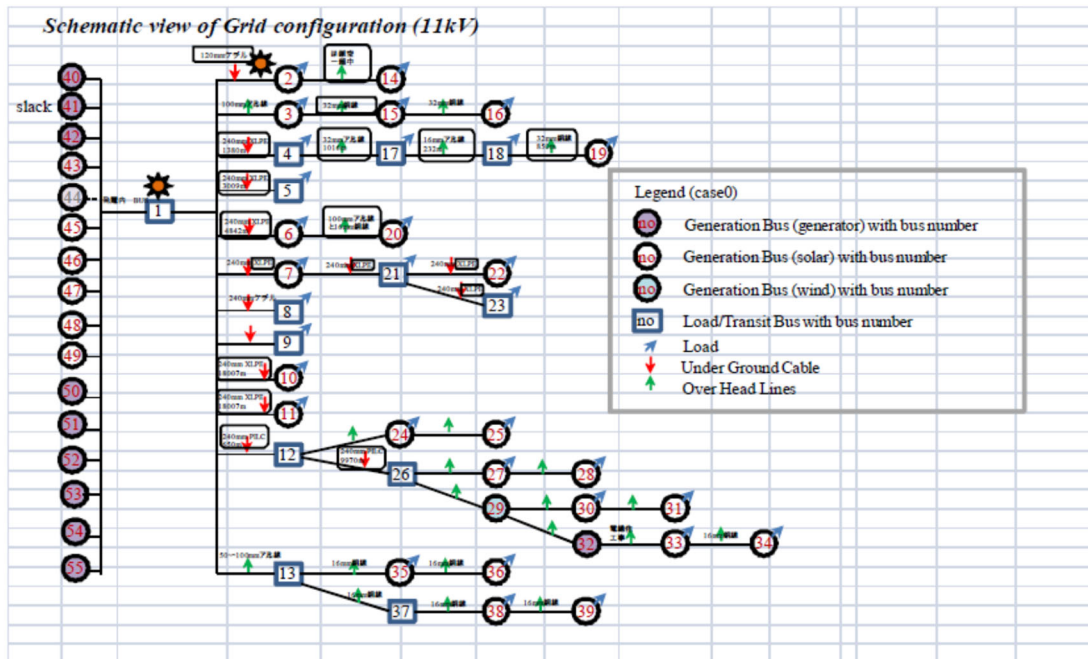


Figure 4: Results of survey of transmission lines and line types in the St. Kitts system

PV,蓄電池を考慮した電力需要の均し処理

(蓄電池の最大出力より、蓄電池容量を算定)

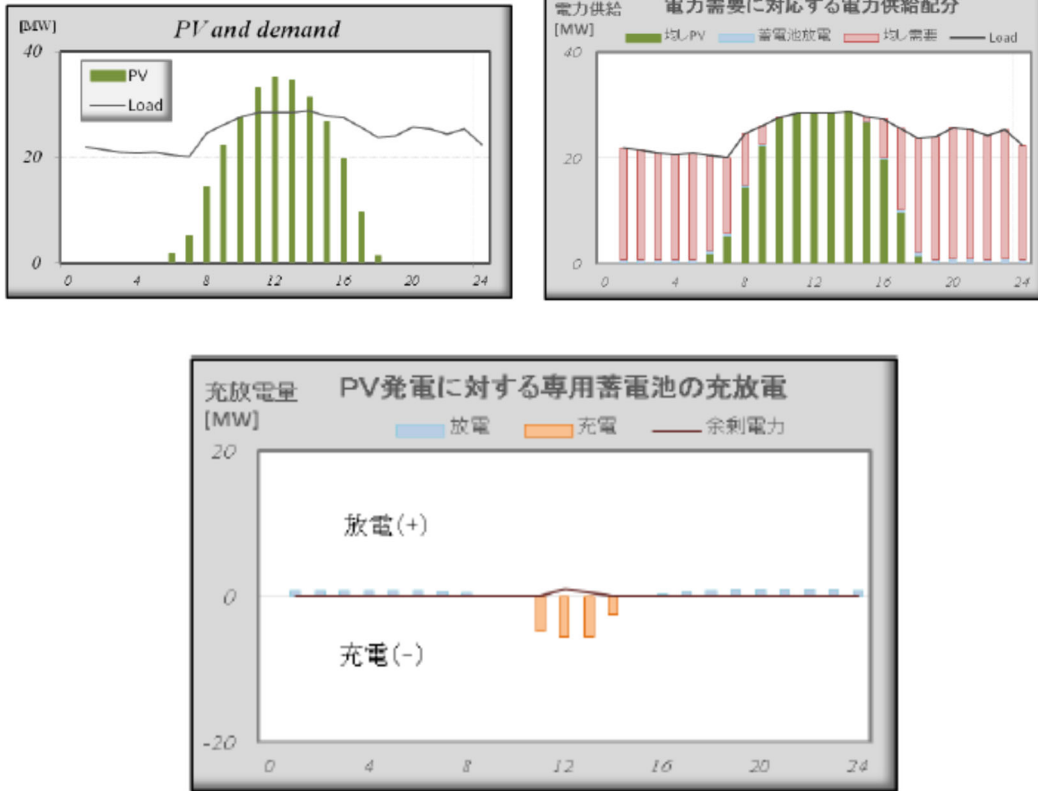
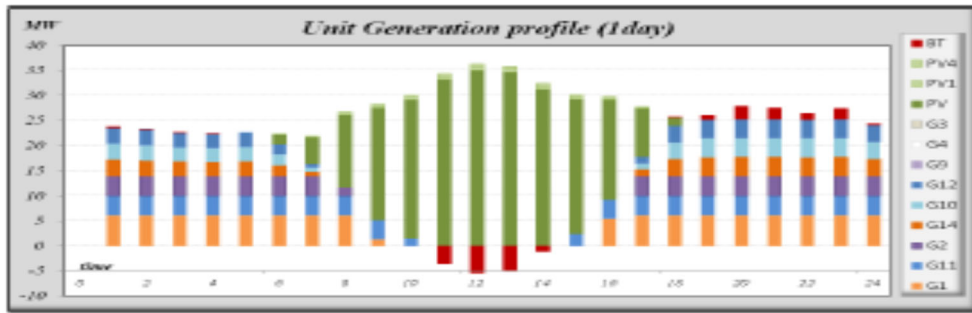


Figure 5: Diagram of the equalization process for electricity demand considering PV and batteries



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

Figure 6: Diagram of determining optimal batteries and minimum required capacity through multi-stage economic load dispatch

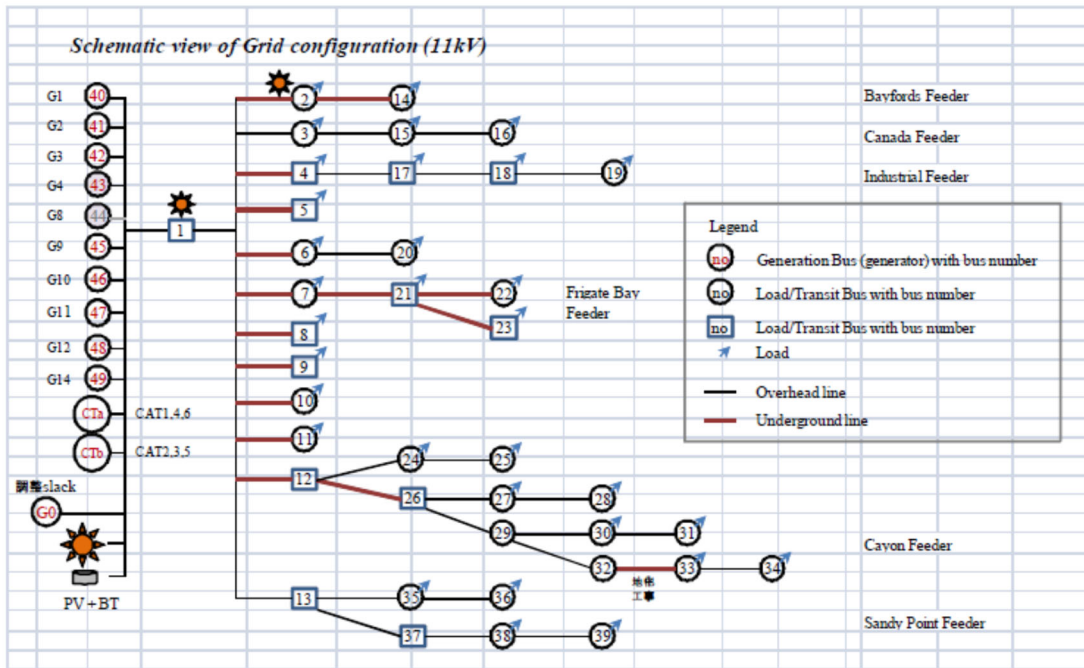
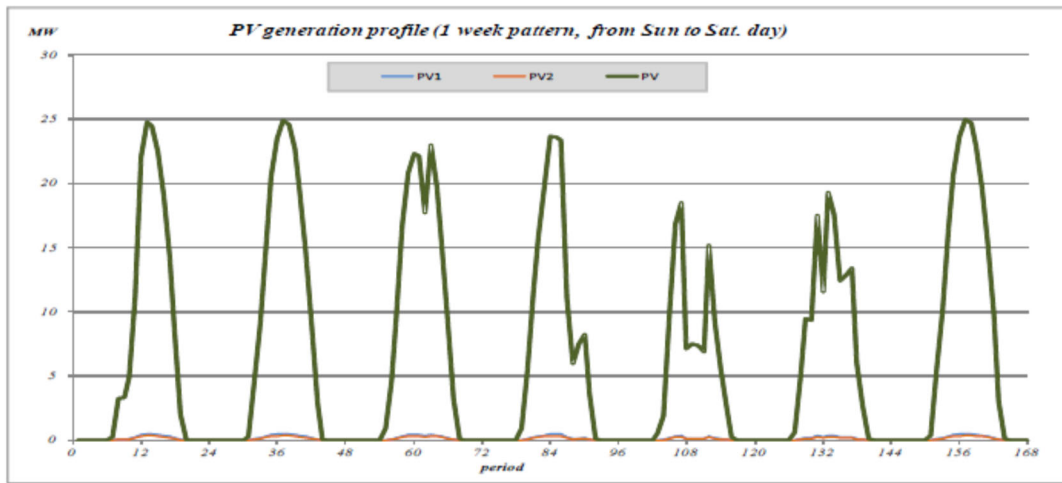


Figure 7: Schematic system diagram used in the grid analysis simulation (current system needs to be confirmed)



日	Partial Rain
月	Fine
火	Partially Cloud
水	Partial rain
木	Rain
金	Cloudy
土	Fine

Figure 8: Example of a PV scenario used in a grid analysis simulation

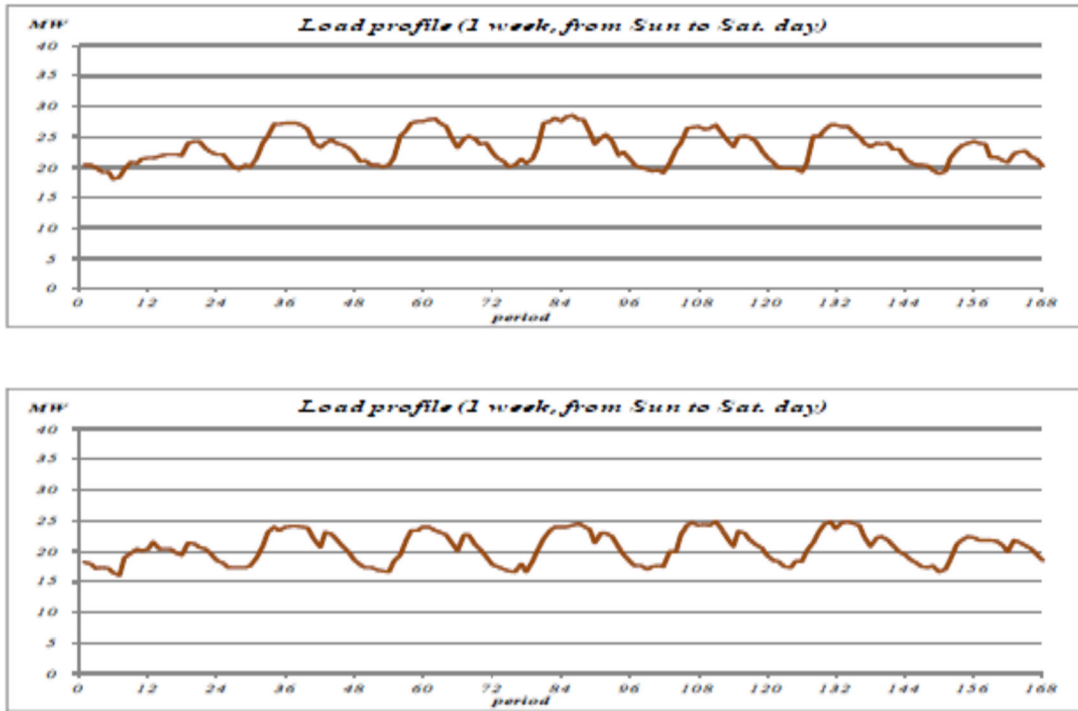


Figure 9: Load patterns used in the grid analysis simulation (obtained from the field)



Figure 10: Time-series transition image of generator and active power output and bus line voltage values based on multi-stage tidal current calculation (case-1)

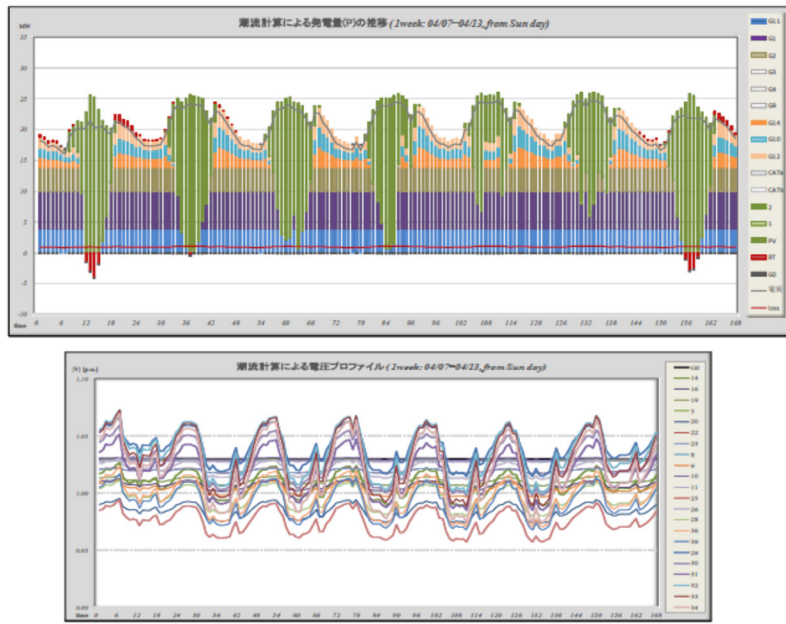


Figure 11: Time-series transition image of generator and active power output and bus line voltage values based on multi-stage tidal current calculation (case-2)

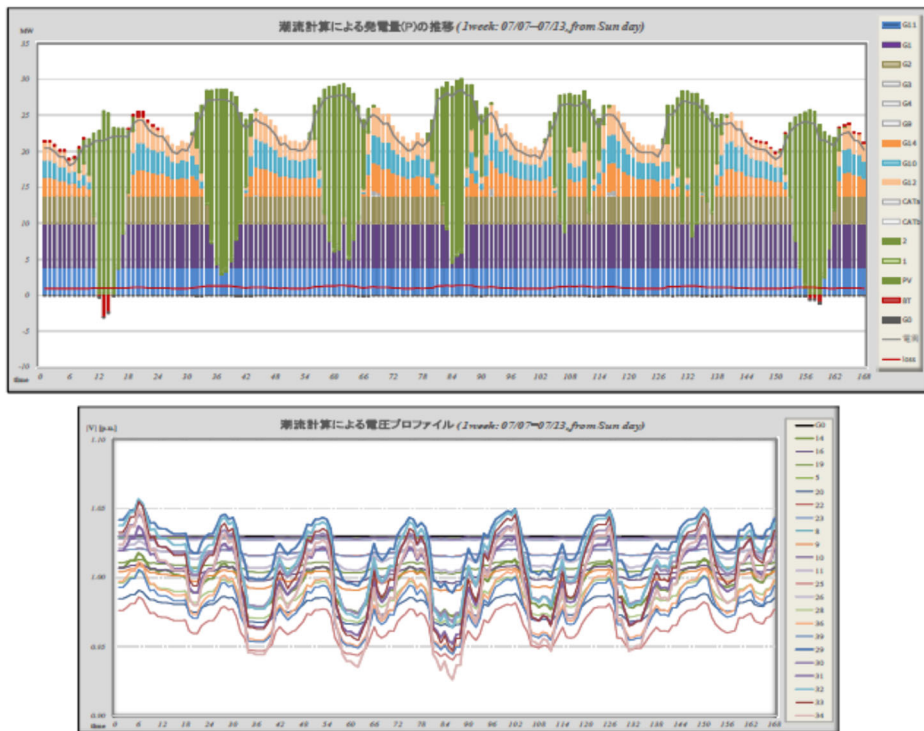


Figure 12: Time-series transition image of generator and active power output and bus line voltage values based on multi-stage tidal current calculation (case-3)

Appendix B: Microgrid Analysis Formulation and Solution Method (meeting materials)

Prepared by Energy and Environment Technology Research Institute

1. Outline

Microgrid analysis can be broadly divided into transient analysis and steady-state analysis. Transient Analysis traces the state of the grid from the moment of a major change in the grid (e.g., accident, interruption, etc.) in microseconds, using differential equations that describe the grid state. Static Analysis is the analysis at the point where the transient state advances for a certain period and then settles down to a certain state and requires the steady-state values to be obtained by numerical analysis in a specified discrete-time cross-section.

This section presents a general discussion of the following representative steady-state analysis.

- (1) Tidal Current Calculation (Power Flow)
- (2) Economic Load Dispatch
- (3) Dynamic Economic Load Dispatch
- (4) Optimal Power Flow
- (5) Start-up and shutdown planning issues (omitted)

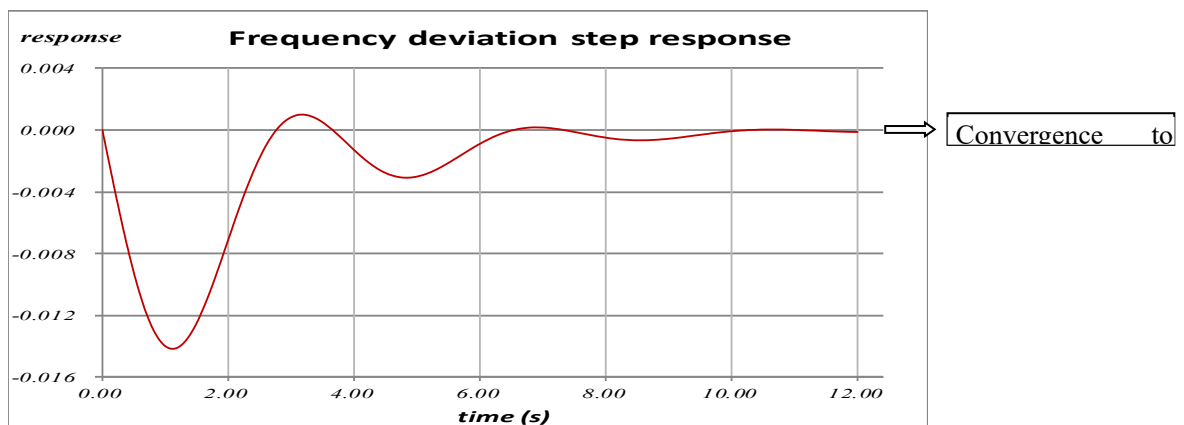


Figure1: Example of frequency deviation fluctuation analysis after a large load change occurs in the grid (LFC)

2. AC Circuit Basics

AC circuits use voltage and current, which are waves, as state quantities. Waves, as is clear from the solution of the differential equation describing a single oscillation

It can be written in the form $C \exp(j(\omega t + \theta))$, which is a general mathematical expression.

Here, the

$$\exp(j(\omega t + \theta)) = \cos(\omega t + \theta) + j \sin(\omega t + \theta) \quad \text{Euler's formula}$$

Angular velocity $\omega = 2\pi f$ f : frequency, θ : phase (radian), C : Amplitude

Thus, the state quantities of an AC circuit are complex, and one state quantity has two state values. That is, amplitude and angle in polar coordinate representation, and real and imaginary parts in rectangular coordinate representation.

- Complex number representation of AC terms (Dot denote complex numbers)

Voltage (Voltage) $\dot{V} = |\dot{V}| e^{j\theta}$

Voltage value $|\dot{V}|$ (voltage magnitude) and voltage phase angle θ

Current $\dot{I} = |\dot{I}| e^{j\delta}$

Power $\dot{S} = |\dot{S}| e^{j\phi} = P + jQ$

P: active power Unit: W

Q: reactive power Unit: VAR

Impedance $\dot{Z} = r + jx$

r: Resistance

x: Inductive resistance (reactance)

Admittance $\dot{Y} = G + jB, \dot{Y} = 1 / \dot{Z}$

G: Conductance

B: Susceptance

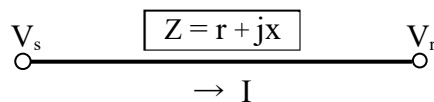
- Basic Formulas for AC Circuits

1) Ohm's Law

$$V = Z\bar{I}$$

$$I = YV$$

2) Voltage drop equation for branch: $V_s - V_r = -Z \cdot I$



3) Kirchhoff's Current Law (KCL)

The sum of the currents flowing into and out of the node is zero.

The sum of the power flows into and out of the node is zero.

4) Kirchhoff's Voltage Law (KVL)

The sum of the voltage changes in the closed circuit is zero.

5) Equations for power, voltage, and current

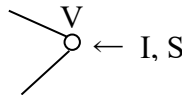
$$S = \dot{S} = \dot{V} \dot{I}^* = |\dot{V}| |\dot{I}| e^{j(\theta - \delta)}$$

(The upper* symbol denotes conjugate complex numbers; $\dot{V} \dot{I}^* = |\dot{V}| |\dot{I}| e^{-j\delta}$)

$$|S| = |\dot{V}| |\dot{I}| = \sqrt{P^2 + Q^2} \text{ (Apparent power: unit VA)}$$

$$I = (S / V)^*$$

Injected current and injected power at node (\dot{S} : injected Power, \dot{I} : injected Current)

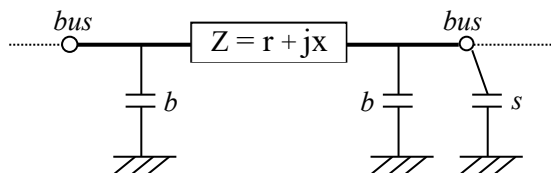


3. Microgrid tidal equation

A transmission and distribution microgrid are a power transmission line designed to meet the power demand of consumers. This transmission line is regarded as a network consisting of nodes (bus) and branches connecting nodes (branches) set up with certain criteria, and the power flow equations derived from the network structure are solved to analyze their power and current flows and voltage distributions.

The nodes of the network are broadly classified into generation nodes and load nodes, and furthermore, generation nodes are generally classified into slack busbars that specify complex voltages and PV-specified busbars that specify generation P-values and $|\dot{V}|$ values. All nodes specify the power load (P and Q values). Branches are given Impedance (resistance and reactance) as branch attributes. The general π -type grid model also allows for the consideration of a Capacitor (capacitor with susceptance b or s), which is responsible for supplying and absorbing reactive power to the nodes and branches.

π -type equivalent circuit of a power transmission line



The power flow equations for the transmission/distribution microgrid constructed by such a model are developed by applying the basic formulas of the AC circuits of the previous period, based on an

undirected graph consisting of a group of buses and a group of branches with bidirectional characteristics. Specifically, the procedure of integrating Ohm's law $I_{sr} = (\dot{V}_s \dot{V}_r) \dot{Z}_{sr} = (\dot{V}_s \dot{V}_r) \dot{Y}_{sr}$ at one branch $s-r$ into the overall structure by applying Kirchhoff's current law can be repeated.

The resulting power flow equation is a simultaneous (nonlinear) quadratic equation for the complex variables V_i ($i=1\dots n$), as shown below. n), as shown below.

$$S_i = -V_i - I_i^* = \sum_j -V_i - Y_{ij}^* - V_j^* \quad (i=1\dots n)$$

Where, V_i is the voltage at node i , $S_i = P_i + jQ_i$ is the specified injected power (sum of generation (+) and load (-)), I_i is the same injected current, Y_{ij} is the i,j components of the overall system admittance matrix and n is the number of nodes.

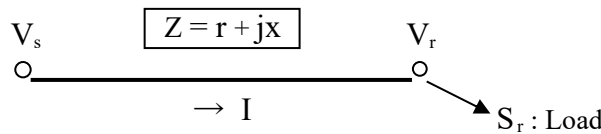
Thus, solving the power flow equation given all S yields the total node voltage V , which can be used to obtain the unknown generation, branch currents and power flow (Power Flow), and system losses.

However, since the tidal equation cannot be solved as is (undefined), it is necessary to specify a single complex voltage by introducing a slack busbar. In addition, the actual number of variables is somewhat smaller than $2n$, since the generation P -value and $|V|$ values may be specified for the generation node as the PV specification bus bar. Correspondingly, the number of tidal equations is also reduced to be the same as the number of variables. That is, the number of tidal equations is 0 and 1 for the slack and PV specified matrices, respectively, since the generation P and Q are unknown for the slack matrix and the generation Q is unknown for the PV specified matrix.

Since there is no direct analytical method for solving the power flow equations, which are a series of nonlinear equations, iterative numerical methods such as the Newton-Raphson method and the Backward/Forward method are applied.

4. Example of analysis of tidal equation

(1) The simplest tidal current equation (2-bar tidal current equation)



- Ohm's law

$$V_s - V_r = \dot{Z} \dot{I}, \quad \dot{I} = (\dot{V}_s \dot{V}_r) \dot{Z}$$

- Injected power law at receiving end r (tidal equation)

$$S_r \dot{V}_r \dot{I}^* = \dot{V}_r ((\dot{V}_s \dot{V}_r) \dot{Z})^* = (\dot{V}_r \dot{V}_s^* \dot{V}_r^2) \dot{Z}^*$$

(Specific example)

With respect to the voltage at the transmission end s (slack bus bar), and with respect to the voltage at the

$$\dots V_s = E (\cos(0) + j\sin(0)) = E \text{ (E: fixed)}$$

The voltage at the receiving end r (load bus bar) is ,

$$\text{Let } V_r = V (\cos\theta + j\sin\theta).$$

And in particular, if $Z=jx$ ($x=1$) (neglecting resistance), then

$$\begin{aligned} S_r = P + jQ &= \{ VE (\cos\theta + j\sin\theta) - V^2 \} / (-j) \\ &= VE(j\cos\theta - \sin\theta) - jV^2 \end{aligned}$$

because of

$$P = -VE\sin\theta$$

$$Q = VE\cos\theta - V^2$$

The binary simultaneous nonlinear equations for V and θ were obtained as

(2) Analysis example by *Micro Grid Designer*

Micro Grid Designer's Power Flow employs the Newton-Raphson and Backward/Forward methods. Especially for large transmission systems, a new method is introduced to the sparse Newton-Raphson method to achieve a fast solution method. The maximum size of the target system is 50,000 bus lines.

Here, the dense Newton-Raphson method for small and medium size is used to analyze the standard Grid model for the Ward-Hale 6 busbar.

Before that, *Micro Grid Designer* uses Per-Unit System (p.u.) for input/output data, which should be explained.

- 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:

$$\text{Per-unit value} = \text{quantity in some unit} / \text{base quantity}$$

Generally, the following two base quantities are given:

V_{base} : The base voltage quantity

S_{base} : 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

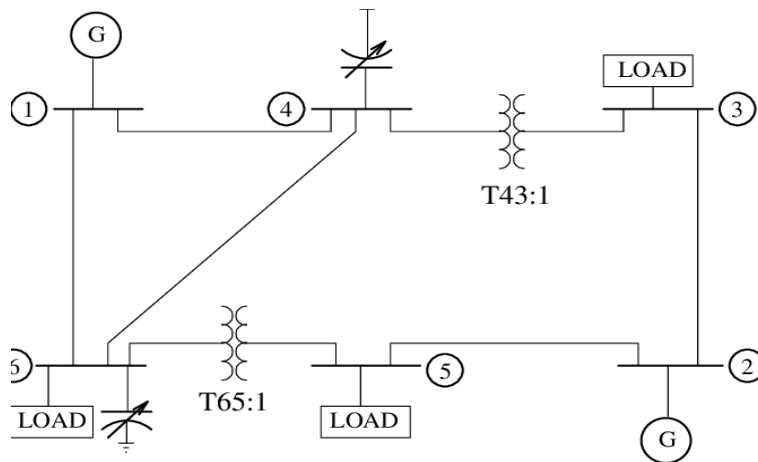
V_{base} : 1 to 132 kV

S_{base} : 100 MVA

So, voltage magnitude 1.0 in p.u. means 100V.

If the power generation and load data (P, Q) are given in units MW and MVA_r respectively, conversion of these values into Per-Unit System is simply done by dividing them by 100(MVA).

Ward-Hale 6-bar model and input data



Input data

```
// Node(bus) data
// Load P,Q Generation P,Q Voltage, initial/specified value
//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:Generation busbar, L:Load busbar, -:Passing/forking point (load busbar with load
0)
// s - susceptance of nodal capacitor (see π-type equivalent circuit)
// cond - VT: slack bus bar, PV: PV specified bus bar, PQ: PQ specified bus bar
// Specify Pl and Ql (usually negative values) for all bus bars.
// Specify |V| and θ for the slack busbar.
// Pg and |V| are specified for the PV specified bus bar.
// Pg and Qg (usually positive values) are specified for the PQ specified generator busbar.
// Leave the Pg and Qg columns blank for the PQ specified load bus bar.
// Note that the power generation (Pg,Qg) of the slack bus bar and the power generation
(Qg) of the PV specified bus bar are
// Determined by tidal current calculations.
// Voltage - All other values are assumed to be initial values for the Newton-Raphson method.
```

```

// 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 (* extension per unit length)
// x - reactance (* extension per unit length)
// b - half susceptance of branch capacitor (see pi-type equivalent circuit)
// tap - transformer existence ( 0: not exist, 1,2: exist )
// If a transformer is present, enter its tap ratio.
// The tap ratio is the transformation ratio according to the forward (tap=1) and reverse
(tap=2) directions.

```

output (data)
See Output-1

5. Economic Load Dispatch (ELD)

Economic load dispatch is performed for the purpose of providing output commands to a group of generators in the system based on demand (load) forecasts. In economic load dispatch, the effective power output value of each generator is determined such that the total fuel cost is minimized. This effective power output value can be used as the P-value of the PVdesignated bus bar when performing the tidal flow calculation for the target system.

The economic load dispatch problem is an optimization problem to find the effective power output of a group of generators that satisfies the supply-demand balance and minimizes the total fuel cost at a certain forecast point in time. Since the quadratic formula for the effective power output is usually used for the fuel cost of generators, the economic load-sharing problem belongs to the quadratic programming problem. However, if a linear expression of the effective power output is used for the fuel cost of the generators, the same problem becomes a linear programming problem.

Formulation of ELDs by quadratic programming problems

$$\min_{\{P(i)\}} \sum_i \text{FuelCost}(i)$$

$$\text{FuelCost}(i) = a P_{ii}^2 + b P_{ii} + c_i \text{ for unit-}i$$

\sum_i indicates the sum with respect to generators (units) ($i=1, \dots, ng$, ng : number

of generators).

s.t. $\sum_i P_i = D(t)$ (Power balance constraint)

$P_{\min,i} \leq P_i \leq P_{\max,i}$ (upper and lower bound constraints for P_i)

where

$D(t)$: demand at a given estimated time- t

P_i : active power generation of unit- i (variable)

$P_{\min,i}$, $P_{\max,i}$: bounds of P_i for unit- i

There are several methods for solving economic load dispatch, such as the quadratic programming problem-only solution method and the iso- λ method, but *MicroGrid Designer* uses an ultra-fast exact solution method that takes advantage of the simple structure of this quadratic programming problem.

- Analysis example of the quadratic programming problem ELD

```
// Input data
5 // #units

// a b c Pmin Pmax
G1 10 2 6 0 5
G2 8 4 4 0 5
G3 6 2 2 2 0 5
G4 4 3 0 0 5
G5 2 1 2 0 5

16 // demand

// Output data
(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
```

6. Dynamic Economic Load Dispatch

Dynamic ELDs are a multi-period extension of the single-period ELDs described above. However, the ELDs are not solved for each period in sequence, but rather an improved method is used that

introduces constraints between periods so that the solutions in adjacent periods are consistent. This has the advantage of enabling long-term dispatch scheduling that considers the operability of a group of generators. In addition to generators, batteries and renewable energy sources can also be considered.

Dynamic ELD is a large-scale nonlinear optimization problem for the entire period and requires an efficient method for solving it; *MicroGrid Designer uses a* generic interior point method module that takes advantage of the sparsity of the problem in question to find the optimal solution at high speed.

- **Multi-stage ELD formulation**

$$\min_{\{P(t)\}} \sum_t \sum_i \text{FuelCost}(t,i)$$

$$\text{FuelCost}(t,i) = a P_{ii}(t)^2 + b P_{ii}(t) + c_i \text{ for unit-}i \text{ at time-}t$$

\sum_i indicates the sum with respect to generators (units) ($i=1, \dots, ng$, ng : number of generators).

\sum_t indicates the sum with respect to periods ($t=1, \dots, T$, T : number of periods).

s.t. $\sum_i P_i(t) = D(t)$ for each time- t (Power balance constraint)

$P_i(t)$ upper and lower bound constraints:

$$P_{\min,i}(t) \leq P_i(t) \leq P_{\max,i}(t) \text{ for each unit-}i \text{ at every time-}t$$

where

$D(t)$: demand at time- t

$P_i(t)$: power generation of unit- i at time- t (variable)

$P_{\min,i}(t), P_{\max,i}(t)$: bounds of $P_i(t)$ for unit- i at time- t

Ramp constraints:

$$rl(i) \leq P_i(t) - P_i(t-1) \leq ru(i) \text{ for each unit-}i \text{ at every time-}t$$

where $rl(i)$: max. ramp down < 0 ,

$ru(i)$: max. ramp up > 0 for unit- i

Inventory constraints:

$$\sum_t P_i(t) = \text{lot}(i) \text{ or } \leq, \geq$$

where $\text{lot}(i)$: final lot size in a time interval for some unit- i

This constraint is used primarily for batteries.

- Example of Dynamic ELD Analysis

System configuration

8 thermal power generators (G1 to G8): Maximum output 60 to 800MW

(Input data)

Initial generation (MW), fuel cost quadratic function coefficients (a, b,c)

(Constraint data)

Min/max output (MW), max ramp-down, ramp-up (MW/h)

One battery model (BT): 1, simple battery model with a maximum output of 150 MW

(Input data)

Operating hours: Daytime discharge (+) (10-16h), Nighttime charge (-) (1-4h,21-24h)

(Constraint data)

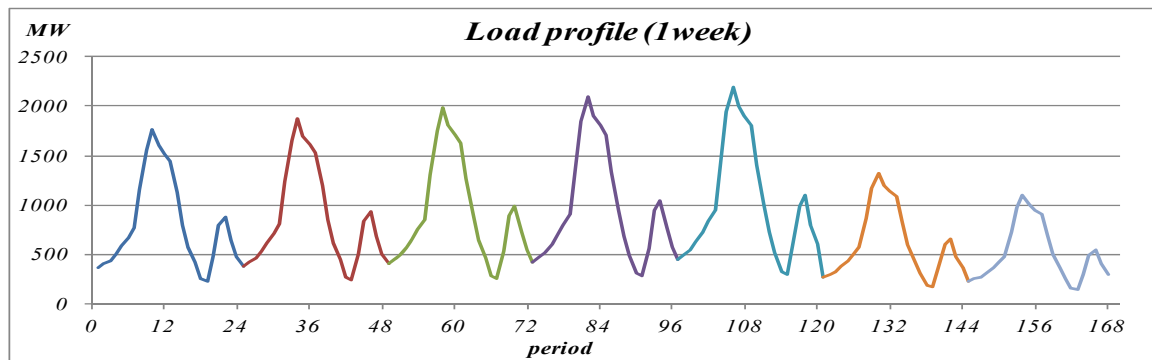
Max. ramp down: -50MW/h, max.ramp up: +50MW/h

Total charge/discharge = discharge - 0.7*charge = 0 for every 24 hours

Analysis period: 1 week (168h), unit period: 1h

Load profiles for the analysis period

Created using load data used in the 8-unit start-up and shutdown planning problem.



- Analysis Results

Number of variables $P_i(t)$: $1512 = 9 \times 168$

HI/LO limit constraints for variables : 1512×2

Number of equation constraints : $168 + 7$

(Power balance constraints + charge/discharge constraints)

Number of inequality constraints : 3008 (Ramp constraints)

Calculation time : 1.80 sec

See Output-2 and the generation profiles for each unit for the optimal solution.

(Input data)

```
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. 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 // Discharge (+)
- 1 4 -150. -0.0 0.7 // Charge (-)
- 21 24 -150.-0.0 0.7 // Charge(-)
end
// inventory constraints
// unit ope lotFinal step
BT = 0.0 24 // discharge - 0.7 charge = 0 at every 24 hours
end
```

7. Optimal Power Flow (OPF)

Economic load dispatch was based on load forecasting to find the effective power output value of the generator that minimizes the total fuel cost. This has the disadvantage that the network configuration of the grid is not considered and load dispatch including grid losses cannot be performed.

Optimal tidal flow calculation is a method that compensates for such shortcomings of economic load dispatch and can find the effective power output value of a generator that minimizes the total fuel cost under the load balance constraints of the system. The optimal tidal flow calculation can also be given functions such as imposing branch power flow restrictions (tidal flow constraints) to control congestion or changing the evaluation function to analyze different objectives.

Optimal tidal current computation is a large-scale nonlinear optimization problem with many nonlinear and constraint conditions, and an efficient method is required for its solution. The GMRES method is also introduced to obtain the optimal solution at high speed.

The variables in the optimal tidal flow calculation are the active and reactive power of the generating bus lines and the complex voltage of each bus line. As with the economic load dispatch, the optimal tidal flow calculation is performed only for the single period for which the load forecast was performed.

- Formulation of optimal tidal flow calculation (fuel cost minimization)

$$\min_{\{V,P,Q\}} \sum_i \text{FuelCost}(i)$$

$$\text{FuelCost}(i) = a P_{ii}^2 + b P_{ii} + c_i \text{ for unit-}i$$

\sum_i indicates the sum with respect to generators (units) ($i=1..ng$, ng : number of generators).

s.t.

(upper and lower bound constraints on variables)

$$P_{\min,i} \leq P_i \leq P_{\max,i} \text{ (upper and lower constraints for } P_i \text{) } (i=1..ng)$$

$$Q_{\min,i} \leq Q_i \leq Q_{\max,i} \text{ (upper and lower constraints for } Q_i \text{) } (i=1..ng)$$

$$V_{\min,j} \leq V_j \leq V_{\max,j} \text{ (upper and lower bound constraints for } V_j \text{) } (j=1..n,$$

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 constraint)

$$\sum_j \dot{V}_i \dot{Y}_{ij}^* \dot{V}_j^* = \dot{G}_i + \dot{L}_i \quad (j=1..n, i=1.... n)$$

where

V_i : complex voltage of node- i

Y_{ij} : complex (i,j) element of nodal admittance matrix

... G_i : complex generation at node- i

$P_k + jQ_k$ if the node is a generation bus- k , 0 otherwise.

L_i : complex load at node- i (fixed)

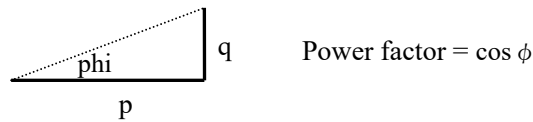
(Power factor constraint)

$$\gamma_{\min,k} \leq (Q/P)_k \leq \gamma_{\max,k} \quad (k: \text{subset of generation buses, given})$$

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



(Branch power flow constraint)

$$|P_{ij}| \leq P_{\max,ij} \quad (i, j : \text{subset of Branches, given})$$

where

P_{ij} : active power flow in branches i - j

$P_{\max,ij}$: upper bound of P_{ij}

- Analysis example of optimal tidal flow calculation

The EAST 10-unit system model published by the Institute of Electrical Engineers of Japan was used to obtain the optimal solution that minimizes the fuel cost with the *Micro Grid Designer* optimal tidal current calculation module. The EAST 10-unit system model is a system simulating the Kanto area with 10 generators and 47 bus lines. The EAST10 system model is a 10-generator 47-mainline system simulating the Kanto area.

Figure: EAST10 aircraft system model and impedance map

Input data: List after figure

Output data: Output-3

IEEJ EAST10 aircraft system model and impedance map

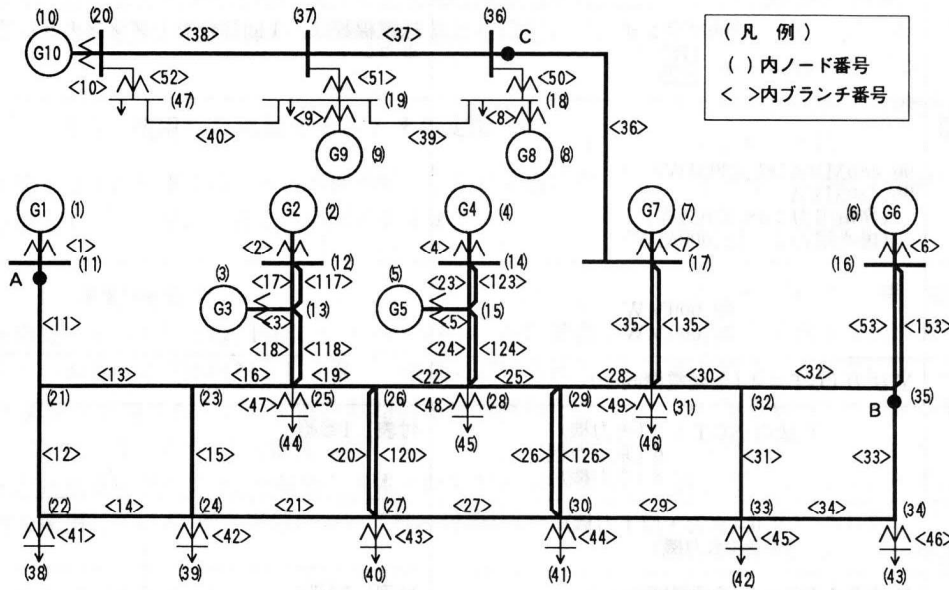


図4.1 電気学会 EAST10機系統モデル系統図(ノード番号, ブランチ番号, 事故点含む)

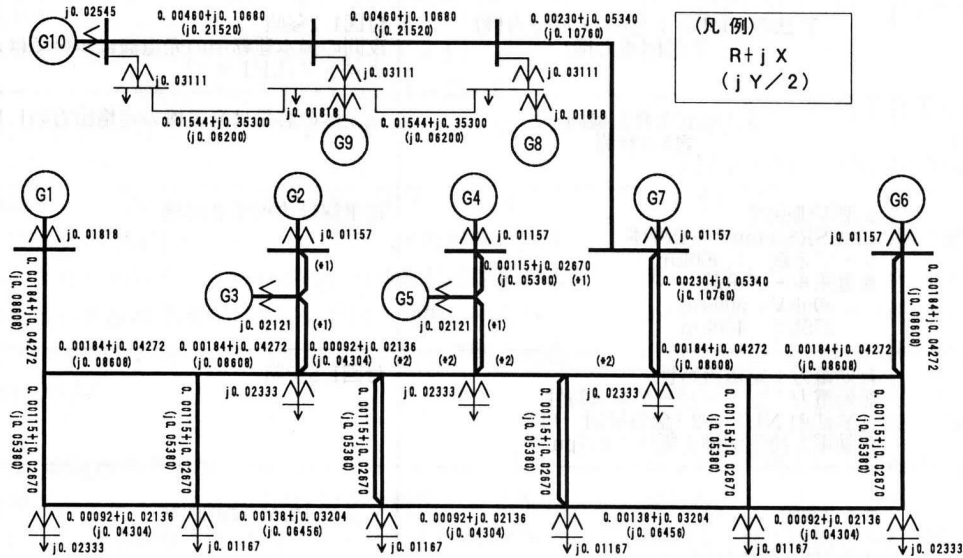


図4.2 電気学会 EAST10機系統モデルインピーダンスマップ

注：送電線定数は2回線トータルの値

単位：pu (1000MVAベース)

(Input data)

// 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 0.000000 0.018180 0.000000 1 1.128210 0
T02 2 12 0.000000 0.011570 0.000000 1 1.128210 0
T03 3 13 0.000000 0.021210 0.000000 1 1.070000 0
T04 4 14 0.000000 0.011570 0.000000 1 1.128210 0
T05 5 15 0.000000 0.021210 0.000000 1 1.075000 0
T06 6 16 0.000000 0.011570 0.000000 1 1.128210 0
T07 7 17 0.000000 0.011570 0.000000 1 1.128210 0
T08 8 18 0.000000 0.018180 0.000000 1 1.025640 0
T09 9 19 0.000000 0.018180 0.000000 1 1.025640 0
T10 10 20 0.000000 0.025450 0.000000 1 1.128210 0
T11 22 38 0.000000 0.023330 0.000000 1 0.952380 0
T12 24 39 0.000000 0.011670 0.000000 1 0.952380 0
T13 27 40 0.000000 0.011670 0.000000 1 0.952380 0
T14 30 41 0.000000 0.011670 0.000000 1 0.952380 0
T15 33 42 0.000000 0.011670 0.000000 1 0.952380 0
t16 34 43 0.000000 0.023330 0.000000 1 0.952380 0
t17 25 44 0.000000 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 the IPM formulation.
// If not, dual feasibility will not be improved and IPM convergence will degrade.

END

Supplementary Data Standard Models for Microgrid and Other Analyses

● Output-1 (Tidal current calculation)

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 ($|V|, \text{angle}$) for all buses was printed in polar/rad form: $|V| \angle (\text{phase angle})$

*) The complex current injection (I) for each bus was printed in rectangular form,

computed as the sum of the 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 was printed (right: $P+jQ = V*\text{conj}(I)$; 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 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 was printed in rectangular form.
- *) The complex current (Is) for each bus was printed in rectangular form ($I_s = (j*sus)*V$).
- *) The complex power computation (P,Q) for each bus was printed ($P+jQ = V*\text{conj}(I_s) \rightarrow P=0$).
- *) 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 was printed in rectangular form (Ploss,Qloss). power loss = $S_a - S_c$

*) The total branch power loss in all branches was printed.

*) Also the total P,Q losses in the grid were printed if some nodal capacitances exist.

total P,Q losses = total branch power losses - total P,Q in 'Nodal capacitance flows'.

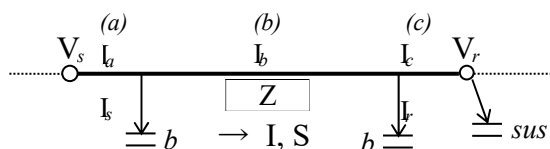
This value was compared with that in 'Nodal Solution'. If they are nearly equal, 'ok' is printed, '?' otherwise.

*) Output form $I_a \rightarrow I_b \rightarrow I_c$ $S_a \rightarrow S_c$ 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 circuit



$$I_b = (V_s - V_r) / Z$$

$$I_a = \dot{I}_b + \dot{I}_s \quad \dot{I}_c = \dot{I}_b - \dot{I}_r \quad \dot{I}_s = \dot{Y}_b \dot{V}_s, \quad \dot{I}_r = \dot{Y}_b \dot{V}_r, \quad \dot{Y}_b = jb \text{ (admittance of the capacitor)}$$

$$S_a = V_s \cdot I_a^* - S_c = V_r \cdot I_c^* \quad (S = P + jQ)$$

(note) $\dot{I}_a = -\dot{I}_c$, if $b = 0$

● **Output-2 (Multistage economic load dispatch)**

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	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	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	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	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	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	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	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	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	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	0.0000	0.0000	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	0.0000	0.0000	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	0.0000	0.0000	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	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	0.0000	0.0000	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	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	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	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	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	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	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	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	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	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	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	0.0000	0.0000	185.3148	300.0000	-5.3148 480.0000 5351.4896
1005.0000												

----- (Abbreviation)

136 16 0.0000 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 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 0.0000 250.0000 245.0000 -0.0000 495.0000 5494.5123
1005.0000

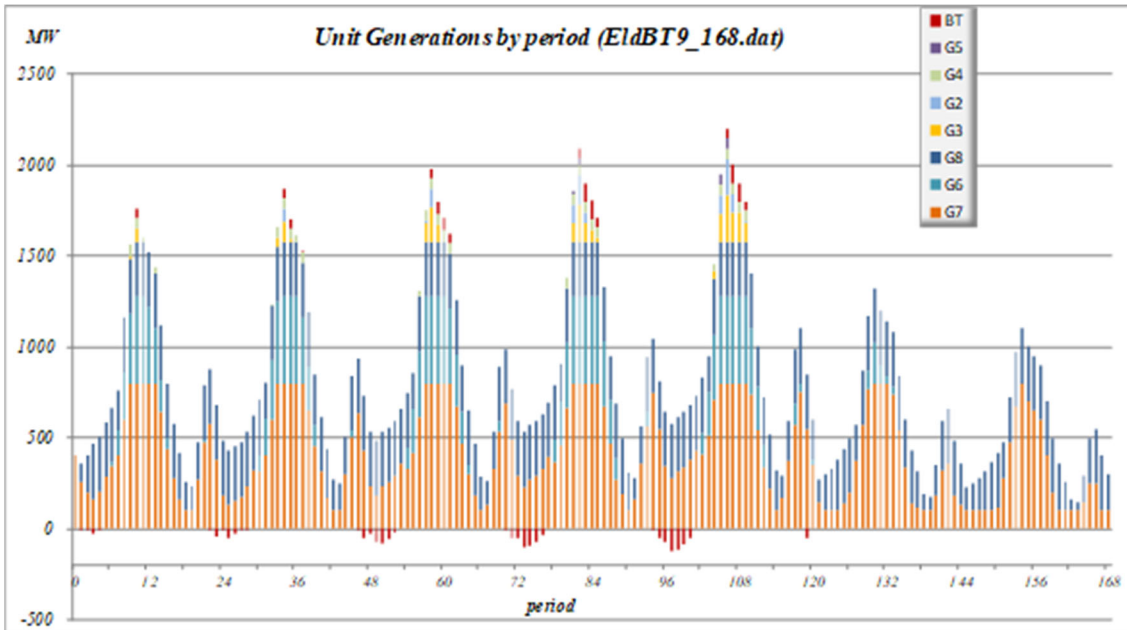
166 22 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 250.0000 300.0000 -0.0000 550.0000 6088.5153
1005.0000

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

***Generation profiles for each unit (G2-G8,BT)**



G1 has never generated power due to high fuel costs (same as the result of the start-up shutdown plan).

● Output-3 (Optimal Tidal Current Calculation)

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 0.0006
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

Appendix C: Fast Solutions for Large-Scale Distribution System Tidal Flow Calculations

March 2020

Prepared by Energy and Environment Technology Research Institute

1. Outline

Many methods have been proposed for calculating tidal currents in power systems, including the early Gauss-Seidel and Implicit Zbus Gauss methods, the Newton-Raphson method, and its modified versions (e.g., the Decoupled method), the Backward/Forward method and its variants, and others. Backward/Forward method and its variants. Although performance comparisons of these methods have been conducted in the past, they are insufficient because they are old and do not target large-scale systems, and it is not clear how fast they can solve up to what scale of systems. Therefore, in this paper, we will compare the performance of the standard solution method again based on the current computer environment and software technology. For this purpose, we will develop a new program that does not depend on the existing tidal current calculation programs and conduct numerical experiments and performance comparisons for a large-scale distribution system on a high-speed PC using this program. The Newton-Raphson method employs a fast LU decomposition of the Jacobian sparse matrix, while the Backward/Forward method employs a fast B/F sweep with topological ordering based on graph theory. The Newton-Raphson method employs a fast LU decomposition of the Jacobian sparse matrix, and the Backward/Forward method employs a fast B/F sweep based on topological ordering. Both methods can consider the topological characteristics of the distribution system, such as radial or weakly meshed (i.e., small number of loops).

2. Tidal equation of power system

A power transmission and distribution system are a power transmission line designed to meet the power demand of consumers. To analyze the flow of power and current and voltage distribution in this transmission line, the power flow equation is derived from the network structure (graph with attributes) consisting of nodes (bus) and branches (branches) connecting the nodes, which are set based on certain criteria. Here, the state quantities power, current, and voltage are all complex numbers, and power is given the name active power (P: Active Power) for the real part and reactive power (Q: Reactive Power) for the imaginary part. Complex voltage (V) is often expressed in terms

of voltage value $|V|$ and voltage phase angle δ (radian) using the exponential representation of complex numbers, $V = |V|e^{j\delta} = |V|\cos\delta + j|V|\sin\delta$. Here, complex numbers are denoted by the upper dot symbol and j is used as the imaginary unit.

Nodes in the network are broadly classified into generation nodes and load nodes that specify P and Q values. Generation nodes are generally further classified into an infinite bus bar (slack bus bar) that specifies complex voltage and a PV bus bar that specifies P and $|V|$ values. The branches are given Impedance (resistance and reactance) as branch attributes. In the general π -type grid model, Susceptance, which is the imaginary part of Admittance, the reciprocal of Impedance, can be considered as a node and a branch. A device with a susceptance function is called a shunt capacitor. The power transmission and distribution power system constructed by such a model can be viewed as an undirected graph consisting of a group of buses and a group of branches with bidirectional characteristics. Based on this graph, the power flow equations can be developed by applying the basic equations for AC circuits shown below.

- Basic equation of an AC circuit (above * symbols indicate conjugate complex numbers)

(1) Ohm's Law

$$V = Z \cdot I \quad (V: \text{Voltage}, I: \text{Current}, Z: \text{Impedance})$$

$$I = Y \cdot V \quad (V: \text{Voltage}, I: \text{Current}, Y: \text{Admittance})$$

(2) Kirchhoff's Current Law (KCL)

The sum of the currents flowing into and out of the node is zero.

The sum of the power flows into and out of the node is zero.

(3) Kirchhoff's Voltage Law (KVL)

The sum of the voltages in the closed circuit is zero.

$$\text{Voltage drop equation for branch endpoint } 1 \rightarrow 2: \dot{V}_1 - \dot{V}_2 = \dot{Z} \dot{I}$$

(4) Injected power law at node

$$S = V \dot{I}^* \quad (S: \text{Injected Power}, V: \text{Voltage}, I: \text{Injected Current})$$

$$I = (S / V)^*$$

The power flow equation derived from the above formula is as follows

$$(A) \dot{I} = [Y][V]$$

$$(B) -S_i = \dot{V}_i ([\dot{Y}][\dot{V}])_i^* \quad (i=1, \dots, n)$$

where $[V]$ is the voltage vector for all nodes, $[\dot{I}]$ is the same injection current vector, $S_i = P_i + jQ_i$ is the specified injection power (generation+, load-), $[Y]$ is the system-wide symmetric admittance matrix derived from Kirchhoff's current law (Y_{bus} matrix), n is the number of nodes n denotes the number of nodes. Equation (B) is the nonlinear equation for the node voltage, called the power flow equation, and the node voltage is obtained by solving it given S_i . Equation (A) is the basic equation of a linear AC circuit needed to create equation (B), and the node injection current vector can be calculated when the node voltage is obtained from the same equation. This shows that the power

system is based on linear AC circuit theory, but that the nonlinearity of the power current arises primarily from the boundary condition of the power value specification.

However, to solve the tidal current equation, the solution to the equation cannot be obtained by equation (B) alone, and the boundary conditions on the generation side must also be given. The method devised for this purpose is the introduction of a slack bus. That is, by providing at least one complex voltage-specified node (slack bus), the indefiniteness of the power flow equation can be avoided. In addition, since the generation node may specify P-values and $|V|$ values as PV busbars, it is necessary to consider the boundary conditions for these values. The principal way to handle these boundary conditions is to consider the voltage variable as a fixed value and remove it from the variables if voltage is specified, and to remove the line of the power flow equation related to the P or Q value if power is specified. As a result, the size of the power flow equation (number of variables = number of equations) becomes somewhat smaller than $2n$.

The detailed contents of the power flow equation described here can be found in the following references.

* Source: Tokyo Electric Power Company, Internet Electric Power Course, Calculation of power system tidal currents using the Newton-Raphson method.

3. Solution of the power flow equation

As mentioned in the previous section, solving the power flow equations is equivalent to solving a multidimensional nonlinear simultaneous equation. Since there is no direct analytical method for solving these equations, we must rely on iterative numerical methods. In most such methods, the nonlinear simultaneous equations are approximated linearly, and the operations are repeated until the convergence condition is satisfied. The solution methods are classified according to the method of linear approximation, and the most elementary method is the Gauss-Seidel method, in which all nonlinear and off-diagonal terms are replaced by the values obtained in the previous iteration to make them constant terms. The Newton-Raphson method, which is commonly used for numerical solution of nonlinear problems, linearizes the nonlinear PQ mismatch function by its gradient information (Jacobian). Another solution method that is often used is to approximate the power flow equation to a linear AC circuit equation, and the Implicit Zbus Gauss method and the Current Injection method are examples of solution methods that employ this linearization. This method iteratively solves the simultaneous linear equations for $[\dot{V}]$ by approximating the right-hand side of equation (A) $[Y][V] = [I]$ as $\dot{I} = (\dot{S} / \dot{V})_p^*$ with the voltage \dot{V}_p obtained at the previous iteration. The Backward/Forward method realizes this solution idea in a procedural way without using matrices. In this method, Kirchhoff's law (KCL, KVL) is directly applied by graph search to obtain a solution equivalent to the method for constructing the admittance matrix $[Y]$.

The above is an overview of the solution methods for the power flow equation, and the Backward/Forward method is described in detail next.

3.1 Solving the power flow equation by the Backward/Forward method

The Backward/Forward method emerged as an alternative solution to the traditional method for transmission systems (a family of Newton- Raphson methods) that directly solves the power flow equations [1,7]. This solution method was able to achieve simple and fast performance by eliminating the complex procedure of manipulating large complex matrices for radial distribution systems without loops. Subsequently, the Backward/Forward method was extended to consider loop structures and voltage control busses (PV busbars) [14,18] and further applied to three-phase unbalanced tidal flow calculations [26]. In addition, many other variants of the Backward/Forward method have been proposed up to now, and detailed survey papers [47] have been published on their contents, which can be referred to.

The basic method and extensions of the Backward/Forward method are described below.

3.2 Backward/Forward method for systems without loop structure

A radial system without loops (cycles) means that it is a tree-structured graph. According to graph theory, a graph without cycles can be converted into a semi-ordered set by topological ordering, i.e., all nodes can be visited in order from a given starting point, allowing sequential processing. Based on this principle, Forward Sweep is a method of calculating voltage drop according to Kirchhoff's voltage law by visiting all nodes sequentially, starting from the root (slack bus) of the tree. Conversely, the Backward Sweep method starts from every leaf of a tree and adds current according to Kirchhoff's current law while sequentially visiting the roots of the tree. The Backward/Forward method is executed as an iterative process flow as shown below.

(1) Assumption of voltage (V) at all nodes (flat start)

(2) Repeat the following process until the convergence condition is satisfied

a) Setting of equivalent injection currents at all nodes

$$I_i = (\dot{S}_i / \dot{V}_i)^* - jY_{ci} \cdot V_i \quad (i=1, \dots, n) \quad (Y_{ci} : \text{susceptance at node } i)$$

b) Addition of injection current at all nodes by Backward Sweep and setting of branch current

$$I_{sr} = -I_r \quad (s: \text{sending end node}, r: \text{receiving end node})$$

$$I_s = -I_s + I_r$$

c) Voltage drop calculation at all nodes by Forward Sweep

$$V_r = V_s - Z_{sr} \cdot I_{sr} \quad (s: \text{sending end node}, r: \text{receiving end node})$$

d) Voltage increment calculation and convergence determination at all nodes

$$\| \dot{V}_i - \dot{V}_{iold} \| < \epsilon \quad (i=1, \dots, n, i \neq \text{root})$$

The above method is called the Current Summation method as a classification of the Backward/Forward method because the current is accumulated from downstream to upstream in the Backward Sweep process. On the other hand, the Power Summation method, which accumulates the power flow, is performed as an iterative process flow as shown below. The power summation method is characterized by its consideration of power loss at branches, which improves convergence compared to the current summation method (see below).

- (1) Assumption of voltage (V) at all nodes (flat start)
- (2) Repeat the following process until the convergence condition is satisfied

- a) Setting of equivalent injection power at all nodes

$$P_i = -S_i - V_i (jY_{ci} - V)_i^* \quad (i=1 \dots n) \quad (Y_{ci} : \text{susceptance at node } i)$$

- b) Addition of injected power at all nodes by BackwardSweep and setting of branch current

$$I_{sr} = (\dot{P}_r / \dot{V})_r^* \quad (s: \text{sending end node}, r: \text{receiving end node})$$

$$P_s = -P_s + P_r + |I_{sr}|^2 Z_{sr} \quad (\text{The third term on the right side is power loss.})$$

- c) Voltage drop calculation at all nodes by ForwardSweep

$$V_r = V_s - Z_{sr} I_{sr} \quad (s: \text{sending end node}, r: \text{receiving end node})$$

- d) Voltage increments calculation and convergence determination at all nodes

$$\| \dot{V}_i - \dot{V}_{iold} \| < \varepsilon \quad (i=1 \dots n, i \neq \text{root})$$

Here, a graph search method is used to determine the order of branches for backward/forward sweep. There are two types of graph search methods: breadth first search (BFS), which gives priority to branches, and depth first search (DFS), which gives priority to connections. The following methods can be considered in applying this technique.

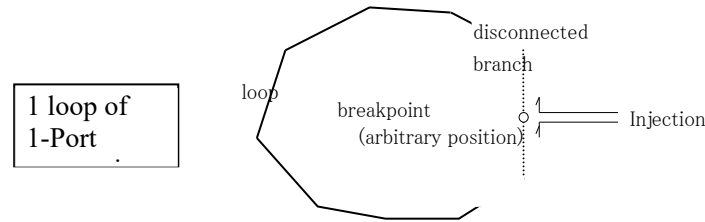
- A) Perform a graph search each time a Backward/Forward Sweep is performed.
- B) Perform a single graph search first, store the resulting order of branch visits, and process them in the same order as the visits or in reverse order when Backward/Forward Sweep is performed.

In our numerical experiments here, the method A) considerably increases the computation time due to the overhead required for graph search, so we recommend the method B) for large-scale phylogenies. Since the number of branches doubles when the phylogeny is represented as an undirected graph, there is an advantage in using a visit-order array of directed branches, which is half the size of an undirected graph. The advantage of using an undirected graph is that, in the case of a complex (looped) large-scale network, it is possible to avoid input errors in branch start and end point data due to the unclear orientation of intermediate branch flows (in a directed graph, reachability is lost if the correct orientation is not input). When a multi-feeder system from multiple distribution substations is operated radially by switching, the imprecision of the direction of the intermediate branch flow due to the state of the switches will be noticeable.

Regarding the difference between BFS and DFS, there was no difference in the computation time required for Backward/Forward Sweep, but DFS was several to several tens of times faster than BFS, although the time required for the graph search itself was shorter in the large-scale system. However, in the system with the loop structure described below, the convergence performance of Backward/Forward Sweep differs between BFS and DFS, since BFS and DFS produce different results in finding loops.

3.3 Backward/Forward method for systems with loop structure

Here, we propose a method based on the Multi-Port Compensation method [14,18], which transforms a system with a loop structure into a radial system without loops and applies the Backward/Forward method described above. The Multi-Port Compensation method is based on the idea of "converting a loop into a radial system by disconnecting one of its branches at a break point" and "supplementing with complex current injection at that point to eliminate the voltage mismatch at the break point resulting from the tidal current calculation". If there are multiple loops, the breakpoints are set for the number of loops (Multi-Port conversion), and the replenishment of current injection is considered the same number of times. The replenishing current injection is obtained by preparing a sensitivity matrix using Thevenin's Theorem in linear circuits.



In the proposed solution method, the discovery of the loop and the setting of the cut branch that establishes the break point are done during the graph search using the cycle discovery method in graph theory. The last branch of the discovered loop is set as the break branch, and this branch is set as open. During the graph search, the only branch information with an incoming connection to each discovered node is also stored so that a path can be traced from each node to the root. Using this backward path, a sensitivity matrix $Z=(Z_{ij})$ by loop impedance with K loops is created as follows.

- (1) Self-impedance: $Z_{ii}=\sum Z_{i=S_i,l}$ for loop $_i$ ($i=1\dots .K$)
- (2) Mutual impedance: $Z_{ij}=\sum Z_{i=M_{ij},l} \text{sign}(l)$ for loop $_i$ & loop $_j$ ($i,j=1\dots .K, i\neq j$)

where Z_l denotes the impedance of the branch $_l$ belonging to the following set.

$$S_i=(P_i^+ \cup P_i^-) - (P_i^+ \cap P_i^-) + B_i$$

$$M_{ij}=(P_i^+ \cap P_j^+) \cup (P_i^- \cap P_j^-) \text{ (sign}(l)=+1) \\ \cup (P_i^+ \cap P_j^-) \cup (P_i^- \cap P_j^+) \text{ (sign}(l)=-1)$$

B_i : disconnected branch of loop $_i$

P_i^+ : set of branches that make up the *positive path* from one endpoint of the disconnected branch to

the root

P_i : set of branches that make up the *negative path* from the other endpoint of the disconnected branch_{*i*} to the root

Using this sensitivity matrix, the incremental amount of supplemental injection current at the break point can be obtained by solving the following simultaneous linear equations

$$\mathbf{Z} [\dot{\mathbf{I}}_d] = [\dot{\mathbf{V}}]_d$$

where $[\mathbf{V}_d]$ is the vector of voltage mismatch values at all break points (voltage difference at both ends of the disconnected branch - voltage drop at the disconnected branch), $[\mathbf{I}_d]$ is the vector of incremental replenishment injection currents at all break points, which are accumulated as complex currents flowing in the corresponding disconnected branch. The size of this equation is $2K$. The size of this equation is $2K$.

In the proposed solution based on the Multi-Port Compensation method, in each iteration, the current in the disconnected branch obtained from the above equation is converted to the supplemental injected power at both end nodes (one flowing in, the other flowing out) by the formula $\cdot S = \cdot V (I)^*$, which is added to the original injected power at both end nodes and add it to the original injected power at both end nodes for use in the next iteration.

Therefore, algorithmically, there are no major changes to the processing framework of the Backward/Forward method, only the addition of routines for finding loops and setting up disconnected branches, creating sensitivity matrices, and calculating and adding replenishment quantities.

3.4 Backward/Forward method for systems with PV bus bar

The first attempt to introduce the PVmatrix into the Backward/Forward method was made in the literature [14], which was later improved to a method that also uses the sensitivity matrix to handle the PVmatrix [18]. Furthermore, this method has seen progress in terms of improved convergence [25,35].

The basic idea of the PVbusbar processing based on the Multi-Port Compensation method is to create a fictitious branch between each PV busbar and the root node, which is not connected to the grid. The difference between the PV bus bar processing and the loop processing is that the virtual branch does not have a break point, but instead, a reactive power replenishment function is given to the PVbus bar for specified voltage control in the PVbus bar. Instead, the virtual branch is given the function of replenishing the reactive power to the PV bus bar for the specified voltage control of the PV bus bar.

In other words, the virtual branch serves as a shunt capacitor.

Since the PV busbars specify the $P, |V|$ values, only the real part of the difference between the voltage values in the PV busbars and the specified values is used in the calculation of the complex voltage mismatch value vector described above. Therefore, the size of the sensitivity matrix is $2K+p$, where K is the number of loops and p is the number of PV bus bars. Correspondingly, to remove unnecessary parts of the sensitivity matrix and to facilitate matrix manipulation, rearranging the rows and columns and performing a sign transformation of the replenishment injection currents transforms the format of the sensitivity matrix as follows.

$$\begin{pmatrix} X & R \\ -R & X \end{pmatrix} \begin{pmatrix} -I_i \\ +I_r \end{pmatrix} = \begin{pmatrix} V_r \\ V_i \end{pmatrix} \quad \boxed{\begin{matrix} Z=R+jX \\ V=V_r +jV_i \quad \dot{I} = I_r +jI_i \end{matrix}}$$

where the left-hand side matrix is the transformed sensitivity matrix ($\dim X=K+p, \dim R=K$), the left-hand side vector is the incremental vector of replenishment injection current at all loop breakpoints and PVbusbars, and the right-hand side constant term vector is the vector of voltage mismatch values at the same locations.

The revised calculation formula of $(|-V|_{sp} / |-V|-1)Re(\dot{V})$ is used as the voltage mismatch value in the PV bus bar [35]. Here, \dot{V} is the complex voltage of the PV bus bar obtained in the iterative process of the Backward/Forward method, and $||V|_{sp}$ is the specified voltage value at the PVbus bar in question. Using the incremental amount of replenishment injection current I_i obtained from the above simultaneous linear equations, the incremental amount of reactive power replenishment to the PV bus bar is calculated as $I_i |V|^2 / Re(\dot{V})$ [35], which is added to the reactive power provided by the virtual branch in question. The cumulative value is set as the amount of injected reactive power in the PV bus bar concerned to be used in the next iteration of the Backward/Forward method.

In the proposed solution method, after obtaining the above replenishment quantities, a process is added to normalize the complex voltage \dot{V} of each PV bus bar to $|\dot{V}|_{sp}$ for the purpose of convergence stability. The above is an overview of the processing of the PV busbar based on the Multi-Port Compensation method, which is, in principle, identical to the loop processing. Therefore, algorithmically, there is no major change in the processing framework of the Backward/Forward method, and we only need to add routines for creating a virtual branch, creating a sensitivity matrix considering the PV busbar, and calculating and adding the replenishment amount.

4. Simulation of tidal currents in large and radial distribution systems

Numerical experiments were conducted to verify the performance of the tidal current calculation programs using the Backward/Forward and Newton-Raphson methods developed based on the proposed solution method, which are described below. Simulations on a radial distribution system are described here, while simulations on a distribution system with a loop structure and PVbus bar are

described in the next section. The developed programs were written in C and C++ languages.

4.1 Creating a model for simulation

A virtual large-scale distribution system (Radial Distribution network) without loops is randomly generated as a directed graph with a tree structure and used for numerical experiments. The roots of the tree are slack buses, the leaves of the tree are load nodes (PQ-specified nodes), and the rest are intermediate passages and branching points (PQ nodes with a specified value of zero). PQ values for load nodes were randomly generated from the range $P[0.1,1.0]$, $Q[0.0,0.05]$. Random values were also generated for branch attributes, with the range $R[0.01,0.05]$ for resistance and the ratio $R/X[1.0,10.0]$ for reactance. Other susceptance minutes (Shunt Capacitor) involved in the branch and node are ignored. The voltage phase angle of the slack bus was set to zero, and the voltage values were empirically set as a function of the sum of P and R values as a tentative estimate. However, since the appropriate value has not been evaluated or calculated, the following corrections are made based on the results of tidal current calculations using this provisional estimate.

- (1) If the tidal current calculations do not converge, the estimated voltage value of the slack bus is increased, assuming that voltage collapse is occurring.
- (2) If the tidal current calculations converge and the voltage phase angles of the nodes are all close to zero, the estimated voltage value of the slack bus that is too high voltage is reduced.

The R/X ratios of the branch attributes used in the numerical experiments are in the range of so-called Ill-conditioned values (3 to 5 or more) and are said to often not converge in the Newton-Raphson series.

4.2 Simulation results

Numerical experiments were conducted by randomly generating a large-scale distribution system with $n=500,1000,2000,5000,10000,20000,30000,40000,50000$ nodes and $n-1$ branches. The convergence conditions for both the Newton-Raphson method in polar coordinates and the Backward/Forward method in Cartesian coordinates were 10^{-4} as the convergence error due to mismatch of PQ values and 10^{-6} as the convergence incremental error of the complex voltage components at all load nodes, respectively.

The results of the numerical experiments are shown in Table 1. In all cases, the Backward/Forward method gave a solution, but the Newton-Raphson method did not give a solution for the case $n=50000$ due to insufficient memory. Except for this case, a visual comparison of the obtained voltage values indicates that both methods give almost identical solutions within acceptable limits (there is a paper [17] that proves the absence of tidal multi-residuals in real power distribution systems). (There is a paper that proves that tidal multi-resistance does not exist in real distribution systems [17].) However, because the number of nodes is huge, we have not performed a complete

matching. In the results of the 126-bus bar system reported at the workshop, the voltage distributions (voltage values and phase angles: unit - degree) by both solution methods were in perfect agreement up to four decimal places. The PC used for the numerical experiments was a Dell Precision T1500 (Intel Core i7, 64-bit OS, 2.80 GHz, 16 GB physical memory).

Table 1 Results of numerical experiments on a large distribution system

Node(<i>n</i>)	burden node	Slack voltage	number of repetitions		final error		Execution time (s)		velocity ratio
			N/R	B/F	N/R	B/F	N/R	B/F	
500	240	5.00	5	12	2.619e-	5.888e-7	0.031	0.016	1.94
1000	483	10.00	5	14	9.683e-	7.246e-7	0.062	0.031	2.00
2000	1012	20.00	4	6	1.274e-	3.812e-7	0.203	0.016	12.69
5000	2510	20.00	6	19	1.985e-	5.763e-7	1.856	0.031	59.87
10000	5125	30.00	5	8	3.392e-	4.554e-7	6.147	0.047	130.8
20000	10387	40.00	6	13	3.201e-	6.207e-7	29.312	0.046	637.2
30000	15920	40.00	6	13	2.474e-	3.497e-7	65.848	0.093	708.0
40000	21142	50.00	6	16	1.756e-	5.346e-7	116.610	0.109	1069.8
50000	27346	50.00	-	19	-	5.062e-7	-	0.234	-

Note: The Backward/Forward method uses DFS for graph search. However, the execution time by DFS is not included in the table above.

Note that the results shown in Table 1 differ from those reported in the workshop in the following points.

- (1) The program for the Backward/Forward method was completely revised (program name: DnetFlow) to improve the generality of the network structure. The overhead for this change resulted in some degradation of speed performance. The revisions include the use of undirected graphs, consideration of multi-feeder systems, a change from node numbers to node names, and the detection and warning termination of isolated node groups.
- (2) The backward/forward method was revised from the current-accumulation method to the power-accumulation method.
- (3) The Backward/Forward method implemented both DFS and BFS for graph search.

The figure below illustrates the convergence status in the Backward/Forward method, picking up the cases with $n=2000$, 20000 , and 50000 nodes from the results shown in Table 1. The horizontal axis indicates the number of iterations, and the vertical axis indicates the convergence incremental error of the complex voltage component. The figure shows that the Backward/Forward method exhibits a multiconvex convergence shape regardless of the number of nodes.

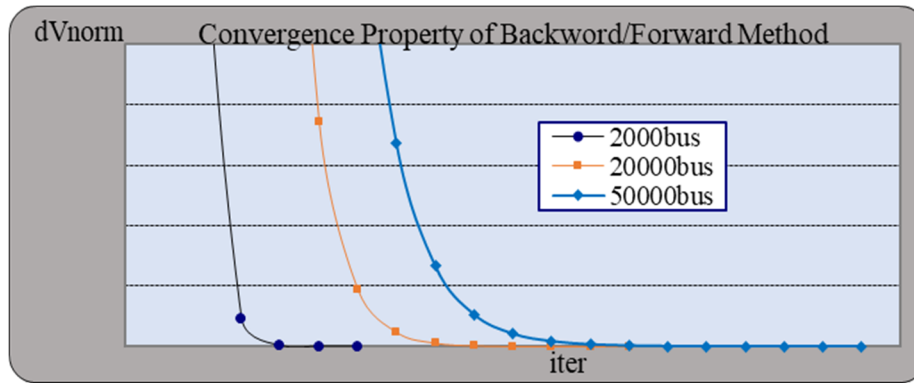


Figure 1 Multiconvex Convergence Shapes in the Backward/Forward Method

4.3 Summary of simulations

The author's expectation before conducting numerical experiments was that "the Backward/Forward method takes less time per iteration, but the number of iterations tends to increase. Therefore, in total, the Backward/Forward method is at best several times faster than the Newton-Raphson method. This is what the authors meant. However, the results of the numerical experiments exceeded this expectation by a wide margin, showing that the speed ratio (Table 1) tends to increase significantly with the number of nodes (more than 100 times for tens of thousands of nodes).

Based on these results, we conclude that the Backward/Forward method is suitable for large-scale distribution systems. In particular, the Backward/Forward method, which is simple and fast, is the key to success in the problem of distribution system reconfiguration, which requires an enormous number of tidal flow calculations.

5. Supplemental simulation of tidal currents using the Backward/Forward method

5.1 Comparison of power-accumulation and current-accumulation methods

To compare the convergence performance of the Current Summation method and the Power Summation method in the Backward/Forward method, numerical experiments were conducted on the large-scale distribution system model used in 4.2. Table 2 shows the results. The PC used in the numerical experiments is a Dell Optiplex GX745 (Celeron(R) D CPU 3.06 GHz, 2.99 GB physical memory).

Table 2 Comparison results from numerical experiments on a large distribution system

Node(<i>n</i>)	burden node	Slack voltage	number of repetitions		final error		Execution time (sec)		velocity ratio
			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) Power integration method, (C) Current integration method

The results demonstrate that the power stacking method is superior to the current stacking method in terms of the number of iterations and execution time.

5.2 Simulation in a system with a weak loop structure and PV busbar

To verify the performance of the proposed Backward/Forward method based on the Multi-Port Compensation method, numerical experiments were conducted on the 126-bus bar system reported in the workshop. To this system, up to three branches and three PV nodes were added to form a loop, and tidal current calculations were performed for each combination. The candidate loop branches were (1) 20-98, (2) 107-122, and (3) 42-65, and the candidate PV nodes were A: 30, B: 77, and C: 124. The attributes of all loop branches are set to $r=0.001$ and $x=0.001$, and the P and V values of all PV nodes are set to 1.0 respectively.

The following 14 cases were considered in the numerical experiments.

- Case 0 Case 0: Power distribution system for testing
- Case 1 Loop 1: Loop 1 is added.
- Case 2 Loop 1) and 2) are added.
- Case 3 Loop 1: Add loops 1), 2), and 3).
- Case A Case A: PVnode A is set
- Case B Case A: PVnode B is set
- Case C Case C: PVnode C is set up.
- Case AB Case AB: PVnodes A and B are set
- Case AC Case AC: PVnodes A and C are set
- Case BC Case BC: PVnodes B and C are set
- Case ABC Case ABC: PVnodes A, B, and C are set
- Case ABC1 Case ABC1: Set PVnodes A, B, and C, and add loop ①.
- Case ABC2 Case ABC2: Set PVnodes A, B, and C, and add loops (1) and (2).
- Case ABC3 Case ABC3: Set PVnodes A, B, and C, and add loops (1), (2), and (3).

The results of the numerical experiments are shown in Table 3. The obtained voltage distributions are consistent with the results of the Newton/Raphson method in all cases. The results for the number of iterations shown in the same table indicate that the Multi-Port Compensation method has stable

convergence characteristics. It can also be read that the convergence performance degrades with the addition of loops or the setting of the PVnode, and the degree of degradation is greater for the PVnode setting than for the addition of loops. However, we refrain from making any conclusive statements about the convergence characteristics of the Multi-Port Compensation method, since this is a numerical experiment based on a single example. Further verification in a large-scale system will be necessary. In the original paper [14], it is also noted that the convergence characteristics of the method depend on the number of loops and the number of PV nodes, but it should be noted that no significant trend supporting this was obtained in the numerical experiments.

The proposed backward/forward method employs a flat start with power stacking method (excluding PV nodes), and the convergence condition is 10^{-6} , as the incremental error of the complex voltage components (Cartesian coordinates) at all load nodes. The PC used for the numerical experiments was a Dell Optiplex GX745 (Celeron(R) D CPU 3.06 GHz, 299G B physical memory).

The figure below also illustrates the convergence status of the proposed Backward/Forward method for Case 0 and Case ABC3 among the cases considered. The figure shows that partial irregularities appear in the convergence shape when the loop structure and PVnode are introduced simultaneously. However, since irregularities do not appear in the loop structure alone, and irregularities appear in all cases involving PVnode A, it can be concluded that the position of the PVnode in the system may have a negative impact on convergence.

Table 3 Results of numerical experiments on 126 bus bar distribution system

Case (e.g., receptacle, condition, event, legal action, letter style, etc.)	Number of repetitions	Final error (dV)	PQ mismatch	Run time (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

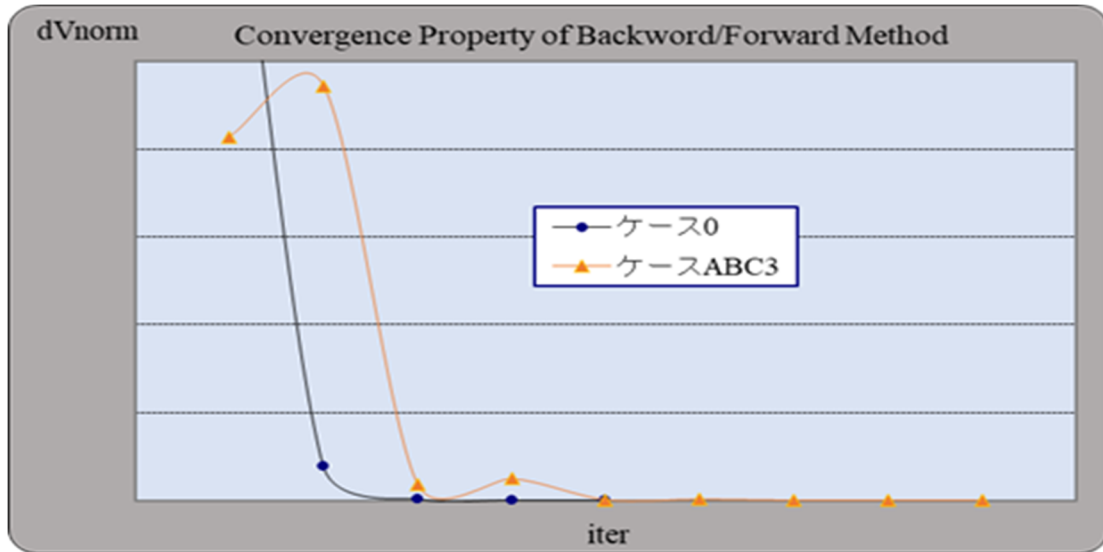
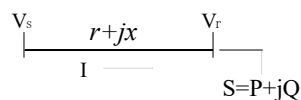


Figure 2 Convergence status by the proposed Backward/Forward method

5.3 Convergence of the Backward/Forward Method

In general, the power flow equation has no solution when the system exceeds its Maximum Possible Loading Point. It is also known that the convergence performance of the numerical solution method deteriorates under heavy load conditions close to the Maximum Possible Loading Point. This phenomenon is like the phenomenon that the Newton-Raphson method for solving nonlinear equations is prone to oscillations due to the numerical instability of the Jacobian when a heavy-root solution is obtained. To illustrate this, PVcurves are often used in tidal current equations. For reference, the analytical solution of the one-branch tidal current equation shown below, and the resulting PVcurves are illustrated in the figure below.



From the basic equation of the AC circuit, the following equation holds

$$I = (S/V_r)^* \cdot V_s = V_r + (r + jx) \cdot I$$

From the above equations, the following equation is derived

$$V_s \dot{V}_r^* = V_r^2 + (rP + xQ) + j(xP - rQ), \text{ where } V_r^2 \dot{V}_r^*$$

$$\text{Re}(\dot{V}_s \dot{V}_r^*) = V_r^2 + (rP + xQ)$$

$$\text{Im}(\dot{V}_s \dot{V}_r^*) = xP - rQ$$

By taking the sum of squares of the second and third equations above, the following equation is obtained

$$V_s^2 V_r^2 = V_r^4 + 2(rP + xQ) V_r^2 + (r^2 + x^2)(P^2 + Q^2)$$

Eventually, the following multiple quadratic equation (Biquadratic equation) was obtained that

gives the analytical solution of the power flow equation.

$$V_r^4 - [V_s^2 - 2(rP + xQ)]V_r^2 + (r^2 + x^2)(P^2 + Q^2) = 0$$

By solving this well-known multiple quadratic equation, the endpoint voltage corresponding to the startpoint voltage for a given endpoint load can be obtained.

In this equation, the PV curve shown in the figure below shows the relationship between V_r and P with V_s and Q fixed. The figure shows that there are usually two solutions for V_r , and they are the multiple roots at the maximum possible load point. However, there is an argument that "the lower solution is close to zero in the normal operation of the actual distribution system and can be considered negligible as a solution, so no multiple roots can be taken to occur" [17].

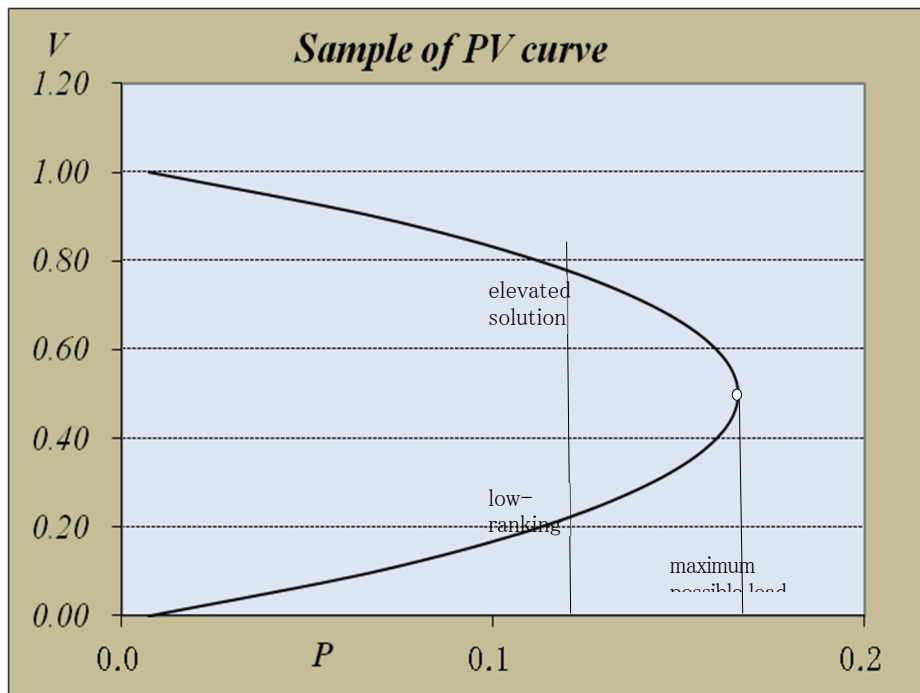
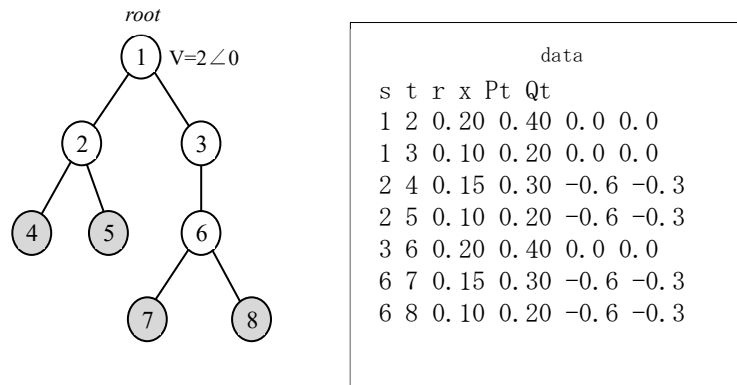


Figure 3: Heavy roots at the maximum possible load point of the solution of V_r

Similarly, the relationship between V_r and Q with V_s and P fixed can be defined as a QV curve like the one shown above; from the characteristics of the PV and QV curves, we can say that the endpoint voltage value (higher solution) is higher when the endpoint load P or Q is smaller. This fact is utilized as a principle of reactive power compensation for voltage control. Note that the condition for the maximum possible load point is derived from the multiple root condition $b^2 - 4ac = 0$ of the quadratic equation $ax^2 + bx + c$, so this left-hand side value (for non-negative values where a feasible solution exists) can be used as an index value for voltage stability [46]. From the same condition, it is

also possible to calculate the Maximum Load Factor at which voltage collapse occurs for a given V_s and P,Q [46].

The convergence performance of the numerical solution of the power flow equation deteriorates under heavy load conditions and the reasons for this are described above. To understand this trend in practice, we performed numerical experiments on a simple 8-bar radial system as shown below.



This 8-bus bar system is heavily loaded, and no solution exists with a Load Factor of 1.02.

The figure below shows the relationship between the number of iterations and the incremental error of the complex voltage component when solving this 8-bus bar system using the Backward/Forward method with the load factor decreasing from 1.0 to 0.9, 0.8, and 0.6.

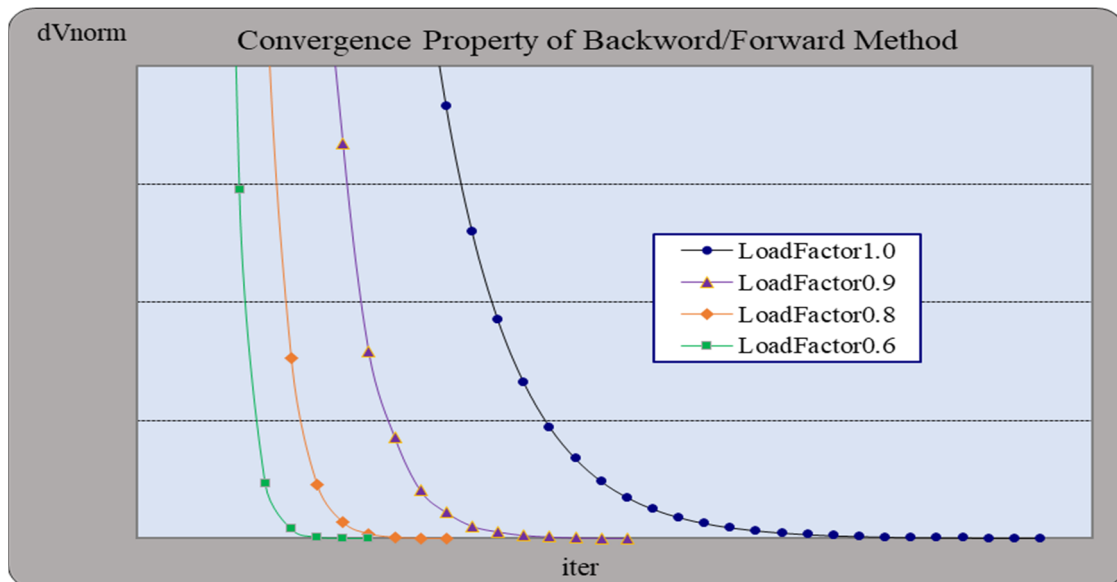


Figure 4: Convergence performance degrades as heavy load conditions are reached

The figure shows that the number of iterations increased from 9, 12, 19, and 35, respectively, as the

load factor increased from 0.6, 0.8, 0.9, and 1.0, demonstrating that the convergence performance of the backward/forward method (using the power pileup method) deteriorates with increasing heavy load conditions. The backward/forward method (based on the power stacking method) shows that the convergence performance degrades as the heavy load condition increases. It also suggests that the convergence performance of the backward/forward method does not necessarily depend on the size of the system, i.e., smaller systems do not converge in fewer iterations. The number of iterations using the Newton-Raphson method for the same system increased with increasing load factor of 0.6, 0.8, 0.9, and 1.0, respectively, from 5, 5, 6, and 7, but not at the same rate as that of the Backward/Forward method.

6. Summary and future issues

In this paper, basic studies of power flow calculation methods are conducted, and the Newton-Raphson method and the Backward/Forward method, which are representative solution methods, are implemented and numerically tested on a large-scale distribution system with 500 to 50,000 nodes, and their performance is compared. The results demonstrate that the Backward/Forward method is more than 100 times faster than the Newton-Raphson method for large-scale distribution systems with tens of thousands of nodes without loop structures and PVbus bars. This high speed indicates that the Backward/Forward method is very effective for tidal flow calculation and its planning and operation problems in large-scale distribution systems. To take advantage of this advantage, we have also extended the method to the Multi-Port Compensation method, which can handle loop structures and PVbusbars, to make the Backward/Forward method applicable to distribution systems with loop operations or distributed power supplies. 126 busbars numerical experiments on a test system showed that the Multi-Port Compensation method has good convergence performance, so it is expected that this method will be used in the future.

The remaining issues are: (1) to make the Backward/Forward method with Multi-Port Compensation developed in this study capable of handling various load models (ZIP models and voltage-dependent load models) and their mixed models, (2) to consider voltage control devices (transformers, SVRs, SVCs, etc.), and (3) to make the method applicable to 3-phase unbalanced systems. (3) Enable the method to be applied to 3-phase unbalanced systems.

END

7. Representative references (in chronological order)

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Appendix D: CATAPLLER Generator Data (collected locally, 2019)

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	Caterpillar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 (セントキットでは定格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				

G1				G2				G3				G4				STATION LOAD			
MW:0 LF %:0				MW:2.844 LF %:73				MW:2.932 LF %:75				MW:2.684 LF %:69				MW: 20.522			
Volts: 0.047 A B C n/a 0.059				Volts: 11373 A B C 11363 11370				Volts: 11367 A B C 11385 11337				Volts: 11350 A B C 11378 11316				FEEDERS			
Current: 0 n/a 0				Current: 157 154 156				Current: 152 151 154				Current: 145 142 143				MW Ia Ib Ic			
PF: -1 Freq:40				PF: 0.93 Freq:60.05				PF: 0.96 Freq:60.01				PF: 0.95 Freq:60.01				BNth: 4.1 233 0 227			
-2147385343 EXH 1 M Brg 01: 29.2				A Bank B Bank				A Bank B Bank				A Bank B Bank				PZto: 2.5 133 0 131			
-2147385343 EXH 2 M Brg 02: 29.3				440.5 EXH 1 394 LO T: 55.7				424.9 EXH 1 352.2 LO T: 57.7				424.1 EXH 1 395 LO T: 58.2				Cayon: 2.4 136 0 140			
-2147385343 EXH 3 M Brg 03: 30				465.3 EXH 2 379.4 LO Pr: 4.76				448.2 EXH 2 406.3 LO Pr: 4.76				379.2 EXH 2 349.7 LO Pr: 4.49				SPT: 2.1 113 0 122			
-2147385343 EXH 4 M Brg 04: 28.7				432.3 EXH 3 454.6 FO T In: 35.8				394.4 EXH 3 427.8 FO T In: 36.5				412.4 EXH 3 402.8 FO T In: 38.8				SEP2: 2.3 121 0 119			
-2147385343 EXH 5 M Brg 05: 28.6				460.3 EXH 4 396 FO Pr In: 20.87				406.9 EXH 4 440.1 FO Pr In: 0.91				424.9 EXH 4 364.9 FO Pr In: 3.26				SEP1: 0.2 9 0 9			
-2147385343 EXH 6 M Brg 06: 28.2				451.7 EXH 5 412 Noz T In: 45.4				397.4 EXH 5 396.6 Noz T In: 48.4				389.5 EXH 5 420 Noz T In: 47.8				BSth: 2.7 202 200 201			
-2147385343 EXH 7 M Brg 07: 26.6				439.2 EXH 6 420.2 Noz Pr: 0				429.4 EXH 6 384.5 Noz Pr: 0				312.2 EXH 6 401.3 Noz Pr: 0				ByFdi: 1.9 107 108 102			
-2147385343 EXH 8 M Brg 08: 26.6				435.5 Exh 7 412.6 AMP: 1.37				393.3 Exh 7 428.6 AMP: 1.39				407.1 Exh 7 400.1 AMP: 1.33				Cda: -0.6 27 29 29			
0.09 AMP M Brg 09: 29				449.5 Exh 8 368.8 AMT: 50.3				484.3 Exh 8 472.4 AMT 52.6				432.1 Exh 8 375.5 AMT 54.4				IntSi: 2.5 138 140 134			
30.9 AMT Th. Brg: 28.7				461.8 Exh 9 403.2 LT T Out: 42.9				481.2 Exh 9 480.8 LT T Out 46.7				421.2 Exh 9 437.4 LT T Out 48.5				SSMC: 0.849 46 47 45			
8 Tbo Spd				26535 Tbo Spd 26579 LT Pr: 0				26125 Tbo Spd 26667 LT Pr: 2.83				25788 Tbo Spd 25700 LT Pr: 2.97				F/B: 1.6 81 85 87			
Tbo Out Tbo In --				483.7 Tbo In 458.1 HT T Out: 84.2				450.9 Tbo In 372.6 HT T Out: 82.2				439 Tbo In 439 HT T Out: 80.2							
6.84 Control Air Em. Air 6.85				401.9 Tbo Out 388.2 HT Pr: 2.51				387.4 Tbo Out 398.3 HT Pr: 2.73				379 Tbo Out 373.5 HT Pr: 2.47							
-0.06 LO Pr LO.Eng In 29.3				S.Air Pr: 12.2				S.Air Pr: 9.11				S.Air Pr: 9.42							
LO.Eng Out 28.5				MB1 73.7 MB2 80.3															
31.5 JW T JW Pr 0.23				MB3 79.9 MB4 77.9															
				MB5 73.8 MB6 79.7															
				MB7 77.4 MB8 79.9															
				MB9 80.5 MB10 79.7															

ALL CHANNELS:G9DAQ1 - Google Chrome

192.168.30.171/cgi-bin/moni/allch.cgi

Channel	Status	Value
G9 Alt Winding B	H	82.1
G9 Mech Trip	H	0
G9 B-Gear Engage	H	0
G9 L.F.O. A/F Pr		1.63
G9 L.F.O. Tank L	L H	92
G9 Dump Tank L	H H	-25
G9 Exh T Diff 1	t L H T	-14.60
G9 Exh T Diff 2	t L H T	-9.00
G9 Exh T Diff 3	t L H T	-2.30
G9 Exh T Diff 4	t L H T	19.60
G9 Exh T Diff 5	t L H T	41.50
G9 Exh T Diff 6	t L H T	17.20
G9 Exh T Diff 7	t L H T	8.20
G9 Exh T Diff 8	t L H T	-60.90

G9				G10				G12			
MW: 2.768 LF %:81				MW:3.051 LF %:78				MW:3.124 LF %:80			
Volts: 11.395 A B C 11.406 11.303				Volts: 11400 A B C 11433 11423				Volts: 11400 A B C 11410 11392			
Current: 148 148 149				Current: 160 167 169				Current: 172 168 171			
PF: -0.9476 Freq:60.03				PF: 0.93 Freq:60.05				PF: 0.93 Freq:60.01			
BANK				G11				G14			
510.5 EXH 1				MW:3.109 LF %:80				MW:0 LF %:0			
516.6 EXH 2				Volts: 11413 A B C 11434 11423				Volts: 0 A B C 0 0 0			
521.9 EXH 3				Current: 170 170 170				Current: 0 0 0			
543.7 EXH 4				PF: 0.93 Freq:60.05				PF: 0 Freq:0			
566.6 EXH 5											
542.3 EXH 6											
534.2 EXH 7											
464.1 EXH 8											
16497 Turbo Spd											
0.88 AMP											
48.3 AMT											
81.2 JW Out T											
2.72 JW Pr											
81.1 VCC Out T											
6.49 VCC Pr/A											
91.33 POR Ave											
4.81 LO Pr/A											
76.2 LO OUT T											



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

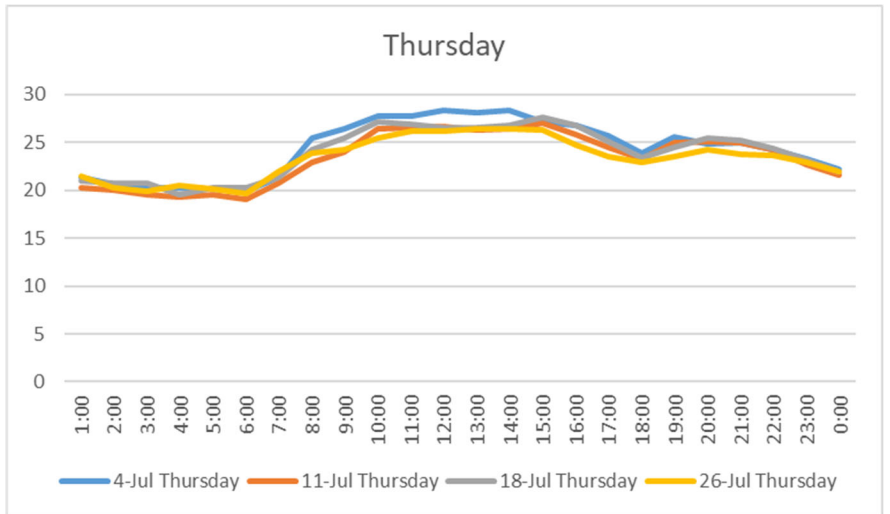
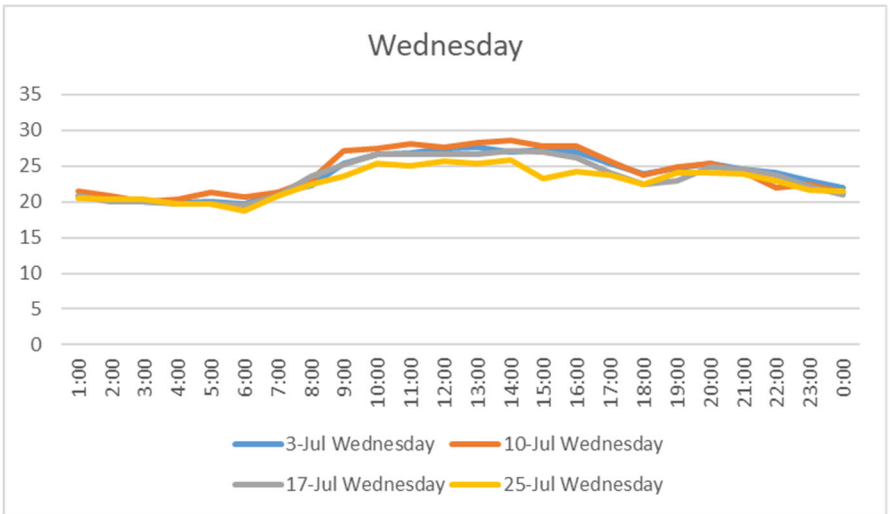
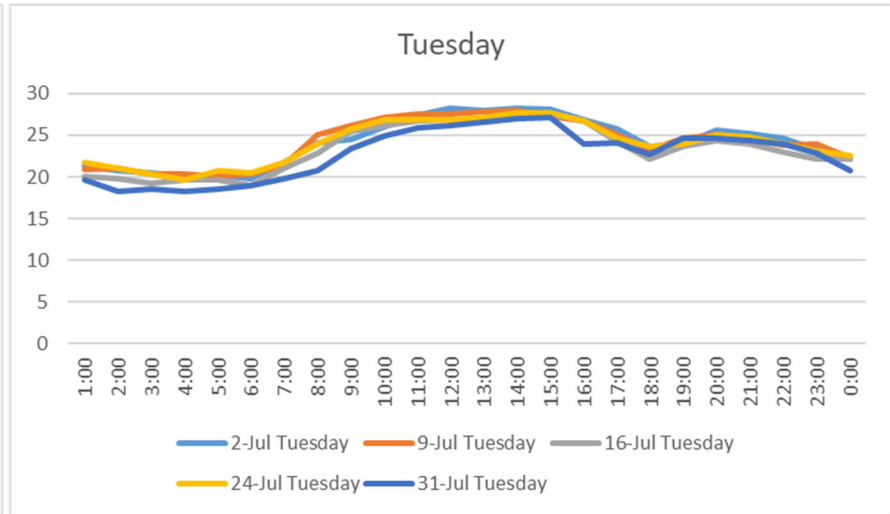
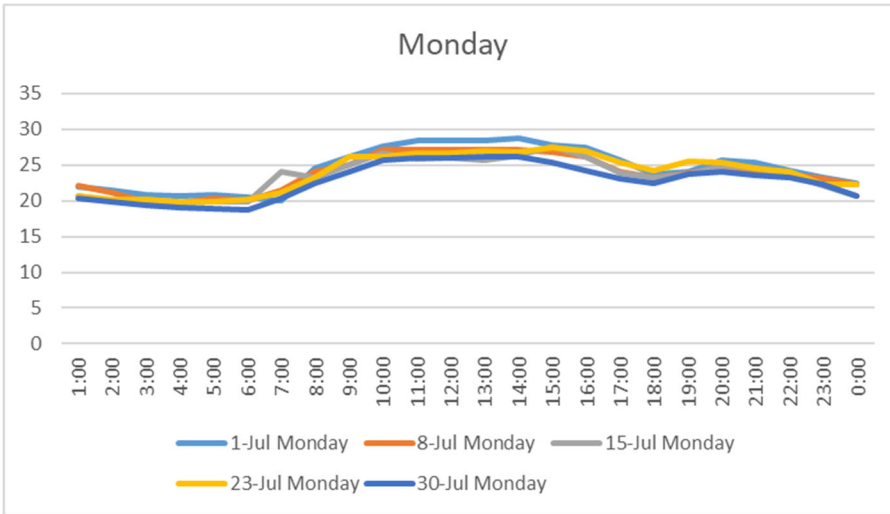
Appendix F: hourly loads_1 week x 3 cases in 2019 (collected locally, 2019)

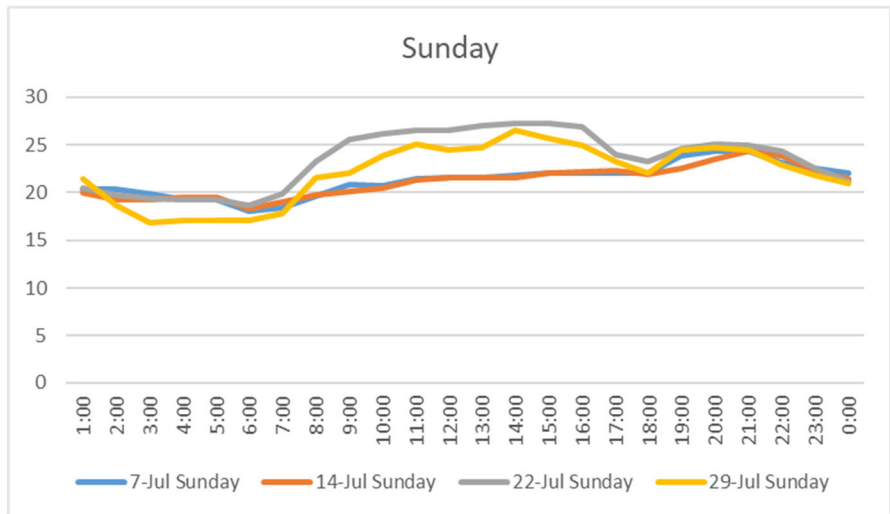
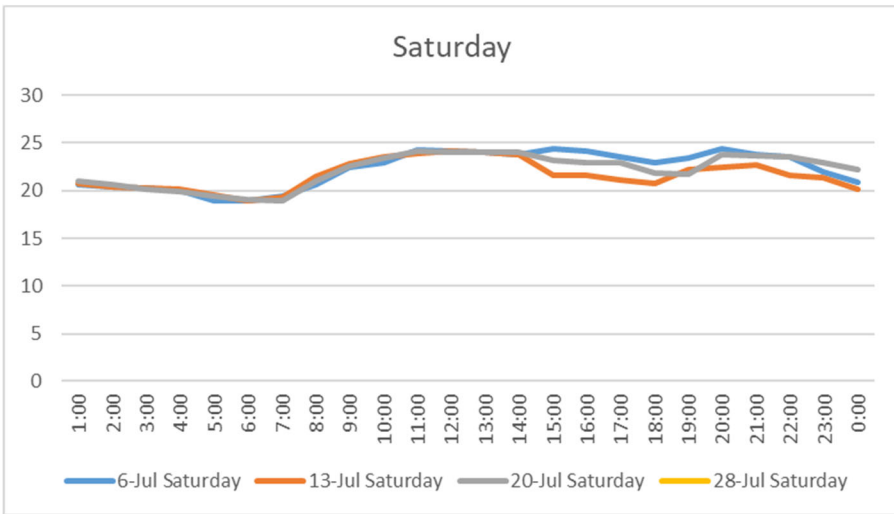
	Case 1: March							Case 2: April						Case 3: July							
	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	8-Mar	9-Mar	7-Apr	8-Apr	9-Apr	10-Apr	11-Apr	12-Apr	13-Apr	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul
	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	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
17:00	17.7	21.4	20.8	21.1	21.4	20.7	20.2	19.6	21.9	21.5	23.5	22.2	22.4	20.9	22.1	24	25	25.6	24.5	24	21.1
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
19:00	21.3	23	22.4	22.6	22.5	22.4	22.4	21.3	23.1	22.7	22.9	23.2	22.2	21.8	23.9	23.9	24.6	24.8	25	23.9	22.2
20:00	20.9	22.7	21.8	22.4	22.1	22.3	21.6	21.2	22.8	22.7	22.9	23	22.3	21.5	24.3	24.5	25.1	25.4	25.1	23.8	22.5
21:00	20.8	22.1	20.9	21.2	20.7	21.4	21.5	20.6	21.9	21.1	22.3	22	21.8	21	24.3	24	24.7	24.3	25	24	22.7
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	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
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday
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	20.1	20.9	21	21.1	21	21	20.5	20.6	21.7	20.5	21.5	20.9	21.4	20.6	20.3	19.7
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	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
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	20.1	20.7	20.2	20.2	19.5	19.4	20.2	20.3	20.3	19.9	20.2	16.8	20.1	19.3	18.6
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	19.7	19.5	19.9	19.9	19.6	19.2	19.9	19.7	19.7	20.5	20.3	17.1	19.8	19.1	18.3
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	19.7	20.3	20	19.4	18.6	19.3	19.9	20.7	19.7	20.1	20.2	17.1	19.8	18.9	18.6
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	19.5	20.3	19.6	19.1	18.1	18.6	20.2	20.5	18.7	19.7	19.3	17.1	18.8	18.7	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	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
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	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	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	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	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	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	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	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	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	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	28.5	28	27.7	28.1	25.2	24	21.5	27.2	27.8	28.3	26.3	26.7	24	21.5	25.7	27	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	28.8	28.3	27	28.3	25	23.8	21.8	27.2	27.9	28.6	26.4	26.7	23.8	21.5	26.3	27.5	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	27.8	28.1	27.3	27.2	25.4	24.4	22.1	26.8	27.3	27.8	27	25.8	21.6	22	27.7	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	27.4	26.9	26.9	26.8	26.5	24.2	22.1	26.2	26.7	27.8	25.8	25	21.6	22.2	26.1	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	25.6	25.7	25.4	25.7	24.4	23.6	22.1	24	25	25.6	24.5	24	21.1	22.3	23.9	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	23.7	23.7	23.9	23.9	23.1	23	22	23.2	23.2	23.8	23.3	23.3	20.8	21.9	23.3	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
19:00	24	23.9	24.7	25.6	23.7	23.4	23.9	23.9	24.6	24.8	25	23.9	22.2	22.5	23.7	23.7	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	25.7	25.6	25.3	24.8	23.9	24.4	24.3	24.5	25.1	25.4	25.1	23.8	22.5	23.5	24.9	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	25.4	25.2	24.6	25	23.3	23.8	24.3	24	24.7	24.3	25	24	22.7	24.3	24.5	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	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	23.7	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	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	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	22.4	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	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

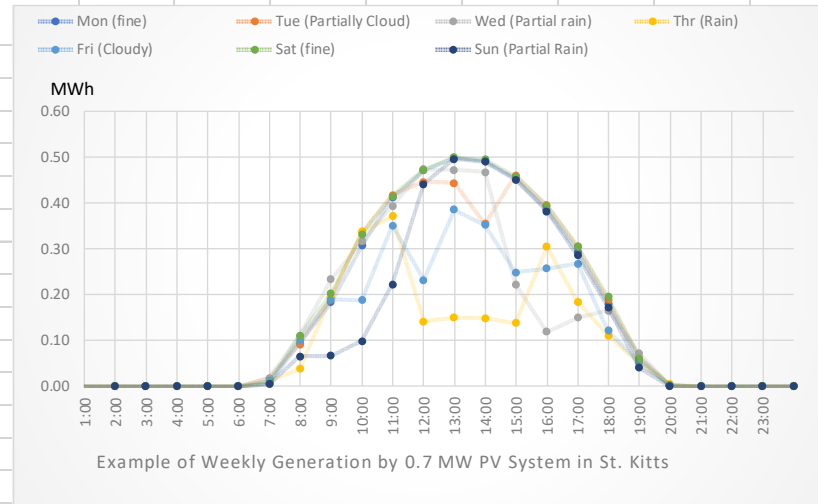
1Month





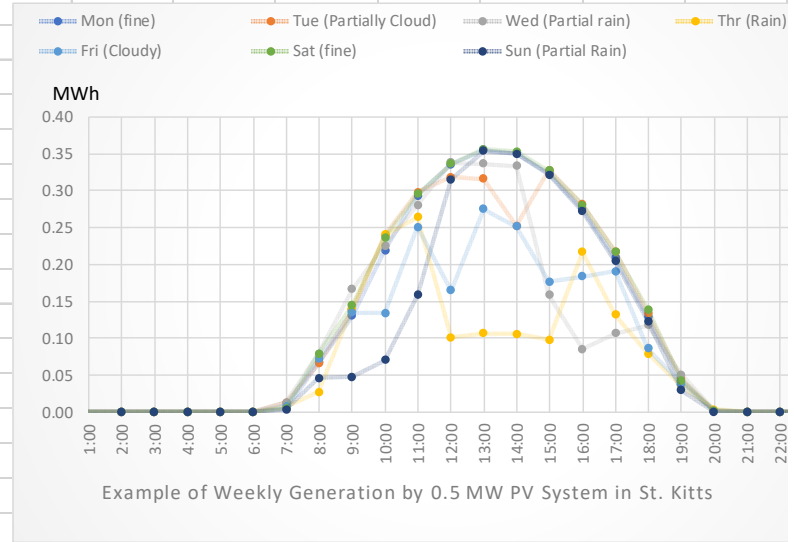
Hourly Generation MWh in an example of a week by 0.7 MW PV system in St. Kitts

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	



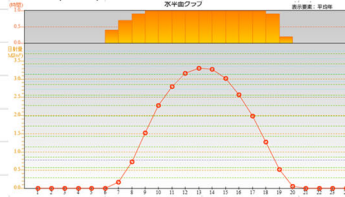
Hourly Generation MWh in an example of a week by 0.5 MW PV system in St. Kitts

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	

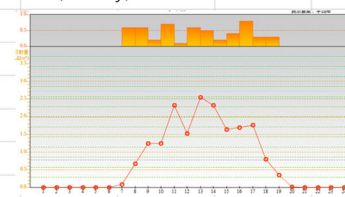


									http://app0.infoc.nedo.go.jp/metpv/metpv.html
Hateruma	20-Jun	16-Jul	17-Jun	10-Jun	25-Jun	27-Jun	27-Jun		
Time	Mon(fine)	Tue (Parti	Wed (Part	Thr (Rain)	Fri (Cloud	Sat (fine)	Sun (Partial Rain)		
1:00	0	0	0	0	0	0	0		
2:00	0	0	0	0	0	0	0		
3:00	0	0	0	0	0	0	0		
4:00	0	0	0	0	0	0	0		
5:00	0	0	0	0	0	0	0		
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						

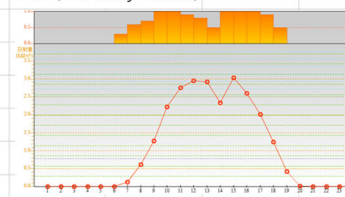
Mon(fine)



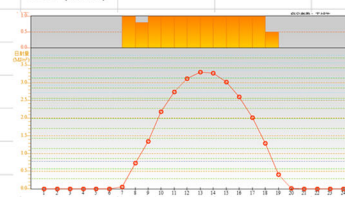
Fri (Cloudy)



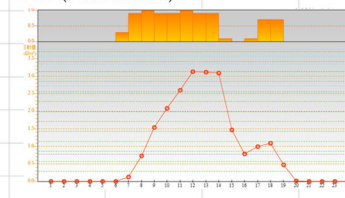
Tue (Partially Cloud)



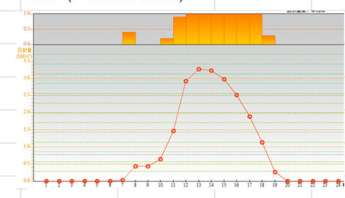
Sat (fine)



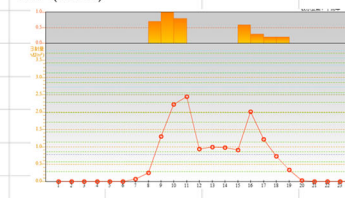
Wed (Partial rain)



Sun (Partial Rain)



Thr (Rain)



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 KITT'S
AND NEVIS

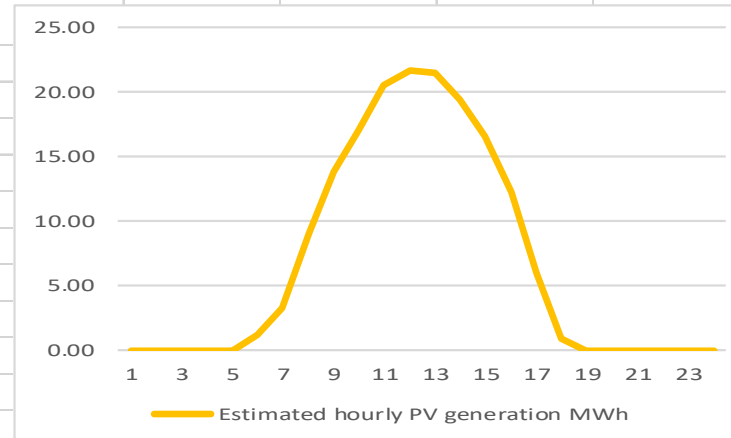
SAINT JAMES
WINDWARD

SAINT GEORGE
GINGERLAND

5 km

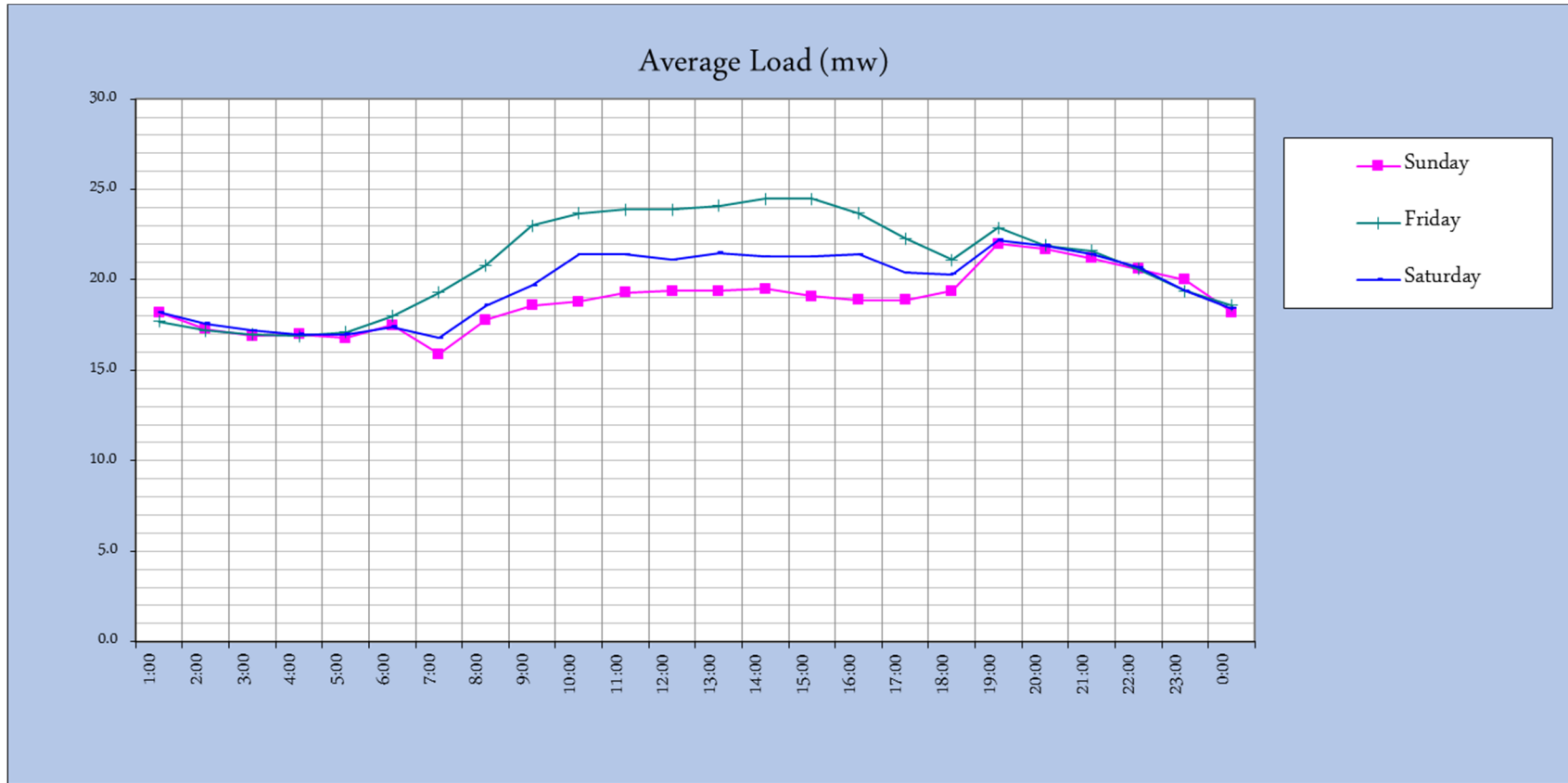
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		GTI	6 kWh/m2					
		PV output	4.663 kWh/kWp/day					
Hourly PV generation estimation in St Kitts								
Time	Coeff. Hourly dist. Estimated	Hourly irradiation kWh/m2	Hourly PV kWh/kWp	Estimated hourly PV generation MWh				
1:00	0.00	0.00	0.00	0.00				
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		

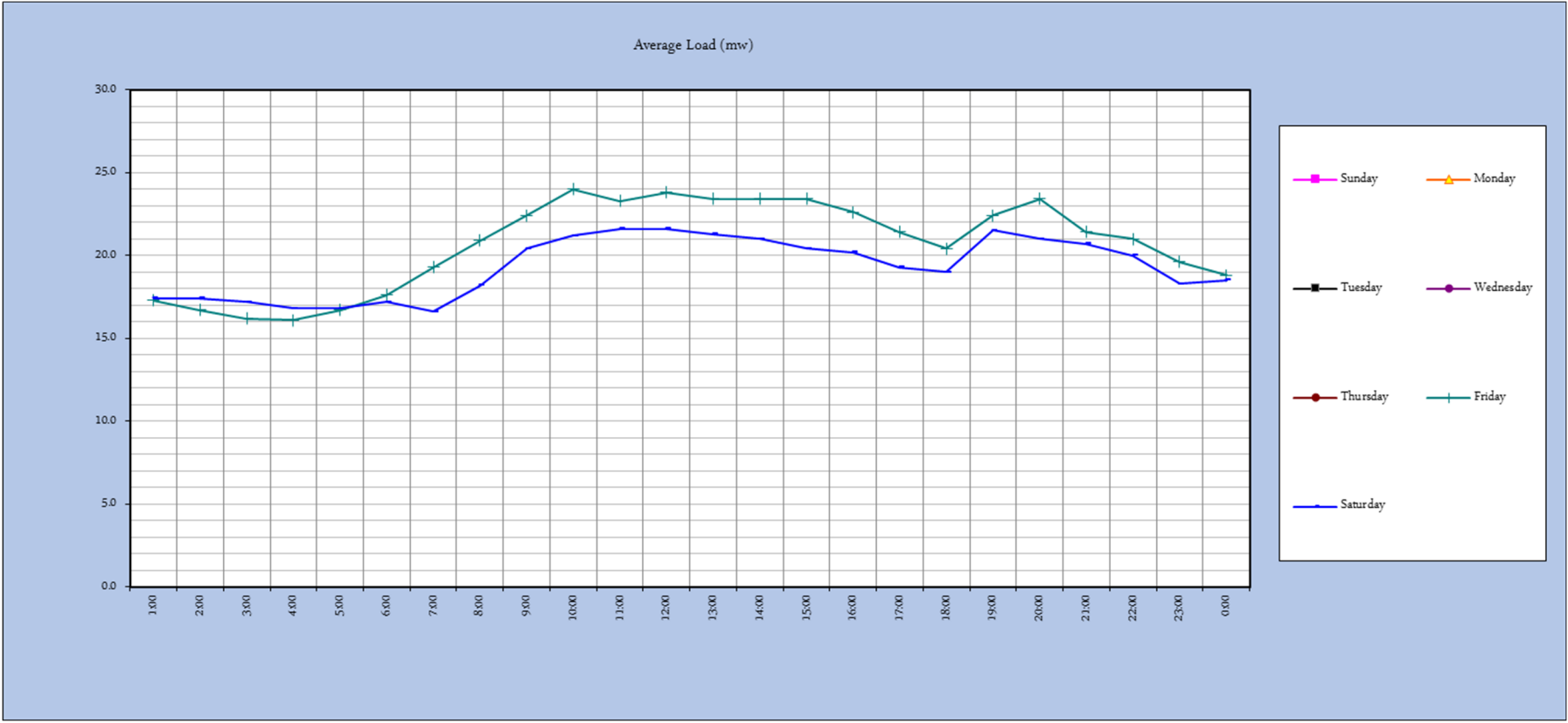


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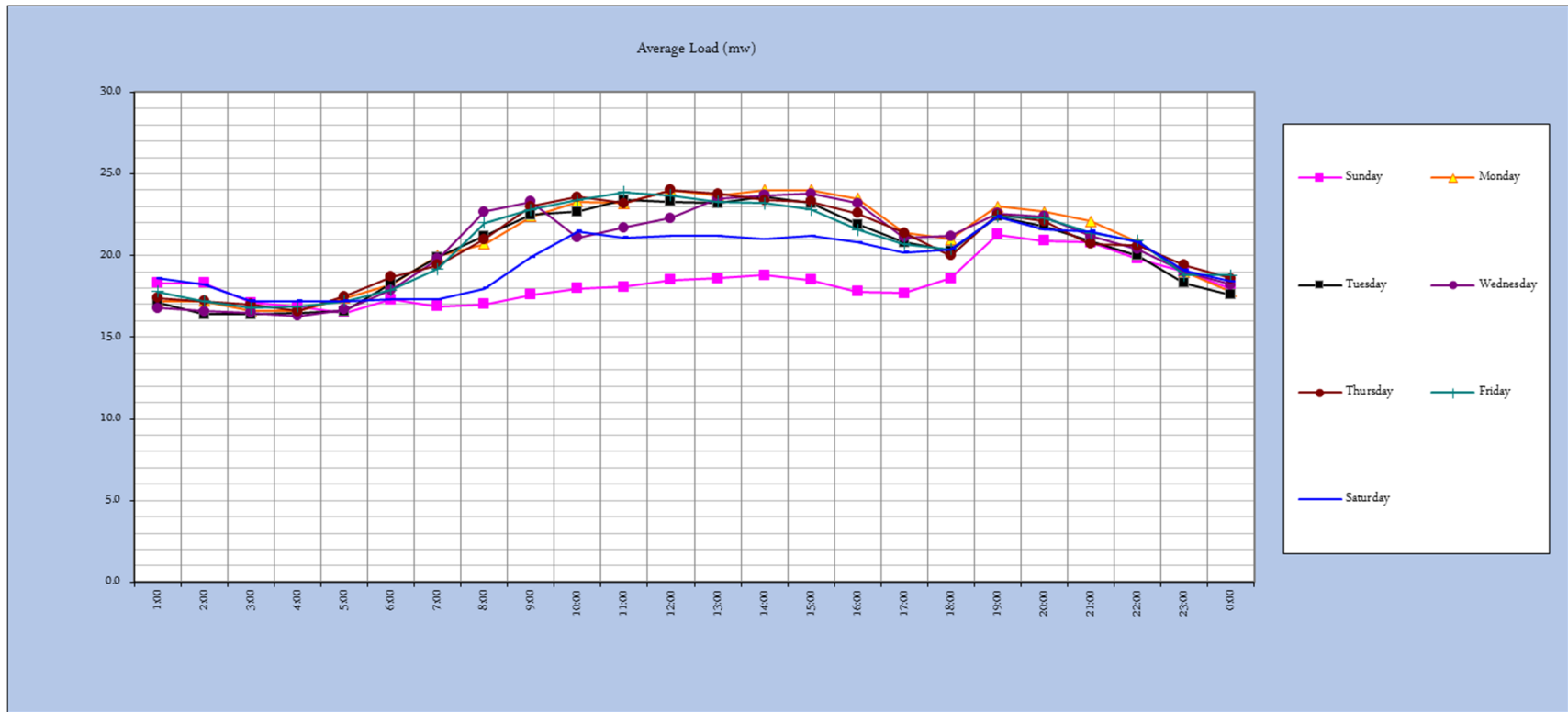
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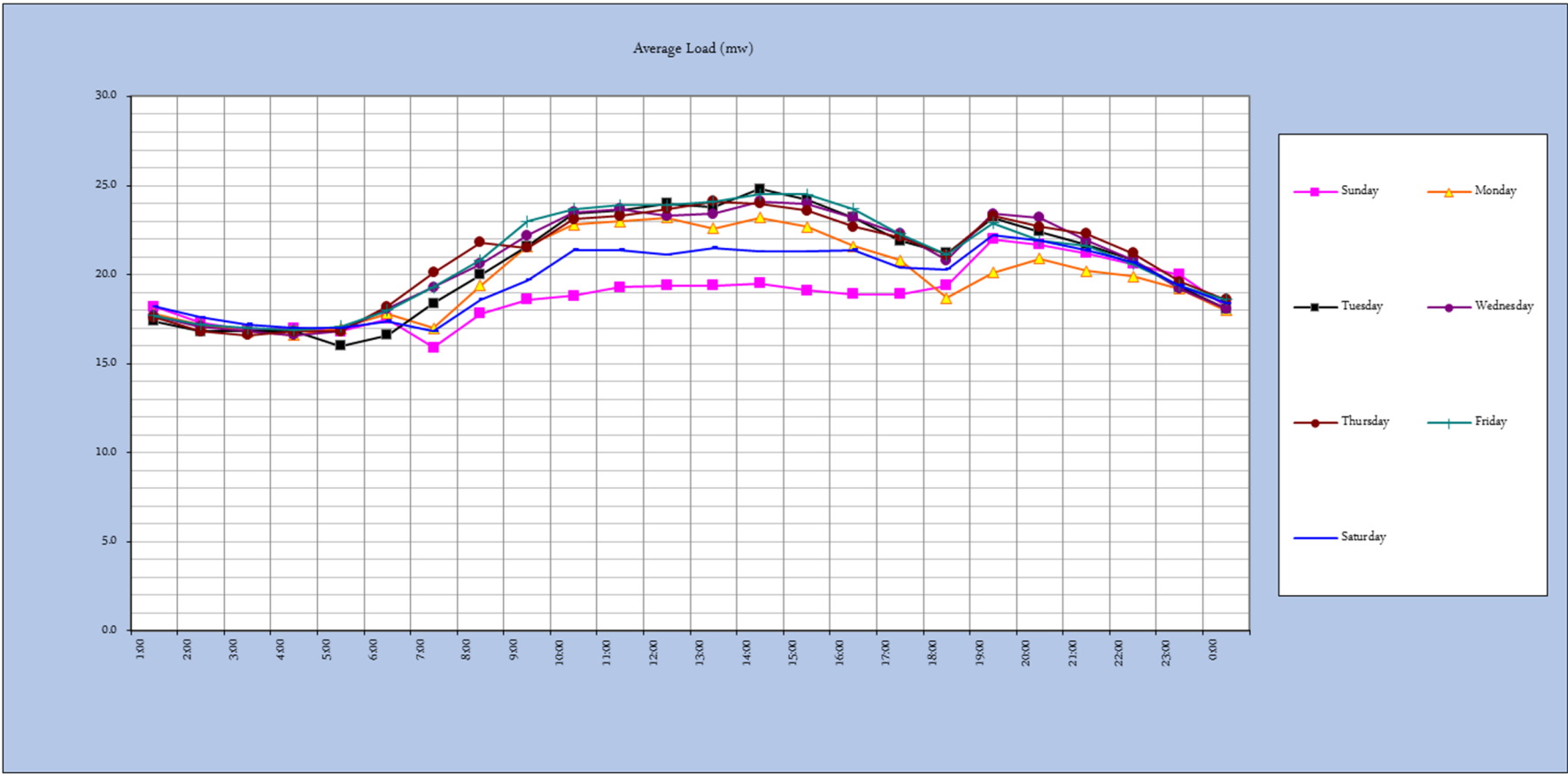
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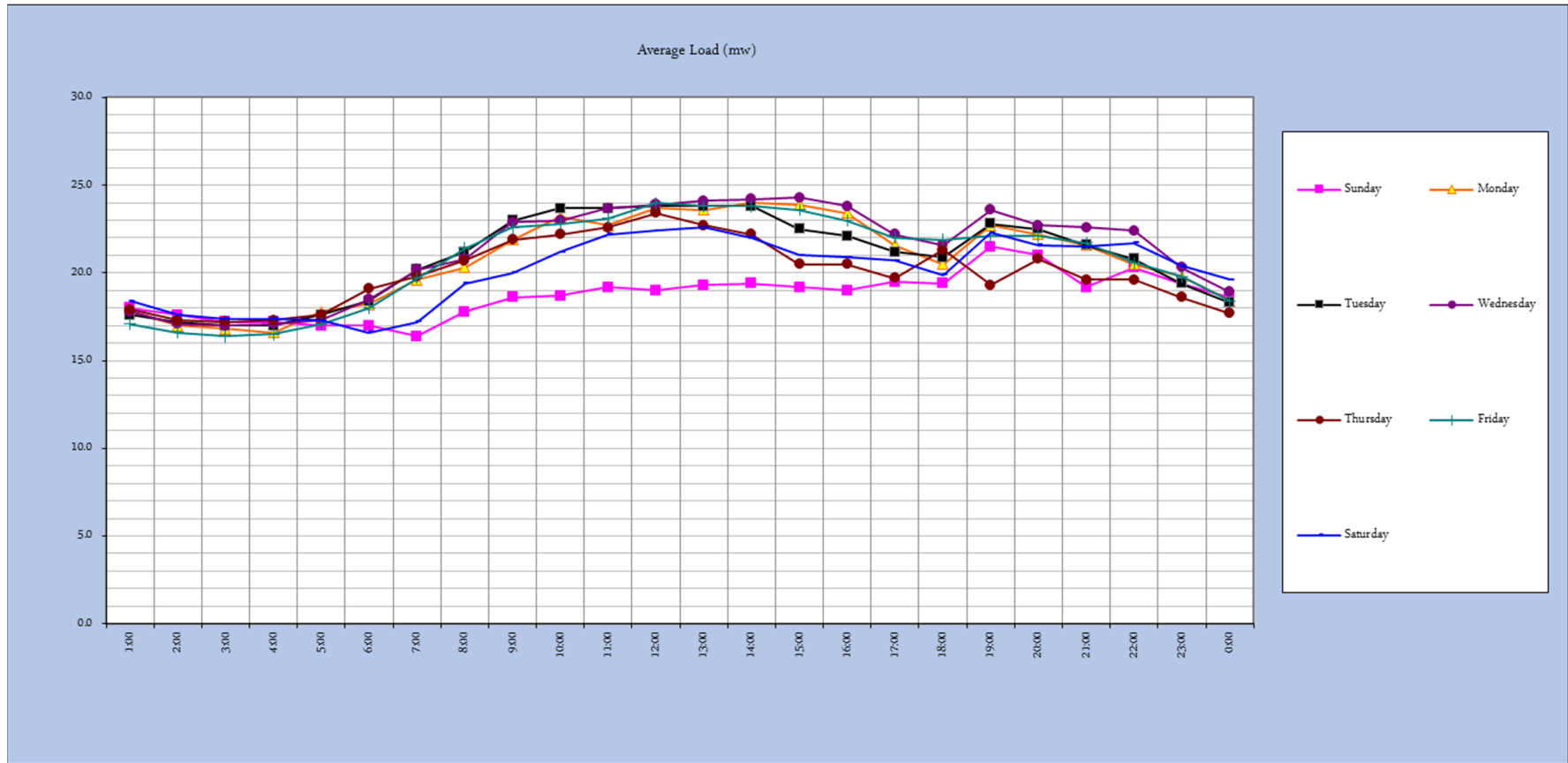
Hourly Load & Averages



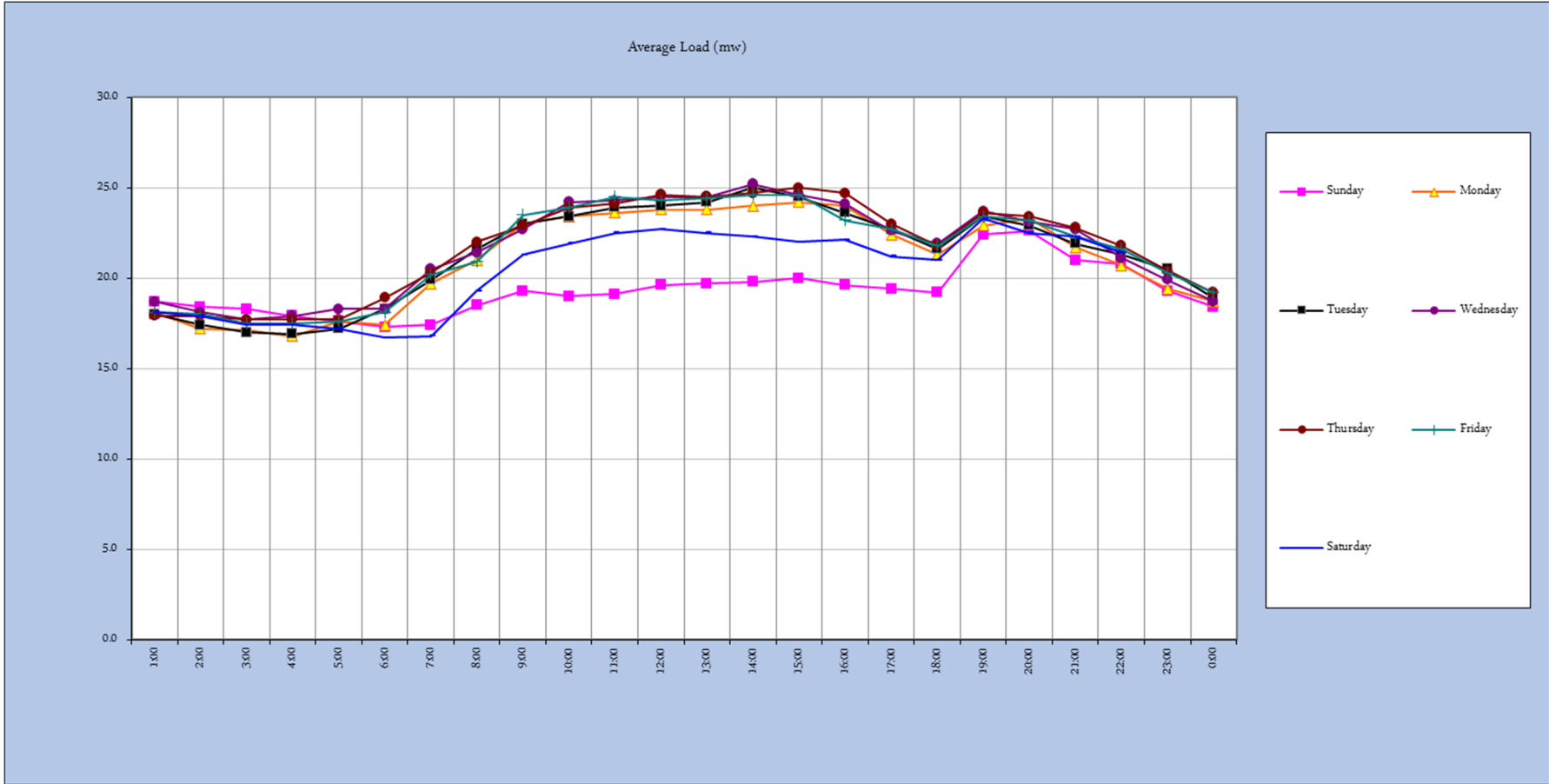
Hourly Load & Averages



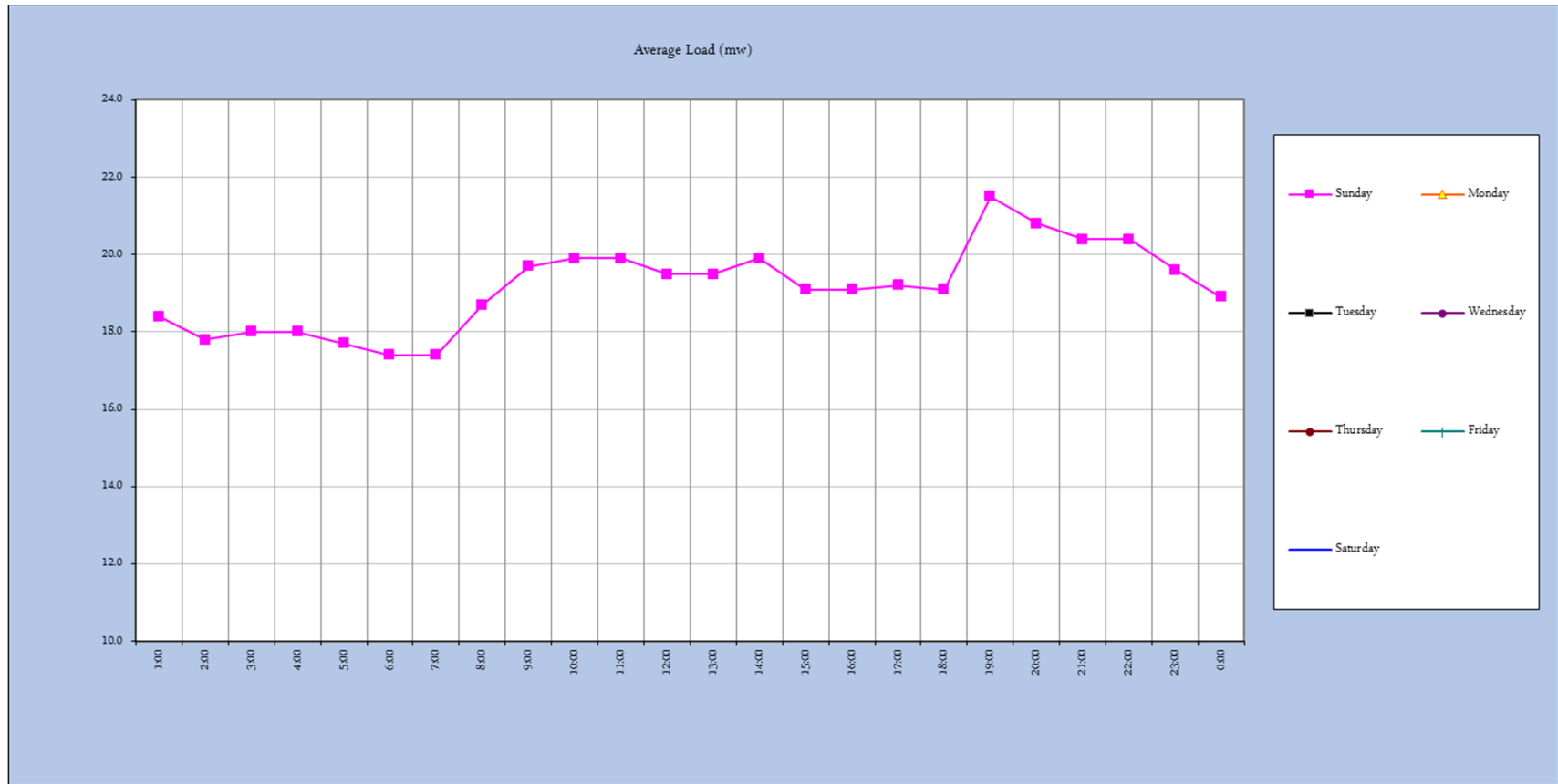
Hourly Load & Averages



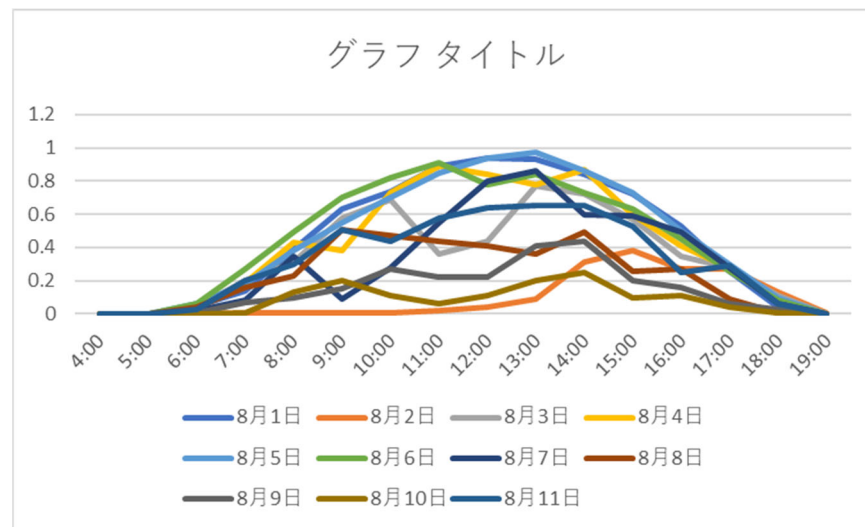
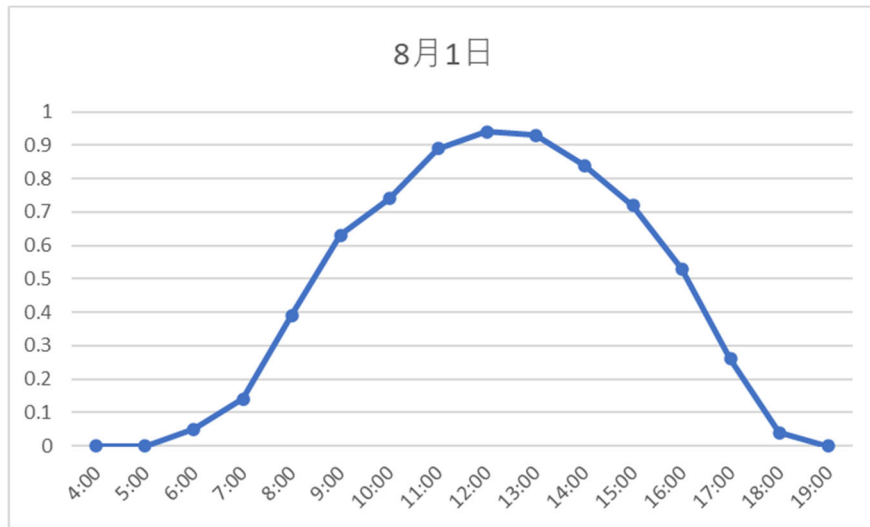
Hourly Load & Averages



Hourly Load & Averages



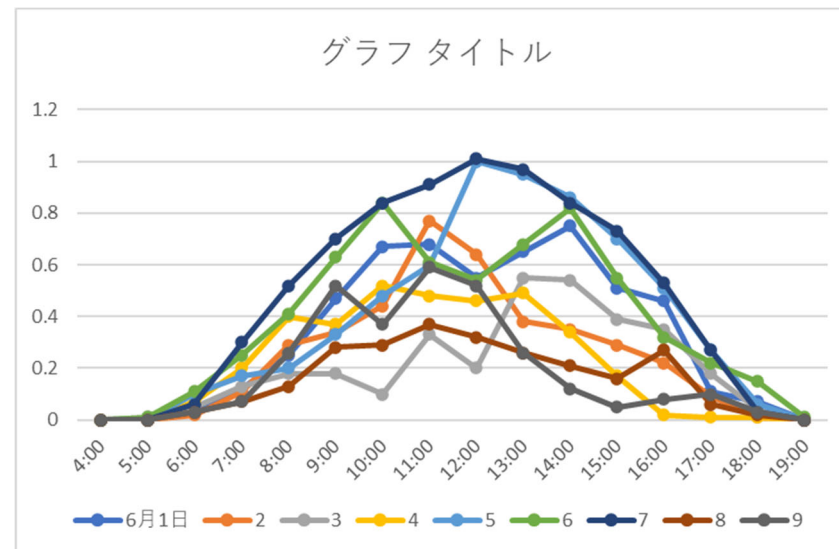
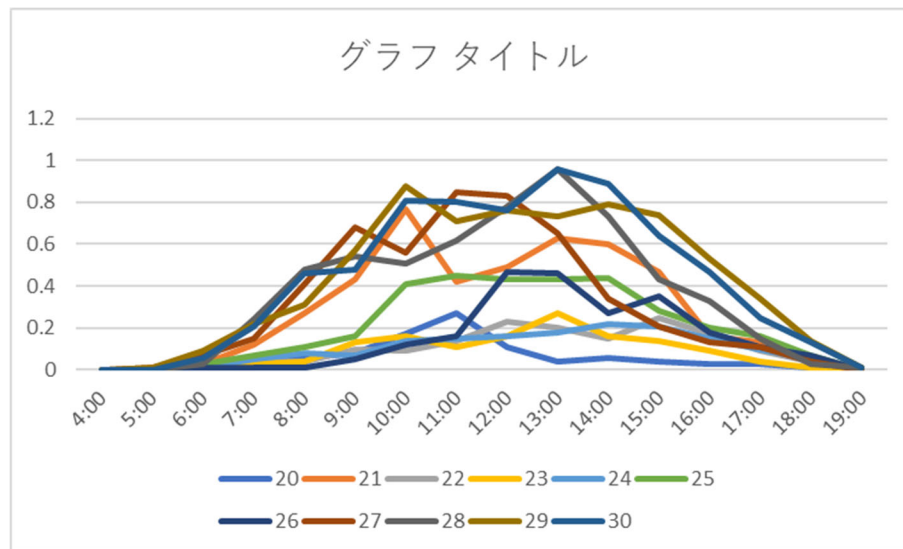
Hourly Load & Averages



August 2019

	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

June 2019



June 2019

Appendix H: Separate Formats for St_Kitts_Minimum Load, etc. (collected locally, 2019)

2.4 Dynamic Stability Analysis							Table 1.3		April 2019		
Table 2-8 Dispatch at Minimum Load							Existing SKELEC Generation		Generators Fuel Eff (1). docx		
Generator	Pgen MW	Pmin MW	Pmax MW	Spinning		Down	Ramp Capability		Generators Fuel Efficiency (kWh/gal)		
				Reserve MW	%Loading MW	Reserve MW	kW/sec	MW/h	UNIT	70%	逆数
Generator#1	5.80	1.22	6.13	0.00	94.60%	4.58	122.00	439.20	Generator#1	18.08	5.531
Generator#2	3.34	0.77	3.87	0.52	86.50%	2.58	77.40	278.64	Generator#2	18.01	5.552
Generator#3	3.50	0.77	3.89	0.39	89.80%	2.72	77.92	280.51	Generator#3	17.38	5.754
Generator#4	3.60	0.77	3.89	0.29	92.40%	2.82	77.92	280.51	Generator#4	17.23	5.804
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#9	17.90	5.587
Generator#10	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51	Generator#10	17.99	5.559
Generator#11	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51	Generator#11	18.47	5.414
Generator#12	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51	Generator#12	17.99	5.559
Generator#14	0.00	0.77	3.89	0.00	0.00%	0.00	77.92	280.51	Generator#14	-	
Generator CAT1		0.41	1.65				55.00	198.00	Generator CAT1	17.50	5.715
Generator CAT2		0.41	1.65				55.00	198.00	Generator CAT2	16.00	6.248
Generator CAT3		0.41	1.65				55.00	198.00	Generator CAT3	16.00	6.248
Generator CAT4		0.41	1.65				55.00	198.00	Generator CAT4	17.50	5.715
Generator CAT5		0.41	1.65				55.00	198.00	Generator CAT5	16.00	6.248
Generator CAT6		0.41	1.65				55.00	198.00	Generator CAT6	17.50	5.715
sum	16.24	5.99	27.68								
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											

Appendix I: Report on 27th Nov 2019, St. Kitts, Report on the results of the field trip by Nippon Koei Co.

St. Kitts Island Business Trip Report related to Grid analysis
27/11/2019 NIPPON KOEI, Niimi

1. Outline of Activities

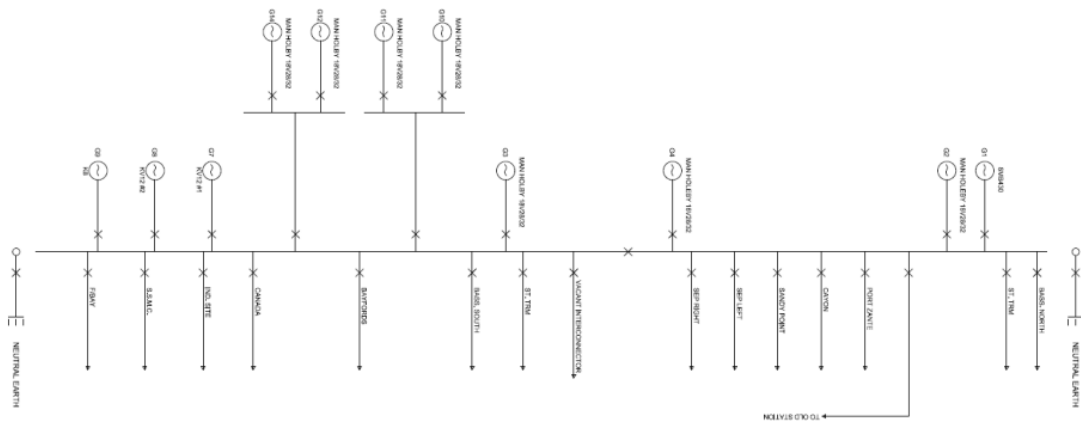
- Explanation of the current status of Grid analysis to SKELEC
- Hearings with SKELEC on additional necessary information
- Gathered information through site visits with SKELEC
- Promote GridSim (tentative name) at JCC.
(Response was positive, and SKELEC and MPI are willing to cooperate.)

2. Information Collected

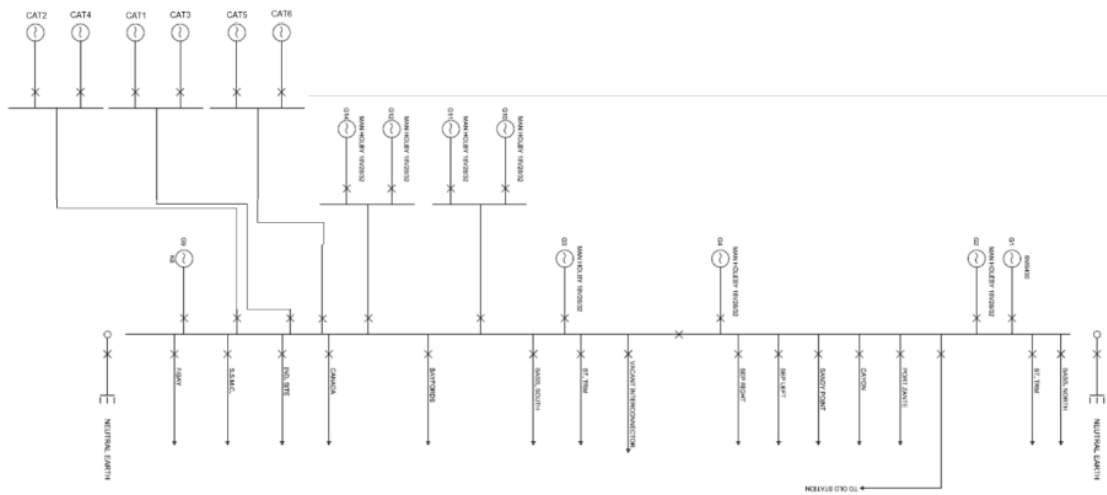
- 500kW PV at Basseterre has not been operating since about August. It is currently shutting down. The feeder to which it is connected is Bayfords.
- The 1.2MW PV installed at SKELEC is also currently out of service due to a breakdown, and since it is under warranty, the entire unit will be removed and a new one of similar size will be installed. They are currently waiting for a response from the Taiwanese contractor.
- For the 34MW Laclanche project, the PPA was signed for 16MW base and 18MW Max, and SKELEC will not pay for the excess of 16MW. The excess is stored in batteries and sold after sunset.
- The power is generated at 11.3 kV and transmitted to 11 kV at the end of the line. There is no voltage drop problem.
- Feeder load at Canon is about 2.2 MW during the day and 3.2 MW at night. The feeder will reach its limit when Wind's 5 MW is added.
- The necessary data for simulation is provided. Heat rate, active power, reactive power, cost of maintenance, etc. can be provided.
- 2MW nameplate capacity, actual output 1.6MW x 6 units CAT diesel generators were installed (4 units were installed in March and 2 more units were installed). The numbers are CAT1, CAT2, ...CAT6, all the same models. The actual output is reduced by High-Speed Diesel, according to the manufacturer's recommendation. Is it because the temperature is too hot?
- The latest F/S results for Raidos cannot be provided as they have not yet been officially issued.

- Inverter specifications and other information on the 34MW Laclanche project cannot be provided as they are still confidential.
- Two Caterpillar diesel engine generators were added to CAT 5 and 6 (nameplate rating 2 MW, actual operational rating 1.6 MW). The connection points are as shown in the single wire connection diagram in the following figure.

● Before



● After



- All six Caterpillar diesel engine generators are said to have the same specifications. Photo of CAT5 nameplate.
- The following table shows the generation status and load of each feeder during the daytime on 30th October.

Feeder	Day Peak	Night Peak
Baseterre 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
Basetrre south	4.9	3.1
Bayfords	1.0	1.4
SSMC/Airport	0.8	0.8
CANADA	1.2	1.2

- The Lodge switchyard has a simple design with only a remote controller and switchgear in a duplex configuration. Other switchyards have a similar configuration.
- No phase regulator has been installed.

3. Changes to the grid analysis

- Addition of generators CAT5 and CAT6
- Deletion of generators G7 and G8
- Connection of 500kW PV to Bayfords feeder was changed.
- Program based on power sales contracts of 16 MW and 18 MW Max for the 34 MW Laclanche PV project.
- The singularity of the node was adjusted in reference to other nodes due to data anomalies.

Appendix J: Description of Fast Tidal Current Calculation Programs for Large Transmission and Distribution Systems

Prepared by Energy and Environment Technology Research Institute

1. Background and History

Many methods have been proposed for calculating tidal currents in power systems, including the Newton-Raphson method for power transmission systems and the Backward/Forward method for power distribution systems. Although performance comparisons of these methods have been performed in the past, it was not clear how fast they could solve the problem up to what scale of the system.

Therefore, in FY2011, we performed comparative simulations between the Newton-Raphson method and the Backward/Forward method for a large-scale power distribution system and demonstrated the superiority of the Backward/Forward method.

However, although the backward/forward method can handle weak loop networks, its applicability to transmission systems with many loops was unknown.

In addition, the Newton-Raphson approach is essential to rigorously solve the optimal tidal current calculation as a nonlinear programming problem. Based on these perspectives, in FY2012, we conducted the following two studies for a large-scale transmission system: (1) a major modification and speed-up of the Newton-Raphson method developed in FY2011, and (2) an attempt to implement the Newton-Raphson method using the iterative method for solving linear equations, which is a recent theoretical achievement. (2) An attempt to implement the Newton-Raphson method with the "iterative method for linear equations," which is a recent theoretical achievement.

In (1), the Jacobian sparse matrix creation and its LU decomposition are accelerated (hereinafter referred to as the improved Newton-Raphson method), and in (2), the restart-type GMRES (Generalized Minimal Residual method) method, a typical iterative solution method for asymmetric simultaneous linear equations, is implemented. (2) the implementation of the Newton-GMRES method, which applies the restarted GMRES (Generalized Minimal Residual method) method, a typical iterative solution method for asymmetric linear systems, to the Newton equations. Here, both are named the EETRI method.

2. Simulation results for large distribution systems (2011, 2012)

A virtual large-scale distribution system without loops (Radial Distribution network) was randomly generated as a directed graph with a tree structure and used for numerical experiments (see Tables 1

and 2). The roots of the tree are slack buses, the leaves of the tree are load nodes (PQ specified nodes), and the rest are intermediate passages and branches (PQ nodes with specified value zero). Note that the R/X ratio of the branches is used [1.0,10.0] and all Susceptance is ignored.

As a result, the modified Newton-Raphson method achieves a speedup of about 230 times faster than the 2011 results for the n=40000 case. However, since the computation time is about 4 times longer than that of the Backward/Forward method, the superiority of the Backward/Forward method remains unchallenged.

Table 1 Results of Numerical Experiments on Large-Scale Distribution Systems (2011)

Node(n)	burden node	Slack voltage	number of repetitions		Final error (PQmismatch)		Execution time (s)		velocity ratio
			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 method

B/F: Backward/Forward method

Table 2 Results of Numerical Experiments on Large-Scale Distribution Systems (2012)

Node(n)	non-zero number of elements (e.g. in a matrix)	fill-in rate		number of repetitions		Final error (PQmismatch)		Execution time (s)		velocity ratio
		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: Modified Newton-Raphson method

N_G: Newton-GMRES method

Number of non-zero elements: Number of non-zero elements in the Jacobian of the Newton equation

Fill-in rate: Number of non-zero elements in the complete LU decomposition / Number of non-zero elements above (modified Newton-Raphson method)

: Number of non-zero elements of incomplete LU decomposition/number of non-zero elements above

(Newton-GMRES method)

where, at each iteration by the Newton method

- ① In the modified Newton-Raphson method, a full LU decomposition is performed first, followed by a single quadrature operation.
- (2) In the Newton-GMRES method, incomplete LU decomposition is performed first, and then convergence improvement by the GMRES method is performed multiple times in subsequent quadrature operations. Incomplete LU decomposition is less expensive than complete LU decomposition but requires post-processing.

3. Simulation results for large transmission systems (2012)

A hypothetical large-scale transmission system with many loops was randomly generated as an undirected graph and used for numerical experiments. Here, a random graph was generated by giving an average node order (number of connected branches: degree) of 2.5 (if the number of nodes is n , then the number of branches is $m=1.25n$ and the number of loops is $m-n+1$), and a standard π -type model transmission system was created by classifying the group of nodes as follows.

- (1) Generating nodes are assigned in order of decreasing in-degree, with the first generating node as the slack node and the subsequent ones as the PV nodes. The total number of generators is fixed at 51.
- (2) All nodes with an out-degree (out-degree) of zero shall be load nodes (PQ-designated nodes), and all other nodes shall be intermediate transit and branch points (PQ nodes with a designated value of zero).

Note that the R/X ratio for the branches was used [1.0,10.0] and Susceptance was set randomly for the branches and nodes.

Table 3 Results of Numerical Experiments on Large-Scale Transmission Systems (2012)

Node(n)	non-zero number of elements (e.g. in a matrix)	fill-in rate		number of repetitions		Final error (PQmismatch)		Execution time (s)		velocity ratio
		N_R	N_G	N_R	N_G	N_R	N_G	N_R	N_G	
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

As a result, the Newton-GMRES method was slower than the modified Newton-Raphson method for large distribution systems without loops, but the Newton-GMRES method was faster than the modified Newton-Raphson method for large transmission systems with many loops. In a tree-structured distribution system, the admittance matrix and its Jacobian matrix are band-shaped matrices, and the

fact that the Jacobian matrix can be efficiently fully LU-decomposed is the reason why the improved Newton-Raphson method was faster.

4. Examples of application of the EETRI method

- (1) The problem of optimal placement of distributed power sources in a power distribution system

Tidal current calculation (B/F) 159,0544 times in 126 bus bar distribution system in about 31 seconds

- (2) Time-series dependent stochastic tidal current calculation in distribution systems

Tidal current calculations (B/F) on 126 bus bar distribution system 288,000 times in about 87 seconds

- (3) Various meta-solving methods for continuous-type single-objective OPFs in power distribution systems

Tidal current calculations (modified Newton-Raphson) on 126 bus bar distribution system approx. 1,8200 times approx. 17* seconds (10-trials)

- (4) Meta-solving methods for continuous and discrete multi-objective OPFs in power distribution systems

Tidal current calculations on 126 bus bar distribution system (modified Newton-Raphson) 1,2951 times about 12* seconds (1-trial)

- (5) Switch Combination Problem in Power Distribution System

Tidal current calculation (B/F) 163,6290 times in 126 bus bar distribution system in about 29 seconds