Appendix 5-2-2 Attendant list, and Q&A, of the 2nd Energy Efficiency Workshop (St. Kitts and Nevis)

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE

List of Participants from St. Kits and Nevis **Total** **24**

List of Participants for Physical Attendance (16 an **Venue: Courtyard by Marriott Bridgetown, Barbados**

No	Name	Agency	Positionn	Participation
1	Bertill Conroy Browne	MPI	Director	in person
2	Denasio Frank	MPI	Energy Officer	in person
3	Curtis Morton	NIA	Electrical Inspector	in person
4	Deora Raoul Pemberton	NIA	Director of the Dept. Physical Planner	in person
5	Haniff Woods	SKELEC	Operations Engineer	in person
6	Collin Williams	SKELEC	Meter Manager	in person
7	Rhondel Philip	SKELEC	T&D Planning and Development Manager	in person
8	Claricia Langley-Stevens	SKELEC	Safety and Security Manager	in person
9	Nelson Horatio Ald Junior Stapleton	NEVLEC	Distribution Manager	in person
10	Starett France	NEVLEC	Planing Officer	in person
11	Resean Maynard	NEVLEC	Linesman II	in person
12	Clayon Everton	NEVLEC	Linesman II	in person
13	Gavin Walters	NWD	Electrical Tech II	in person
14	Sharma Browne	NWD	Electrical Tech II	in person
15	Collin Brown	SKELEC	Engineer	online
16	Jonathan Kelly	SKELEC	Engineering Manager	online
17	Kristel Pemberton	NEVLEC	Customer Service Supervisor	online
18	Ronell Pemberton	NEVLEC	Project Engineer	online
19	Keane Mark	SKELEC	Generation Maintenance Engineer	online
20	Ian Ward	NEVLEC	Chief Engineer	online
21	Shallianda Gomez	SKELEC	Metering Administrator	online
22	Wycliffe Clarke	SKELEC	T&D Control and Operations Supervisor	online
23	Jessie Hunkins	NIA	Physcial Planning Nevis	online
24	Royan Matthew	SKELEC	Engineer	online

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on EE in 16-17 Jan 2023 (St.Kitts&Nevis): Q&A

No	Day	Type	Question	Name	Answer
1	16-Jan	Question	Was the reduction in energy usage a result of educating the Japanese people or was it because of government policy?	Nelson Stapleton, NEVLEC	The Japanese buyer is influenced by the energy efficiency of the appliance they are purchasing. This is further compounded by the fact that recent energy prices spike-up. Also, there is an Energy Efficiency Centre that plays a role to promote and educate people regarding energy efficiency related matters. The Minister also awards the persons and manufactures who made significant improvements in their energy efficiency. Apart from that there are government policy and that are regulated by law, the Act of Rational Use of Energy usually called as EE law. Two ministries are responsible for the EE law, Ministry of Economic Trade and Industry (METI) as well as the Ministry of Land, Infrastructure, Transport and Tourism.
2	16-Jan	Question	Has there been any challenges to the regulations by manufacturers?	Colin Williams, SKELEC	The program which functions as MEPS is voluntary but most of manufacturers follow the standards. While there is no penalty if the standard is not followed, most of manufacturers follow the standards in the real world.
3	16-Jan	Question	In St. Kitts and Nevis electric water heaters are used almost in every household. Is this a problem in Japan because I notice that it was not taken into consideration in your energy efficiency study?	Colin Williams, SKELEC	Water heater demand is limited in residential sector as refrigerator, lighting and AC shares 73% of total power consumption. IN hot water supply field, the first option is to consider solar water heater in the region where lots of solar radiation exists. In addition, heat pump water heater with CO2 refrigerant has been diffused in Japan. DENSO, Central Research Institute of Electric Power Industry and Tokyo Electric Power Company came together to develop the HP water heater. This type of water heater has become very popular among the Japanese people. The total sales has exceed 2 million units. It costs approximately $10,000US for the unit and installation depending on the size and installation situation.
4	16-Jan	Question	Does the Tokyo Electric Power Company have different rates at various times at the day?	Colin Williams, SKELEC	JET gave a breakdown of time of use and how rates are applied to different times of the day to residential customers.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on EE in 16-17 Jan 2023 (St.Kitts&Nevis): Q&A

No	Day	Type	Question	Name	Answer
5	16-Jan	Question	The targets that were set for the appliances, are they relying on improvement in the technology and approach or discovery of new techniques to improve their energy efficiency?	Colin Williams, SKELEC	The present efficiency in use at all household can not be obtained, and this was set as EE Index =1. Old appliances are being used and operated at present. Assumed future EE Index was set in consideration with technologies already at our hands. In the material, section "The Promising Energy Efficient Technologies in Non-industrial Sectors" shows the examples of existing EE technologies.
6	16-Jan	Question	Why the energy savings associated with retro fitting buildings and homes are so small in comparison with the improvement in terms of lighting?	Nelson Stapleton, NEVLEC	That was the expected improvement by the Japanese government as it was geared towards new buildings. My understanding is that the government did expect more EE improvements in new buildings rather than retrofitting buildings according to the breakdown / data toward energy saving target.
7	17-Jan	Question	Wouldn’t it be that a lower temperature will lead to higher energy consumption?	Dr. Bertille Browne, MPI	Yes. This is my typo. Setting AC with upper temperature will lead to a reduction in power consumption, 10 % power reduction by changing AC setting 1° C higher.
8	17-Jan	Question	Does the data logger measure direct current?	Dr. Bertille Browne, MPI	The data logger that will be handed over cannot measure direct current.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on EE in 16-17 Jan 2023 (St.Kitts&Nevis): Q&A

No	Day	Type	Question	Name	Answer
9	17-Jan	Question	Was there a change to a more efficient cooling system?	Colin Williams, SKELEC	Yes. The existing absorption chillers were removed as well as co-gen removal. Instead, highly efficient air sourced heat pumps were adopted and more power came from the grid.

Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

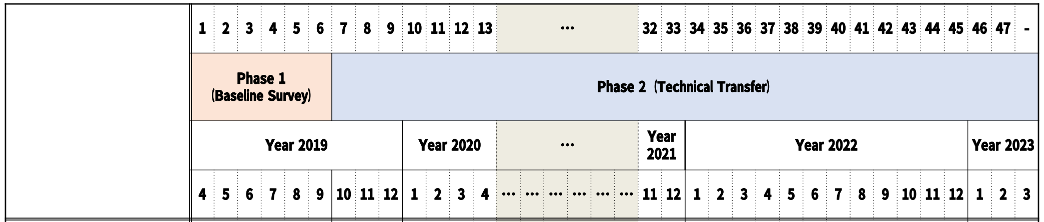
Consideration of Large VRE into Grid

Introduction for Seminar on Grid Stability and Large RE

October 2022

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

Overall Project Schedule



Output 1
The basic information is confirmed for the capacity building for the introduction of RE

Output 3
The human and institution capacity are enhanced for the mass introduction of RE

Output 2
The basic information is confirmed for the capacity building for the promotion of EE

Output 4
The human and institution capacity are enhanced for the promotion of EE

RE and Grid Stability activity is to:
- introduce computer modelling for grid analysis and examine issues associated with a large penetration of VRE
- introduce micro-grid concept in one of the agreed areas and develop modelling based on existing grid data.
- propose the way to enhance resiliency by use of asset management system.
- consider and propose the necessary technologies for achieving the RE goals, including grid stabilization,
- consider and propose additional policy legal system for achieving RE goals
- Prepare training plan, provide recommendation on policy

Key T/C Activities for RE and Brid Stability

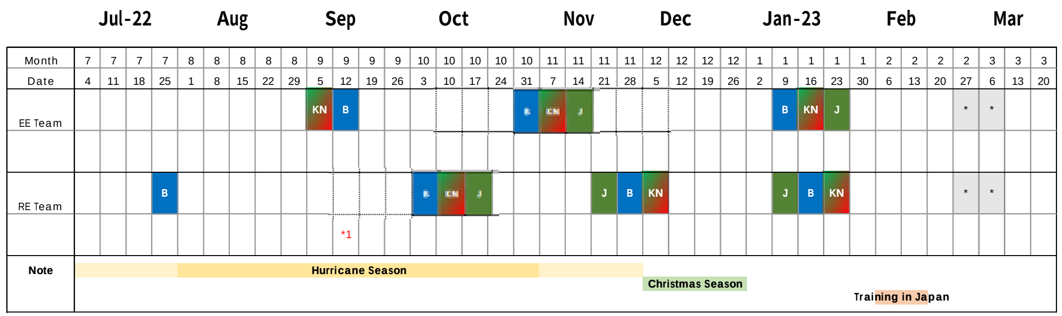
Barbados
- Training and Provision of Grid simulation software
- Micro-grid concept study at Coverley Village

Jamaica
- Training for grid simulation
- Micro-grid concept study at Bogue area

St Kitts &Nevis
- Provision of Grid simulation software and training
- Introduction of network asset management

✓ **Discussion for grid code update**
✓ **Suggestion for RE policy with reviewing affordability of RE**

Overall Schedule



B Barbados
J Jamaica
KN St. Kitts and Nevis (Activity in Barbados or Saint Lucia with Virtual Meeting / depending on the restriction by JICA)
* 3 Countries in 2 Weeks
*1 To be discussed [1st RE activity of St. Kitts and Nevis), and also 1st EE/RE activities of Jamaica]

Possibility of training in Japan depends on COVID-19 situation. It might be shifted to Apr 2023.

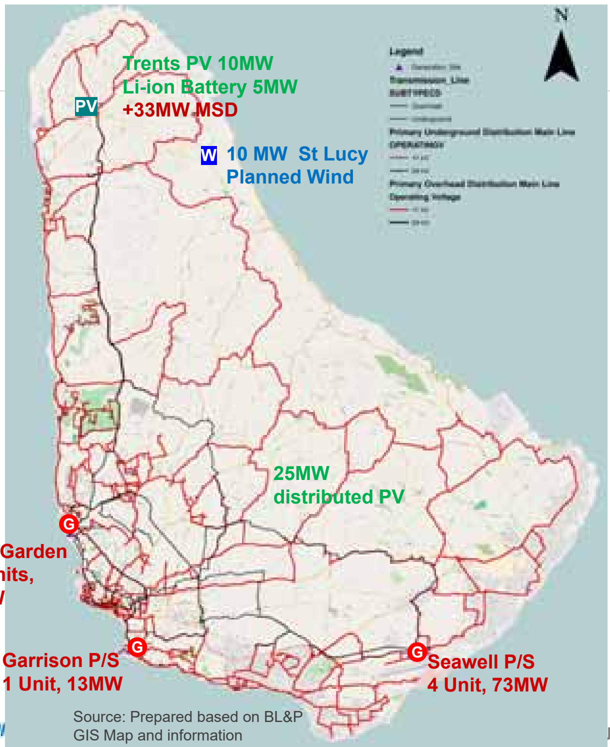
Seminar on Grid Stability with Large RE

Day	Title	Objective	Details
Day-1	Basics of Power System Engineering for Grid Stability Simulation	To review basic principal and necessary formula for conducting load flow analysis	1. What is Power System?: Three-phase AC, Single line network description 2. Per Unit Method: 3. Modeling of Power System Equipment: Tr.Line Transformer, Generator & Load 4. Active Power & Frequency: Frequency control, Area requirement 5. Reactive Power & Voltage: P-V Curve, Reactive power resource 6. Practice of Modeling of Grid
Day-2	Basics and Exercise for Load Flow Analysis	To understand the principal and method for Load Flow Analysis , DC Flow Method, and conduct exercise with the software "Microgrid/VPP Designer"	1. Overview of Load Flow Analysis: Purpose, Methods, Modeling of grid 2. Newton-Raphson Method: Theory, Characteristics 3. DC Flow Method: Theory, Simple method to solve load flow manually 4. Exercise of DC Flow Method, 5. Practice on Microgrid/VPP Designer 6. Load Flow Analysis & Evaluation of sample Grid
Day-3	Analysis of Grid Stability and LFC/ELD	To understand the method of grid stability analysis, with Steady State Stability, Transient Stability Equal Area Criterion, LFC (Load Frequency Control) and ELD (Economic Load Dispatching)	1. Overview of Stability: Definition, Methods, Swing equation 2. Stability Model: Simplified grid model, Equivalent circuit of synchronous generator 3. Equal Area Criterion: Theory, Simple method to solve stability manually 4. Available Transmission Capacity & Spinning Reserve 5. Exercise of Equal Area Criterion, 6. Practice on Mircogrid/VPP Designer and LFC/ELD 7. Stability Analysis, Evaluation of Barbados Grid

Summary: Barbados

Fields	Findings	Project Activities
1. Energy Efficiency	• Energy Source: Electricity (54%) , Oil (42%) • Load Curve: Bactrian camel type • Annual Peak Demand: about 150MW • Peak Period: 2pm - 3pm, 7pm-8pm	Priority 1: VRF Priority 2: BEMS Priority 3: Optimized operation with inverter
2. Renewable Energy	• 100% RE target incl. fuel by 2030 • 14% RE (generation), 2% of RE (energy base) • Good RE potential, but project plan not concrete • 10MW Trents PV + 65 MW Roof top	Confirmation of affordability and feasibility of 100% RE target Training for grid simulation Micro-grid concept study
3. Grid Stabilization	• 5MW, 20 MWh BESS, 400 USD/MWh installed • 40-200 MW BESS is planned for procurement • 0.02 Hz with 1MW fluctuation, Ramp Rate 3MW/min • Fuel increase for spinning reserve	
4. O&M of Thermal Power Generation	• Thermal power plant: total 16 units (10 units for base load and 6 units for peak load • Installed Capacity: Total 255.5MW+32 MW • Predictive Maintenance: Conducted twice a year	-LFC and ELD simulation
5. Human Resources and Capacity Building	• MEWE's Energy Conservation and Renewable Energy Unit: 3 employees • Most of capacity building is done by OJT	JET experts select topics and develop the most suitable curriculum for technology transfer period

Barbados Grid and PS



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

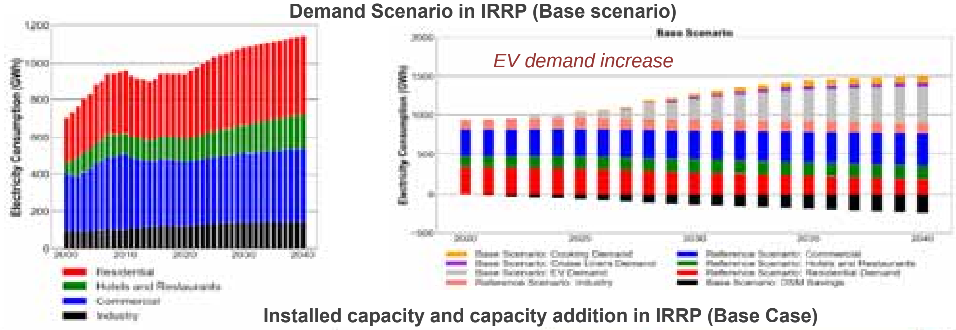
Location		MW/u	Qy	MW	Remark
Existing					
Total thermal power				232	
	Spring Field	12	3	36	LSD Engine
	Spring Field	12.5	1	12.5	LSD Engine
	Spring Field	30	2	60	LSD Engine
	Spring Field	20	2	40	Steam Turbine
	Spring Field	17.5	1	17.5	Gas Tubine
	Spring Field Total		9	166	
	Garrison	13	1	13	Gas Tubine
	Seawell	13	1	13	Gas Tubine
	Seawell	20	2	40	Gas Tubine
Total PV				70	
	Trents	10	1	10	PV
	Distributed PV		LS	60	PV
Total Battery				5	
	Trents	1	LS	5	BESS
Planned					
Total Planned RE				40	
	Trents	33	1	33	CEB MSD Planned
	St Lucy	10	1	10	Wind Planned
	St Tomas	30	1	30	Vaucluse Biomass

Tentative. Please let us confirm the status and update if any.

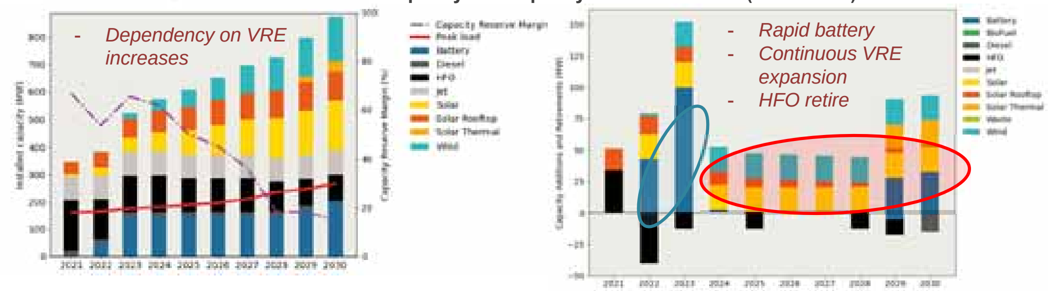
Barbados Demand&Installed capacity in IRRP

Source: IRRP Draft 2021, MottMacDonald

Demand Scenario in IRRP (Base scenario)



Installed capacity and capacity addition in IRRP (Base Case)



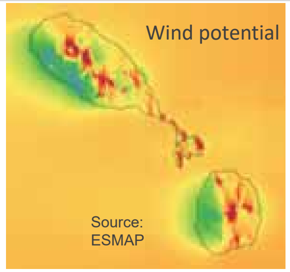
Summary (St Kits and Nevis)

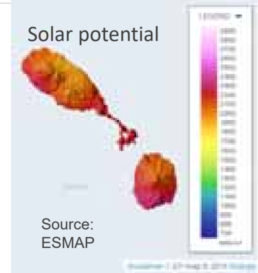
Fields	Findings	Project Activity
Energy Efficiency	• Energy Source: Electricity (63%) , Oil (37%) • Load Curve: Bactrian camel type • Annual Peak Demand: about 25MW (St. Kitts) about 10MW or more (Nevis) • Peak Period: around 11am, 6pm-8pm (St. Kitts) around 12am, 6pm-8pm (Nevis)	Priority 1: Optimized operation with inverter Priority 2: Mini split AC with inverter Priority 3: VRF
Renewable Energy	• 100% RE by 2020 target • 0.7+0.5 MW PV (St.Kitts), damaged • 2MW wind operated at 1.1 MW (Nevis) • Bellevue 5.4 MW wind, Leclanche 35MW PV	Monitoring RE project incl. geothermal Training for grid simulation Introduction of asset management
Grid Stabilization	• 6MW 34 MWh BESS planned for 35MW PV • Output suppression conducted in NEVLEC	
O&M of Thermal Power Generation	• Thermal power plant: total 13 units (St. Kitts), total 8 units (Nevis) • Installed Capacity: total 44.9MW (St. Kitts) total 21.3 MW (Nevis) • Peak demand 24MW (StK), 9.83 MW(Nevis)	-
Human Resources and Capacity Building	• MPI's Energy Division: 4 employees • Most of capacity building is done by OJT • There is no systematic HR development.	JET experts select topics and develop curriculum for technology transfer

RE: Status in St.Kitts & Navis

RE Projects in St. Kitts and Navis

Location/Project	Type	Capacity MW	Generation GWh estimated	Year
S: SCASPA	PV	0.7	NA	2013
S: SKELEC	PV	0.5	1	2015
N: Windwatt	Wind	2.2	5.25	2011
N: NREI Geothermal	Geo	10-30	NA	2025
S: Leclanche	PV	35	43.8	2020
S: Bellevue	Wind	5.7	NA	NA
S: NW Geothermal	Geo	18-36	NA	NA





Necessary consideration for future RE

1) Grid stability analysis for new 35MW PV system
2) Update of geothermal development
3) Interconnection (11kV, 66 kV)?

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

Summary: Jamaica

*1 JPS Annual Report 2021 *2 IRP Feb 2020
*3 Interview to JPS *4 Transmission Code

Fields	Findings	Project Activities
Energy Efficiency	• Energy Source: Oil (53%) , Electricity (37%) • Peak Demand: 654.5MW (2018)→622MW (2021)*1 • Generated 4356 GWh (2018)→4,303 GWh (2021)*1 • 1833 kWh/customer/yr, 0.34 USc/kWh (2021)*1 • Peak Period: 6:30pm – 8:30pm	Priority 1: BEMS Priority 2: Mini split AC with inverter Priority 3: LED
Renewable Energy	• RE target 33% by 2030, 49% by 2037 *2 • Hydro 28.6 MW, VRE 175 MW (PV utility 53+ distributed 20? , wind 102) *2, RE 15% of grid • Rooftop 20MW? *3	Recommendation for 50% RE target Micro-grid concept study Introduction of asset management
Grid Stabilization	• >50.5Hz:0.5sec, <49.5 Hz: 20 sec, <48Hz:0.5 sec *4 • RE Fluctuation affects gird stability*3 • JPS 21.5MW/16.6MWh Li BESS +3MW flywheels	
O&M of Thermal Power Generation	• Thermal power plant: total 20 units including IPP • Installed Capacity: Total 1036.5MW including GTCC in Old Harbour P/S (190MW) • Heat rate 11,330(2017)→9,392 (2022) kj/kWh *1 • Predictive Maintenance: Considering to apply	-
Human Resources and Capacity Building	• MSET's Energy Division: 14 employees • Most of capacity building is done by OJT • There is no systematic HR development.	JET experts select topics and develop the most suitable curriculum for technology transfer period

RE Status in Jamaica

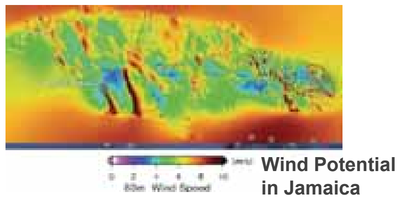
Challenges for RE & Grid:

✓ Increasing RE capacity >15%. Grid stability and power cut issue
  ✓ Feeder cut at 49.5 Hz
✓ System losses 26.3% (2018) →28.3% (2021)
✓ Large number of distributed PV, available database?
✓ Wind & PV potential unevenly distributed →less smoothing

Source: JPS, 2019

VRE Projects in Jamica

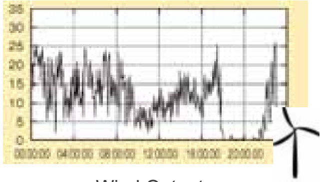
Location/Project		Capacity MW	Generation GWh estimated	Year	Tariff USc/kWh	Investment mil USD
Wigton I	Wind	20.7	52	2004	10.21	26
Wigton II	Wind	18	47	2010	10.723	45
Wigton III	Wind	24	63	2016	13.4	46.5
Munro	Wind	3	10.5	2010	(JPS)	
BMR Wind	Wind	36.3	120	2016	12.9	90
Content Solar (WRB)	PV	20	34	2016	18.8	65
Independent roof-top	PV	20?			--	
Eight River (EREC)	PV	33.1		2019	8.5	
Wigton IV	Wind	34		?		
VRE under operation		**142**	**326.5**			



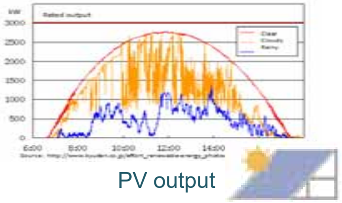
Source: Sustainable Energy Roadmap 2013

Source: Prepared by JET with several data sources

Characteristics of VRE


Wind Output

Wind
- Unpredictable generation output change
- produce ramps according to weather condition
- Depending on geographic areas, fluctuation comes at once if it installed in the same valley


PV output

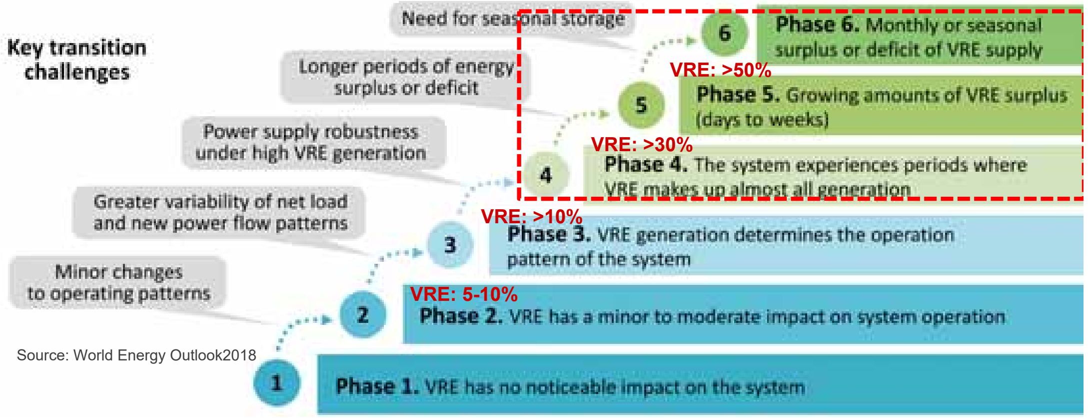
PV
- No output in night-time and rainy day
- Large fluctuation in tropical climate (likely to change 80% in a minute)

Both (VRE):
- It does not always generate when needed. **Load-supply matching** is an issue Time coincidence of VRE, there can be times when there is too much supply. Curtailment of VRE is necessary →**energy storage/control cost need to be considered.**

Caribbean Islands:
- Lower cost than tariff →rapid private investment
- Limited area for transmission
- Frequent change of weather condition
- Limited stable RE (hydropower/geothermal)

Challenges for
- **Cost for stability** : who covers?
- Technical and regulatory matters

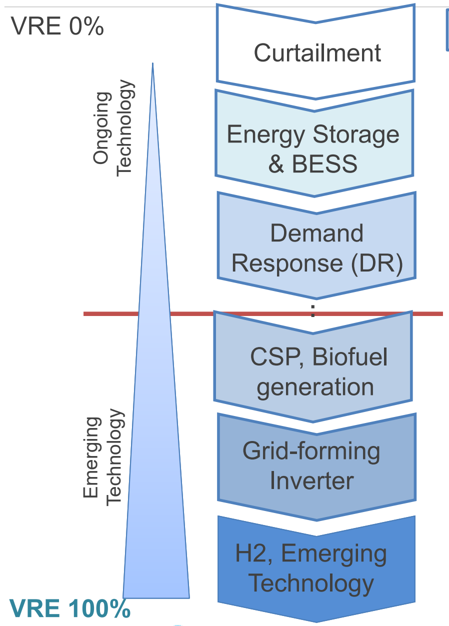
Transition Changes of RE Penetratic



Source: World Energy Outlook2018

Phase-3	Increased level of uncertainty and variability by higher share of VRE. System flexibility is important for integrating VRE to in the supply-demand balance.
Phase-4	VRE provides majority of electricity. It **requires advanced technical options** to ensure system stability, causing **changes in operational/regulatory approaches.**
Phase-5	VRE output exceeds power demand. The demand is entirely supplied by VRE and further VRE additions face the of **substantial curtailment.**
Phase-6	Determined by a surplus or deficit of VRE supply on seasonal or inter-annual timescales. This drives a possible need for seasonal storage and use of **synthetic fuels or hydrogen**

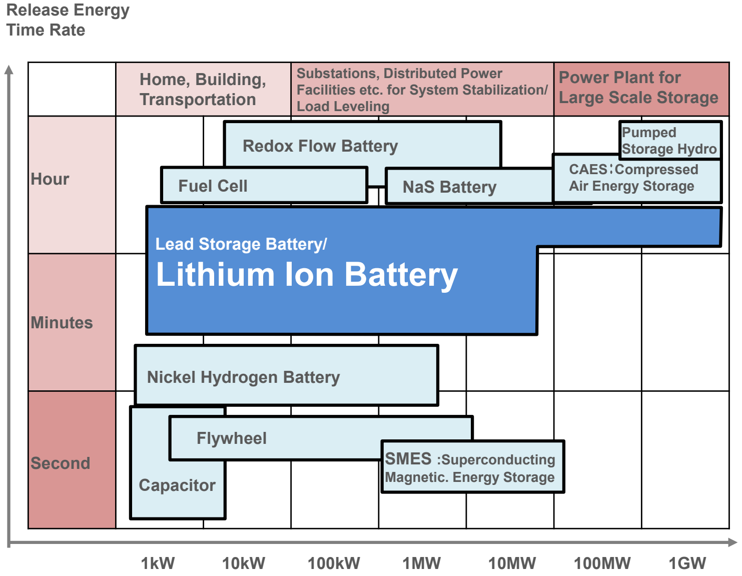
Arrangement toward 100% RE

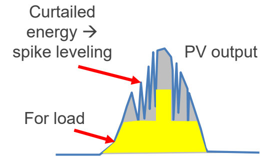


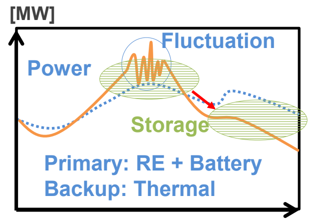
Voltage and frequency Stabilization
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- EV charging time shift
- Demand side management
- Regulatory framework change, **review of grid code**

Insufficient Inertia, Synchronizing Force
- **Synchronous condenser, Statcom**
- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale storage

Battery and Energy Storage
Positioning for Energy Storage Technology



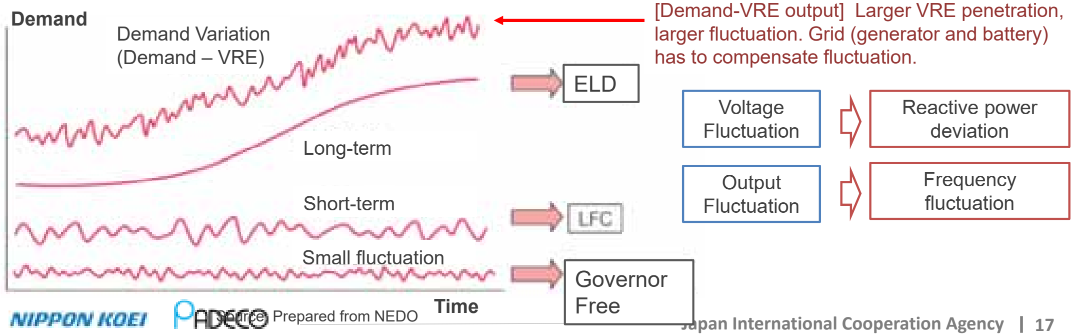




Source: NEDO Renewable Energy Technology White Paper Chapter 9

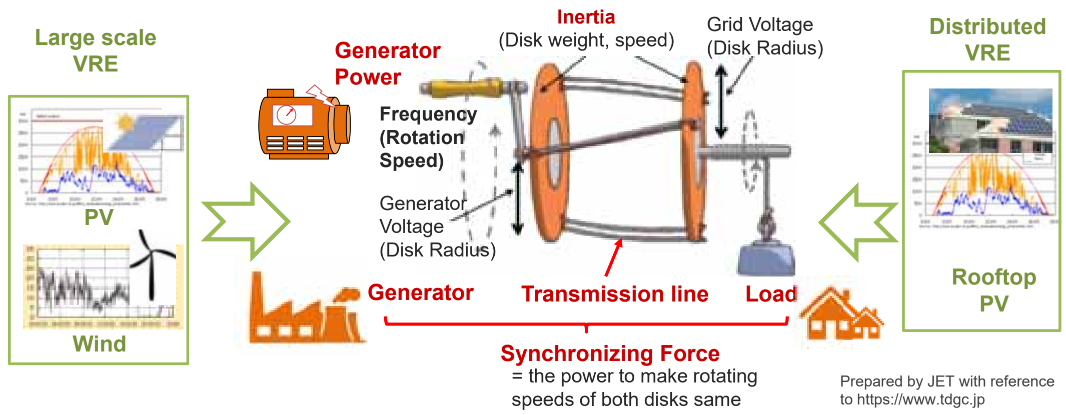
Grid Stabilization: GF, LFC, ELD

Control Type	Frequency	Description
Governor Free (GF)	Within one minute	Generator detects rotation fluctuation and automatically controls rotation so that frequency is kept at suitable level
Load Frequency Control (LFC)	Minutes-ten minutes	This involves the sensing of the bus bar frequency and compares with the tie line power frequency. The difference of the signal is given to speed changer of generator, so that the frequency of the tie line is maintained as constant
Economic Load Dispatch (ELD)	More than ten minutes (preparatory setting)	Most economical load distribution between a number of generator units is considered with different heat late at each load range. Optimum operation of generators at each generating station at various station load levels (unit commitment) are settled.



Source: Prepared from NEDO

Inertia and Synchronizing Force with RE

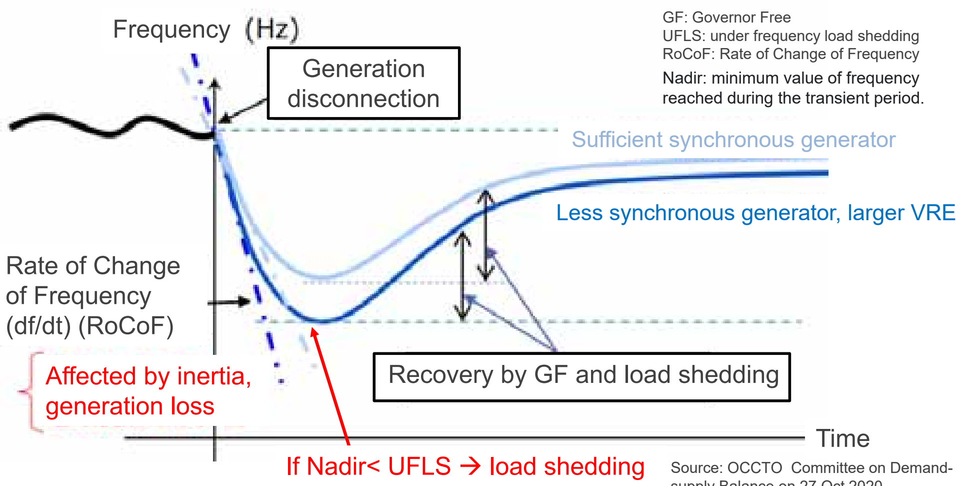


Inertia: The force to keep the rotation of disk when load is changed
Synchronizing Force: The force to keep rotation speed of disks. It keeps back to the same rotation when generation power and load is varied, without entangling transmission line.

Fluctuation of large scale VRE affects to generator at generation side and load side
→ Inertia and Synchronizing Force need to be enhanced for grid with large VRE

Inertia and Synchronizing Force with RE

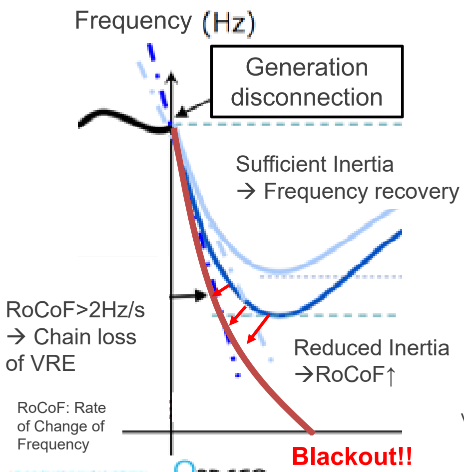
Synchronous generator: The power source establishes voltage and frequency with reactive power, and combines with generators by synchronizing force
VRE/BESS with inverter: DC converted to AC. There is no rotation, no synchronizing force. It monitors grid AC voltage and wave and adjust accordingly → no contribution for stability

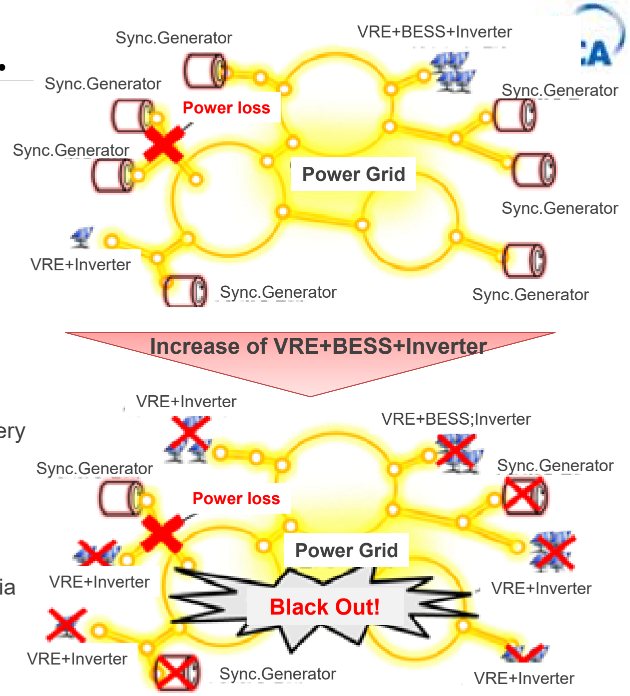


Source: OCCTO Committee on Demand-supply Balance on 27 Oct 2020

Black-out when insufficient Sync. Gen.

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



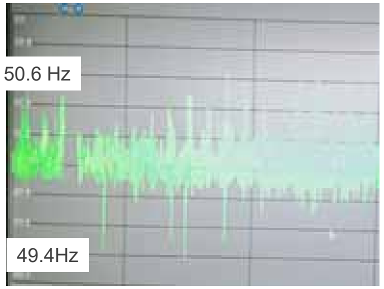


Source: Transmission and Grid Council, Japan

Consideration for Larger VRE/BESS Penetration

- Increased application of PV and Wind :
  - Is Battery sufficient measurement?
  - To what extent can utility scale PV and wind be operated without affect on grid power quality?
  - How much can a feeder accommodate distributed PV and BESS?

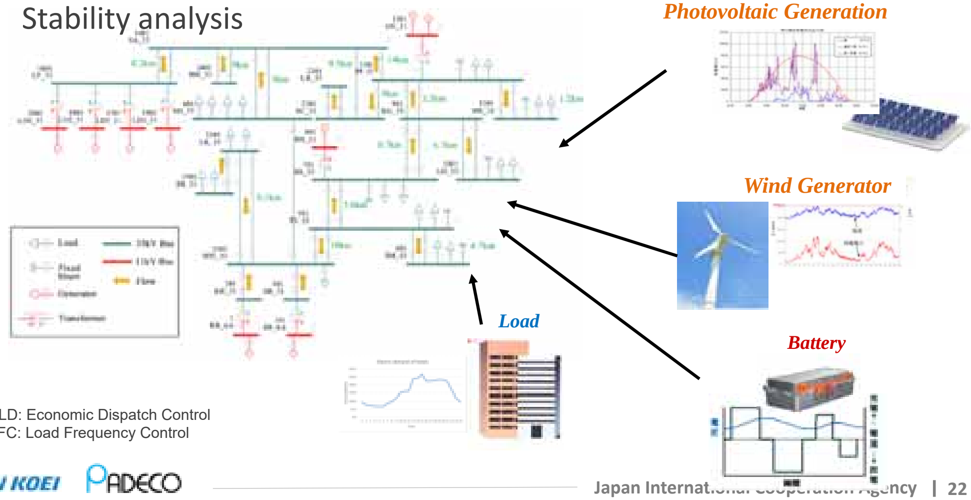
- Planning with **grid simulation** is necessary.
  - Load flow analysis
  - Stability analysis
- Grid code needs to be checked for condition of grid connection of VRE and BESS



Example of frequency fluctuation with VRE

Grid Stability Simulation

- Simulation of National Grid Model based on asset data
- Analysis of Issues and Solutions
- Power flow analysis: **Frequency, Active/Reactive power**
- ELD/LFC Calculation
- Stability analysis



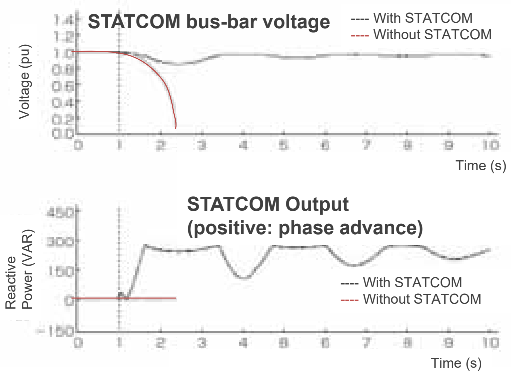
ELD: Economic Dispatch Control
LFC: Load Frequency Control

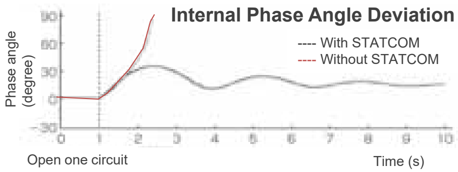
SCO and STATCOM for Reactive Power

SCO (Synchronous Condenser) :
SCO is DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. Though changing field excitation, SCO adjusts reactive power and provides reactive power at the time of voltage drop.


https://energy-shift.com/news/af737655-0462-4655-81ae-b17d86b5784d

STATCOM (STATic synchronous COMpensator) :
For compensation of reactive power, it generates/absorbs reactive power, and stabilize voltage continuously at high speed by self-commutated inverter.

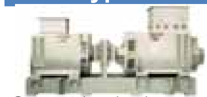
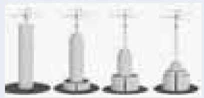
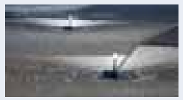




Source: Enhancement of Steady−State Stability and Suppression of Over−Voltage using 450MVA GCT−STATCOM, Mitsubishi Denki Giho, pp.52-55, Vol.87, No.11, 2013.

https://www.hitachi.co.jp/products/energy/STATCOM/about/index.html

Emerging technology for large RE with Grid stabilization : Generation with Inertia and Synchronous Power

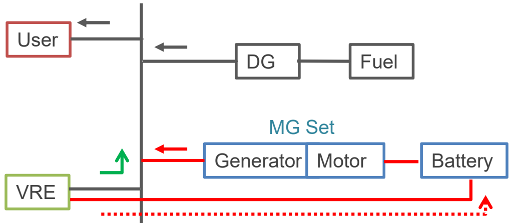
Type of Technology		Advantage	Develop stage
 Source: taiyo-electric	Motor generator (MG)	- Energy in battery provides synchronization and inertia - Small scale supply, for micro grid	- Used as frequency conversion - Commercial operation
 energyvault.com/gravity	Gravity Storage Battery	- Gravity of recycled Concrete block 35ton/nos - Provides inertia - Half cost of Li-ion battery	Pre-commercial, 35 MWh, 4MW per tower η=85% 52.5GW planned in USA
 /www.nedo.go.jp/news/press/AA5_100756.html	CAES (Compressed air energy storage)	- Compressed high pressure air - (Liquid air may be developed) - Provides inertia	-demonstration by NEDO - 900 MW in California - η=70-80%
 electrek.co/	CSP (concentrating solar power) Solar thermal	- With turbine, provides inertia and synchronization - Cost decrease expected, higher efficiency than PV, η=50%	- Commercial operation at Ivanpah392MW 22 bil USD - Heat storage (molten solt, etc) under development
 Source: CIGRE	Grid-forming inverter	- Dynamic active/reactive power, FRT, frequency control, inertia - Applicable to existing PV - (Smart Inv: FRT, VRT, voltage support)	- Under development - (Smart inverter by IEEE1547, Mandatory in Hawai)

Option For 100% RE: Battery Motor Generator set (MG Set)

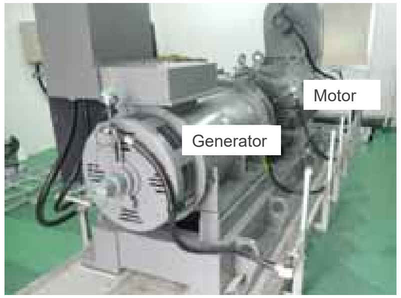
Hateruma Island: Southern most island in Japan
- Area：12.73 km2 , Population 527, hh 272 (2016)
- Peak power: 770 kW (2016)
- Generation: DG (Bunkar-A, total 1,250kW)
- Wind (245kW✕2, total 490kW)
- Lead-acid Batt (600kW/1,500kWh)
- **MG Set: Rated 300 kW**

Wind generator

Photo: https://www.kankyo-business.jp/news/011605.php



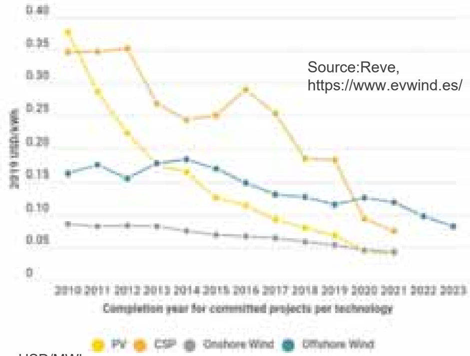
MG set is driven by battery charged from VRE and provides power with inertia → possible method to achieve 100% RE with inertia

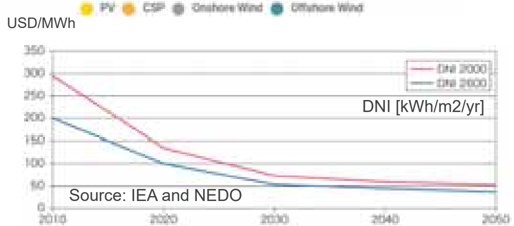


https://www.okiden.co.jp/shared/pdf/news_release/2017/180328.pdf

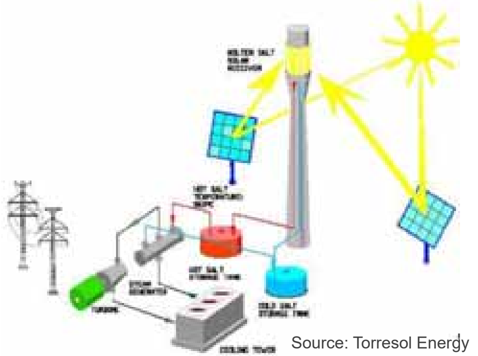
Option for 100% RE: CSP

Concentrating Solar Thermal Power (CSP)





- Rapid cost reduction (47% in 2010-2019)
- Combination with molten-salt heat storage
- Inertial power can be supplied



- DNI (Direct normal irradiation)
  - Barbados: 1600-2000 kWh/m²/yr
  - St Kitts&Nevis:1600-2300 kWh/m²/yr
  - Jamaica: 1300-2200 kWh/m²/yr

Example of Grid Code

Country	UK	Ireland	Germany	Japan
Grid Code	The Grid Code	EirGrid Grid Code	Technical Connection Rules fore MV	Grid Code
Regulator	Ofgen (regulator)	TSO	VDE (Association)	OCCTO
Main Items of Grid Code	- Frequency and time for operation continue - Active power increase/ decrease at the time of frequency increase/ decrease - Active power Droop according to frequency change rate - Voltage, harmonic wave, flicker at nodes - FRT requirement at the time of voltage drop - Reactive power supply - Black start and Protection of grid and generators	- Frequency and time for operation continue - Active power decrease/ Increase at the time of frequency increase/ decrease - Governor control rate - FRT requirement at the time of voltage drop - Reactive power supply - Speed of power increase/ decrease with load dispatch order - Lower limit of load - Spinning reserve requirement	-Frequency and voltage that need continuous operation -Active power increase/ decrease at the time of frequency increase/ decrease - FRT requirement at the time of voltage drop - Reactive power supply at the time of voltage change - Active power limit at the time of large voltage change - Protection of grid and generators	(under preparation)

OCCTO: Organization for Cross-regional Coordination of Transmission Operators, Japan
FRT: Fault Ride Through

Appendix

Resilience for RE

23 Aug 2018 Awaji, Japan
https://www.sankei.com/west/news/180828/wst1808280043-n1.html
600 kW, Fallen at 25.6m/s wind while 60m/s design
- Additional moment due to Excess of high speed
- Missing control power supply

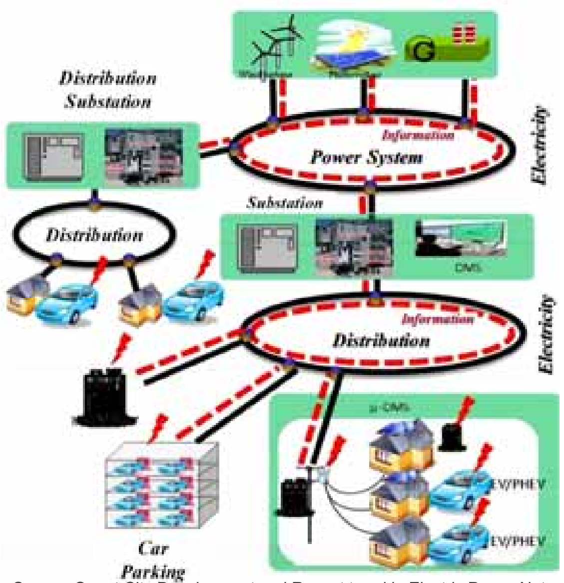
9 Sep 2019 Kanto, Japan
@kadowaki_kozo
Damage of roof-top structure by high speed wind

26 Jul 2019 Himeji, Japan
https://www.dailyshincho.jp/article/2018/07260800/?photo=1
Landslide by a heavy rain

For enhancement of resilience:

- ✓ Design Standard with higher rank hurricane
- ✓ Autonomous Micro-grid
- ✓ Fast recovery with GIS and Asset management

Microgrid Concept

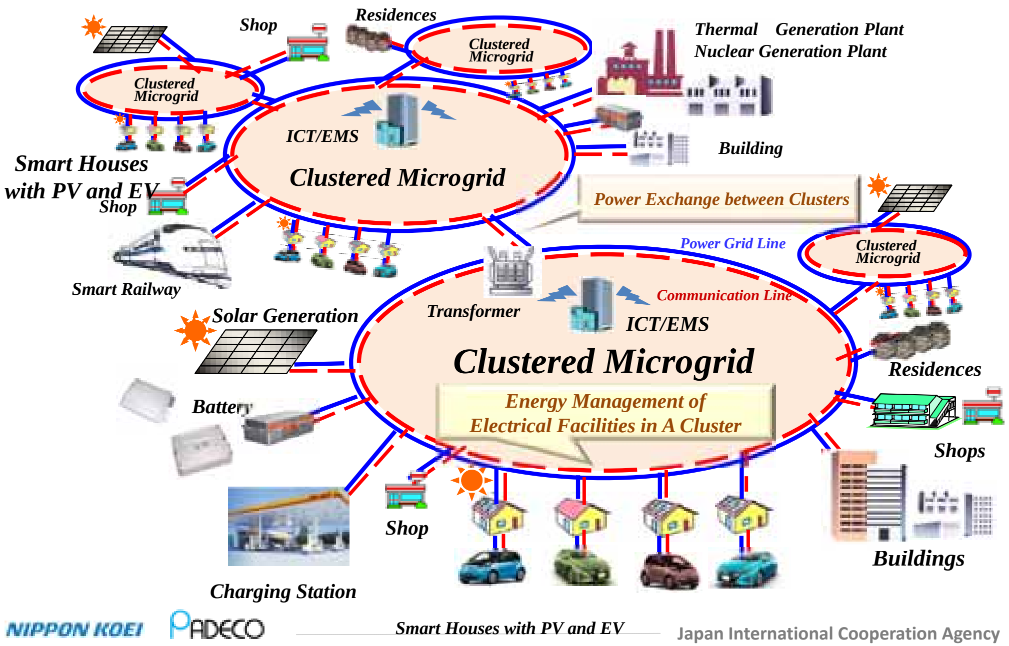


Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

Concept of Micro-grid

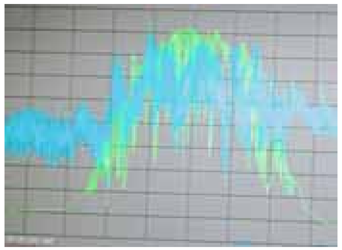
- ✓ Respective Micro-grid is connected each other, and each Micro-grid can work independently
- ✓ Local energy production for local consumption
  - ✓ Generation: PV, wind, biomass, DG, GT, battery, etc.
  - ✓ Demand: industry, commercial, home, EV, etc.
- ✓ No transmission → loss saving
- ✓ With IoT, control system, EMS, demand response, smart meters
- ✓ Enhance resiliency

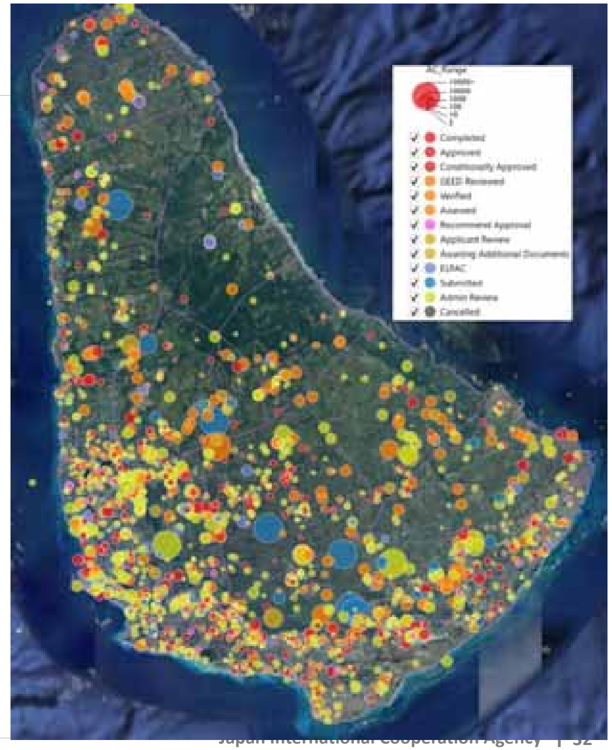
Microgrid for Resilient System
-- Autonomous Micro Grid



PV Installation and Plans in Barbados

- Needs for confirmation of feeder holding capacity considering fluctuation
- Utility Scale PV is planned for future





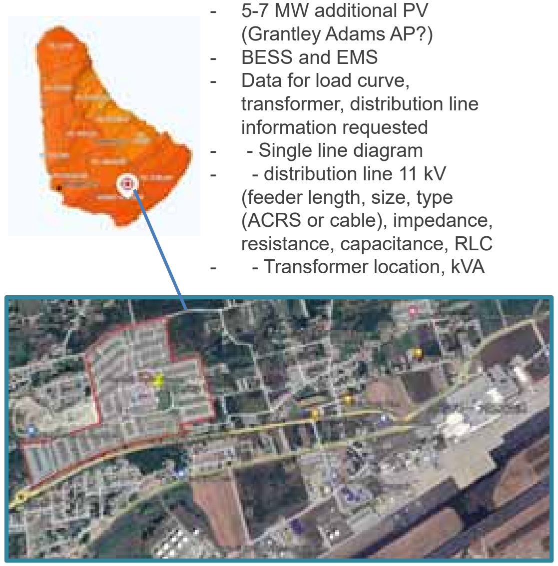
Source: GIS by JET, based on MEB Database
Latitude and Longitude data needs to be reconfirmed

Planning of Microgrid of Coverley Village

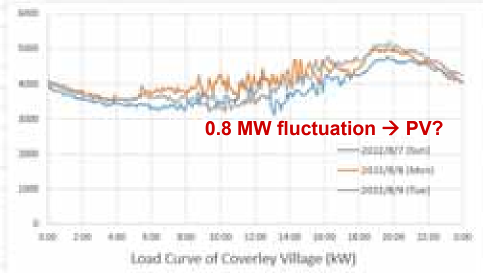
- Requested data: Location of transformer, existing PV, LV line alignment (GIS), location shunt capacitors(ShC) or static var compensators(SVC or STATCOM) if any
- Two autonomous Microgrid connecting Coverley Village Microgrid and Airport Microgrid can be preposed

Micro-grid Concept: Coverley Village

Microgrid/Smart Grid Demonstration: Model study for 100% RE



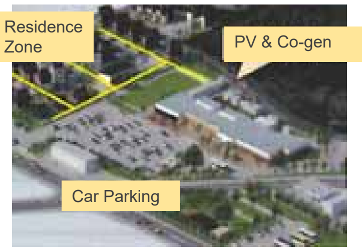
- 3 kW rooftop PV
- 5-7 MW additional PV (Grantley Adams AP?)
- BESS and EMS
- Data for load curve, transformer, distribution line information requested
- - Single line diagram
- - distribution line 11 kV (feeder length, size, type (ACRS or cable), impedance, resistance, capacitance, RLC
- - Transformer location, kVA



Example of system, to be reviewed

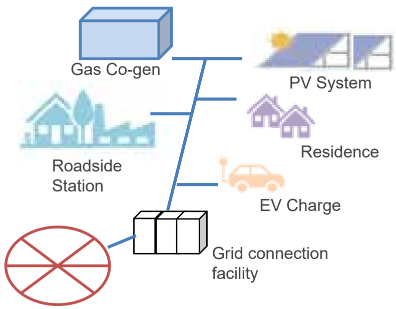
Nos of houses	1026	nos
Roof area for PV	30	m2/house
Commercial/official roof	300	m2 (6 facilities)
Total roof area	31,080	m2
PV Capacity	3108	kWp
Specific PV generation	4.917	kWh/kW/day
PV generation energy	15,282	kWh/day
Peak demand	4,104	kW
Electric energy demand	41,329	kWh/day
External PV	6,622	kWp
BESS capacity	80	MWh
BESS output	4	MWh

Microgrid for Resilience: Mutsuzawa Road Side Station



Mutsuzawa Road Side Station

- Gas co-generation (80kWx2), PV system (20kW), Solar heating (37 kW) EV charger,
- Independent power supply for residence zone
- Thermal supply for hot spring by co-gen
- Microgrid area connected with grid
- Continuous supply during Typhoon (large scale regional power cut approx. 1 week) in Sep 2019
  - 1000 utilized power supply, shower, toilet for emergency
  - Regional Disaster-prevention facility
  - All power lines are underground

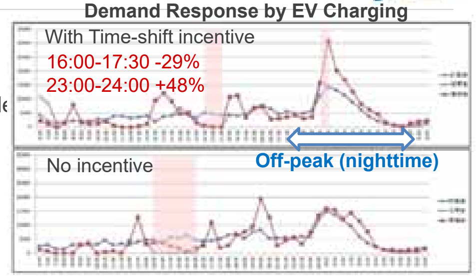


https://www.env.go.jp/press/files/jp/113284.pdf

Recommendation of DR and EV

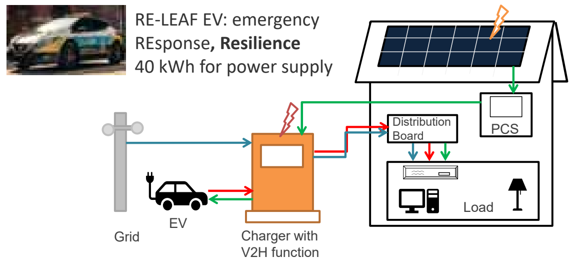
(1) TOU or Unit charge rate according to load curve and weather and PV output with EMS
(Ex.) Range-1 : Daytime, sunny , lowest
Range-2 : Daytime, sunny/cloudy / off-peak, middle
Range-4: Rain and evening, peak-time highest

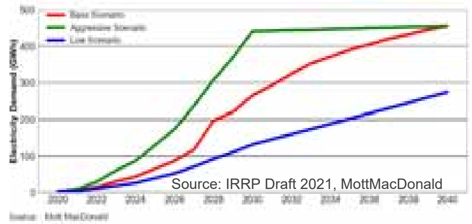
Demand Response by EV Charging



https://xtech.nikkei.com/dm/article/FEATURE/20150120/399714/?P=5

(2) Promotion of EV with Vehicle-to-Home (V2H), Vehicle- to-Grid (V2G)
- V2H is applicable for specific existing model of EV
- Emergency power supply to home





(3) Promotion of solar assisted car
- 60 kWh, 400→725km , >47,600ASD (33,320 USD)
- Load to grid is mitigated

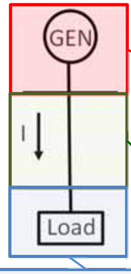
https://www.drive.com.au/

Grid Simulation: for Optimization of Load Flow Analysis

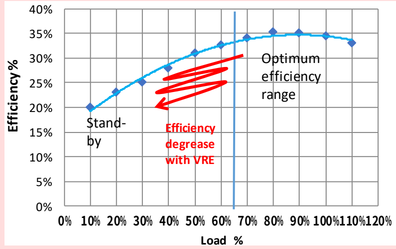
Microgrid Designer consists of tools of Economic Load Dispatch (ELD) and load flow analysis modules, developed by Energy & Environment Technology Research Institute, Japan (Venture company of Waseda Univ).

Module	Function
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 optimal 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 Load Flow Analysis Module	Steady-state analysis tool whose target is to determine the voltages, currents, and real and reactive power flows in a system under a given load conditions and planning ahead for various hypothetical situations
Multi Stage Load Flow Analysis Module	Chronological power flow analysis for time varying loads to determine the transitions of voltages, currents, and real and reactive power flows in a system over time horizon.

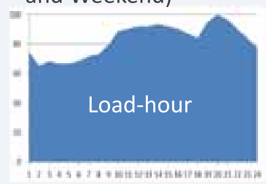
Input Data



Generators (DE,GT,ST,GE)
- Max. and min. output
- Ramp rate
- Load – cost curve or Load – efficiency curve



Load
- Average Load in each feeder
- Load Power Factor
- Load – hour curve (Weekday and Weekend)

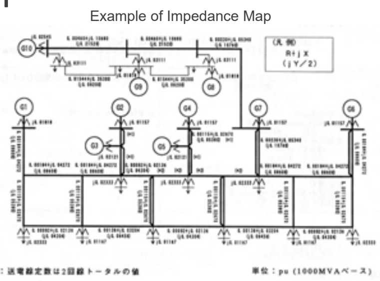


Transmission Line, Substation

[Common]
- Power flow limitation
- Voltage Magnitude

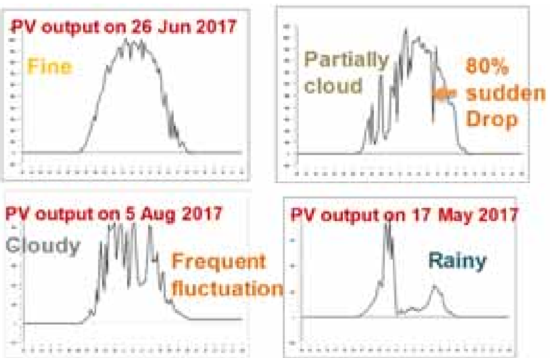
[Option 1]
- Impedance Map

[Option 2]
- Shunt Capacitor
- Cable length
- Cable capacitance [μF/km]

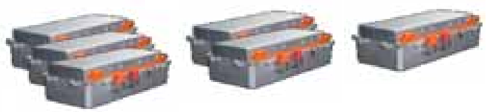


Input Data

Necessary Data
- Fuel efficiency (heat rate) of each DG generator units at each load range
- PV generation 24 hr curve

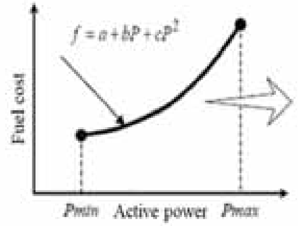


Battery
- Sum of MWh

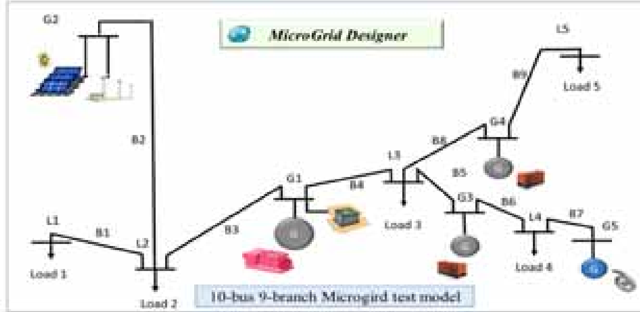


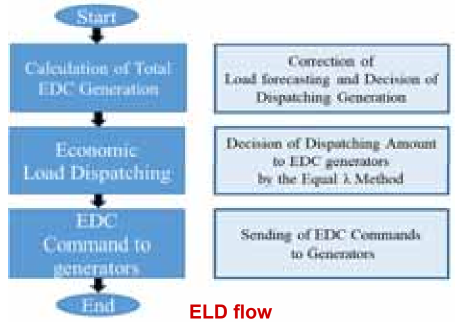
Battery A	5MWh
Battery B	3MWh
Battery C	1MWh
Sum of Battery Capacity	**9MWh**

ELD example with IEEE Microgrid Model

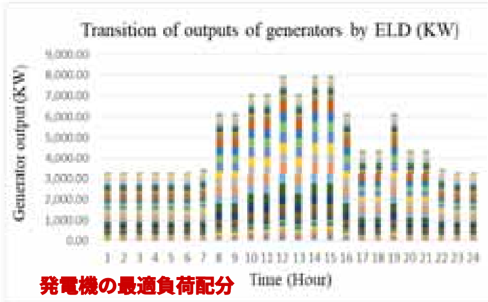


Load-fuel efficiency curve





ELD flow



発電機の最適負荷配分

Seminar on Grid Stability with Large RE Day 1

References & Schedule

JICA Expert Team, Nippon Koei Co., Ltd.

Seminar on Grid Stability with Large RE

- Day 1
  1. What is Power System: Three-Phase AC, Single line network description
  2. Per Unit Method: Definition, Example
  3. Modeling of Power System Equipment: Transmission line, Transformer, Generator, Load
  4. Active Power & Frequency: Frequency control, Area requirement
  5. Reactive Power & Voltage: P-V Curve, Reactive power source
  6. Practice of Modeling of Grid
- Day 2
  1. Overview of Load Flow Analysis: Purpose, Methods, Modeling of grid
  2. Newton-Raphson Method: Theory, Characteristics
  3. DC Flow Method: Simple method to solve load flow manually
  4. Exercise of DC Flow Method
  5. Practice on Microgrid/VPP Designer
  6. Load Flow Analysis and Evaluation of Barbados Grid
- Day 3
  1. Overview of Stability: Definition, Methods, Swing equation
  2. Stability Model: Simplified grid model, Equivalent circuit of synchronous generator
  3. Equal Area Criterion: Theory, Simple method to solve stability manually
  4. Available Transmission Capacity & Spinning Reserve
  5. Exercise of Equal Area Criterion
  6. Practice on Microgrid/VPP Designer and LFC/ELD
  7. Stability Analysis and Evaluation of Barbados Grid
- All figures in the materials of grid stability lectures are from
  " M.Kato & H.Taoka, *Fundamental Power System Engineering*, Suurikogaku-sha, 2011. "

Fundamental Power System Engineering

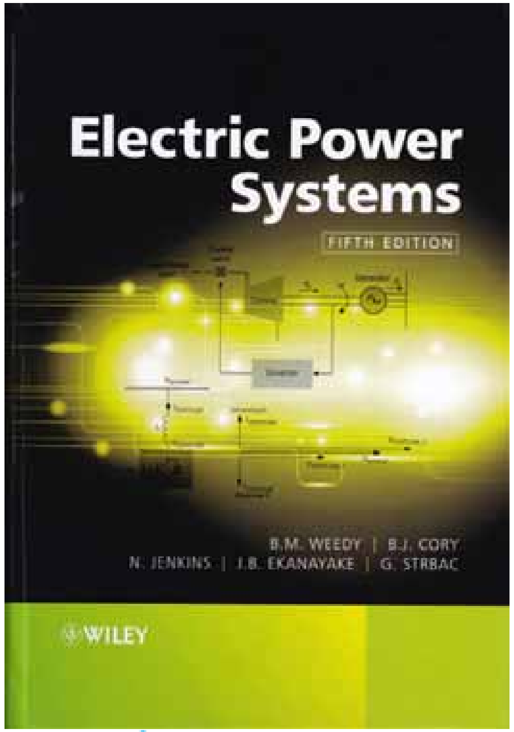
Essence of Power System Analysis and Control

M. Kato & H. Taoka

Suurikougaku-sha,

Tokyo, Japan

2011



Electric Power Systems

Fifth Edition

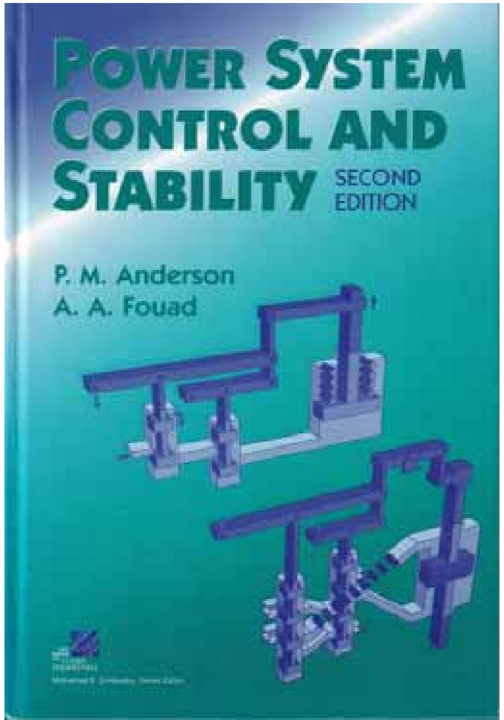
All-inclusive

B. M. Weedy, B. J. Cory,

N. Jenkins, J. B. Ekanayake & G. Strbac

John Wiley & Sons, Chichester, West Sussex, UK

2012



Power System Control and Stability

Second Edition

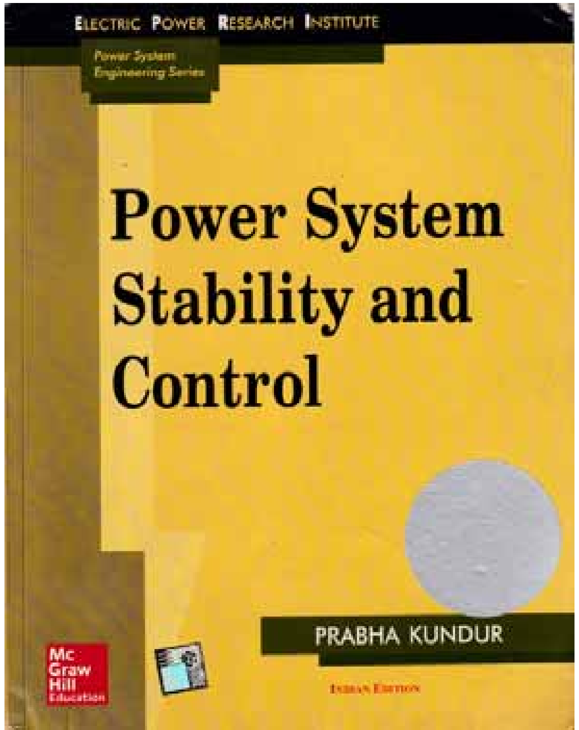
Classic Textbook of Stability

P. M. Anderson &

A. A. Fouad

IEEE Press, Piscataway, USA, 2003

First Edition: Iowa State University Press, Ames, Iowa, USA, 1977



Power System Stability and Control

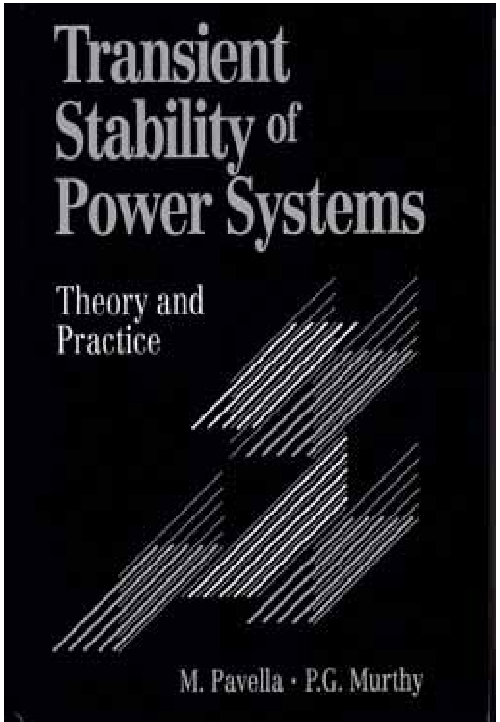
Widely Read Textbook

P. Kundur

McGraw-Hill,

New York, USA

1994



Transient Stability of Power Systems

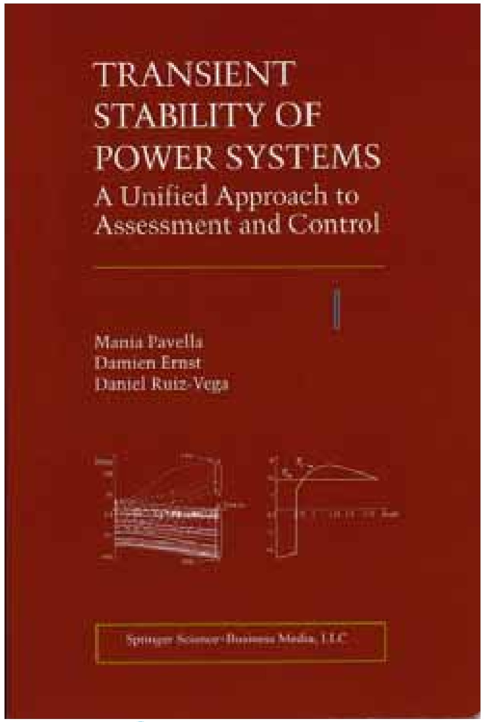
Theory and Practice

Transient Stability Analysis Methods

M. Pavella & P. G. Murthy

John Wiley & Sons, Chichester, West Sussex, UK

1994



Transient Stability of Power Systems

A Unified Approach to Assessment and Control

Application of Equal Area Criterion

M. Pavella, D. Ernst &

D. Ruiz-Vega

Springer Science+Business Media, New York, USA

2000

Seminar on Grid Stability with Large RE Day 1

Basics of Power System Engineering for Grid Stability Simulation

JICA Expert Team, Nippon Koei Co., Ltd.

Contents

1. What is Power System?

- Understand the role of power system engineer
- Recognize the relationship among voltage, current, active power, reactive power, frequency, and other characteristics of electricity
- Know several tools or methods, and learn their usage.
- Innovate current power systems to new type power systems with RE

Role of Power System Engineer

- Supply electricity to all the customers in stable
  - Continuously
  - With no or few failures
  - Minimize the influence of disturbance after faults
- Keep the quality of electricity
  - Constant voltage
  - Constant frequency
  - Less distortion or harmonics

Grid Stability

- If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.

Referred from
P.M. Anderson & A.A. Fouad, "Power System Control and Stability," IEEE Press, Piscataway, USA, 2003

To supply electricity to all the customers in stable

=> We are going to solve "Grid Stability" problem.

Characteristics of Power System

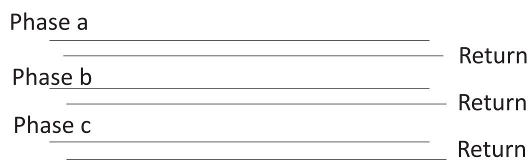
- Flow of Electricity
  - DC (Direct Current): Difficult to change voltage and switch off circuit
  - AC (Alternative Current): Stability problem
- AC
  - Single Phase & Three Phase
- Components of Power System
  - Transmission Line
  - Transformer & Switchgear (Substation)
  - Generator (Synchronous Generator, Photovoltaic, Wind Power)
  - Load

Methods of Power System Analysis

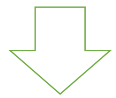
- Steady State: under Small Disturbance
  - Voltage, Power, Angle are constant at a certain time
  - It keeps the same state under small disturbance
  - ->Load Flow Analysis, Eigenvalue Analysis
- Transient State: under Large Disturbance
  - Voltage, Power, Angle are changing
  - ->Equal Area Criterion, Energy Function Method, Transient Stability Analysis (Electro-Mechanical Transient, Electro-Magnetic Transient)

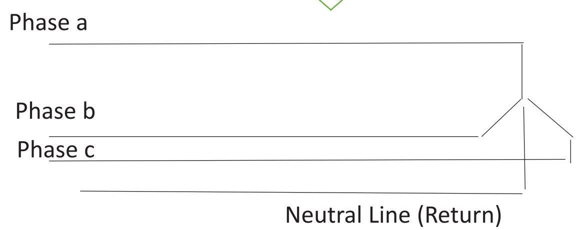
Single-Phase to Three-Phase

- Single transmission line
  - Require 2 lines



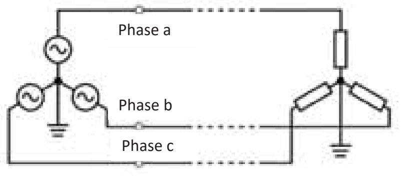
- Three-Phase transmission line
  - Require 3 or 4 lines (+ neutral line)
  - 3 times capacity

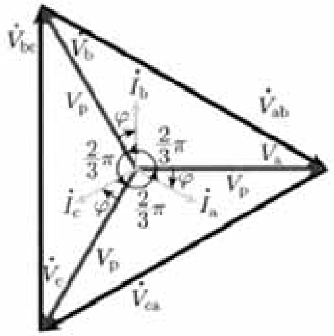




Three-Phase AC Circuit

- Single transmission line
- Three-Phase transmission line
- Caution to magnitude and angle



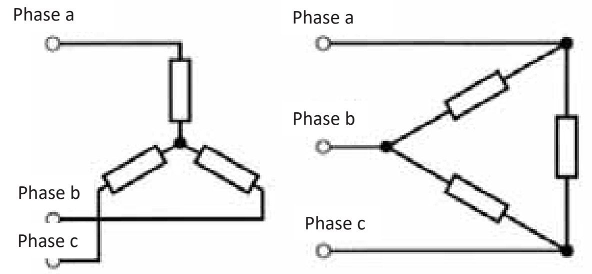


Va, Vb, Vc: Phase Voltage
Vac, Vbc, Vca: Line-to-Line Voltage
Ia, Ib, Ic: Phase Current
Iab, Ibc, Ica: Line Current

Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

3-Phase Load

- Connection of 3-Phase line
  - Y(Wye) Connection
  - Δ(Delta) Connection



Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Phase Voltage & Line-to-Line Voltage

- Phase Voltage : Va, Vb, Vc
  - Y(Wye) Connection→Line to Neutral
  - Δ(Delta) Connection→Line to Line
- Line-to-Line Voltage: Vab, Vbc, Vca

$$\begin{cases} \dot{V}_{ab} = \dot{V}_a - \dot{V}_b \\ \dot{V}_{bc} = \dot{V}_b - \dot{V}_c \\ \dot{V}_{ca} = \dot{V}_c - \dot{V}_a \end{cases}$$

- Y(Wye) Conection
  - Line Voltage＝√3 × Phase Voltage
- Δ(Delta) Connection
  - Line Voltage＝Phase Voltage

$$\begin{cases} \dot{V}_a = V_p e^{j0} = V_p\angle 0 \\ \dot{V}_b = V_p e^{j\frac{2}{3}\pi} = V_p\angle\frac{2}{3}\pi \\ \dot{V}_c = V_p e^{j\frac{4}{3}\pi} = V_p\angle\frac{4}{3}\pi \end{cases}$$

- Vp : peak value of Phase Voltage

Va, Vb, Vc: Phase Voltage
Vac, Vbc, Vca: Line-to-Line Voltage
Ia, Ib, Ic: Phase Current
Iab, Ibc, Ica: Line Current

$$\dot{V}_{ab} = V_p - V_p e^{j\frac{2}{3}\pi} = V_p\frac{3-j\sqrt{3}}{2} = \sqrt{3}\,V_p e^{j(-\frac{\pi}{6})}$$
$$\dot{V}_{bc} = V_p e^{j\frac{2}{3}\pi} - V_p e^{j\frac{4}{3}\pi} = \sqrt{3}\,V_p e^{j(\frac{2}{3}\pi-\frac{\pi}{6})}$$
$$\dot{V}_{ca} = V_p e^{j\frac{4}{3}\pi} - V_p = \sqrt{3}\,V_p e^{j(\frac{4}{3}\pi-\frac{\pi}{6})}$$

Phase Current & Line Current

- Phase Current : Ia, Ib, Ic
  - Y Connection→Current between Neutral and Termnal
  - Δ Connection→Current between Two Terminals
- Line Current : Iab, Ibc, Ica

$$\begin{cases} \dot{I}_a = \dot{I}_{ab} - \dot{I}_{ca} \\ \dot{I}_b = \dot{I}_{bc} - \dot{I}_{ab} \\ \dot{I}_c = \dot{I}_{ca} - \dot{I}_{bc} \end{cases}$$

- Y Connection→Line Current＝Phase Current
- Δ Connection→Line Current＝√3 × Phase Current

$$\begin{cases} \dot{I}_a = I_p\angle-\varphi \\ \dot{I}_b = I_p\angle\left(\frac{2}{3}\pi-\varphi\right) = I_p\angle(120^\circ-\varphi) \\ \dot{I}_c = I_p\angle\left(\frac{4}{3}\pi-\varphi\right) = I_p\angle(240^\circ-\varphi) \end{cases}$$

- Ip : peak value of Phase Current

$$\dot{I}_n = \dot{I}_a + \dot{I}_b + \dot{I}_c = 0$$

Va, Vb, Vc: Phase Voltage
Vac, Vbc, Vca: Line-to-Line Voltage
Ia, Ib, Ic: Phase Current
Iab, Ibc, Ica: Line Current

Φ:Angle between Votalge and Current
cosΦ : Power Factor

Three-Phase AC Parameters

- Phase Voltage（Maximum）＝√2 × Phase Voltage（rms）
- Line-to-Line Voltage（rms）: Rated Voltage
- Line Current（rms）: Rated Currnet
- Three-Phase VA (Apparent Power): Rated Capacity

- Three-Phase VA＝3 × Phase Voltage × Phase Current
  ＝√3 × Line-to-Line Voltage（√3 × Phase Voltage）
  × Line Current（Phase Current）: Y Connection
  ＝√3 × Line-to-Line Voltage（Phase Voltage）
  × Line Current（√3 × Phase Current）: Δ Connection
- Three-Phase P(Active Power) ＝Three-Phase VA × cosθ
- Three-Phase Q(Reactive Power)＝ Three-Phase VA × sinθ
- Θ: Phase Angle between Phase Voltage and Phase Current
- cosθ: Power Factor

2. Per Unit Method

- Normalize variables in power systems
- Make it easy to get the solution of power system static and dynamic state
- Solve several voltage networks in one set of equations

- Rated capacity to 1.0
  - Equipment(ex. Generator): Rated Capacitor
  - Grid: Total Capacity or Total Load (need not to set to maximum amount of capacity)
- Rated voltage to 1.0
  - Each Transmission Line can be set to 1.0

Per Unit Value & Actual Value

- Normalize a value to one that is based on unit number 1.0
- For each equipment
  - Rated capacity -> 1.0
  - Rated voltage -> 1.0
- For grid
  - Total capacity of grid -> 1.0
  - Rated voltage of transmission line -> 1.0

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

$$\dot{V}_p = \frac{\dot{V}}{V_{base}}, \quad \dot{I}_p = \frac{\dot{I}}{I_{base}}, \quad \dot{Z}_p = \frac{\dot{Z}}{Z_{base}}$$

$$V_{base} = I_{base} Z_{base}$$

$$\frac{\dot{V}}{V_{base}} = \frac{\dot{I}}{I_{base}} \frac{\dot{Z}}{Z_{base}}$$

$$\dot{V}_p = \dot{I}_p \dot{Z}_p$$

$$(VA)_{base} = V_{base} I_{base}$$

$$Y_{base} = \frac{1}{Z_{base}}$$

V: Voltage, I: Current, Z: Impedance
Vbase: Base Voltage, Ibase: Base Current
Zbase: Base Impedance, Ybase: Base Admitanse
(VA)base: Base Apparent Power
Vp: Per Unit Voltage, Ip: Per Unit Current
Zp: Per Unit Impedance

Conversion to Per Unit Base Value

- The way to set base value of per unit for impedance
- ex.) From generator's self-capacitor base to system capacitor base

$$Z_{NEW,base} = \frac{V_{base}^2}{(VA)_{NEW,base}} \qquad \dot{Z}_{NEW,p} = \frac{\dot{Z}}{Z_{NEW,base}} = \frac{\dot{Z}\,(VA)_{NEW,base}}{V_{base}^2}$$

$$Z_{OLD,base} = \frac{V_{base}^2}{(VA)_{OLD,base}} \qquad \dot{Z}_{OLD,p} = \frac{\dot{Z}}{Z_{OLD,base}} = \frac{\dot{Z}\,(VA)_{OLD,base}}{V_{base}^2}$$

$$\dot{Z}_{NEW,p} = \frac{(VA)_{NEW,base}}{(VA)_{OLD,base}} \dot{Z}_{OLD,p}$$

V:Voltage, I:Current, Z:Impedance
Vbase: Base Voltage, Ibase:Base Current
Zbase:Base Impedance, Ybase:Base Admitance
(VA)base:Base Apparent Power
Vp:Per Unit Voltage, Ip:Per Unit Current
Zp:Per Unit Impedance

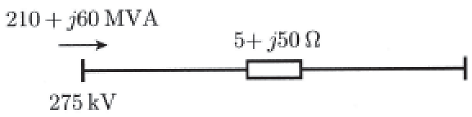
Example of Conversion to Per Unit

(1) Calculate Base Value

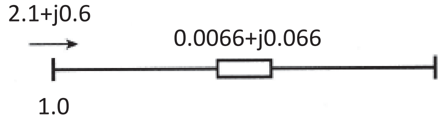
Vbase=275kV

(VA)base=100MVA

$$Z_{\mathrm{Ybase}} = \frac{(275 \times 10^3)^2}{100 \times 10^6} = 756\ \Omega$$



(2) Change Actual Value to Per Unit Value



$$\dot{Z}_{\mathrm{p}} = \frac{5+j50}{756} = 0.0066 + j0.066$$

$$2.1 + j0.6 = 1.0\dot{I}_{\mathrm{p}}^*$$

$$\dot{I}_{\mathrm{p}} = 2.1 - j0.6$$

$$\dot{S}_{\mathrm{sp}} = \dot{V}_{\mathrm{sp}}\dot{I}_{\mathrm{p}}^*$$

$$\dot{V}_{\mathrm{rp}} = \dot{V}_{\mathrm{sp}} - \dot{I}_{\mathrm{p}}\dot{Z}_{\mathrm{p}} = 1.0 - (2.1 - j0.6)(0.0066 + j0.066) = 0.947 - j0.135$$

$$\dot{S}_{\mathrm{rp}} = \dot{V}_{\mathrm{rp}}\dot{I}_{\mathrm{p}}^* = (0.947 - j0.135)(2.1 + j0.6) = 2.07 + j0.285$$

$$\dot{S}_{\mathrm{r}} = (2.07 + j0.285)100\ \mathrm{MVA} = 207 + j28.5\ \mathrm{MVA}$$

$$\dot{V}_{\mathrm{r}} = (0.947 - j0.135)275\ \mathrm{kV} = 260 - j37.1\ \mathrm{kV}$$

$$|\dot{V}_{\mathrm{r}}| = 263\ \mathrm{kV}$$

Figure is cited from

M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Example of Per Unit Value

- Vbase=11.5kV
- (VA)base=100MVA
- Ibase=100/11.5=8.7kA
- Zbase=Vbase^2/(VA)base=11.5^2/100=1.32Ω
  - R=0.15Ω/km, X=0.15Ω/km
  - Length =6km
  - Rpu=0.15x6/1.32=0.7
  - Xpu=0.15x6/1.32=0.7
  - Zpu=$\sqrt{0.7*0.7+0.7*0.7}$=1.0 => |Z|=1.32Ω

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rpu: Resistance in Per Unit, Xpu: Reactance in Per Unit

The Meaning of Per Unit

- The meaning:

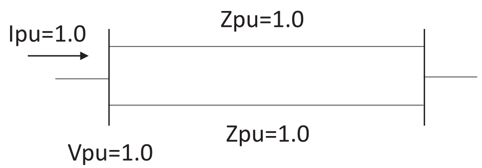
1pu(|Z|=1.32Ω) impedance transmission line can send 1pu(100MVA) power by 1pu(11.5kV) voltage. Its current is 1pu(8.7kA).

This will be maximum capacity of transmission line.

If transmission line has 2 circuits, its total impedance will be 0.5pu(0.66Ω), and the maximum capacity will be twice(2pu:200MVA).

Vpu: Voltage in Per Unit
(VA)pu: Base Apparent Power in Per Unit
Ipu: Current in Per Unit
Zpu: Impedance in Per Unit
Rpu: Resistance in Per Unit
Xpu: Reactance in Per Unit

2 Circuit Transmission Line

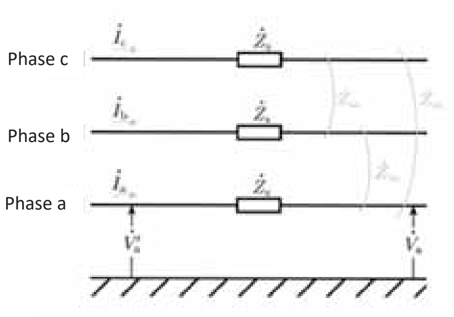


3. Modeling of Power System Equipment

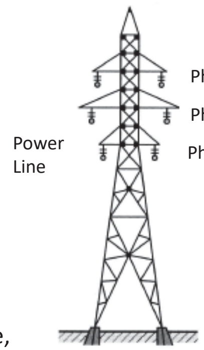
- Make it easy to analyze feature of power system equipment
- Modeling of Components of Power System
  - Transmission Line
  - Transformer & Switchgear (Substation)
  - Generator (Synchronous Generator, Photovoltaic, Wind Power)
  - Load

Transmission Line

- In a 3-Phase balanced system, we may consider only correct phase circuit same as single phase circuit.



Ia, Ib, Ic: Phase Current
Zs: Line Impedance
Va', Va: Phase Voltage
(Sending Terminal Voltage,
Receiving Terminal Voltage)



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

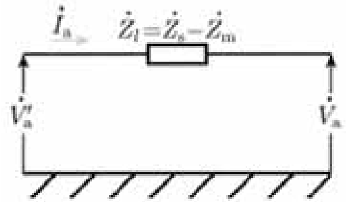
Impedance of Transmission Line

- Impedance of Transmission Line

$$\dot{Z}_s = R + j\omega L_s$$

$$\dot{V}'_a - \dot{V}_a = \dot{I}_a\dot{Z}_s + \dot{I}_b\dot{Z}_m + \dot{I}_c\dot{Z}_m = \dot{I}_a(\dot{Z}_s - \dot{Z}_m) = \dot{I}_a\dot{Z}_l$$

$$\dot{Z}_m = j\omega L_m$$



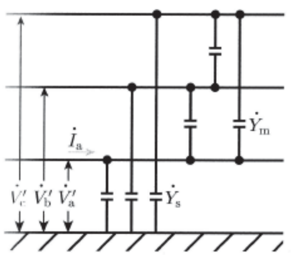
Zs: Self Impedance, Zm: Mutual Impedance
Z_l=Zs-Zm : Line Impedance, Sum of self and mutual impedance
R: Line Resistance
Ls: Self Inductance, Lm: Mutual Inductance
Ia, Ib, Ic: Phase Current
Va', Va: Phase Voltage
(Sending Terminal Voltage, Receiving Terminal Voltage)

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

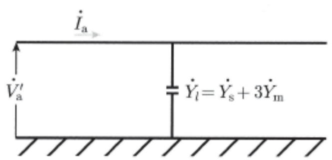
Admittance of Transmission Line

- Admittance of Transmission Line

$$\dot{I}_a = \dot{V}'_a\dot{Y}_s + (\dot{V}'_a - \dot{V}'_b)\dot{Y}_m + (\dot{V}'_a - \dot{V}'_c)\dot{Y}_m = \dot{V}'_a(\dot{Y}_s + 3\dot{Y}_m) = \dot{V}'_a\dot{Y}_l$$



Va', Vb', Vc':Phase Voltage of Sending Terminal
Ys: Line Admitance, Ym: Mutual Admitance,
Yl=Ys+3Ym
Ia: Line Current of a-phase

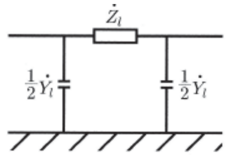


Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

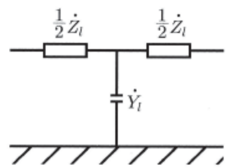
Equivalent Circuit of Transmission Line

Two types of Equivalent Circuit

- Π (pai) Model
  - Divide line admittance into sending node side and receiving node side
  - No need to add another node



- T (tee) Model
  - Divide line impedance into sending node side and receiving node side
  - Need to add another middle point node



Zl: Impedance of Transmission Line
Yl: Admitance of Transmission Line

Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

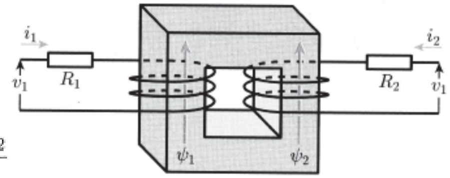
Transformer

- Mathematical equations of transformer

Φ1: primary side flux
Φ2: secondary side flux
L1: primary side self inductance
L2: secondary side self inductance
M1: primary side mutual inductance
M2: secondary side muual inductance
Ω: angular velocity

$$\begin{cases} v_1 = i_1 R_1 + \dfrac{d\psi_1}{dt} \\ v_2 = i_2 R_2 + \dfrac{d\psi_2}{dt} \end{cases}$$

$$\begin{cases} \psi_1 = L_1 i_1 + M_{12} i_2 \\ \psi_2 = M_{21} i_1 + L_2 i_2 \end{cases} \qquad r = \frac{M_{12}}{L_2}$$



$$\begin{cases} \dot V_1 = \dot I_1 R_1 + j\omega(L_1 \dot I_1 + M_{12}\dot I_2) = (R_1 + j\omega L_1)\dot I_1 + j\omega M_{12}\dot I_2 \\ \dot V_2 = \dot I_2 R_2 + j\omega(M_{21}\dot I_1 + L_2 \dot I_2) = j\omega M_{21}\dot I_1 + (R_2 + j\omega L_2)\dot I_2 \end{cases}$$

Figure is cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Equivalent Circuit of Transformer

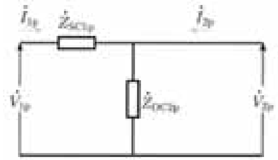
- Relationship of per unit base values

$$\frac{r\dot I_1}{I_{2\mathrm{base}}} = \frac{r\dot I_1}{rI_{1\mathrm{base}}} = \dot I_{1\mathrm{p}} \qquad rI_{1\mathrm{base}} = I_{2\mathrm{base}},\quad Z_{1\mathrm{base}} = r^2 Z_{2\mathrm{base}}$$

$$\frac{\dot I_2}{rI_{1\mathrm{base}}} = \frac{\dot I_2}{I_{2\mathrm{base}}} = \dot I_{2\mathrm{p}},\quad \frac{r^2 \dot Z_{\mathrm{OC2}}}{Z_{1\mathrm{base}}} = \frac{\dot Z_{\mathrm{OC2}}}{Z_{2\mathrm{base}}} = \dot Z_{\mathrm{OC2p}}$$

- Equivalent Circuit and Equation

$$\begin{cases} \dot V_{1\mathrm{p}} = \dot I_{1\mathrm{p}} \dot Z_{\mathrm{SC1p}} + (\dot I_{1\mathrm{p}} + \dot I_{2\mathrm{p}})\dot Z_{\mathrm{OC2p}} \\ \dot V_{2\mathrm{p}} = (\dot I_{1\mathrm{p}} + \dot I_{2\mathrm{p}})\dot Z_{\mathrm{OC2p}} \end{cases}$$



I1: Primary side Current, I2 secondary side Current, r: Transformer Ratio
I1base: Primary side Base Current, I2base: Secondary side Base Current
Z1base: Primary side Base Impedance, Z2base: Secondary side Base Impedance
V1p, V2p, I1p, I2p: Per Unit Voltage and Current of Primary, Secondary Circuit
Zsc1, Zsc1p: Short Circuit Impedance from Primary side and its per unit value
Zoc2, Zoc2p: Secondary side Open Circuit Impedance and its per unit value

Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Transformer in Per Unit

- Per Unit Model of Transformer

$$\begin{aligned} (VA)_{2\mathrm{base}} &= V_{2\mathrm{base}} I_{2\mathrm{base}} = I_{2\mathrm{base}}^2 Z_{2\mathrm{base}} \\ &= \frac{r^2 I_{1\mathrm{base}}^2 Z_{1\mathrm{base}}}{r^2} \\ &= I_{1\mathrm{base}}^2 Z_{1\mathrm{base}} \\ &= (VA)_{1\mathrm{base}} \end{aligned}$$

$$\begin{cases} V_{1\mathrm{base}} = I_{1\mathrm{base}} Z_{1\mathrm{base}} \\ V_{2\mathrm{base}} = I_{2\mathrm{base}} Z_{2\mathrm{base}} \end{cases}$$

- Transformer ratio

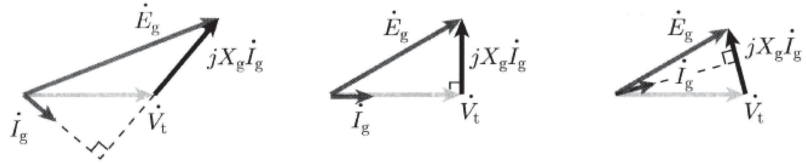
$$\frac{V_{1\mathrm{base}}}{V_{2\mathrm{base}}} = \frac{\dfrac{(VA)_{1\mathrm{base}}}{I_{1\mathrm{base}}}}{\dfrac{(VA)_{2\mathrm{base}}}{I_{2\mathrm{base}}}} = \frac{I_{2\mathrm{base}}}{I_{1\mathrm{base}}} = \frac{rI_{1\mathrm{base}}}{I_{1\mathrm{base}}} = r$$

r: Transformer Ratio
I1base: Primary side Base Current, I2base: Secondary side Base Current
Z1base: Primary side Base Impedance, Z2base: Secondary side Base Impedance
(VA)1base: Primary side Base Apparent Power
(VA)2base: Secondary side Base Apparent Power

Synchronous Generator

- Phasor Model of Synchronous Generator

$$\dot V_t = \dot E_g - jX_g \dot I_g$$



Lag Power Factor=1 Lead

Vt: Terminal Voltage, Eg: Internal Electromotive Force
Xg: Amature Impedance, Ig: Armature Current

Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Output of Synchronous Generator

Induced Electromotive Force $\dot{E}_g = E_g e^{j\delta}$

$$P + jQ = \dot{V}_t \dot{I}_g^*$$
$$= V_t \left(\frac{E_g e^{j\delta} - V_t}{jX_g} \right)^*$$
$$= \frac{V_t E_g}{X_g} \sin\delta + j \left(\frac{V_t E_g}{X_g} \cos\delta - \frac{V_t^2}{X_g} \right)$$

$$P = \frac{V_t E_g}{X_g} \sin\delta$$

$$Q = \frac{V_t E_g}{X_g} \cos\delta - \frac{V_t^2}{X_g}$$

Vt: Terminal Voltage, Eg: Induced Electromotive Force
Xg: Armature Impedance, Ig: Armature Current
P: Active Power Output, Q: Reactive Power Output
δ: Internal Electromotive Force Angle
Po: Rated Active Power

Load (Customer)

- Numerical Model
  - Constant Impedance (**Z**=R+jX)
  - Constant Power (**S**=P+jQ)
  - Constant Current (**I**=a+jb)
  - -> easy to include into network equations of power system

How to Make a Model of Renewable Energy Generator

- Photovoltaic Generator & Wind Turbine Generator
  - Negative load model
  - Maximum Power Point Control
  - Follow the Voltage of Grid
  - Constant Power Factor -> Constant Power or Current
  - -> similar mode of Load
- Diesel Generator & Biofuel Generator
  - Synchronous Generator model
  - Automatic Voltage Regulator -> Constant Voltage
  - Power System Stabilizer -> Control Active Power
  - Governor & Turbine -> Control Frequency
  - -> similar model of synchronous generator

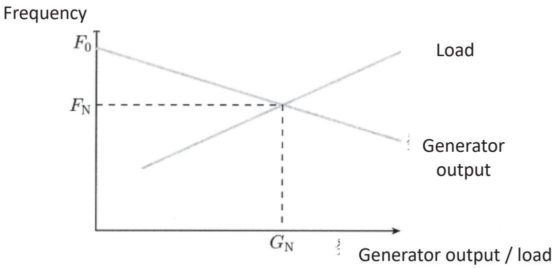
4. Active Power & Frequency

- Difference of active power between generator output and load is proportional to frequency.
- If generation power is larger than load, frequency will increase.
- Oppositely, if generation power will be less than load, frequency will decrease.
- Control method of load is different according to its responsibility.

Active Power & Frequency

- Power-Frequency Characteristic
- Power of synchronous generators increase according to frequency.

F0: No-load frequency
FN: Frequency under normal operation
GN: Power of synchronous generatos under normal operation



- Proportion
- Inverse proportion
- -> crossing point is
  an operating point.

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Several Frequency Control Systems

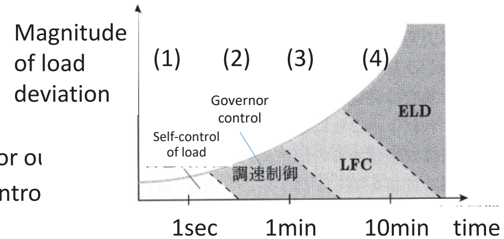
- Frequency Control Scheme is categorized to 4 stages.

(1) Self-control of load
Quick response of Load according to its characteristic

(2) Turbine Governor control
Synchronous generator has
Conventional inverter doesn't have

(3) Load Frequency Control
Feedback frequency and change generator ou
according to PI (Proportional-Integral) contro
as the following equation:
$\Delta PG = (K1+K2/s)\Delta f$

(4) Economic Load Dispatching
Select most cost effective generator among LFC generators



EMS: Energy Management System
-> operated in central control center
ΔPG: Generator Output Change
Δf: Frequency Change
K1: Proportional Gain
K2: Integral Gain

Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Power–Frequency Coefficients

- Power-Frequency Coefficients is a constant depending on the governor and load characteristics.

$$\%K_G = \frac{100}{F_0 - F_N}\ \%\mathrm{MW/Hz}$$

$$\varepsilon = \frac{F_0 - F_N}{F_N} \times 100\,\%$$

$$\%K_G = \frac{100 \times 100}{\varepsilon \times F_N}\ \%\mathrm{MW/Hz}$$

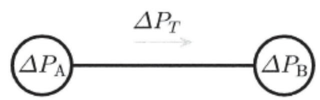
$$\Delta P + (\Delta G - \Delta L) = 0$$
$$\Delta P = (K_G + K_L)\Delta F$$

$$K = K_G + K_L\ [\mathrm{MW/Hz}]$$

F0: Rated Frequency
FN: Current Frequency
ΔG: Generator Output Change
ΔL: Load Change
ΔP: Chang of Power
ΔF: Change of Frequency
KG: Gain for Generator Output Change
KL: Gain for Load Change
K: Power-Frequency Coefficient

Power Systems Connected by a Tie-Line

- Two interconnected power systems



$$\Delta P_A = \Delta G_A - \Delta L_A$$
$$\Delta P_B = \Delta G_B - \Delta L_B$$

Area Requirement (supply and demand balance and tie line flow)

$$\Delta P_A = K_A \Delta F + \Delta P_T$$
$$\Delta P_B = K_B \Delta F - \Delta P_T$$

Frequency of Interconnected grids are collected as the following equations.

$$\begin{cases} \Delta F = \dfrac{\Delta P_A + \Delta P_B}{K_A + K_B} \\ \Delta P_T = \dfrac{K_B \Delta P_A - K_A \Delta P_B}{K_A + K_B} \end{cases}$$

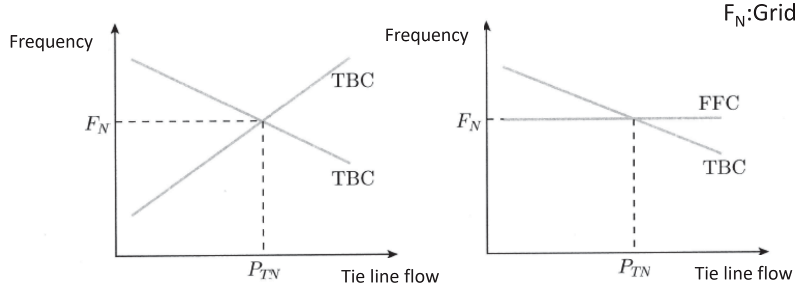
F0: Rated Frequency
F: Frequency of Interconnected Grid
ΔG: Generator Output Change
ΔL: Load Change
ΔP: Chang of Power
ΔF: Change of Frequency
KG: Gain for Generator Output Chang
KL: Gain for Load Change
K: Power-Frequency Coefficient

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Relationship between generator, load and frequency

- FFC: Flat Frequency Control
  - To keep frequency constant in a grid
- TBC: Tie Line Load Frequency Bias Control
  - To keep area requirement (supply and demand balance and tie line flow) zero in a grid

F_N:Grid Freqency



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

5. Reactive Power & Voltage

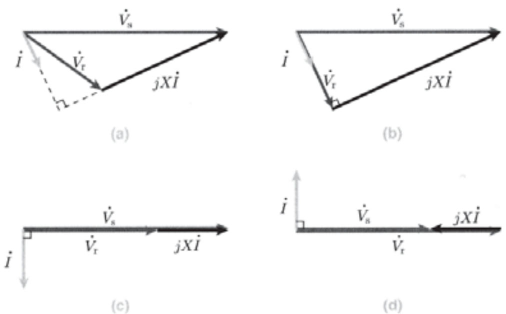
- Most of load consumes reactive power and its voltage will decrease.
- In order to keep voltage to a certain value, reactive power should be provided.
- Provider of reactive power
  - Synchronous generator
  - Synchronous Condenser/Capacitor (SC, SCO)
  - Static Var Compensator (SVC)
  - Static Synchronous Compensator (STATCOM)
  - Voltage Reactive Power Control (VQC)

Reactive Power & Voltage

- Relationship between Reactive Power and Voltage

$$\dot{V}_r = \dot{V}_s - jX\dot{I}$$

(a) Usual load
(b) Power factor=1
(c) Power factor=0,
Lagging load (only inductance)
(d) Power factor=0,
Leading load (only capacitance)



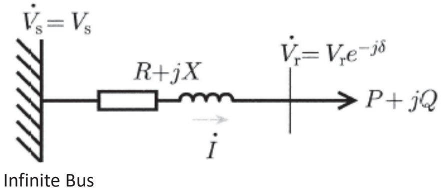
Vs: Sending Terminal Voltage, Vr: Receiving Terminal Voltage
I: Tiransmission Line Curent
X: Transmission Line Impedance

Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Reactive Power

- Sensitivity of P & Q

$$P + jQ = \dot{V}_r \dot{I}^*$$
$$= V_r e^{-j\delta}\left(\frac{V_s - V_r e^{-j\delta}}{R + jX}\right)^*$$
$$= \frac{V_s V_r e^{-j\delta} - V_r^2}{R - jX}$$
$$RP + XQ + V_r^2 = V_s V_r \cos\delta$$
$$RQ - XP = -V_s V_r \sin\delta$$
$$(RP + XQ + V_r^2)^2 + (RQ - XP)^2 = V_s^2 V_r^2$$
$$\frac{\partial V_r}{\partial P} = -\frac{(R^2 + X^2)P + RV_r^2}{V_r(2XQ + 2RP + 2V_r^2 - V_s^2)}$$
$$\frac{\partial V_r}{\partial Q} = -\frac{(R^2 + X^2)Q + XV_r^2}{V_r(2XQ + 2RP + 2V_r^2 - V_s^2)}$$



Vs: Sending Terminal Voltage
Vr: Receiving Terminal Voltage
P: Active Load Power
Q: Reactive Load Power
R: Line Resistance
X: Line Reactance

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Reactive Power

- Sensitivity of reactive power is larger than that of active power for voltage.

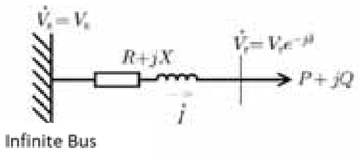
$$\begin{cases}\Delta V_{r,P} = \left(\frac{\partial V_r}{\partial P}\right)\Delta P \\ \Delta V_{r,Q} = \left(\frac{\partial V_r}{\partial Q}\right)\Delta Q\end{cases} \qquad \frac{\partial V_r}{\partial P} = -\frac{(R^2+X^2)P + RV_r^2}{V_r(2XQ+2RP+2V_r^2-V_s^2)} \qquad \frac{\partial V_r}{\partial Q} = -\frac{(R^2+X^2)Q + XV_r^2}{V_r(2XQ+2RP+2V_r^2-V_s^2)}$$

$$\rho = \frac{\Delta V_{r,P}}{\Delta V_{r,Q}} = \frac{(R^2+X^2)P + RV_r^2}{(R^2+X^2)Q + XV_r^2} = \frac{ZP+RC}{ZQ+XC} \ll 1$$

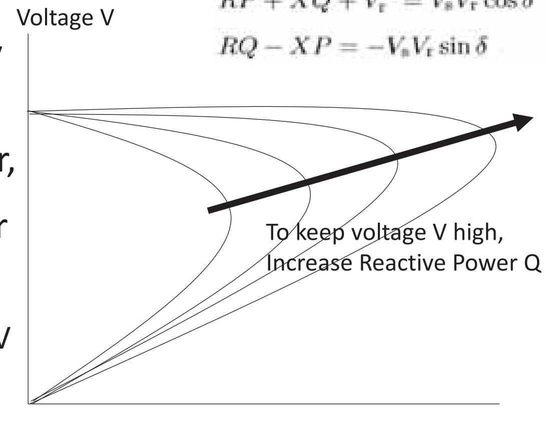
ΔVr,p: Sensitivity of Active Power to Voltage
ΔVr,q: Sensitivity of Reactive Power to Voltage
Vs: sending Terminal Voltage, Vr: Receiving Terminal Voltage
P: Active Load Power, Q: Reactive Load Power
R: Line Resistance, X: Line Reactance
$C=Vr^2/Z$: Short Circuit capacity

P-V Curve & Q(Reactive Pow

- From the right equations, relationship of active power P and Voltage V can be solved into the figure.
- If Reactive Power Q increase, voltage V will be up and active power P of load will increase.
- In order to keep voltage V as normal value, increase reactive power Q of load by adding Shunt Capacitor, Synchronous Condenser or Static Var Compensator (SVC, STATCOM) to the load node.
- Caution!!: Too much Q drops V and causes power system blackout.



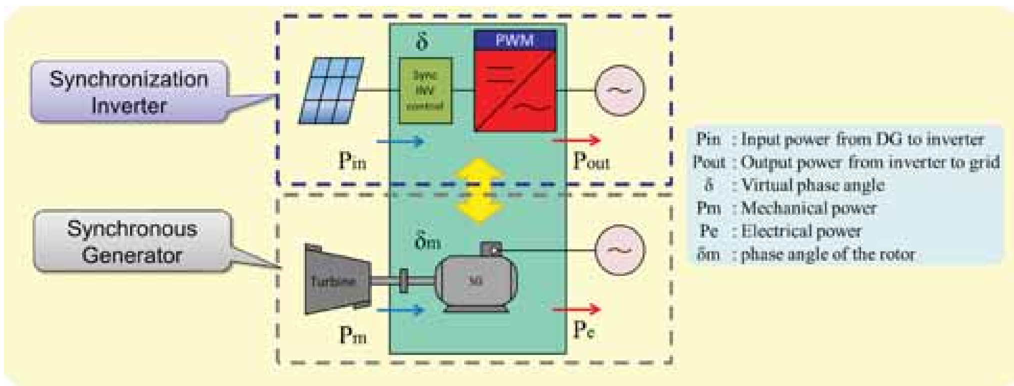
$$RP + XQ + V_r^2 = V_s V_r \cos\delta$$
$$RQ - XP = -V_s V_r \sin\delta$$



IBR(Inverter Based Resources) Types

- Grid Following Inverter
  - Current Source Inverter
  - Control output current as adjusting voltage to grid's
- Grid Forming Inverter
  - Voltage Source Inverter
  - Virtual Synchronous Generator
  - Control output voltage and its frequency as adjusting power to grid's
  - Supply Virtual Inertia to Grid
  - Source: PV, WT(Wind Turbine), EV(Electric Vehicle), Battery

Concept of Virtual Inertia



Source: M. Kawai, Y. Sakai, H. Sugiyama, H. Taoka "Frequency Improvement of a Power System with a Distributed Generator using Synchronization Inverter," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), CIGRE SC C6 Colloquium, Sep. 2015.

Control Algorithm for Virtual Inertia

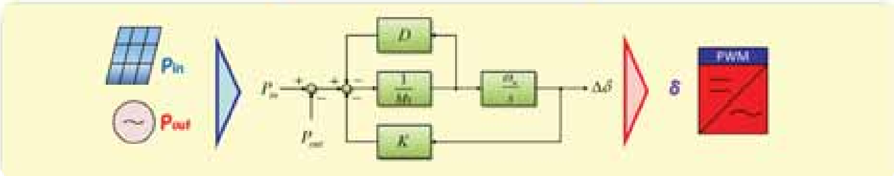
The control method of Synchronization Inverter is expressed by the swing equation. This equation is added damping term and synchronizing power term.

$$\frac{M}{\omega_n}\frac{d^2\delta_m}{dt^2}+\frac{D}{\omega_n}\frac{d\delta_m}{dt}+K\delta_m=P_m-P_e$$

This swing equation of the Synchronization Inverter is solved for virtual phase angle δ.

The transfer function of voltage value

$$\delta=\frac{\frac{1}{M}\omega_n}{s^2+\frac{D}{M}s+\frac{K}{M}\omega_n}(P_m-P_{out})$$



Source: M. Kawai, Y. Sakai, H. Sugiyama, H. Taoka "Frequency Improvement of a Power System with a Distributed Generator using Synchronization Inverter," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), CIGRE SC C6 Colloquium, Sep. 2015.

SCR(Short Circuit Ratio)

- SCR is the factor to be considered for grid stability.
- SCR=AC System Capacity/Rated IBR Capacity
  - SCR>3 -------- High SCR, Stable
  - 3>SCR>2 ----- Low SCR
  - 2>SCR -------- Very Low SCR
- Discussed in IEEE Std 1204-1997(R2003)
  - IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities
  - Recognized by ANSI(American National Standards Institute

Sources for High SCR Grid

- V2G(Vehicle to Grid) of EV(Electric Vehicle)
- BESS(Battery Energy Source System)
  - Battery with control circuits
- Biofuel Generator
- Solar Thermal Generator

  and
- Renewable Energy Resources (PV, WT) with Grid Forming Inverter
- These resources can supply inertia to grid.

ATC(Available Transmission Capacity)

- Transmission capacity needs to be calculated to see whether RE can be transmitted from source location to demand place.
- Power Equation
  - $P=\frac{V_iV_j}{X}sin\delta$
- Synchronizing Force
  - $\frac{dP}{d\delta}=\frac{V_iV_j}{X}cos\delta$
- Available Transmission Capacity from Heat Capacity Limit

$$P_{loss}=R*(\frac{V_i}{X})^2 \quad < \quad P_{\mathrm{LOSSMAX}}$$

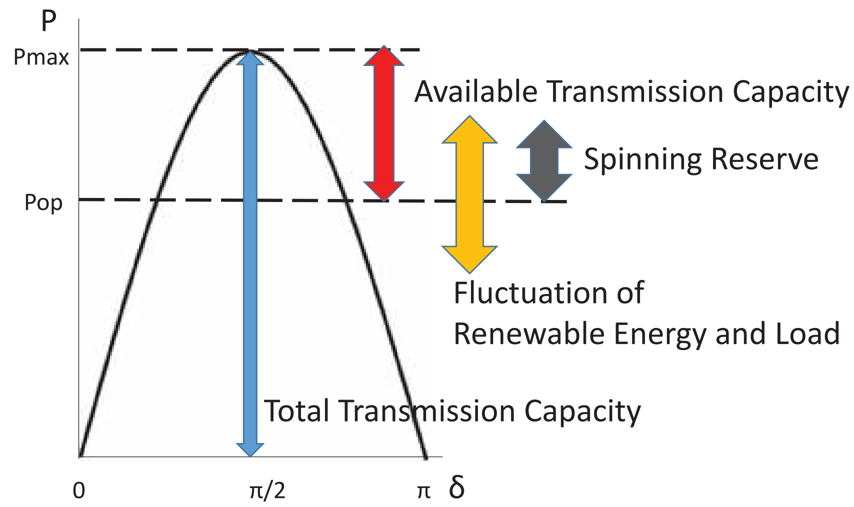
- Available Transmission Capacity from Transient Stability

$$P=\frac{V_iV_j}{X}\boldsymbol{sin\delta} \quad \rightarrow \quad P_{\mathrm{ATC}}=\frac{V_iV_j}{X}-P_{\mathrm{OP}}$$

Spinning Reserve

- In order to get electrical power under abnormal condition of grid, spinning reserve should be kept even if RE is installed. (under development)
- Spinning reserve should be more than mixed fluctuation of load and renewable energy.
  -> RE, EV and Battery with inertia is required for large RE penetration.
- Best Energy Mix
  -> Energy mix of several resources will be helpful for improving grid stability.
- RE Sources for Spinning Reserve: EV, Battery, Biofuel or Diesel Generator, etc.

Available Transmission Capacity & Spinning Reserve



P-δ curve for RE and SCO

(g) Photovoltaics

Change Pmax

(h) Wind Power

Change Pmax and Phase

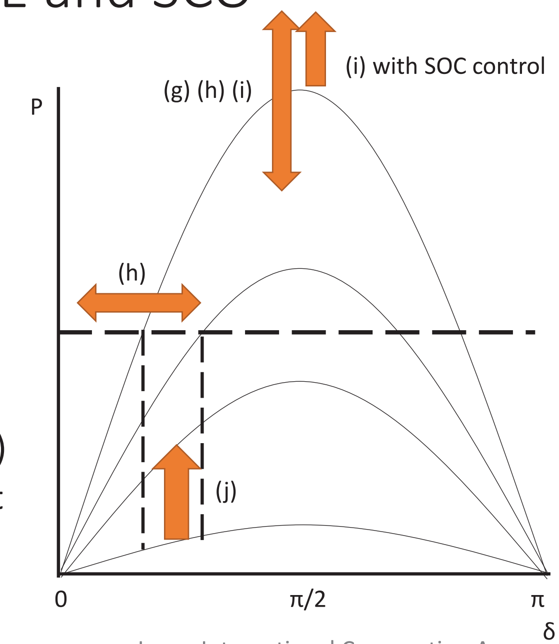
(i) Battery

Change Pmax

(j) SCO

(Synchronous Condenser)

Change P during fault



6. Practice of Modeling Grid

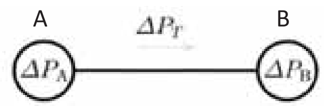
- Per Unit Calculation
  - Calculation of base current and impedance for several base voltage and base capacity
- Active Power - Frequency Relationship
  - Calculation of Area Requirement
  - The way to calculate Microgrid Interconnection
- Reactive Power - Voltage Relationship
  - Calculation of voltage and sensitivity in a small grid

Exercise 1

- Base voltage Vbase and base capacity (VA)base is as follows:
  - Vbase=50.0kV
  - (VA)base=100MVA
- (1) Calculate base current Ibase and base impedance Zbase.
- (2) When the resistance R and reactance X of transmission line is R=0.04Ω/km and X=0.06Ω/km, and the length of transmission line is 8km, calculate line impedance Z=R+jX in per unit.

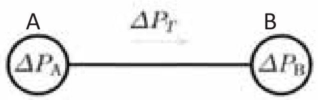
Exercise 2

- The two power systems, A and B, having capacities of 1000MW and 500MW, respectively, are interconnected through TBC(Tie Line Load Frequency Bias Control). The power-frequency coefficients of both power systems are 1.0%MW/0.1Hz.
- Please calculate the change of frequency and the tie line power flow ΔP_T, when the capacity of power system A decreased by 30MW.



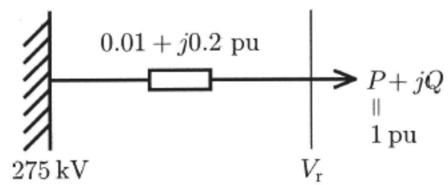
Exercise 3

- The two power systems, A and B, having capacities of 300MW and 500MW, respectively, are interconnected through TBC(Tie Line Load Frequency Bias Control). The power-frequency coefficients of both power systems are 1.0%MW/0.1Hz.
- Calculate area requirements (change of capacity) of power system A and B, when the frequency decreased by 0.1Hz and the tie line power flow ΔP_T from power system A to power system B increased by 50MW.



Exercise 4

- The voltage of infinite bus is 275kV, line impedance is 0.01+j0.2pu, active power of lagged load is 1.0, and its power factor is 0.98.
- Calculate reactive power Q and terminal voltage of the load.
- Calculate P & Q sensitivity ratio $\rho = \dfrac{\partial V_r / \partial P}{\partial V_r / \partial Q}$.



Exercise 1,2 Answer

- Exercise 1
  - (1) Ibase=(VA)base/Vbase=100MVA/50kV=2kA
    Zbase=Vbase/Ibase=50kV/2kA=25Ω
  - (2) R=0.04*8/25=0.0128
    X=0.06*8/25=0.0192
    Z=0.0128+j0.0192

- Exercise 2
  KA=0.01x1000=10[MW/0,1Hz]=100[MW/Hz]
  KB=0.01x500=5[MW/0.1Hz]=50[MW/Hz]
  ΔF=-30/(100+50)=-0.2[Hz]
  ΔPT=50x(-30)/(100+50)=-10.0MW

Exercise 3,4 Answer

- Exercise 3
  KA=0.01x300=3[MW/0.1Hz]=30[MW/Hz]
  KB=0.01x500=5[MW/0.1Hz]=50[MW/Hz]
  ΔRA=50+30x(-0.1)=47[MW]
  A should be decreased by 47MW.
  ΔRB=-50+50x(-0.1)=-55[MW]
  B should be increased by 55MW
- Exercise 4
  tan θ=0.2 Q=Ptanθ=0.20[pu]
  $(0.01x1+0.2x0.20+Vr^2)2+(0.01x0.2-0.2x1)^2=Vr^2$
  $Vrp^2=0.85$ Vrp=0.92
  Vr=275x0.92=253kV
  $ρ=((0.01^2+0.2^2)*1+0.01*0.92^2))/((0.01^2+0.2^2)*0.2+0.2*0.85^2)$
  =0.049/0.18=0.27

Per Unit Example 1

- Vbase=11.5kV
- (VA)base=100MVA

- Ibase=100/11.5=8.70kA
- $Zbase=Vbase^2/(VA)base=11.5^2/100=1.32Ω$
  - R=0.15Ω/km, X=0.15Ω/km
  - Length =5km
  - Rpu=0.15x5/1.32=0.57
  - Xpu=0.15x5/1.32=0.57

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

Per Unit Example 2

- Vbase=24.9kV
- (VA)base=100MVA

- Ibase=100/24.9=4.0kA
- $Zbase=Vbase^2/(VA)base=24.9^2/100=6.2Ω$
  - R=0.05Ω/km, X=0.10Ω/km
  - Length =5km
  - Rpu=0.05x5/6.2=0.04
  - Xpu=0.10x5/6.2=0.08

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

Per Unit Example 3

- Vbase=49.0kV
- (VA)base=100MVA
- Ibase=100/49.0=2.04kA
- Zbase=Vbase^2/(VA)base=49.0^2/100=24.0Ω
  - R=0.04Ω/km, X=0.08Ω/km
  - Length =5km
  - Rpu=0.04x5/24.0=0.008
  - Xpu=0.08x5/24.0=0.017

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

Per Unit Example 4

- Vbase=11.4kV
- (VA)base=100MVA
- Ibase=100/11.4=8.8kA
- Zbase=Vbase^2/(VA)base=11.4^2/100=1.3Ω
  - R=0.15Ω/km, X=0.15Ω/km
  - Length =5km
  - Rpu=0.15x5/1.3=0.58
  - Xpu=0.15x5/1.3=0.58

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

Per Unit Example 5

- Vbase=66.0kV
- (VA)base=100MVA
- Ibase=100/66.0=1.52kA
- Zbase=Vbase^2/(VA)base=66.0^2/100=43.6Ω
  - R=0.04Ω/km, X=0.08Ω/km
  - Length =5km
  - Rpu=0.04x5/43.6=0.005
  - Xpu=0.08x5/43.6=0.009

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

Seminar on Grid Stability with Large RE Day 2

Basics and Exercise for Load Flow Analysis

JICA Expert Team, Nippon Koei Co., Ltd.

Contents

1. Overview of Load Flow Analysis

- Steady state analysis under small disturbance
- System is explained as linear model.
- Voltage, power, angle are constant at a certain time
- It is assumed to be kept as the same value under small disturbance at a certain time.
- -> Load Flow Analysis: Solve algebraic equations
- -> Eigenvalue Analysis: Solve differential equations

Load Flow Analysis

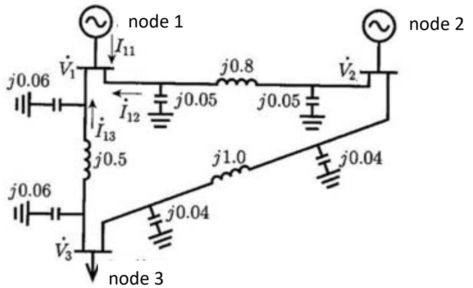
- Node Admittance Matrix
  - Relationship between voltage and current for multiple nodes in a power system
- Power Equation
  - Relationship between power and voltage
- DC Flow Method (manual calculation)
  - Simplified Load Flow Calculation of Three-phase AC Transmission Line
  - Solve relationship between power and voltage angle
- Newton Raphson Method
  - Solve relationship between power and voltage in vector

Node Admittance Matrix

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_N \end{bmatrix} = \begin{bmatrix} \dot{Y}_{11} & \dot{Y}_{12} & \cdots & \dot{Y}_{1N} \\ \dot{Y}_{21} & \dot{Y}_{22} & \cdots & \dot{Y}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \dot{Y}_{N1} & \dot{Y}_{N2} & \cdots & \dot{Y}_{NN} \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \vdots \\ \dot{V}_N \end{bmatrix}$$

Describe Network Structure

Y= 1/(R+JωL) ＋jωC
R:Resistance
C:Capacitance
L: Inductance

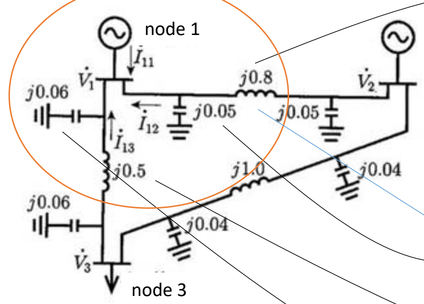


- Calculation example of power flow in 3 nodes network

V1,,,Vn: Node(Bus) Voltage
I1,,,In: Btanch(Line) Current
Yij: Admitance between earch node

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Node Admittance Matrix



Driving Point Admittance

$$\dot{Y}_{11} = j0.05 + j0.06 + \frac{1}{j0.8} + \frac{1}{j0.5} = -j3.14$$

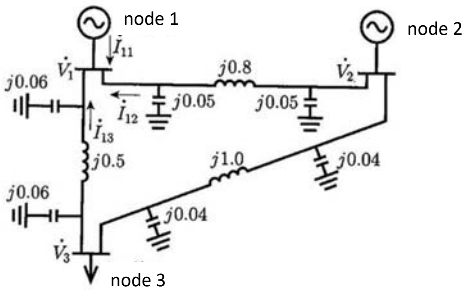
- Y11,Y22,Y33:
  - Driving Point Admittance
- Y12,Y21,Y13,Y31,Y23,Y32:
  - Transfer Admittance

Transfer Admittance

$$\dot{Y}_{12} = \dot{Y}_{21} = -\frac{1}{j0.8} = j1.25$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Node Admittance Matrix



$$\dot{Y}_{11} = j0.05 + j0.06 + \frac{1}{j0.8} + \frac{1}{j0.5} = -j3.14$$

$$\dot{Y}_{22} = j0.05 + j0.04 + \frac{1}{j0.8} + \frac{1}{j1.0} = -j2.16$$

$$\dot{Y}_{33} = j0.04 + j0.06 + \frac{1}{j1.0} + \frac{1}{j0.5} = -j2.9$$

$$\dot{Y}_{12} = \dot{Y}_{21} = -\frac{1}{j0.8} = j1.25$$

$$\dot{Y}_{13} = \dot{Y}_{31} = -\frac{1}{j0.5} = j2.0$$

$$\dot{Y}_{23} = \dot{Y}_{32} = -\frac{1}{j1.0} = j1.0$$

- Y_{11}, Y_{22}, Y_{33}:
  - Driving Point Admittance
- $Y_{12}, Y_{21}, Y_{13}, Y_{31}, Y_{23}, Y_{32}$:
  - Transfer Admittance

$$\boldsymbol{Y} = \begin{bmatrix} -j3.14 & j1.25 & j2.0 \\ j1.25 & -j2.16 & j1.0 \\ j2.0 & j1.0 & -j2.9 \end{bmatrix}$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

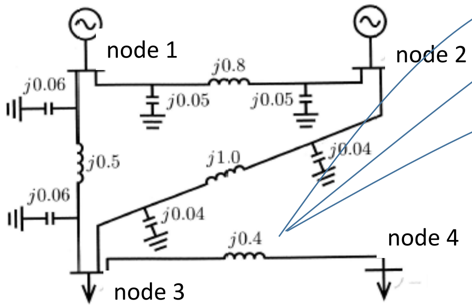
Node Admittance Matrix - Adding new node

- The way to change node admittance matrix for new node

$$\dot{Y}_{33} = -j2.9 + \frac{1}{j0.4} = -j5.4$$

$$\dot{Y}_{44} = \frac{1}{j0.4} = -j2.5$$

$$\dot{Y}_{34} = \dot{Y}_{43} = -\frac{1}{j0.4} = j2.5$$



$$\boldsymbol{Y} = \begin{bmatrix} -j3.14 & j1.25 & j2.0 & 0 \\ j1.25 & -j2.16 & j1.0 & 0 \\ j2.0 & j1.0 & -j5.4 & j2.5 \\ 0 & 0 & j2.5 & -j2.5 \end{bmatrix}$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Methods of Load Flow Analysis

- Gauss-Seidel Method
  - Iterative method to get approximate solution
- Newton-Raphson Method
  - Using Jacobian matrix to get approximate solution
- Fast Decoupled Method
  - Use relationship between active power and angle and relationship between reactive power and voltage
- DC Flow Method
  - Use relationship between active power and angle in the way to solve DC circuit equations

Power Equation

- Voltage and current of node k are described as following equations in complex value.
  - $V_k = e_k + j f_k$, $V_m = e_m + j f_m$
  - $I_k = Y_{km} V_{km}$
- Power Equation of node k is described using Node Admittance Matrix.

$$P_k + jQ_k = \dot{I}_k^* \dot{V}_k = \sum_{m=1}^{N} \dot{Y}_{km}^* \dot{V}_m^* \dot{V}_k$$

$$P_{ks} = \mathrm{Re}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$

$$Q_{ks} = \mathrm{Im}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$

$$V_{ks}^2 = e_k^2 + f_k^2$$

Vi: Node(Bus) Voltage
Ii: Branch(Line) Current
Yij: Admittance between each node
Pi: Node(Bus) Active Power
Qi: Node(Bus) Reactive Power

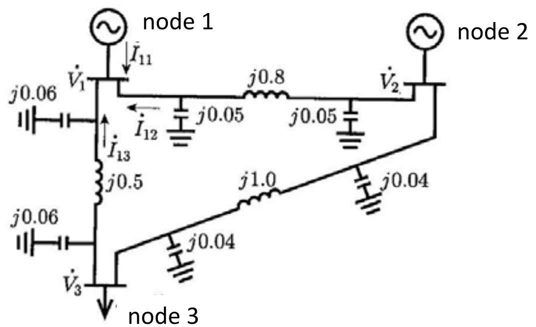
Load Flow Analysis

Necessary items to consider Load flow Analysis
Buses are categorized to the following 3 types.

- Slack (Swing) Node
  - The magnitude and phase angle of the voltage are specified.
  - Node with constant voltage and large capacity is suitable.
  - This node makes up the difference between the scheduled loads and generated power that are caused by the losses in the network.
- P-V Nodes (Generator Nodes)
  - The active power P and voltage magnitude V are specified.
  - The phase angles of the voltages and the reactive power are to be determined.
- P-Q Nodes (Load Nodes or Substation Nodes)
  - The active and reactive powers P, Q are specified.
  - The magnitude and the phase angle of the bus voltages are unknown.

Power Flow Equation
(Example of 3 nodes network)

Make a Power Flow Equations for each nodes



node 1: Slack Bus
node 2: PV Bus
node 3: PQ Bus

$$\begin{aligned} P_{2s} = \mathrm{Re}\{&(j1.25)^*(e_1 + jf_1)^*(e_2 + jf_2) \\ &+ (-j2.16)^*(e_2 + jf_2)^*(e_2 + jf_2) \\ &+ (j1.0)^*(e_3 + jf_3)^*(e_2 + jf_2)\} \\ = {}& 1.25e_1 f_2 - 1.25e_2 f_1 + e_3 f_2 - e_2 f_3 \end{aligned}$$

$$V_{2s}^2 = e_2^2 + f_2^2$$

$$\begin{aligned} P_{3s} = \mathrm{Re}\{&(j2.0)^*(e_1 + jf_1)^*(e_3 + jf_3) \\ &+ (j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) \\ &+ (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3)\} \\ = {}& 2.0e_1 f_3 - 2.0e_3 f_1 + e_2 f_3 - e_3 f_2 \end{aligned}$$

$$\begin{aligned} Q_{3s} = \mathrm{Im}\{&(j2.0)^*(e_1 + jf_1)^*(e_3 + jf_3) \\ &+ (j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) \\ &+ (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3)\} \\ = {}& 2.9e_3^2 + 2.9f_3^2 - 2.0e_1 e_3 - 2.0f_1 f_3 - e_2 e_3 - f_2 f_3 \end{aligned}$$

$$e_1 = V_{1s}, \quad f_1 = 0$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

2. Newton Raphson Method

- Here we describe numerical theory of Newton Raphson Method
- Equation to be solved is one dimensional equation y=f(x).

1. First, for i=0, assume x(i) to a certain value (ex. 1.0).
2. Calculate $$\Delta x^{(i)} = -\frac{f(x^{(i)})}{f'(x^{(i)})}$$
3. Calculate $$x^{(i+1)} = x^{(i)} - \frac{f(x^{(i)})}{f'(x^{(i)})}$$
4. Repeat 2 and 3, until Δx(i)<ε,
   where ε is a accuracy (ex. 0.001).
1. Get answer of x

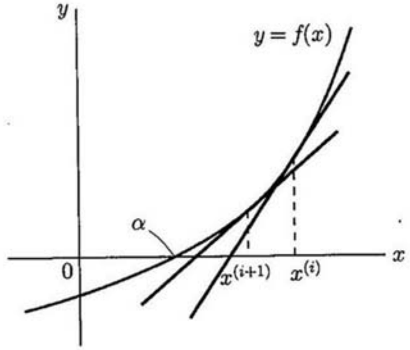


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Newton-Raphson Method

1. Set Node Voltage to 1.0
2. Calculate Jacobian Matrix using modified Voltage (1.0 at first)
3. Calculate ΔP, ΔQ and Δ|V|^2
4. Solve voltage difference ε of each Voltage by eq.(1)
5. Calculate new Voltage by eq.(2)
6. Repeat 2-6 until differences of Voltage are smaller than a certain value

eq.(1)

$$\begin{bmatrix} \Delta P_2 \\ \Delta|\dot{V}_2|^2 \\ \Delta P_3 \\ \Delta Q_3 \end{bmatrix} = -\begin{bmatrix} \frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial e_3} & \frac{\partial P_2}{\partial f_3} \\ \frac{\partial|\dot{V}_2|^2}{\partial e_2} & \frac{\partial|\dot{V}_2|^2}{\partial f_2} & \frac{\partial|\dot{V}_2|^2}{\partial e_3} & \frac{\partial|\dot{V}_2|^2}{\partial f_3} \\ \frac{\partial P_3}{\partial e_2} & \frac{\partial P_3}{\partial f_2} & \frac{\partial P_3}{\partial e_3} & \frac{\partial P_3}{\partial f_3} \\ \frac{\partial Q_3}{\partial e_2} & \frac{\partial Q_3}{\partial f_2} & \frac{\partial Q_3}{\partial e_3} & \frac{\partial Q_3}{\partial f_3} \end{bmatrix} \begin{bmatrix} \varepsilon_1^{(i)} \\ \varepsilon_2^{(i)} \\ \varepsilon_3^{(i)} \\ \varepsilon_4^{(i)} \end{bmatrix}$$

eq.(2)

$$\begin{bmatrix} e_2^{(i+1)} \\ f_2^{(i+1)} \\ e_3^{(i+1)} \\ f_3^{(i+1)} \end{bmatrix} = \begin{bmatrix} e_2^{(i)} \\ f_2^{(i)} \\ e_3^{(i)} \\ f_3^{(i)} \end{bmatrix} + \begin{bmatrix} \varepsilon_1^{(i)} \\ \varepsilon_2^{(i)} \\ \varepsilon_3^{(i)} \\ \varepsilon_4^{(i)} \end{bmatrix}$$

Newton Raphson Method

- For computer solution
- This method is used in Microgrid/VPP Designer.
- This method can get solution, even if load flow is heavy and difficult to get solution by another methods.

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

3. DC Flow Method

- Simplified Load Flow Calculation of Transmission Line
- Set all node voltage to 1.0
- Set all resistance of transmission line to 0.0
- Solve relationship equation below between power and voltage angle for each node

$$P_r = \frac{\delta}{X}$$

δ : Phase Difference of voltages between both side of a transmission line
X : Transmission line inductance
Pr : Active power that flows in a transmission line

DC Flow Method

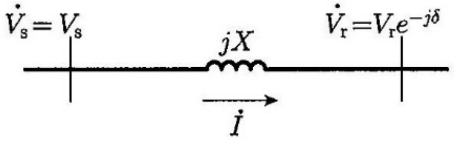
Manual method to calculate power flow.
Easy to calculate in manual.

δ : Phase Difference of voltages Vs, Vr between both side of a transmission line
X : Transmission line inductance
Pr, Qr : Active power that flows through a transmission line

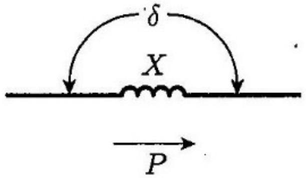
$$P_r + jQ_r = V_r e^{-j\delta} \dot{I}^*$$
$$= V_r e^{-j\delta}\left(\frac{V_s - V_r e^{-j\delta}}{jX}\right)^*$$
$$= \frac{V_s V_r e^{-j\delta} - V_r^2}{-jX}$$
$$= \frac{V_s V_r}{X}\sin\delta + j\frac{V_s V_r \cos\delta - V_r^2}{X}$$

$$P_r = \frac{V_s V_r}{X}\sin\delta$$

$$P_r = \frac{\delta}{X}$$

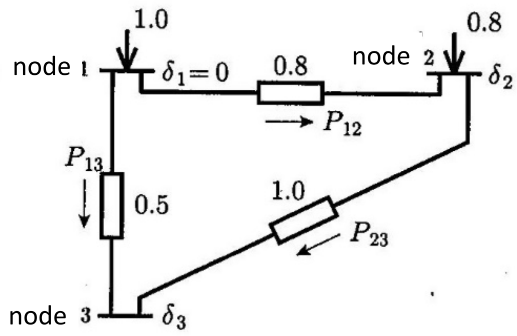


Simplified and Similar to DC circuit solution



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

DC Flow Method
(Example of 3 nodes network)



Power equation of each node is as follows:

$$1.0 = \frac{0-\delta_2}{0.8} + \frac{0-\delta_3}{0.5}$$

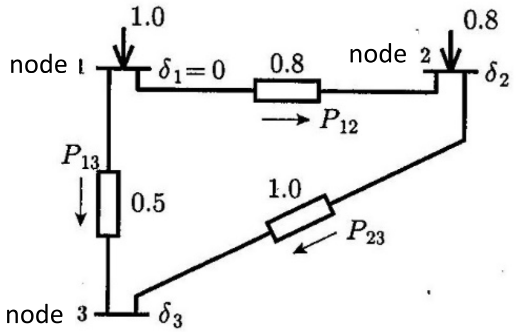
$$0.8 = \frac{\delta_2 - 0}{0.8} + \frac{\delta_2 - \delta_3}{1.0}$$

$$\delta_2 = 0.104$$

$$\delta_3 = -0.565$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

DC Flow Method
(Example of 3 nodes network)



Solution of voltage angle

$$\delta_2 = 0.104$$

$$\delta_3 = -0.565$$

Power flow of transmission line is as follows:

$$P_{12} = \frac{0 - 0.104}{0.8} = -0.130$$

$$P_{13} = \frac{0 - 0.565}{0.5} = 1.13$$

$$P_{23} = \frac{0.104 + 0.565}{1.0} = 0.669$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

4. Exercise of DC Flow method

1. Please make a node admittance matrix of the following grid.
2. Please make a power equation of each node in the following grid.

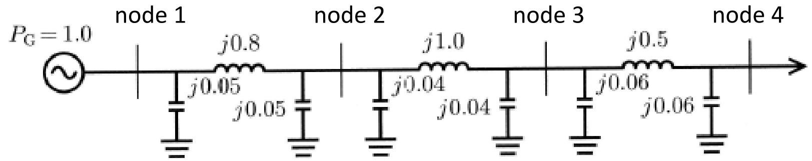
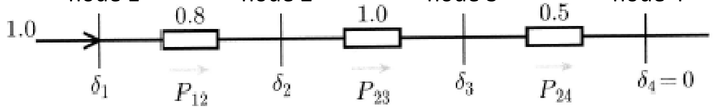


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

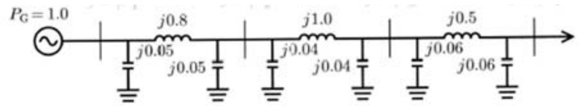
Exercise of DC Flow method

3. Please solve load flow of the following grid using DC Flow Method.



Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Exercise 1 Answer



$$\dot{Y}_{11} = j0.05 + \frac{1}{j0.8} = -j1.20$$

$$\dot{Y}_{22} = j0.05 + j0.04 + \frac{1}{j0.8} + \frac{1}{j1.0} = -j2.16$$

$$\dot{Y}_{33} = j0.04 + j0.06 + \frac{1}{j1.0} + \frac{1}{j0.5} = -j2.90$$

$$\dot{Y}_{44} = j0.06 + \frac{1}{j0.5} = -j1.94$$

1/j0.8=j/(j*j*0.8)=-j/0.8=-j1.25

$$\dot{Y}_{12} = \dot{Y}_{21} = -\frac{1}{j0.8} = j1.25$$

$$\dot{Y}_{23} = \dot{Y}_{32} = -\frac{1}{j1.0} = j1.0$$

$$\dot{Y}_{34} = \dot{Y}_{43} = -\frac{1}{j0.5} = j2.0$$

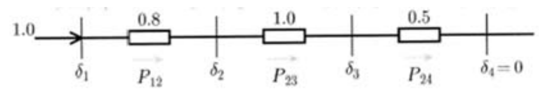
$$\boldsymbol{Y} = \begin{bmatrix} -j1.20 & j1.25 & 0 & 0 \\ j1.25 & -j2.16 & j1.0 & 0 \\ 0 & j1.0 & -j2.90 & j2.0 \\ 0 & 0 & j2.0 & -j1.94 \end{bmatrix}$$

Exercise 2 Answer

$$P_{1s} = \mathrm{Re}\{(-j1.20)^*(e_1 + jf_1)^*(e_1 + jf_1) + (j1.25)^*(e_2 + jf_2)^*(e_1 + jf_1)\}$$
$$= -1.25e_1 f_2 + 1.25 e_2 f_1$$
$$V_{1s}^2 = e_1^2 + f_1^2$$
$$P_{2s} = \mathrm{Re}\{(j1.25)^*(e_1 + jf_1)^*(e_2 + jf_2) + (-j2.16)^*(e_2 + jf_2)^*(e_2 + jf_2) + (j1.0)^*(e_3 + jf_3)^*(e_2 + jf_2)\}$$
$$= -1.25e_2 f_1 + 1.25 e_1 f_2 - e_2 f_3 + e_3 f_2$$
$$Q_{2s} = \mathrm{Im}\{(j1.25)^*(e_1 + jf_1)^*(e_2 + jf_2) + (-j2.16)^*(e_2 + jf_2)^*(e_2 + jf_2) + (j1.0)^*(e_3 + jf_3)^*(e_2 + jf_2)\}$$
$$= -1.25e_1 e_2 - 1.25 f_1 f_2 + 2.16 e_2^2 + 2.16 f_2^2 - e_2 e_3 - f_2 f_3$$
$$P_{3s} = \mathrm{Re}\{(j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) + (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3) + (j2.0)^*(e_4 + jf_4)^*(e_3 + jf_3)\}$$
$$= -e_3 f_2 + e_2 f_3 - 2.0 e_3 f_4 + 2.0 e_4 f_3$$
$$Q_{3s} = \mathrm{Im}\{(j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) + (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3) + (j2.0)^*(e_4 + jf_4)^*(e_3 + jf_3)\}$$
$$= -e_2 e_3 - f_2 f_3 + 2.9 e_3^2 + 2.9 f_3^2 - 2.0 e_3 e_4 - 2.0 f_3 f_4$$

$$e_4 = V_{4s}, \quad f_4 = 0$$

Exercise 3 Answer



$$1.0 = \frac{\delta_1 - \delta_2}{0.8}$$

$$0 = \frac{\delta_2 - \delta_1}{0.8} + \frac{\delta_2 - \delta_3}{1.0}$$

$$0 = \frac{\delta_3 - \delta_2}{1.0} + \frac{\delta_3 - 0}{0.5}$$

$$\delta_1 = 2.3, \quad \delta_2 = 1.5, \quad \delta_3 = 0.5$$

$$P_{12} = 1.0, \quad P_{23} = 1.0, \quad P_{34} = 1.0$$

5. Practice on Microgrid/VPP Designer

- Newton-Raphson Method is used for load flow analysis in Microgrid/VPP Designer.

1. Copy an excel file for load flow analysis.
2. Fill node and branch data in the second and third sheets in an excel file.
3. Push a calculation button in the first sheet of the excel file.
4. The result is in the forth and fifth sheet in the excel file.

Starting Window of Load Flow

Power Flow Calculation

Step

Set node data and branch data

Click "Calculation" button

Node max 200, Branch max 400

Jump to NodeData input sheet

Specification

Maximum iteration	20
Convergence criterion (pu)	0.0001
Acceleration factor	1

Jump to BranchData input sheet

Calculation

Explanation

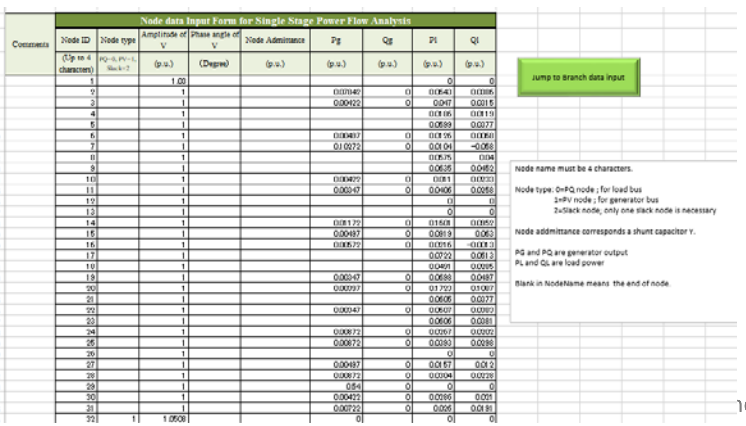
1) Capacity base is not shown here, it is assumed by user.
2) Newton-Raphson method is applied as the solver.
3) Convergence criterion is applied to the amplitude of node voltage.
4) Line addmittance is Y/2 in branch data, not Y.
5) Maximum branch number connected a node must be less than 39.

Node Data

V: Voltage of Node
Pg: Active Power of Generator, Qg: Reactive Power of Generator
Pl: Active Power of Load, Ql: reactive Power of Load

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.)

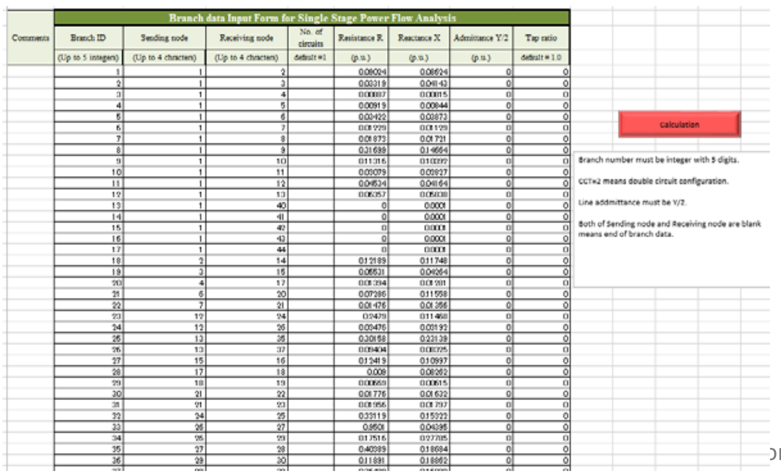


Branch Data

R: Resistance of Line, X: Reactance of Line
Y/2: Half of Admittance of Line
Tap ratio: Tap ratio, if line has a transformer

Branch data Input Form for Single Stage Power Flow Analysis

Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0

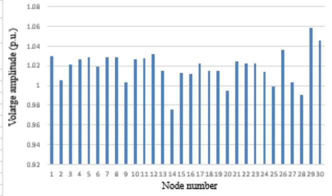


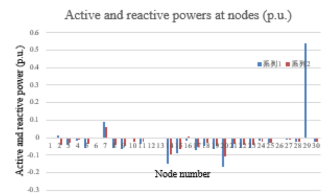
Calculation Results of Node

Specified value is initial value. Obtained value means value after calculation.

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)
1	0	1.03	1.02997	0	0	0	−0.00002	−0.00181	0.00175	90.53
2	0	1	1.00576	0.03	0.0141	−0.0386	0.0141	−0.0386	0.04086	69.96
3	0	1	1.02141	−0.16	−0.0428	−0.0315	−0.0428	−0.0315	0.05203	143.49
4	0	1	1.02704	−0.02	−0.0186	−0.0119	−0.0186	−0.01191	0.0215	147.35
5	0	1	1.02913	−0.01	−0.0599	−0.0377	−0.0599	−0.0377	0.06877	147.8
6	0	1	1.0194	−0.15	−0.0076	−0.0068	−0.0076	−0.0068	0.01	138.03
7	0	1	1.02831	−0.02	0.0923	0.058	0.0923	0.05801	0.10601	−32.16
8	0	1	1.02826	−0.01	−0.0575	−0.04	−0.0575	−0.04	0.06812	145.16
9	0	1	1.00329	0.28	−0.0635	−0.0452	−0.0635	−0.0452	0.07769	144.83
10	0	1	1.02686	0.1	−0.0068	−0.0233	−0.0068	−0.0233	0.02364	106.37
11	0	1	1.02815	−0.01	−0.0371	−0.0258	−0.0371	−0.0258	0.04395	145.17
12	0	1	1.03142	1.83	0	0	0	0	0	176.87
13	0	1	1.01492	0.12	0	0	0	0	0	149.38
14	0	1	0.97575	−0.31	−0.1484	−0.0952	−0.1484	−0.0952	0.18069	147.01
15	0	1	1.01319	−0.21	−0.0869	−0.063	−0.0869	−0.063	0.10594	143.84
16	0	1	1.01138	−0.32	−0.0159	0.0013	−0.0159	0.0013	0.01577	−175.65
17	0	1	1.02284	−0.05	−0.0722	−0.0513	−0.0722	−0.0513	0.08659	144.55
18	0	1	1.01542	−0.54	−0.0491	−0.0285	−0.04911	−0.0285	0.05592	149.33
19	0	1	1.01468	−0.55	−0.0663	−0.0497	−0.06629	−0.04969	0.08165	142.6
20	0	1	0.99437	−0.81	−0.1683	−0.1087	−0.1683	−0.1087	0.20149	146.34
21	0	1	1.02423	−0.06	−0.0605	−0.0377	−0.06049	−0.0377	0.06959	148.01
22	0	1	1.02262	−0.07	−0.0572	−0.0383	−0.0572	−0.0383	0.06732	146.13
23	0	1	1.0224	−0.07	−0.0606	−0.0381	−0.0606	−0.0381	0.07002	147.77
24	0	1	1.01367	2.2	−0.018	−0.0202	−0.018	−0.0202	0.02669	133.91
25	0	1	0.99894	2.49	−0.0306	−0.0298	−0.0306	−0.0298	0.04276	138.25
26	0	1	1.0365	3.21	0	0	0	0	0	−43.03
27	0	1	1.00342	4.96	−0.0107	−0.012	−0.0107	−0.012	0.01602	136.69
28	0	1	0.99025	5.26	−0.0217	−0.0228	−0.0217	−0.0228	0.03179	138.84
29	0	1	1.05802	13.04	0.54	0	0.53999	0	0.51038	13.04
30	0	1	1.04584	12.86	−0.0244	−0.021	−0.0244	−0.021	0.03078	152.14
31	0	1	1.03906	13	−0.0188	−0.0191	−0.0188	−0.0191	0.02579	147.55
32	1	1.0508	1.05081	16.53	0	0	0.00003	−0.11399	0.10847	106.51
33	0	1	1.05793	17.25	−0.0228	−0.0215	−0.0228	−0.0215	0.02962	153.94
34	0	1	1.08536	18.47	0.0846	−0.0215	0.0846	−0.0215	0.08042	32.73
35	0	1	0.98754	0.56	−0.011	−0.0182	−0.011	−0.0182	0.02153	121.71
36	0	1	0.96089	1.37	−0.0314	−0.0407	−0.0314	−0.0407	0.0535	129.02
37	0	1	1.0023	0.21	0	0	0	0	0	−29.21
38	0	1	0.98932	0.54	−0.0178	−0.0208	−0.0178	−0.0208	0.02767	131.1
39	0	1	0.96146	1.29	−0.0458	−0.054	−0.0458	−0.054	0.07365	131.59
40	1	1.03	1.03	0	0.3678	0	0.3678	0.28148	0.44966	−37.43
41	2	1.03	1.03	0	0	0	0.0823	0.28147	0.28472	−73.7
42	1	1.03	1.03	0	0.2727	0	0.2727	0.28148	0.3805	−45.91
43	0	1.03	1.03	0	0	0.3	0	0.29958	0.29085	−90
44	0	1.03	1.02998	0	0	0.12	0	0.12053	0.11703	−90

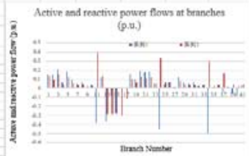


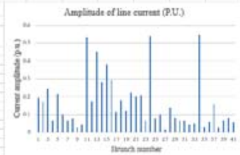


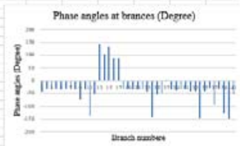
Calculation Results of Branch

Output Form of Obtained Results for Buses by Singel Stage Power Flow Anlysis

Branch ID	Connected nodes		Power flow from node-M		Power flow from node-N		Line current		Tap
(Number)	M	N	P (p.u.)	Q(pu)	P(pu)	Q(pu)	I (pu)	Phase angel (Degree)	
1	1	2	0.14166	0.14058	−0.13826	−0.15764	0.19396	−44.04	
2	1	3	0.14737	0.08902	−0.14641	−0.08382	0.17025	−32.81	
3	1	4	0.20788	0.14413	−0.20712	−0.14358	0.24941	−34.78	
4	1	5	0.05906	0.03774	−0.0599	−0.0377	0.06877	−32.2	
5	1	6	0.18035	0.12192	−0.17868	−0.12019	0.21139	−34.08	
6	1	7	0.08893	0.05998	−0.08861	−0.05954	0.10091	−33.23	
7	1	8	0.03739	0.04006	−0.0373	−0.04	0.05812	−34.64	
8	1	9	0.06541	0.04609	−0.0635	−0.0452	0.07769	−35.17	
9	1	10	0.00685	0.02336	−0.0068	−0.0233	0.02364	−73.63	
10	1	11	0.03718	0.02583	−0.0371	−0.0258	0.04395	−34.83	
11	1	12	−0.28382	0.30498	0.29888	−0.28305	0.32457	−134.17	
12	1	13	0.11543	0.13989	−0.11348	−0.13606	0.17809	−50.47	
13	1	40	−0.3676	−0.26117	0.3676	0.26119	0.44949	142.8	
14	1	41	−0.0823	−0.26117	0.0823	0.26118	0.28444	106.32	
15	1	42	−0.2727	−0.26117	0.2727	0.26118	0.38029	134.12	
16	1	43	0	−0.29938	0	0.2996	0.29087	90	
17	1	44	0	−0.12033	0	0.12033	0.11683	90	
18	2	14	0.15298	0.09904	−0.1484	−0.0952	0.18089	−32.99	
19	3	15	0.10381	0.06232	−0.10263	−0.06173	0.11837	−31.19	
20	4	17	0.16852	0.13173	−0.16762	−0.13109	0.22393	−34.97	
21	6	20	0.17126	0.11336	−0.1683	−0.1087	0.20149	−33.66	
22	7	21	0.17811	0.11405	−0.17840	−0.11427	0.20881	−32.66	
23	12	24	0.0806	0.09083	−0.08021	−0.09028	0.0804	−43.42	
24	12	25	−0.44898	0.33222	0.45711	−0.32291	0.52898	−151.88	
25	13	35	0.04888	0.06087	−0.04368	−0.06057	0.07401	−53.06	
26	13	37	0.08792	0.07721	−0.08893	−0.07833	0.10132	−46.34	
27	13	16	0.01593	−0.00127	−0.0139	0.0013	0.01577	4.39	
28	17	18	0.11562	0.07979	−0.11545	−0.07823	0.13734	−34.66	
29	18	19	0.06656	0.04974	−0.0663	−0.04959	0.08165	−37.4	
30	21	22	0.05726	0.03835	−0.0572	−0.0383	0.06732	−33.67	
31	21	23	0.0607	0.03819	−0.0606	−0.0381	0.07002	−32.23	
32	24	25	0.03121	0.03006	−0.0306	−0.0298	0.04276	−41.73	
33	26	27	0.03496	0.03909	−0.03261	−0.03499	0.0476	−41.88	
34	26	29	−0.49209	0.26782	0.54507	−0.20377	0.55	−148.47	
35	27	28	0.02211	0.02298	−0.0217	−0.0228	0.03179	−41.16	
36	29	30	0.04379	0.04078	−0.04337	−0.04018	0.05883	−29.09	
37	29	32	−0.04883	0.16299	0.05627	−0.15883	0.19082	−93.84	
38	30	31	0.01607	0.01918	−0.0166	−0.0191	0.02570	−32.43	
39	32	33	−0.03624	0.04484	0.0392	−0.0442	0.05963	−129	
40	33	34	−0.08199	0.0227	0.0848	−0.0215	0.08042	−147.27	
41	35	36	0.03265	0.04137	−0.0314	−0.0407	0.0535	−50.95	
42	37	38	0.05695	0.07635	−0.05565	−0.07525	0.10132	−48.54	
43	38	39	0.04763	0.05495	−0.0458	−0.054	0.07388	−55.41	







6. Load Flow Analysis and Evaluation

- DC Flow Method
  - Prepare data
  - Make active power equations
  - Solve voltage angle δ by DC Flow Method
  - Calculate active power flow of transmission lines
- Microgrid/VPP Designer
  - Prepare data
  - Input node and branch data
  - Solve load flow by Newton-Raphson Method

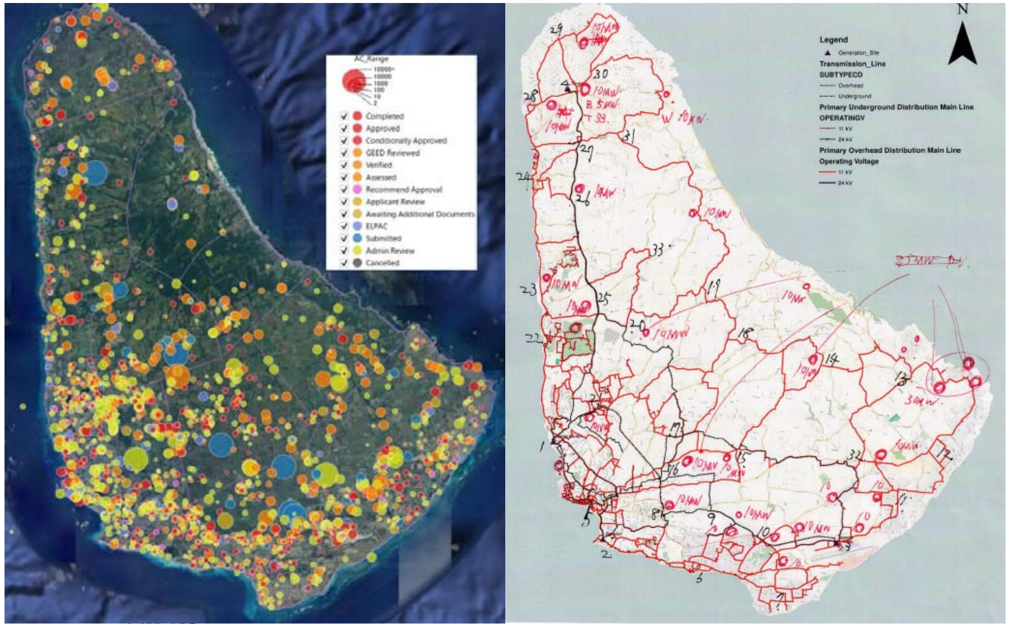
Seminar on Grid Stability with Large RE Day 2 (Exercise)

for Barbados

JICA Expert Team, Nippon Koei Co., Ltd.

Barbados PV Location

Set 1MW PV at node close to red circle points in the right figure



Load Flow Analysis Da… with PV in Barbados

Total capacity is set to 25MW.

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load		
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	PV	WP
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)
1	2	1.05			1.66	0	0	0			
2	1	1.05			0.13	0	0.1	0	0.1		
3	1	1.05			0.53	0	0.09	0	0.1	0.01	
4	1	1.05			0.33	0	0.09	0	0.1	0.01	
5	0	1			0	0	0.8	0	0.8		
6	0	1			0	0	0.2	0	0.2		
7	0	1			0	0	0.19	0	0.2	0.01	
8	0	1			0	0	0.04	0	0.05	0.01	
9	0	1			0	0	−0.01	0	0	0.01	
10	0	1			0	0	0.18	0	0.2	0.02	
11	0	1			0	0	0.14	0	0.15	0.01	
12	0	1			0	0	0.02	0	0.05	0.03	
13	0	1			0	0	0	0	0		
14	0	1			0	0	0.04	0	0.05	0.01	
15	0	1			0	0	−0.01	0	0	0.01	
16	0	1			0	0	0.04	0	0.05	0.01	
17	0	1			0	0	0.05	0	0.05		
18	0	1			0	0	0	0	0		
19	0	1			0	0	0.04	0	0.05	0.01	
20	0	1			0	0	0	0	0		
21	0	1			0	0	0.19	0	0.2	0.01	
22	0	1			0	0	0.19	0	0.2	0.01	
23	0	1			0	0	0.1	0	0.1		
24	0	1			0	0	0.09	0	0.1	0.01	
25	0	1			0	0	−0.01	0	0	0.01	
26	0	1			0	0	−0.01	0	0	0.01	
27	0	1			0	0	0.05	0	0.05		
28	0	1			0	0	0.09	0	0.1	0.01	
29	0	1			0	0	0.04	0	0.05	0.01	
30	0	1			0	0	0	0	0		
31	0	1			0	0	−0.01	0	0	0.01	
32	0	1			0	0	−0.02	0	0	0.02	
33	0	1			0	0	0	0	0		

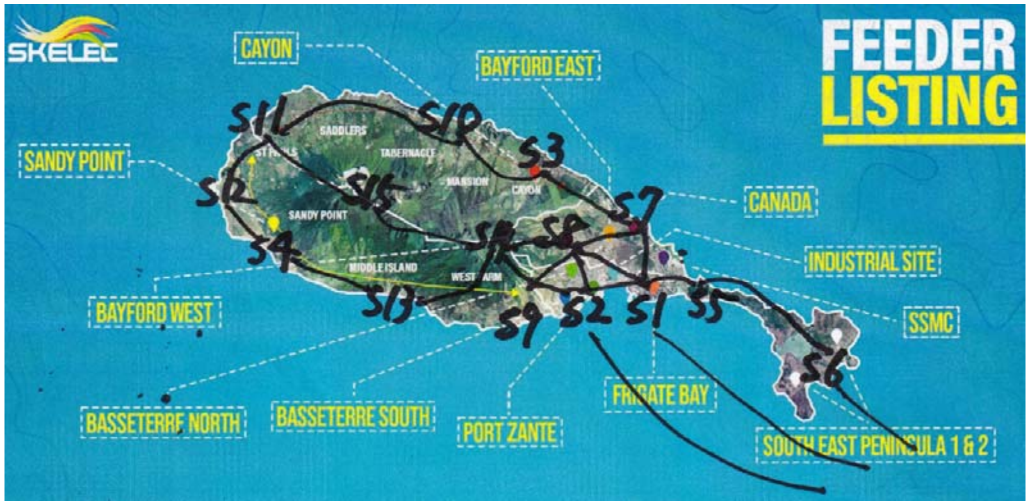
Seminar on Grid Stability with Large RE Day 2 (Exercise)

for Saint Kitts and Nevis

JICA Expert Team, Nippon Koei Co., Ltd.

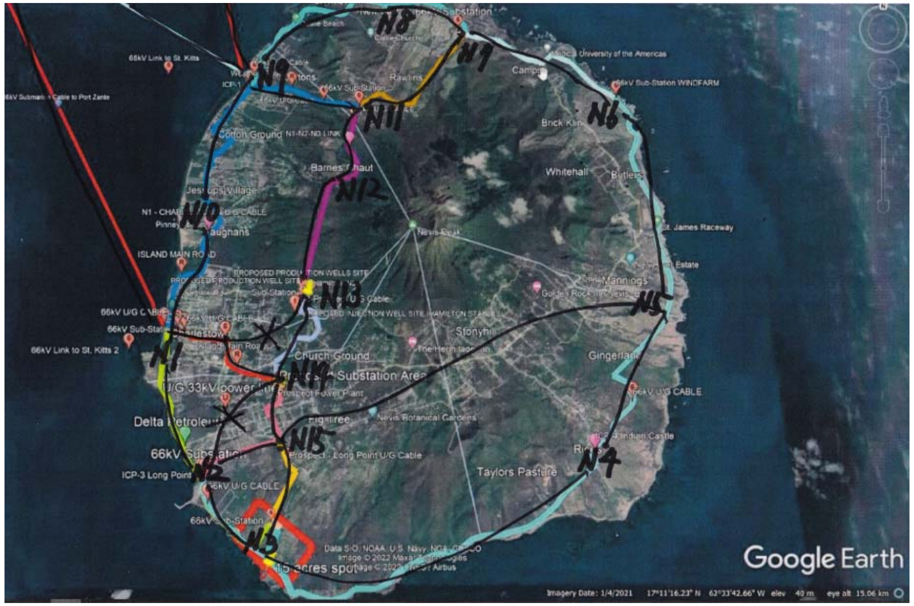
Saint Kitts Assumed Grid

15 nodes



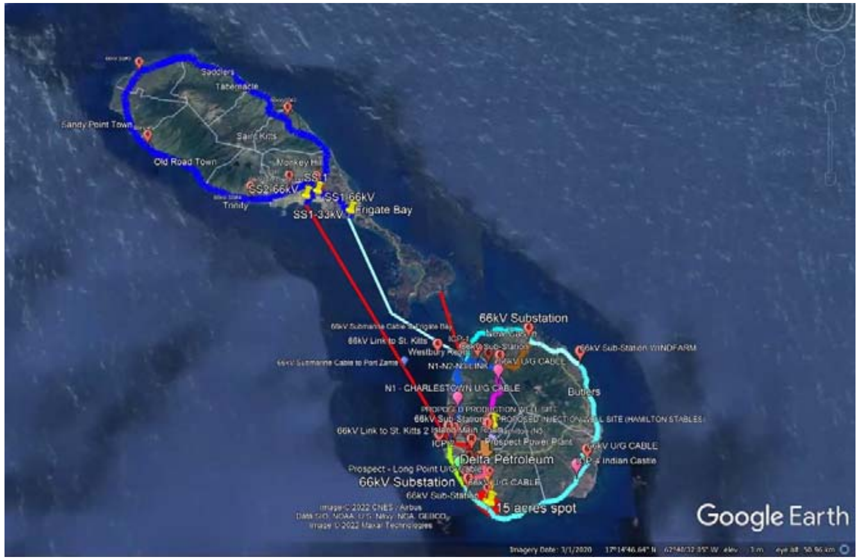
Nevis Assumed Grid

15 nodes



Saint Kitts and Nevis Assumed Grid

30 nodes



Load Flow Data for Saint Kitts and Nevis

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.)
S1	2	1.03			0.3	0	0	0
S2	1	1.03			0.2	0	0	0
S3	1	1.05			0.5	0	0	0
S4	1	1.05			0.1	0	0	0
S5	0	1			0	0	0	0
S6	0	1			0	0	0.1	0
S7	0	1			0	0	0.2	0
S8	0	1			0	0	0.2	0
S9	0	1			0	0	0.2	0
S10	0	1			0	0	0.2	0
S11	0	1			0	0	0.05	0
S12	0	1			0	0	0.05	0
S13	0	1			0	0	0.05	0
S14	0	1			0	0	0.1	0
S15	0	1			0	0	0	0
N1	1	1.05			0.2	0	0.2	0
N2	1	1.05			0.2	0	0.1	0
N3	1	1.05			0.1	0		0
N4	0	1			0	0	0.05	0
N5	1	1.05			0.1	0		0
N6	0	1			0	0	0.1	0
N7	0	1			0	0	0.1	0
N8	0	1			0	0	0.05	0
N9	0	1			0	0	0.1	0
N10	0	1			0	0	0.1	0
N11	0	1			0	0	0.05	0
N12	1	1.05			0.3	0	0	0
N13	0	1			0	0	0	0
N14	0	1			0	0	0	0
N15	0	1			0	0	0	0

Branch data Input Form for Single Stage Power Flow Analysis

Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	S1	S5	1	0.2	0.2	0.01	0
2	S5	S6	1	0.5	0.5	0.01	0
3	S1	S7	1	0.9	1.8	0.01	0
4	S7	S3	1	0.14	0.27	0.02	0
5	S3	S10	1	0.14	0.27	0.02	0
6	S10	S11	1	0.22	0.44	0.02	0
7	S11	S12	1	0.09	0.18	0.01	0
8	S12	S4	1	0.14	0.27	0.02	0
9	S4	S13	1	0.18	0.36	0.02	0
10	S13	S14	1	0.18	0.36	0.02	0
11	S14	S9	1	0.09	0.18	0.01	0
12	S2	S1	1	0.09	0.18	0.01	0
13	S1	S8	1	0.3	0.3	0.01	0
14	S8	S7	1	0.3	0.3	0.01	0
15	S8	S9	1	0.2	0.2	0.01	0
16	S8	S14	1	0.14	0.27	0.02	0
17	S14	S15	1	0.4	0.4	0.01	0
18	S15	S11	1	0.4	0.4	0.01	0
19	S2	S8	1	0.2	0.2	0.01	0
20	S9	S2	1	0.2	0.2	0.01	0
21	N1	N2	1	0.14	0.27	0.02	0
22	N2	N3	1	0.09	0.18	0.01	0
23	N3	N4	1	0.31	0.62	0.02	0
24	N4	N5	1	0.22	0.44	0.02	0
25	N5	N6	1	0.22	0.44	0.02	0
26	N6	N7	1	0.18	0.36	0.02	0
27	N7	N8	1	0.09	0.18	0.01	0
28	N8	N9	1	0.14	0.27	0.02	0
29	N9	N10	1	0.14	0.27	0.02	0
30	N10	N1	1	0.14	0.27	0.02	0
31	N7	N11	1	0.14	0.27	0.02	0
32	N11	N9	1	0.09	0.18	0.01	0
33	N11	N12	1	0.09	0.18	0.01	0
34	N12	N13	1	0.14	0.27	0.02	0
35	N14	N1	1	0.14	0.27	0.02	0
36	N13	N14	1	0.09	0.18	0.01	0
37	N14	N15	1	0.09	0.18	0.01	0
38	N15	N2	1	0.09	0.18	0.01	0
39	N15	N3	1	0.09	0.18	0.01	0
40	N15	N5	1	0.7	0.7	0.01	0
41	S6	N9	1	1	1	0.01	0
42	S1	N9	1	0.44	0.88	0.04	0
43	S2	N1	1	0.44	0.88	0.04	0

Load Flow Analysis Result in Saint Kitts and Nevis

R,X,Y Line Model

Node ID	Node type	Specified voltage	Obtaiened value	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)
S1	2	1.03	1.03	0
S2	1	1.03	1.03	−0.98
S3	1	1.05	1.05	2.48
S4	1	1.05	1.05	−3.43
S5	0	1	1.02586	−1.27
S6	0	1	1.00698	−3.94
S7	0	1	1.02789	−1.55
S8	0	1	1.01492	−2.95
S9	0	1	1.0106	−3.73
S10	0	1	1.04128	−1.49
S11	0	1	1.04735	−3.98
S12	0	1	1.04912	−4.13
S13	0	1	1.03907	−4.52
S14	0	1	1.02205	−4.25
S15	0	1	1.03884	−4.34
N1	1	1.05	1.05	0.11
N2	1	1.05	1.05	1.83
N3	1	1.05	1.05	2.03
N4	0	1	1.0545	0.09
N5	1	1.05	1.05	0.36
N6	0	1	1.04857	−2.82
N7	0	1	1.0508	−3.13
N8	0	1	1.05157	−3.31
N9	0	1	1.05087	−2.63
N10	0	1	1.04901	−2.12
N11	0	1	1.05103	−1.31
N12	1	1.05	1.05	1.89
N13	0	1	1.05806	1.24
N14	0	1	1.05785	0.96
N15	0	1	1.0552	1.46

R,X Line Model

Node ID	Node type	Specified voltage	Obtaiened value	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)
S1	2	1.03	1.03	0
S2	1	1.03	1.03	−0.94
S3	1	1.05	1.05	2.87
S4	1	1.05	1.05	−3.12
S5	0	1	1.01622	−0.82
S6	0	1	0.98273	−2.98
S7	0	1	1.01755	−0.95
S8	0	1	1.00365	−2.32
S9	0	1	0.99798	−3.04
S10	0	1	1.02576	−0.69
S11	0	1	1.0244	−3.02
S12	0	1	1.03193	−3.34
S13	0	1	1.02178	−3.75
S14	0	1	1.00245	−3.4
S15	0	1	1.01342	−3.2
N1	1	1.05	1.05	0.35
N2	1	1.05	1.05	2.1
N3	1	1.05	1.05	2.31
N4	0	1	1.04365	0.63
N5	1	1.05	1.05	0.6
N6	0	1	1.02095	−1.88
N7	0	1	1.01562	−1.99
N8	0	1	1.01431	−2.11
N9	0	1	1.01925	−1.55
N10	0	1	1.02759	−1.31
N11	0	1	1.02777	−0.4
N12	1	1.05	1.05	2.23
N13	0	1	1.05006	1.76
N14	0	1	1.05022	1.45
N15	0	1	1.0505	1.87

X Line Model

Node ID	Node type	Specified voltage	Obtaiened value	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)
S1	2	1.03	1.03	0
S2	1	1.03	1.03	−0.48
S3	1	1.05	1.05001	3.34
S4	1	1.05	1.05	−1.2
S5	0	1	1.0312	−0.74
S6	0	1	1.03492	−2.57
S7	0	1	1.03999	−0.51
S8	0	1	1.0334	−1.75
S9	0	1	1.03322	−2.3
S10	0	1	1.04714	0.12
S11	0	1	1.04568	−1.68
S12	0	1	1.04739	−1.77
S13	0	1	1.04314	−2.31
S14	0	1	1.03648	−2.49
S15	0	1	1.04105	−2.08
N1	1	1.05	1.05	1.26
N2	1	1.05	1.05001	2.67
N3	1	1.05	1.05001	2.85
N4	0	1	1.04988	1.49
N5	1	1.05	1.05	1.68
N6	0	1	1.04713	−0.94
N7	0	1	1.04569	−1.21
N8	0	1	1.04494	−1.36
N9	0	1	1.04387	−0.89
N10	0	1	1.04667	−0.52
N11	0	1	1.04607	0.24
N12	1	1.05	1.05001	2.8
N13	0	1	1.04994	2.41
N14	0	1	1.04992	2.15
N15	0	1	1.04996	2.49

Transmission Line in Saint Kitts and Nevis

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current, Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

- Vbase=11.4kV or 66.0kV
- (VA)base=100MVA
- Ibase=(VA)base/Vbase=8.8kA or 1.5kA
- Zbase=Vbase^2/(VA)base=1.30Ω or 43.6Ω
  - R=0.15Ω/km, X=0.15Ω/km or R=0.04Ω/km, X=0.08Ω/km
  - Length =5km, 3km, 2km, 1km
  - Rpu=0.15x5/1.3=0.58, 0.35, 0.23, 0.11 → 2line circuit:0.29, 0.18, 0.12, 0.06
  - Xpu=0.15x5/1.3=0.58, 0.35, 0.23, 0.11 → 2line circuit:0.29, 0.18, 0.12, 0.06
  - Rpu=0.04x5/43.6=0.005, 0.0026, 0.002 → 2line circuit:0.0025, 0.0013, 0.001
  - Xpu=0.08x5/43.6=0.009, 0.0052, 0.004 → 2line circuit:0.0045, 0.0026, 0.002
- Resistance value (Rpu)
  - In high voltage transmission line Rpu can be ignored into 0.0.
  - In low voltage transmission line value of Rpu is similar to Xpu.
  - Rpu of 11.4kV line is set to the same value of Xpu.
  - Rpu of 66.0kV line is set to half value of Xpu.

Seminar on Grid Stability with Large RE
Day 3
Why Grid Stability?

JICA Expert Team, Nippon Koei Co., Ltd.

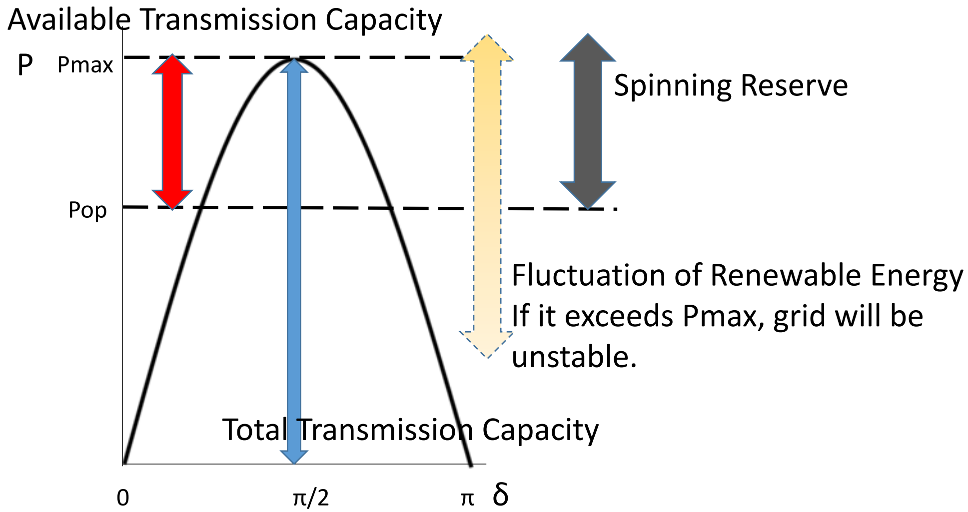
Role of Us: Power System Engineer

- Supply electricity to all the customers in stable
  - Continuously
  - With no or few failures
  - Minimize the influence of disturbance after faults
- Keep the quality of electricity
  - Constant voltage
  - Constant frequency
  - Less distortion or harmonics

Why Grid Stability?

- Steady state
  - Can large amount of RE be installed in the present/planned power system ?
  - Load flow analysis:
    - If we reach at the normal power flow state, there exists actually.
    - From load flow results, adequacy of power flow of transmission line can be assessed. It is evaluated with the maximum capacity of transmission line.
- Transient state
  - Power system with large amount of RE is stable or not?
  - Equal Area Criterion:
    - Power system stability under disturbance can be calculated by using acceleration and deceleration energy.
    - Available Transmission Capacity and Spinning Reserve can be calculated.

Grid Stability Evaluation



How to Make a Model of Renewable Energy Generator

- Photovoltaic Generator & Wind Turbine Generator
  - Negative load model
  - Maximum Power Point Control
  - Follow the Voltage of Grid
  - Constant Power Factor -> Constant Power or Current
  - -> similar mode of Load

- Diesel Generator & Biofuel Generator
  - Synchronous Generator model
  - Automatic Voltage Regulator -> Constant Voltage
  - Power System Stabilizer -> Control Active Power
  - Governor & Turbine -> Control Frequency
  - -> similar model of synchronous generator

Spinning Reserve

- In order to get electrical power under abnormal condition of grid, spinning reserve should be kept even if RE is installed. (under development)
- Spinning reserve should be more than mixed fluctuation of load and renewable energy.

  -> RE, EV and Battery with inertia is required for large RE penetration.
- Best Energy Mix

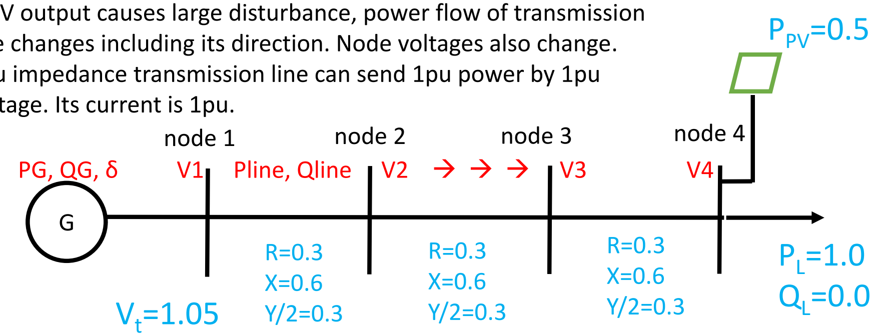
  -> Energy mix of several resources will be helpful for improving grid stability.
- RE Sources for Spinning Reserve: EV, Battery, Biofuel or Diesel Generator, etc.

Evaluation of RE Installation

- To know whether we can install PV or WT?
- Purpose
  - To know how much we can install PV or WT in a particular power line -> Load Flow Analysis
    - If you reach at the calculation results of V, I, flow of transmission line , actual output of generator from set value of P, Q, V, that case is stable at the specified condition.
    - Load Flow Calculation of maximum minimum RE output
    - If you cannot get the solution, that case cannot be in real.
  - To know whether RE installed grid is stable? -> Search operation point through Equal Area Criterion
  - To know how much we can install RE. -> Estimate ATC(Available Transmission Capacity) by Equal Area Criterion

Power System with Installation of PV

If PV output causes large disturbance, power flow of transmission line changes including its direction. Node voltages also change. 1pu impedance transmission line can send 1pu power by 1pu voltage. Its current is 1pu.



Case1 solution : PV is connected
V1=1.05, V2=0.95, V3=1.08, V4=1.07
P12=1.32, P23=0.84, P34=0.57

V4 is larger than V3, V2, V1.
Power flows from node 1 to node 4.
If the output of PV goes down, generator cannot follow

Case2 solution: no PV
V1=1.05, V2=01.20, V3=1.09, V4=0.71
P12=0.81, P23=0.59, P34=0.37

V4 becomes lower than allowable range of voltage in terms of power quality, (generall, 1.1-0.9 is acceptable, depending on Grid Code)

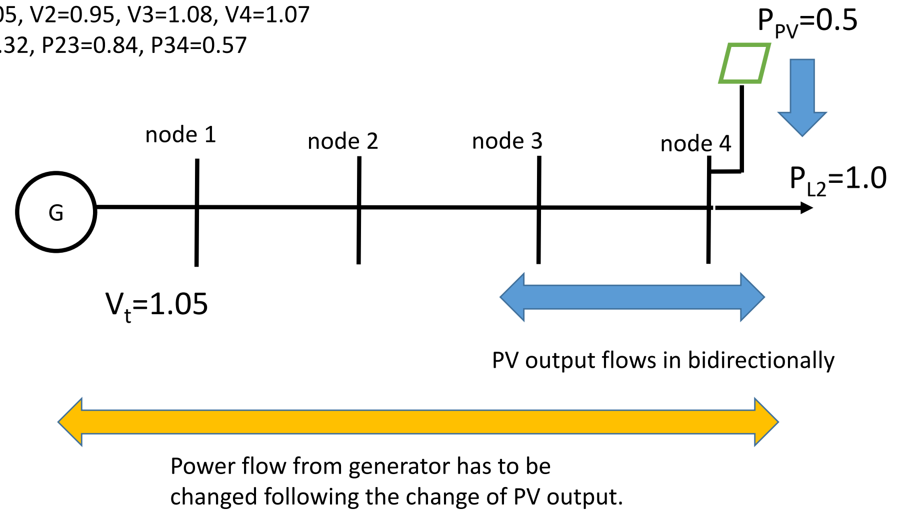
Load Flow Analysis

Buses are categorized to the following 3 types.

- Slack (Swing) Node
  - The magnitude and phase angle of the voltage are specified.
  - Node with constant voltage and large capacity is suitable.
  - This node makes up the difference between the scheduled loads and generated power that are caused by the losses in the network.
- P-V Nodes (Generator Nodes)
  - The active power P and voltage magnitude V are specified.
  - The phase angles of the voltages and the reactive power are to be determined.
- P-Q Nodes (Load Nodes or Substation Nodes)
  - The active and reactive powers P, Q are specified.
  - The magnitude and the phase angle of the bus voltages are unknown.

Transmission Capacity

V1=1.05, V2=0.95, V3=1.08, V4=1.07
P12=1.32, P23=0.84, P34=0.57



The change of PV output is large (from 0 to 100%), and its speed is fast.
It causes unstable oscillation.

Items to be checked for RE

- The amount of PV output should be kept under ATC(Available Transmission Capacity) in transmission line.
- Maximum PV output should be covered by another generators.
- PV fluctuation must be covered by Spinning Reserve, i.e., other thermal or hydro generators
- RE with no control circuit of inertia should be less than 30% from the guideline of SCR(Short Circuit Ratio)

Power Flow Analysis

Set value P & Q → Result V & θ of V
Set value P & V → Result Q & θ of V

For the case set value P & Q :

Data	Input	Output /Result	Evaluation
Generated Power (node)	Generated P (Active Power) and V (voltage). Q (Reactive Power) can be calculated by P and V angle.	V each node	--
Slack node	The main power that can adjust grid (only V is given)	P, Q at slack	--
Load data (node)	P and Q at consumer load **Solar PV data is deducted from Load**	P and Q at consumer load (same as input)	--
Line (Branch)	Resistance R, Reactance X Admittance Y/2 of transmission line spec	I (current) and between nodes & Phase Angle θ against slack generator	--
Voltage (node)	(no data input) For substation, P & Q =0	V (Voltage), phase angle of V at each node	Phase Angle θ of V should be <90º Vpu within grid code range (0.9-1.1)

Seminar on Grid Stability with Large RE Day 3

Analysis of Grid Stability and LFC/ELD

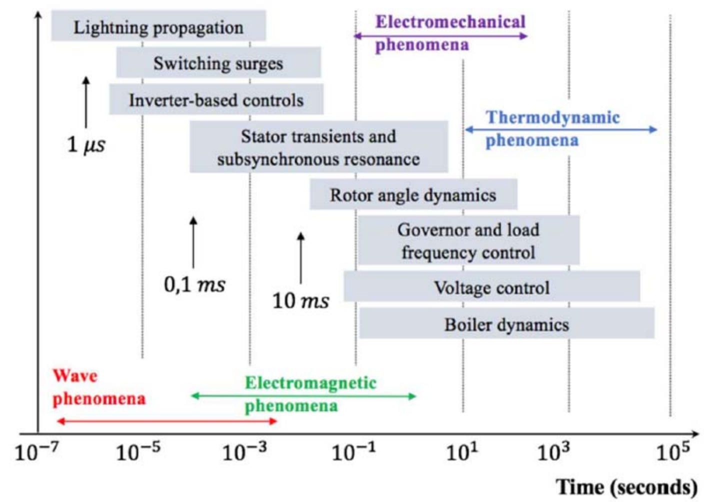
JICA Expert Team, Nippon Koei Co., Ltd.

Contents

1. Overview of Stability

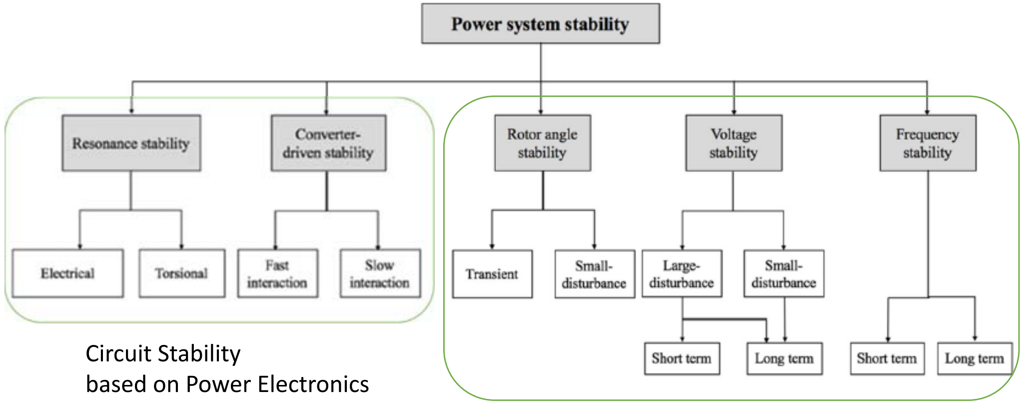
- STABILITY
  - If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.

Time Scale of Power System Dynamic Phenomena



Cited from IEEE Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," IEEE Power & Energy Society Technical Report PES-TR77, Apr., 2020.

Classification of Power System Stability



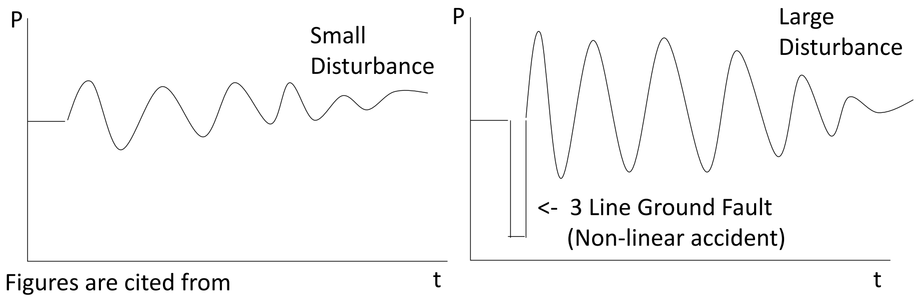
Circuit Stability
based on Power Electronics
Technology

Grid Stability based on Power System
Technology (Subjects in this seminar)

Cited from IEEE Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," IEEE Power & Energy Society Technical Report PES-TR77, Apr., 2020.

Type of Frequency/Voltage S /

- Small Disturbance Stability
  - Disturbance with minor fluctuation of load, generator, and other power system components
  - Linear modelled phenomena
  - ->Eigenvalue Analysis, Equivalent Area Criterion
- Large Disturbance Stability
  - Disturbance with non-linear accidents such as Switching, setting value change, generator trip, sudden load trip, fault in power system components
  - ->Transient Stability Analysis, Equivalent Area Criterion



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Stability Analysis

- Equal Area Criterion (Manual calculation)
  - Simplified Stability Calculation
  - Active Power Flow Dynamics between one Generator and one Load
- Transient Stability Program (Simulation Software)
  - Electro-Mechanical Transient Stability
    - Root Mean Square Value Calculation
    - Dynamics of Power Flow including both Active and Reactive Power
    - PSS/E, ETAP, CYME, DigSILENT,,,
  - Electro-Magnetic Transient Stability
    - Instantaneous Value Calculation
    - Dynamics of Electrical Signal
    - EMTP, EMTDC, PSCAD,,,

Swing Equation

- $M\, d^2\delta/dt^2 = P_m - P_e = \Delta P$
  - This equation describes relationship between power and frequency.

    $f = 2\pi\omega$ $\omega = d\delta/dt$
  - Power will swing by disturbances caused by unbalance between generation power and consuming load.
- P_m: Mechanical Generation Power
  - Synchronous Generator: Controllable by AVR, PSS, Governor,,
  - Renewable Energy Generator:

    Uncontrollable? -> Control power, voltage, etc.

    Uncertainty? -> Predict
- P_e: Electrical Load
  - Customer: Uncertainty-> Predict
  - Fault: Uncertainty, Unpredictable

M: Inertia capacity
δ: Rotor Angle
Pm: Mechanical Power
Pe: Electrical Power
AVR: Automatic Voltage Regulator
PSS: Power System Stabilizer

Swing Equation

- Swing equation is a mechanical model of generator rotor movement.

$$\omega = \frac{d\delta}{dt}$$

$$J\frac{d^2\delta}{dt^2} = T_m - T_e$$

$$\omega J\frac{d^2\delta}{dt^2} = P_m - P_e$$

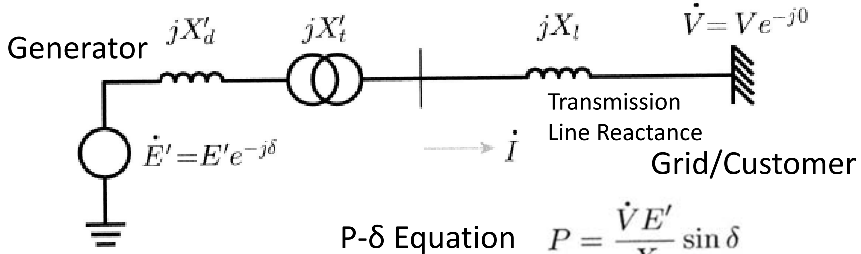
$$M = \omega J$$

$$M\frac{d^2\delta}{dt^2} = P_m - P_e = P_a$$

J: Inertia Moment
M: Inertia Capacity
ω: Angle Speed
δ: Rotor Angle
Tm: Mechanical Torque
Te: Electrical Torque
Pm: Mechanical Power
Pe: Electrical Power

$$\Delta P = (-1/R) \times \Delta f$$

2. Stability Model - Simplified Grid Model-



P-δ Equation $P = \frac{\dot{V}E'}{X}\sin\delta$

$$P + jQ = \dot{V}\dot{I}^*$$
$$= \dot{V}\left\{\frac{E'e^{-j\delta} - \dot{V}}{j(X'_d + X_t + X_l)}\right\}^*$$
$$= \frac{\dot{V}E'}{X'_d + X_t + X_l}\sin\delta + j\frac{\dot{V}E'\cos\delta - \dot{V}^2}{X'_d + X_t + X_l}$$
$$X = X'_d + X_t + X_l$$

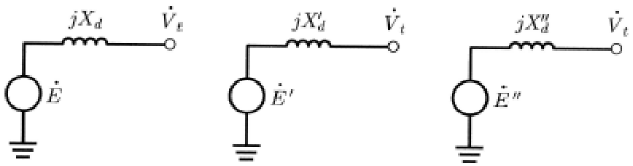
E': Transient Induced Electromotive Force
V: Grid Voltage
Xd': Transient Reactance
Xt': Transformer Reactance
Xl: Transmission Line Reactance
P: Active Power Output
Q: Reactive Power Output

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

3 Types of Equivalent Circuits of Synchronous Generator

- Internal reactance changes into synchronous, transient and subtransient reactance according to the phenomena to solve.
  - Transient Reactance: reactance of the generator during about one second of a fault
  - Subtransient Reactance: reactance of the generator during the first cycle of a fault
- Subtransient reactance is suitable for the analysis with RE sources.

Synchronous Reactance < Transient Reactance < Subtransient Reactance



E: Synchronous Emotional Force
E': Transient Emotional Force
E": Subtransient Emotional Force
Vt: Grit Terminal Voltage
Xd: Synchronous Reactance
Xd': Transient Reactance
Xd": Subtransient Reactance

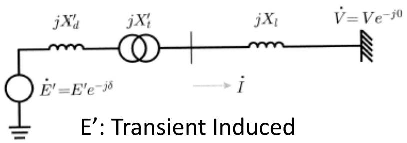
Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

3. Equal Area Criterion

- The equal area criterion is a simple graphical method for concluding the transient stability of two-machine systems or a single machine against an infinite bus.
- This principle does not require the swing equation for the determination of stability conditions.
- The stability conditions are recognized by equating the areas of segments on the power angle diagram between the P-curve and the new power transfer line of the given curve.

P-δ Equation:
derived from power equation

Infinite Bus



E': Transient Induced Electromotive Force

Power equation

$$P + jQ = \dot{V}\dot{I}^*$$
$$= \dot{V}\left\{\frac{E'e^{-j\delta} - \dot{V}}{j(X'_d + X_t + X_l)}\right\}^*$$
$$= \frac{\dot{V}E'}{X'_d + X_t + X_l}\sin\delta + j\frac{\dot{V}E'\cos\delta - \dot{V}^2}{X'_d + X_t + X_l}$$

Active Power which flows from a generator to grid $P = \frac{\dot{V}E'}{X}\sin\delta$ (where $X = X'_d + X_t + X_l$)

Synchronizing Force $S = \frac{dP}{d\delta} = \frac{VE'}{X}\cos\delta$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Equal Area Criterion for Stability Analysis

A: Acceleration Energy
B: Deceleration Energy
Pm: Power in operation
Pmax: Maximum of Power
δ_0: Phase in operation
δ_a: Minimum Phase in disturbance
δ_b: Maximum Phase under disturbnce

*P*max=>ATC

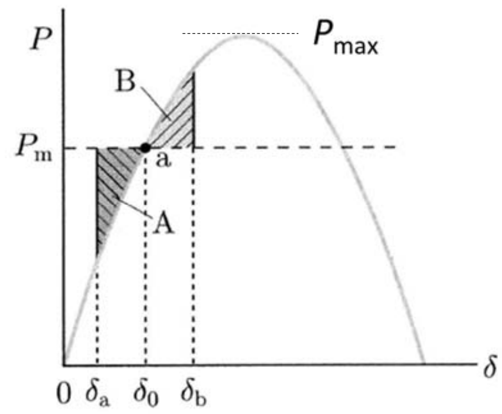


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Equal Area Criterion for Stability Analysis

- $P = \frac{V_i V_j}{X} sin\delta$
  Uncertainty of Pm
  It will be caused by load and renewable energy.
- $\frac{dP}{d\delta} = \frac{V_i V_j}{X} cos\delta$
  Synchronizing Force
  Gradient of Power Curve
  If Pm reaches to Pmax, synchronizing force will be lost.

A: Acceleration Energy
B: Deceleration Energy

*P*max=>ATC

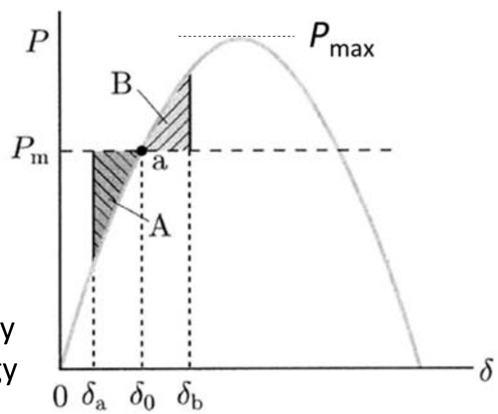
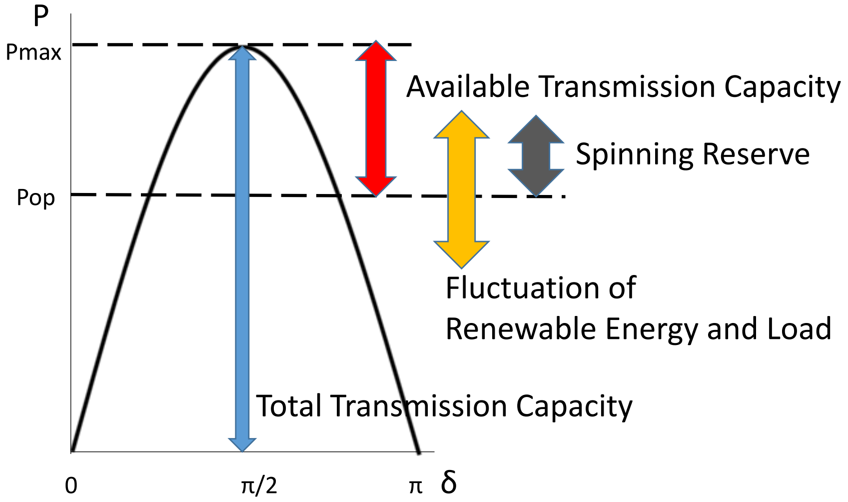


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

4. Available Transmission Capacity & Spinning Reserve

- The Available Transfer Capacity (ATC) is **the transfer capacity remaining available between two interconnected areas for further activity over.**
- Transmission capacity needs to be calculated to see whether RE can be transmitted from source location to demand place.

Available Transmission Capacity & Spinning Reserve



Operation Status

- Operated Generation Power is to be normally 60～70% of total generation capacity.
- The fluctuation of load is 10～20%.
- The fluctuation of renewable energy will be total capacity of renewable energy.
- The fluctuation of generation power will be sum of the fluctuation of load and renewable energy.

- If total demand of grid becomes to 90% over of rated capacity of grid,
  - Spinning reserve will be decreased.
  - Synchronizing force will be very small not to be returned to stable state.

Available Transmission Capacity based on Heat Capacity Limit

- Transmission capacity needs to be calculated to see whether RE can be transmitted from source location to demand place.
- Available Transmission Capacity from Heat Capacity Limit

$$P_{loss} = R * (\frac{V_i}{X})^2 \quad < \quad P_{\mathrm{LOSSMAX}}$$

- Available Transmission Capacity from Transient Stability

$$P = \frac{V_i V_j}{X} \boldsymbol{sin\delta} \quad \rightarrow \quad P_{\mathrm{ATC}} = \frac{V_i V_j}{X} - P_{\mathrm{OP}}$$

Spinning Reserve

- Spinning reserve should be more than mixed fluctuation of load and renewable energy.

→RE, EV and Battery with inertia is required for large RE penetration.

- Best Energy Mix

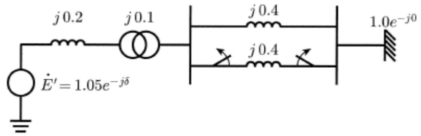
→Energy mix of several resources will be helpful for improving grid stability.

5. Exercise of Equal Area Criterion

- 3LG(3 Line Ground Fault)-> One line Open from 2 line circuit

$V = 1.0, \quad E' = 1.05$

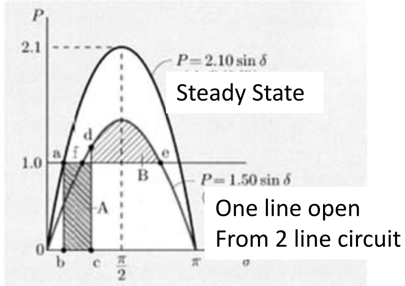
$X = 0.2 + 0.1 + \frac{0.4}{2} = 0.5$



$P = \frac{1.05}{0.5}\sin\delta = 2.10\sin\delta$

$X = 0.2 + 0.1 + 0.4 = 0.7$

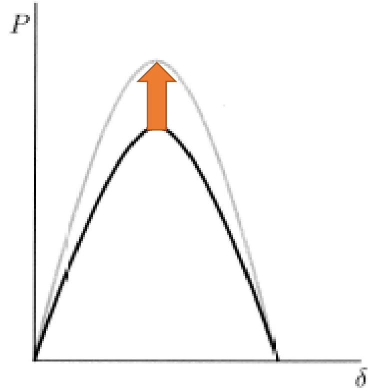
$P = \frac{1.05}{0.7}\sin\delta = 1.50\sin\delta$



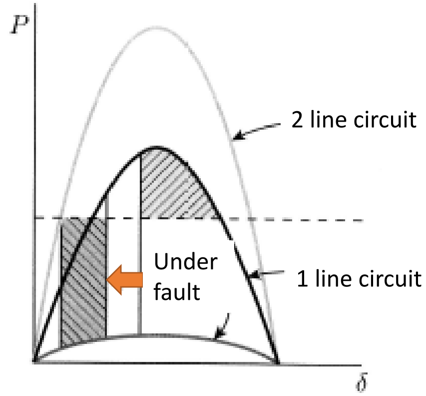
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Solution for stability(1) Explain using Equal Area Criterion Method

(a) Voltage to be High



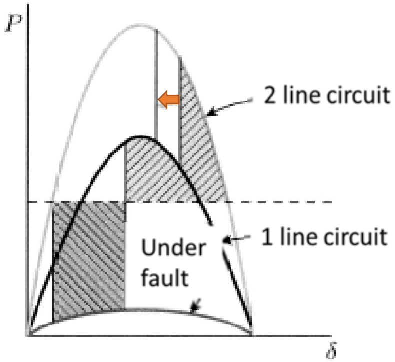
(b) High Speed Circuit Breaker



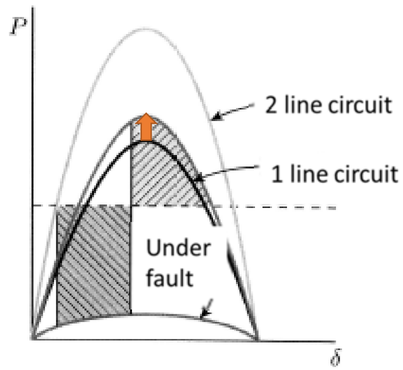
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Solution for stability(2) Explain using Equal Area Criterion Method

(c) High Speed Recloser



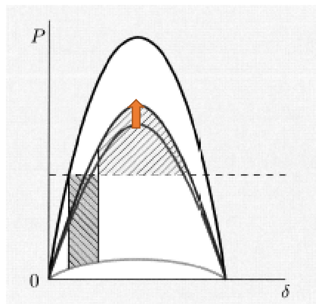
(d) High Speed AVR



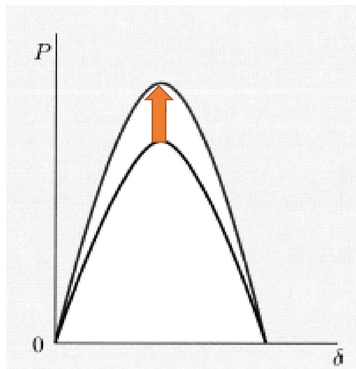
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Solution for stability(3) Explain using Equal Area Criterion Method

(e) Middle Point Switch Gear Station



(f) Series Capacitor



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Equal Area Criterion for RE and SCO

(g) Photovoltaics

Change Pmax

(h) Wind Power

Change Pmax and Phase

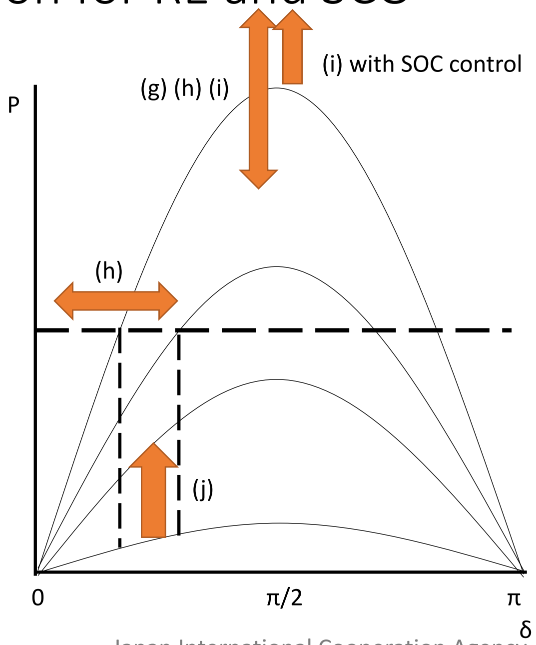
(i) Battery

Change Pmax

(j) SCO

(Synchronous Condenser)

Change P during fault



6. Practice on Microgrid/VPP Designer and LFC/ELD

- Load Frequency Control (LFC)

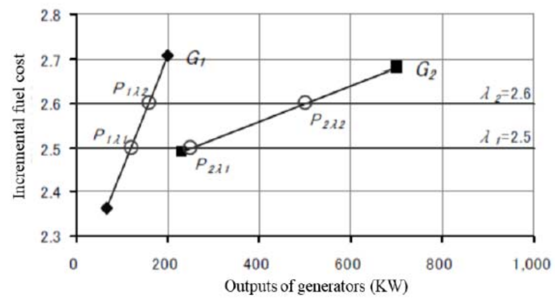
$$\Delta P = (-1/R) \times \Delta f$$

ΔP: Resulting Change of Power
R: Speed Regulation
Δf: Change of Frequency

- Economic Load Dispatching (ELD)
  - Equal λ method

$$f(P) = \sum_{i=1}^{n} f_i(P_i) = \sum_{i=1}^{n} \left(a_i + b_i P_i + c_i P_i^2\right)$$

$$\lambda = \left(\sum_{i=1}^{n} \frac{b_i}{c_i} + 2P_L\right) / \sum_{i=1}^{n} \frac{1}{c_i}$$



Microgrid/VPP Designer

- Calculate large scale power grid including microgrid
- From power flow solution till demand and supply control
- Based on Microsoft Excel Macro

<Functions>

- Load Flow solution
- LFC (Load Frequency Control)
- ELD (Economic Load Dispatching)

VPP: Virtual Power Plant

LFC & ELD Model in Microgrid/VPP Designer

- Simple Grid Model

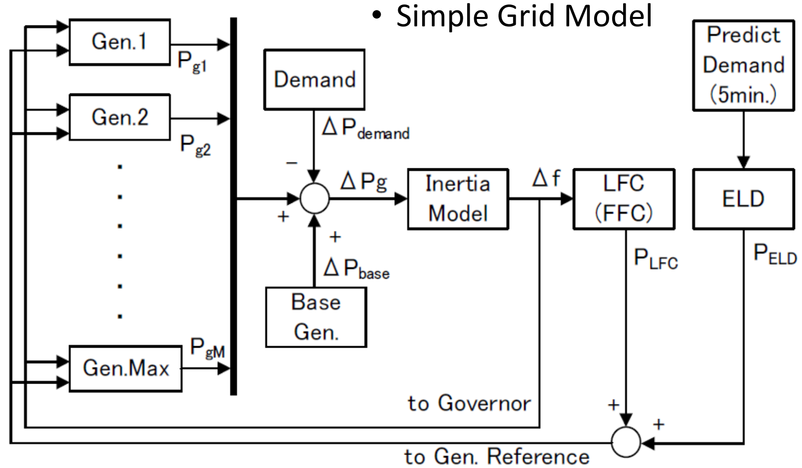


Figure is cited from MicroGrid Designer User and Technical Reference Manual

Inertia Model in Microgrid/VPP Designer

- Dynamics of grid is modelled as first-order lag model as follows:

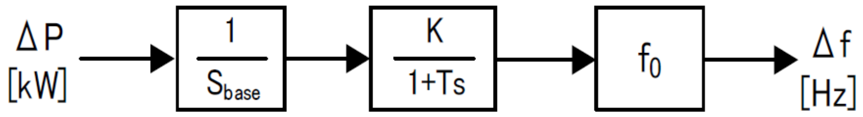
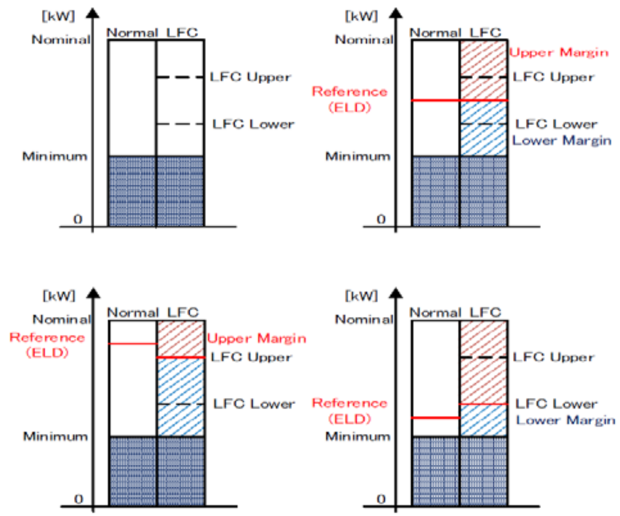


Figure is cited from MicroGrid Designer User and Technical Reference Manual

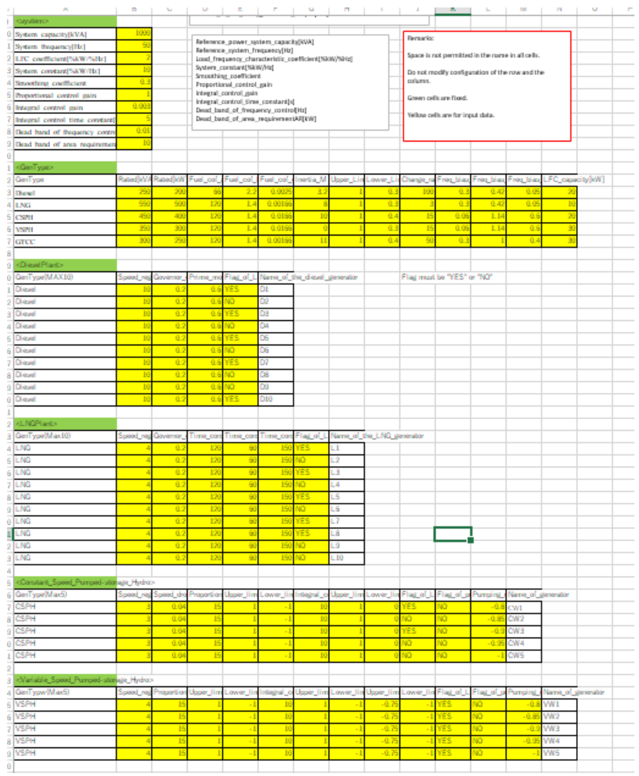
Reference of LFC & ELD

- The reference value of ELD is adjusted to be the upper limit or the lower limit of the generator.

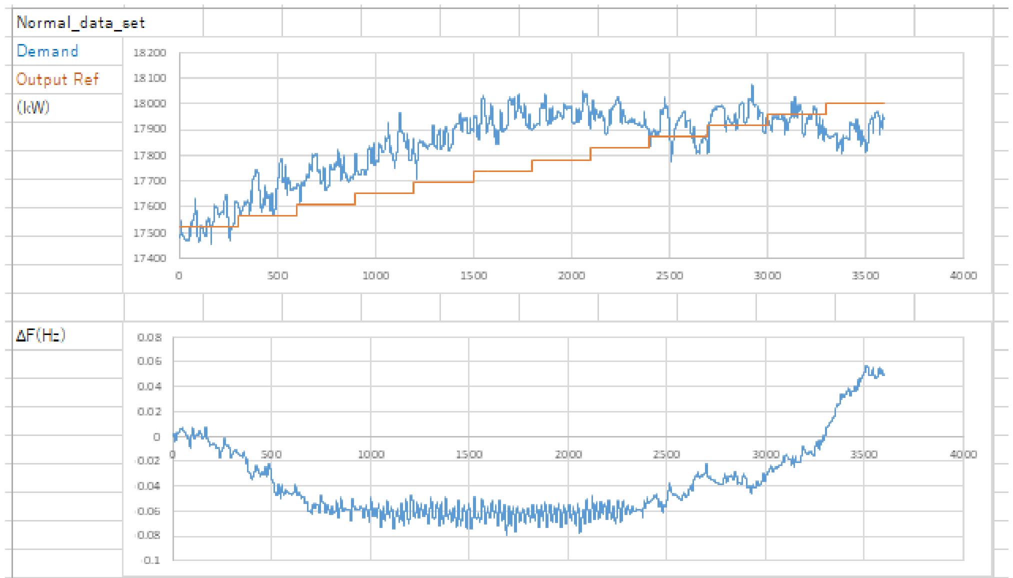


Figures are cited from MicroGrid Designer User and Technical Reference Manual

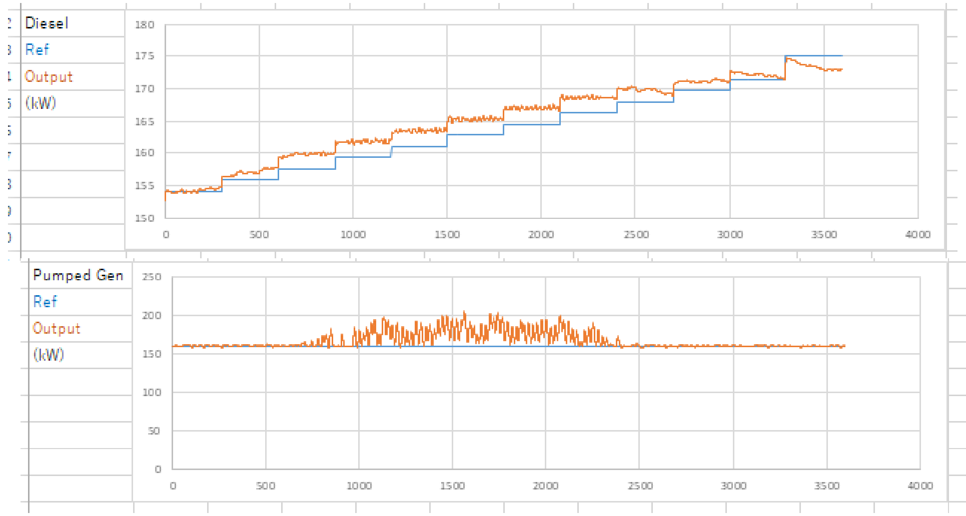
LFC Input Data



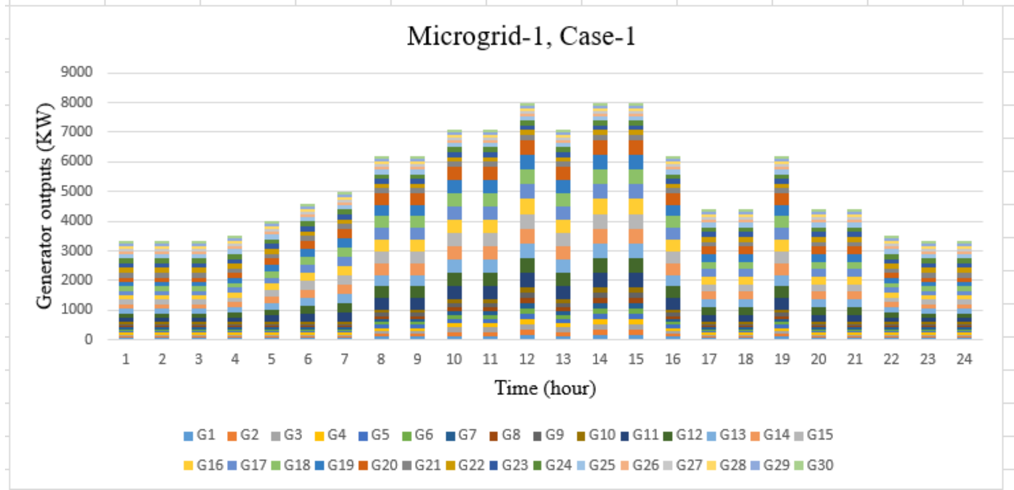
Demand and Frequency -Result of LFC-



Generator Output -Result of LFC-



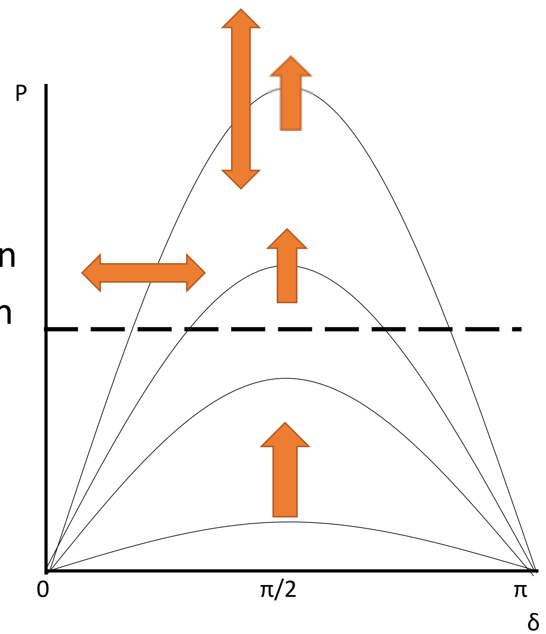
Result of ELD



7. Stability Analysis and Evaluation of Power System

Let's consider and explain the effect of the following equipment to grid stability.

1. Photovoltaic Generation
2. Wind Power Generation
3. Battery
4. SCO (Synchronizing Condenser)
5. Turbine Generator

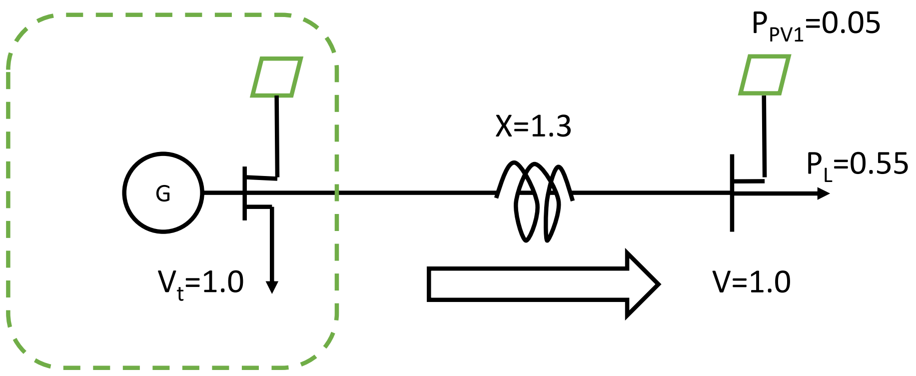


Case Study

- Steps to evaluate stability of Microgrid

1. Load Flow Analysis
2. Equal Area Criterion
3. Short Circuit Ratio
4. Available Transmission Capacity
5. Spinning Reserve

Power System Model (Example)



Treat as one generator

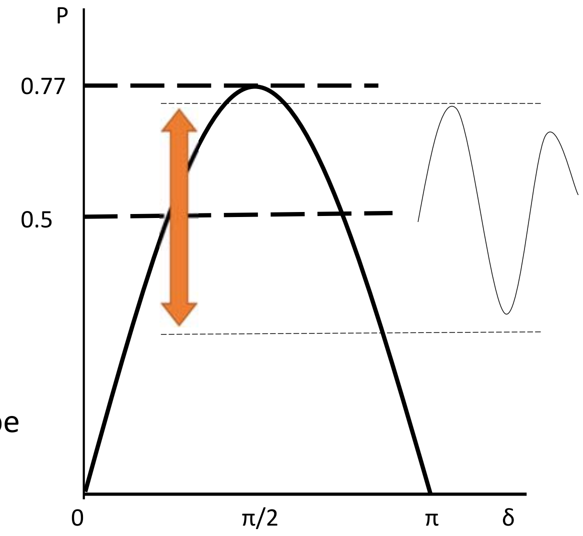
DC Flow Method: P=δ/X

0.55-0.55=δ/1.3

δ=0.65rad=37deg

P-δ Curve and Stability Evaluation

- Pmax=1*1/1.3=0.77
- Pop=0.5
- (a) Currently ΔP_{RE}= 0.15
  -> Stable
- (b) If ΔP_{RE}> 0.27
  -> Unstable
- SCR=Pop/ΔP_{RE} should be over 3
  =(a) 3.33 -> Stable
  =(b) 1.85 -> Unstable
- ATC=0.27
- Spinning Reserve should be more than ΔP_{RE}
  =0.15



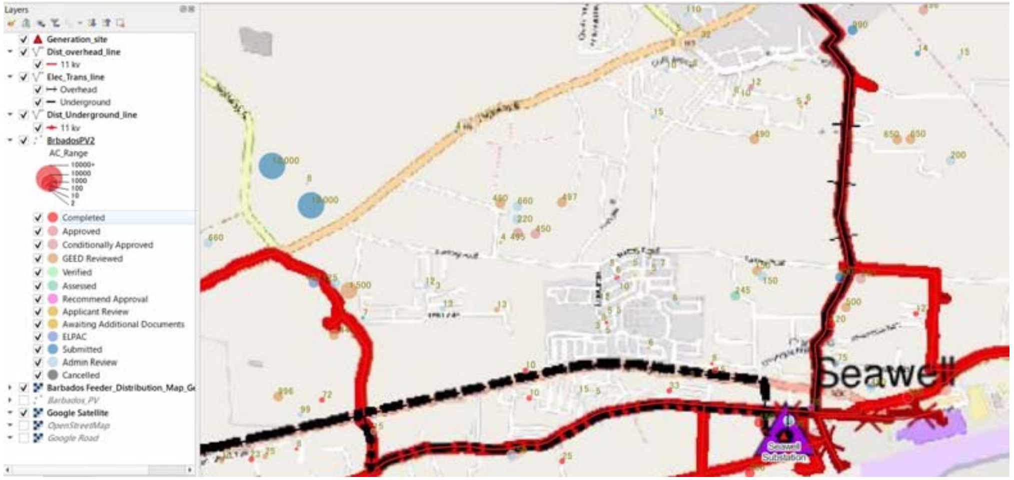
Seminar on Grid Stability with Large RE Day 3 (Exercise)

for Barbados

JICA Expert Team, Nippon Koei Co., Ltd.

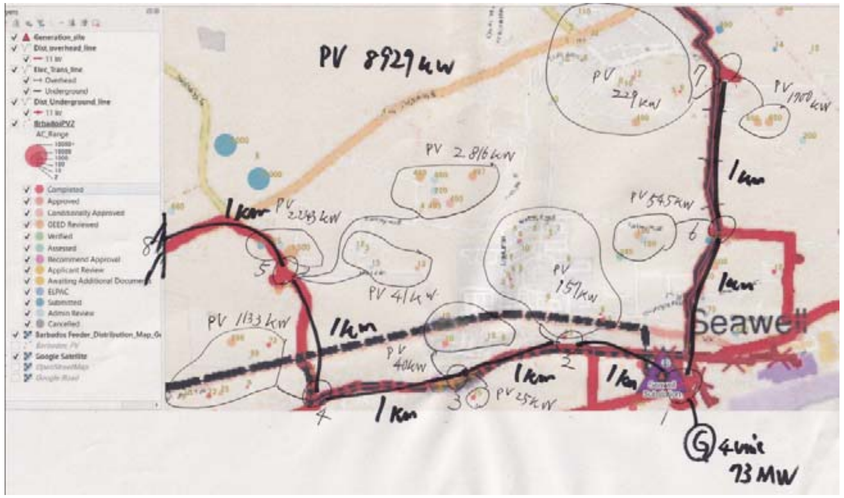
Microgrid (Coverley Villages)

Distribution Line around Coverley Villages

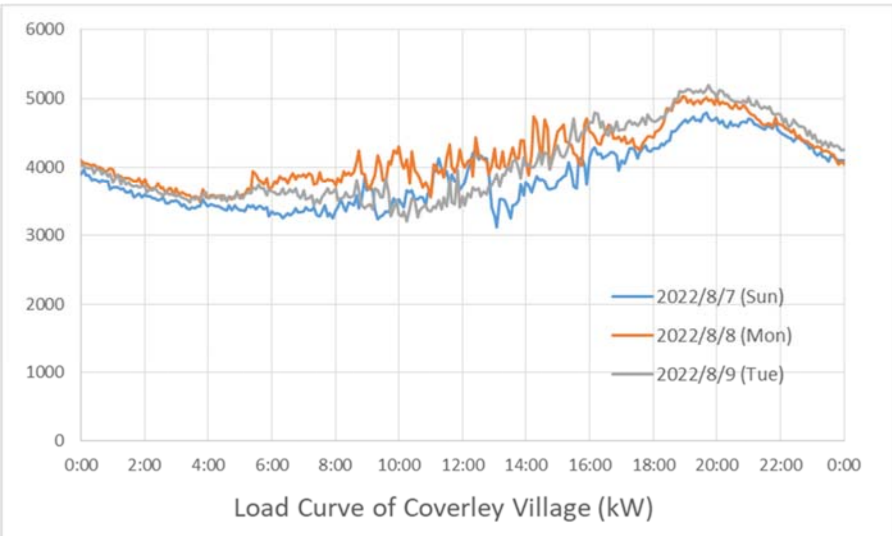


PV allocation and capacity around Coverley Villages

Example of modeling of the grid



Load Curve of Coverley Villages (7,8,9/Aug/2022)



Parameter of Coverley Villages

- Vbase=11.5V
- (VA)base=10MVA

- Ibase=10/11.5=0.87kA
- Zbase=Vbase^2/(VA)base=11.5^2/10=13.2Ω
  - R=0.1Ω/km, X=0.1Ω/km
  - Length =1km
  - Rpu=0.1x1/13.2=0.057
  - Xpu=0.1x1/13.2=0.057

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

Seminar on Grid Stability with Large RE

Appendices

JICA Expert Team, Nippon Koei Co., Ltd.

Exercise 1,2 Answer

- Exercise 1
  (1) Ibase=(VA)base/Vbase=100MVA/50kV=2kA
  Zbase=Vbase/Ibase=50kV/2kA=25Ω
  (2) R=0.04*8/25=0.0128
  X=0.06*8/25=0.0192
  Z=0.0128+j0.0192
- Exercise 2
  KA=0.01x1000=10[MW/0,1Hz]=100[MW/Hz]
  KB=0.01x500=5[MW/0.1Hz]=50[MW/Hz]
  ΔF=-30/(100+50)=-0.2[Hz]
  ΔPT=50x(-30)/(100+50)=-10.0MW

Exercise 3,4 Answer

- Exercise 3
  KA=0.01x300=3[MW/0.1Hz]=30[MW/Hz]
  KB=0.01x500=5[MW/0.1Hz]=50[MW/Hz]
  ΔRA=50+30x(-0.1)=47[MW]
  A should be decreased by 47MW.
  ΔRB=-50+50x(-0.1)=-55[MW]
  B should be increased by 55MW
- Exercise 4
  tan θ=0.2 Q=Ptanθ=0.20[pu]
  $(0.01x1+0.2x0.20+Vr^2)2+(0.01x0.2-0.2x1)^2=Vr^2$
  $Vrp^2=0.85$ Vrp=0.92
  Vr=275x0.92=253kV
  $\rho=((0.01^2+0.2^2)*1+0.01*0.92^2))/((0.01^2+0.2^2)*0.2+0.2*0.85^2)$
  =0.049/0.18=0.27

Transmission Line in Barbados

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

- Vbase=11.5kV or 24.9kV
- (VA)base=100MVA
- Ibase=(VA)base/Vbase=8.7kA or 4.0kA
- $Zbase=Vbase^2/(VA)base$=1.32Ω or 6.2Ω
  - R=0.15Ω/km, X=0.15Ω/km or R=0.05Ω/km, X=0.10Ω/km
  - Length =5km, 3km, 2km, 1km
  - Rpu=0.15x5/1.32=0.57, 0.34, 0.23, 0.1 → 2line circuit:0.3, 0.2, 0.1, 0.05
  - Xpu=0.15x5/1.32=0.57, 0.34, 0.23, 0.1 → 2line circuit:0.3, 0.2, 0.1, 0.05
  - Rpu=0.05x5/6.20=0.04, 0.024, 0.016, 0.008 → 2line circuit:0.02, 0.012, 0.008, 0.004
  - Xpu=0.10x5/6.20=0.08, 0.048, 0.032, 0.016 → 2line circuit:0.04, 0.024, 0.016, 0.008
- Resistance value (Rpu)
  - In high voltage transmission line Rpu can be ignored into 0.0.
  - In low voltage transmission line value of Rpu is similar to Xpu.
  - Rpu of 11.5kV line is set to the same value of Xpu.
  - Rpu of 24.9kV line is set to half value of Xpu.

Parameter of Coverley Villages

- Vbase=11.5V
- (VA)base=10MVA

- Ibase=10/11.5=0.87kA
- Zbase=Vbase^2/(VA)base=11.5^2/10=13.2Ω
  - R=0.1Ω/km, X=0.1Ω/km
  - Length =1km
  - Rpu=0.1x1/13.2=0.057
  - Xpu=0.1x1/13.2=0.057

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

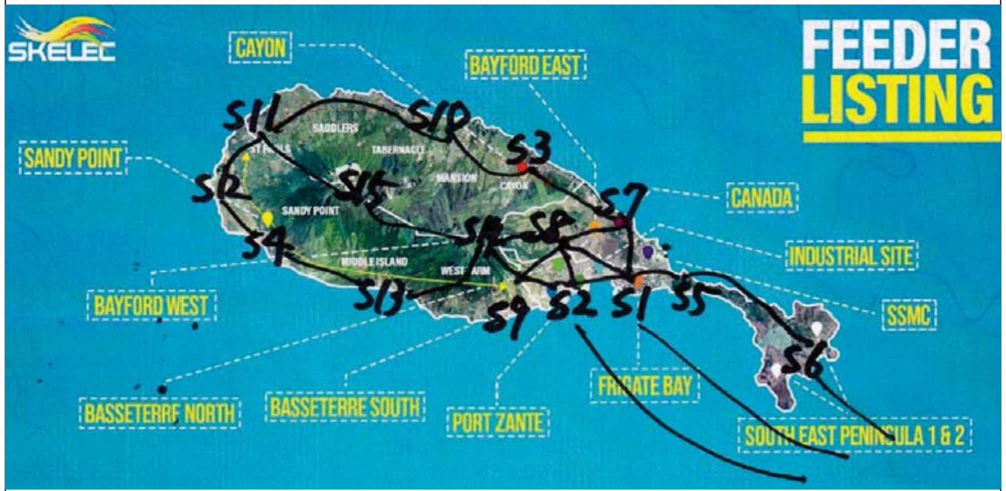
Transmission Line in Saint Kitts and Nevis

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current, Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

- Vbase=11.4kV or 66.0kV
- (VA)base=100MVA
- Ibase=(VA)base/Vbase=8.8kA or 1.5kA
- Zbase=Vbase^2/(VA)base=1.30Ω or 43.6Ω
  - R=0.15Ω/km, X=0.15Ω/km or R=0.04Ω/km, X=0.08Ω/km
  - Length =5km, 3km, 2km, 1km
  - Rpu=0.15x5/1.3=0.58, 0.35, 0.23, 0.11 → 2line circuit:0.29, 0.18, 0.12, 0.06
  - Xpu=0.15x5/1.3=0.58, 0.35, 0.23, 0.11 → 2line circuit:0.29, 0.18, 0.12, 0.06
  - Rpu=0.04x5/43.6=0.005, 0.0026, 0.002 → 2line circuit:0.0092, 0.0052, 0.004
  - Xpu=0.08x5/43.6=0.009, 0.0052, 0.004 → 2line circuit:0.0184, 0.0104, 0.008
- Resistance value (Rpu)
  - In high voltage transmission line Rpu can be ignored into 0.0.
  - In low voltage transmission line value of Rpu is similar to Xpu.
  - Rpu of 11.4kV line is set to the same value of Xpu.
  - Rpu of 66.0kV line is set to half value of Xpu.

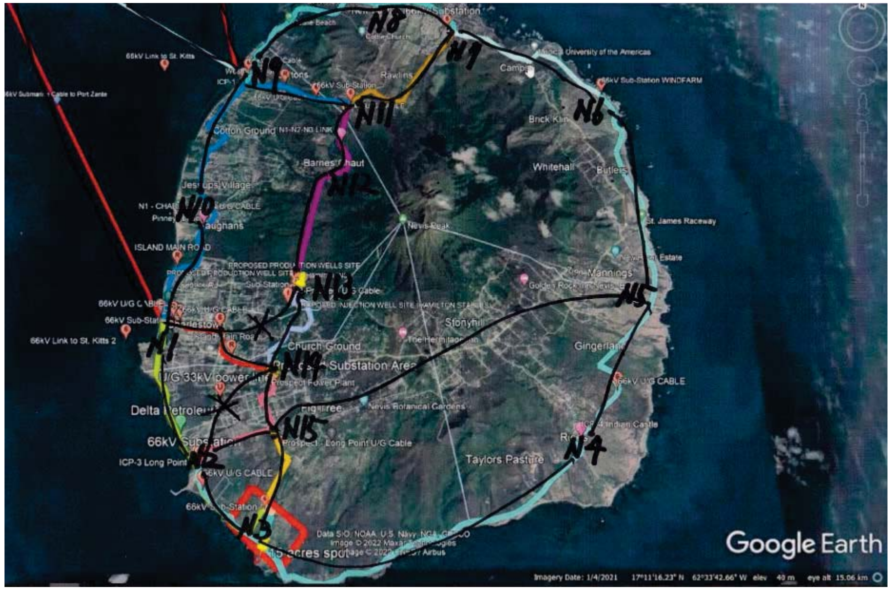
Saint Kitts Assumed Grid

15 nodes



Nevis Assumed Grid

15 nodes



Saint Kitts and Nevis Assumed Grid

30 nodes

Load Flow Data for Saint Kitts and Nevis

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.)
S1	2	1.03			0.3	0	0	0
S2	1	1.03			0.2	0	0	0
S3	1	1.05			0.5	0	0	0
S4	1	1.05			0.1	0	0	0
S5	0	1			0	0	0	0
S6	0	1			0	0	0.1	0
S7	0	1			0	0	0.2	0
S8	0	1			0	0	0.2	0
S9	0	1			0	0	0.2	0
S10	0	1			0	0	0.2	0
S11	0	1			0	0	0.05	0
S12	0	1			0	0	0.05	0
S13	0	1			0	0	0.05	0
S14	0	1			0	0	0.1	0
S15	0	1			0	0	0	0
N1	1	1.05			0.2	0	0.2	0
N2	1	1.05			0.2	0	0.1	0
N3	1	1.05			0.1	0		0
N4	0	1			0	0	0.05	0
N5	1	1.05			0.1	0		0
N6	0	1			0	0	0.1	0
N7	0	1			0	0	0.1	0
N8	0	1			0	0	0.05	0
N9	0	1			0	0	0.1	0
N10	0	1			0	0	0.1	0
N11	0	1			0	0	0.05	0
N12	1	1.05			0.3	0	0	0
N13	0	1			0	0	0	0
N14	0	1			0	0	0	0
N15	0	1			0	0	0	0

Branch data Input Form for Single Stage Power Flow Analysis

Branch ID (Up to 5 integers)	Sending node (Up to 4 chracters)	Receiving node (Up to 4 chracters)	No. of circuits default =1	Resistance R (p.u.)	Reactance X (p.u.)	Admittance Y/2 (p.u.)	Tap ratio default = 1.0
1	S1	S5	1	0.2	0.2	0.01	0
2	S5	S6	1	0.5	0.5	0.01	0
3	S1	S7	1	0.9	1.8	0.01	0
4	S7	S3	1	0.14	0.27	0.02	0
5	S3	S10	1	0.14	0.27	0.02	0
6	S10	S11	1	0.22	0.44	0.02	0
7	S11	S12	1	0.09	0.18	0.01	0
8	S12	S4	1	0.14	0.27	0.02	0
9	S4	S13	1	0.18	0.36	0.02	0
10	S13	S14	1	0.18	0.36	0.02	0
11	S14	S9	1	0.09	0.18	0.01	0
12	S2	S1	1	0.09	0.18	0.01	0
13	S1	S8	1	0.3	0.3	0.01	0
14	S8	S7	1	0.3	0.3	0.01	0
15	S8	S9	1	0.2	0.2	0.01	0
16	S8	S14	1	0.14	0.27	0.02	0
17	S14	S15	1	0.4	0.4	0.01	0
18	S15	S11	1	0.4	0.4	0.01	0
19	S2	S8	1	0.2	0.2	0.01	0
20	S9	S2	1	0.2	0.2	0.01	0
21	N1	N2	1	0.14	0.27	0.02	0
22	N2	N3	1	0.09	0.18	0.01	0
23	N3	N4	1	0.31	0.62	0.02	0
24	N4	N5	1	0.22	0.44	0.02	0
25	N5	N6	1	0.22	0.44	0.02	0
26	N6	N7	1	0.18	0.36	0.02	0
27	N7	N8	1	0.09	0.18	0.01	0
28	N8	N9	1	0.14	0.27	0.02	0
29	N9	N10	1	0.14	0.27	0.02	0
30	N10	N1	1	0.14	0.27	0.02	0
31	N7	N11	1	0.14	0.27	0.02	0
32	N11	N9	1	0.09	0.18	0.01	0
33	N11	N12	1	0.09	0.18	0.01	0
34	N12	N13	1	0.14	0.27	0.02	0
35	N14	N1	1	0.14	0.27	0.02	0
36	N13	N14	1	0.09	0.18	0.01	0
37	N14	N15	1	0.09	0.18	0.01	0
38	N15	N2	1	0.09	0.18	0.01	0
39	N15	N3	1	0.09	0.18	0.01	0
40	N15	N5	1	0.7	0.7	0.01	0
41	S6	N9	1	1	1	0.01	0
42	S1	N9	1	0.44	0.88	0.04	0
43	S2	N1	1	0.44	0.88	0.04	0

Load Flow Analysis Result in Saint Kitts and Nevis

R,X,Y Line Model

Node ID	Node type	Specified voltage	Obtaiened value	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)
S1	2	1.03	1.03	0
S2	1	1.03	1.03	−0.98
S3	1	1.05	1.05	2.48
S4	1	1.05	1.05	−3.43
S5	0	1	1.02586	−1.27
S6	0	1	1.00698	−3.94
S7	0	1	1.02789	−1.55
S8	0	1	1.01492	−2.95
S9	0	1	1.0106	−3.73
S10	0	1	1.04128	−1.49
S11	0	1	1.04735	−3.98
S12	0	1	1.04912	−4.13
S13	0	1	1.03907	−4.52
S14	0	1	1.02205	−4.25
S15	0	1	1.03884	−4.34
N1	1	1.05	1.05	0.11
N2	1	1.05	1.05	1.83
N3	1	1.05	1.05	2.03
N4	0	1	1.0545	0.09
N5	1	1.05	1.05	0.36
N6	0	1	1.04857	−2.82
N7	0	1	1.0508	−3.13
N8	0	1	1.05157	−3.31
N9	0	1	1.05087	−2.63
N10	0	1	1.04901	−2.12
N11	0	1	1.05103	−1.31
N12	1	1.05	1.05	1.89
N13	0	1	1.05806	1.24
N14	0	1	1.05785	0.96
N15	0	1	1.0552	1.46

R,X Line Model

Node ID	Node type	Specified voltage	Obtaiened value	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)
S1	2	1.03	1.03	0
S2	1	1.03	1.03	−0.94
S3	1	1.05	1.05	2.87
S4	1	1.05	1.05	−3.12
S5	0	1	1.01622	−0.82
S6	0	1	0.98273	−2.98
S7	0	1	1.01755	−0.95
S8	0	1	1.00365	−2.32
S9	0	1	0.99798	−3.04
S10	0	1	1.02576	−0.69
S11	0	1	1.0244	−3.02
S12	0	1	1.03193	−3.34
S13	0	1	1.02178	−3.75
S14	0	1	1.00245	−3.4
S15	0	1	1.01342	−3.2
N1	1	1.05	1.05	0.35
N2	1	1.05	1.05	2.1
N3	1	1.05	1.05	2.31
N4	0	1	1.04365	0.63
N5	1	1.05	1.05	0.6
N6	0	1	1.02095	−1.88
N7	0	1	1.01562	−1.99
N8	0	1	1.01431	−2.11
N9	0	1	1.01925	−1.55
N10	0	1	1.02759	−1.31
N11	0	1	1.02777	−0.4
N12	1	1.05	1.05	2.23
N13	0	1	1.05006	1.76
N14	0	1	1.05022	1.45
N15	0	1	1.0505	1.87

X Line Model

Node ID	Node type	Specified voltage	Obtaiened value	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)
S1	2	1.03	1.03	0
S2	1	1.03	1.03	−0.48
S3	1	1.05	1.05001	3.34
S4	1	1.05	1.05	−1.2
S5	0	1	1.0312	−0.74
S6	0	1	1.03492	−2.57
S7	0	1	1.03999	−0.51
S8	0	1	1.0334	−1.75
S9	0	1	1.03322	−2.3
S10	0	1	1.04714	0.12
S11	0	1	1.04568	−1.68
S12	0	1	1.04739	−1.77
S13	0	1	1.04314	−2.31
S14	0	1	1.03648	−2.49
S15	0	1	1.04105	−2.08
N1	1	1.05	1.05	1.26
N2	1	1.05	1.05001	2.67
N3	1	1.05	1.05001	2.85
N4	0	1	1.04988	1.49
N5	1	1.05	1.05	1.68
N6	0	1	1.04713	−0.94
N7	0	1	1.04569	−1.21
N8	0	1	1.04494	−1.36
N9	0	1	1.04387	−0.89
N10	0	1	1.04667	−0.52
N11	0	1	1.04607	0.24
N12	1	1.05	1.05001	2.8
N13	0	1	1.04994	2.41
N14	0	1	1.04992	2.15
N15	0	1	1.04996	2.49

Transmission Line in Saint Kitts and Nevis

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current, Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rp: Per Unit Resistance, Xp: Per Unit Reactance

- Vbase=11.4kV or 66.0kV
- (VA)base=100MVA
- Ibase=(VA)base/Vbase=8.8kA or 1.5kA
- Zbase=Vbase^2/(VA)base=1.30Ω or 43.6Ω
  - R=0.15Ω/km, X=0.15Ω/km or R=0.04Ω/km, X=0.08Ω/km
  - Length =5km, 3km, 2km, 1km
  - Rpu=0.15x5/1.3=0.58, 0.35, 0.23, 0.11 → 2line circuit:0.29, 0.18, 0.12, 0.06
  - Xpu=0.15x5/1.3=0.58, 0.35, 0.23, 0.11 → 2line circuit:0.29, 0.18, 0.12, 0.06
  - Rpu=0.04x5/43.6=0.005, 0.0026, 0.002 → 2line circuit:0.0092, 0.0052, 0.004
  - Xpu=0.08x5/43.6=0.009, 0.0052, 0.004 → 2line circuit:0.0184, 0.0104, 0.008
- Resistance value (Rpu)
  - In high voltage transmission line Rpu can be ignored into 0.0.
  - In low voltage transmission line value of Rpu is similar to Xpu.
  - Rpu of 11.4kV line is set to the same value of Xpu.
  - Rpu of 66.0kV line is set to half value of Xpu.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

- Discussion for Interconnection, RE and Grid Stabilization in St. Kitts and Nevis -

JICA Expert Team

Grid status of St. Kitts and Nevis

For confirmation and update

- St. Kitts
  - Grid Capacity: 48.9 MW, Peak Demand: 26.2MW
  - Generators:
    - Diesel -- 16 Units at Needsmust
    - Wind Power --- 6.6 MW plan at Bellevue (Cayon feeder)
    - PV --- 0.75 (not operating) + 0.5 (some not fully operating) + 1.0 MW fully operation
    - PV --- 34 MW Leclanche (with 6MW, 44 MWh BESS) under design
  - Transmission Line Voltage: 11.2 kV
- Nevis
  - Grid Capacity: 18.5 MW (output 16.8MW), Peak Demand: 9.83MW
  - Generators:
    - Diesel --- 8 Units at Prospect
    - Geothermal Power---- 10-30 MW planned , from 2025
    - Solar Power --- not yet installed, 3- 5 MW is planned
    - 2.2 MW Wind (actual 0.5 MW limit)
  - Transmission Line Voltage: 11.2 kV, upgrade to 66kV planned
  - BESS 3-5 MW planned

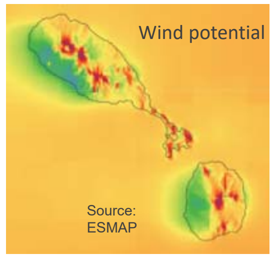
Summary (St Kits and Nevis)

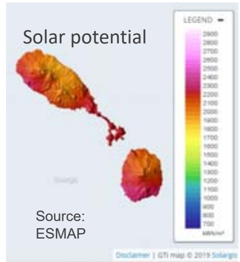
Fields	Findings	Project Activity
Energy Efficiency	• Energy Source: Electricity (63%) , Oil (37%) • Load Curve: Bactrian camel type • Annual Peak Demand: about 25MW (St. Kitts) about 10MW or more (Nevis) • Peak Period: around 11am, 6pm-8pm (St. Kitts) around 12am, 6pm-8pm (Nevis)	Priority 1: Optimized operation with inverter Priority 2: Mini split AC with inverter Priority 3: VRF
Renewable Energy	• 100% RE by 2020 target • 0.7+0.5 MW PV (St.Kitts), damaged • 2MW wind operated at 1.1 MW (Nevis) • Bellevue 5.4 MW wind, Leclanche 35MW PV	Monitoring RE project incl. geothermal Training for grid simulation Introduction of asset management
Grid Stabilization	• 6MW 34 MWh BESS planned for 35MW PV • Output suppression conducted in NEVLEC	
O&M of Thermal Power Generation	• Thermal power plant: total 13 units (St. Kitts), total 8 units (Nevis) • Installed Capacity: total 44.9MW (St. Kitts) total 21.3 MW (Nevis) • Peak demand 24MW (StK), 9.83 MW(Nevis)	-
Human Resources and Capacity Building	• MPI's Energy Division: 4 employees • Most of capacity building is done by OJT • There is no systematic HR development.	JET experts select topics and develop curriculum for technology transfer

RE: Status in St.Kitts & Navis

RE Projects in St. Kitts and Navis

Location/Project	Type	Capacity MW	Generation GWh estimated	Year
S: SCASPA	PV	0.7	NA	2013
S: SKELEC	PV	0.5	1	2015
N: Windwatt	Wind	2.2	5.25	2011
N: NREI Geothermal	Geo	10-30	NA	2025
S: Leclanche	PV	35	43.8	2020
S: Bellevue	Wind	5.7	NA	NA
S: NW Geothermal	Geo	18-36	NA	NA





Necessary consideration for future RE

1) Grid stability analysis for new 35MW PV system
2) Update of geothermal development
3) Interconnection (11kV, 66 kV)?

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

Plan of Install Geothermal Power Plant and Grid Improvement in Nevis

For confirmation and update

- Phase 1:
  Power Grid Reinforcement from 11KV to 66KV
- Phase 2:
  Expand 66KV transmission, Install 30 MW Geothermal at N3, Connect into St. Kitts Power System
- Phase 3:
  Hydrogen Based Project at Long Point, Install 15 MW Geothermal at N3
- Phase 4:
  66KV from Long Point to Camp (Circular Line complete), Offshore Wind at 50 MW, Additional Geothermal from 15MW to 30MW at N1, Expansion of Hydrogen Based Project

Question for Interconnection between St. Kitts and Nevis

Confirmation

- StKits 70% 11 kV UG, mixture of 30% OH line
- Nevis 99% OH line
- Functions to be installed such as frequency control
  - No central control is planned. LDC need to be discussed.
- Current for Interconnection
  - AC Cable under the sea.
  - DC Line and Converter Station?
- Rated Capacity and Operation Capacity
- Length of Interconnection Cable
  - Distance between two islands : 6-7 km
  - Cable length from capital to other capital: >20km
    (Charlestown to Basseterre, all underground/submarine)
- Direction :bi-directional

Load Flow Analysis

- DC Flow Method (manual calculation)
  - Simplified Load(Power) Flow Calculation of Transmission Line
- Microgrid/VPP Designer (Software)
  - Newton Raphson Method
  - Load Flow Calculation to monitor current status of grid
  - Planning Tools for Demand and Supply Control
    - LFC(Load Frequency Control)
    - ELD(Economic Load Dispatching)

Stability Analysis

- Equivalent Area Criterion (Manual calculation)
  - Simplified Stability Calculation
- Transient Stability Program (Simulation Software)
  - Electro-Mechanical Transient Stability
    - Root Mean Square Value Calculation
    - PSS/E, ETAP, CYME, DigSILENT,,,
  - Electro-Magnetic Transient Stability
    - Instantaneous Value Calculation
    - EMTP, EMTDC, PSCAD,,,

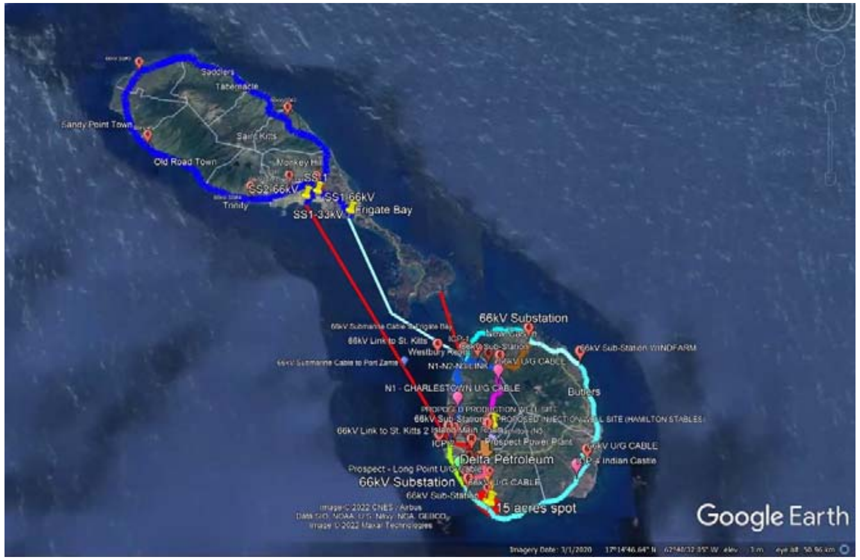
Tools Used for Power System Analysis

Confirmation

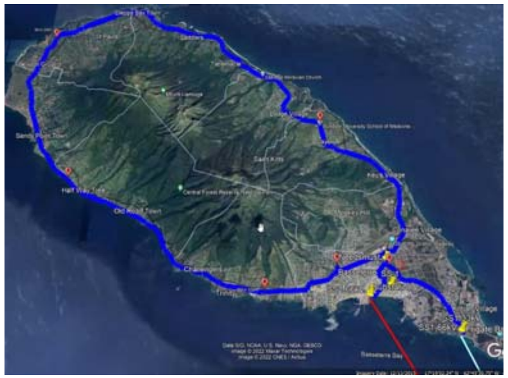
- Tools
  - SKELEC has PLEXOS
  - NEVLEC has ETAP but license expired, DigSILENT will be purchased, PLEXOS is installed for optimization
  - → ETAP and PLEXOS capacity building is requested
- Load Flow Analysis by Microgrid/VPP Designer
  - We have analyzed a base load case with wind power at Cayon
  - If you give us other option cases, we will analyze.
  - We will have a lecture of power system analysis for load flow and grid stability with demonstrating your grid in next trip (Sep-Oct 2022) at Barbados or St Lucia (2-3 days program)

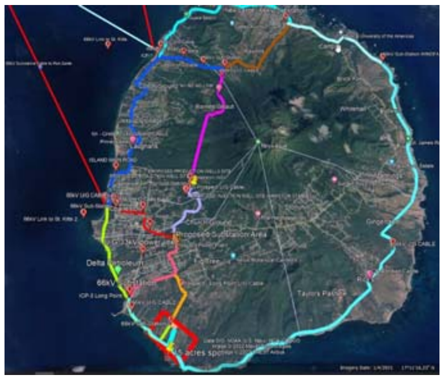
Saint Kitts and Nevis Ass... Grid for Discussion

30 nodes



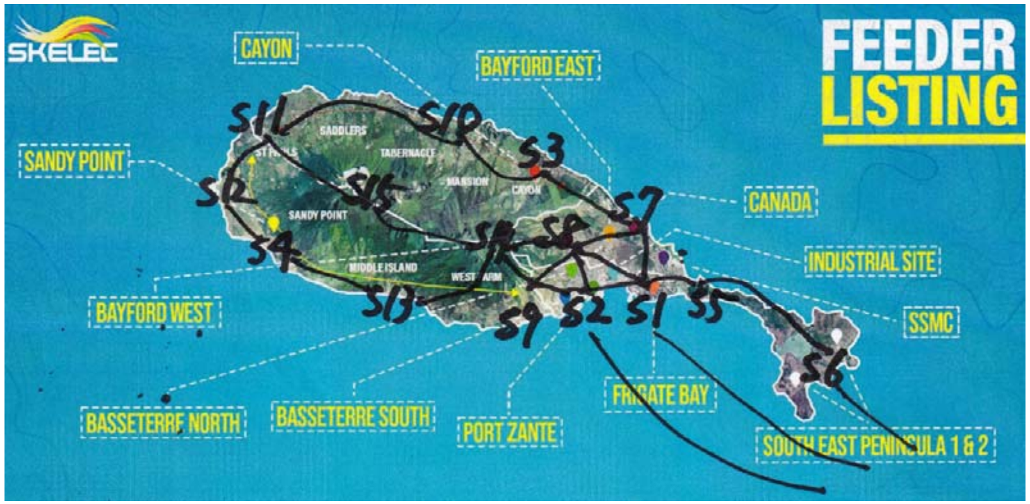
Plan of assumed 66 kV interconnection





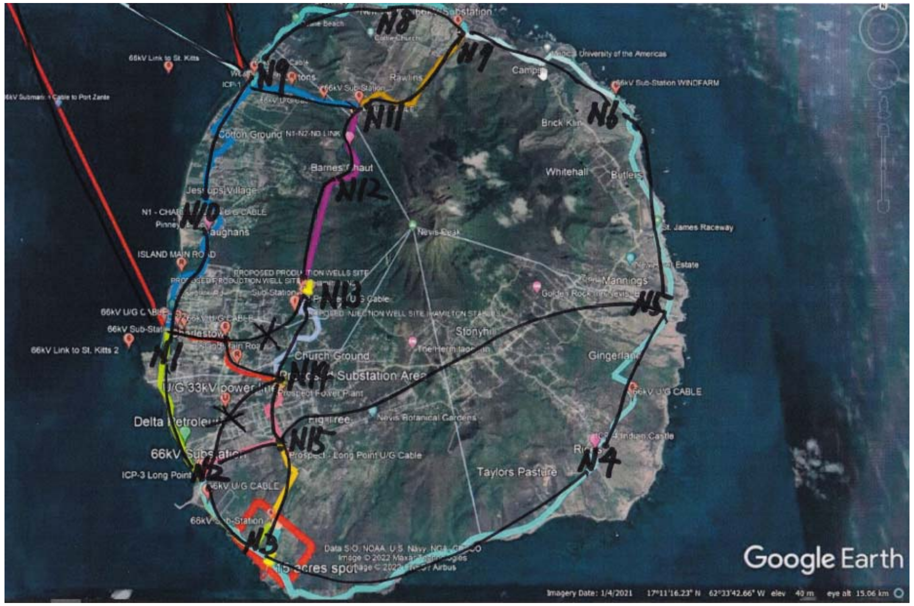
Saint Kitts Assumed Grid

15 nodes

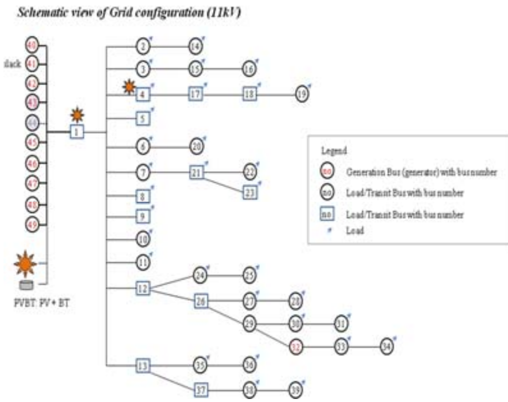


Nevis Assumed Grid

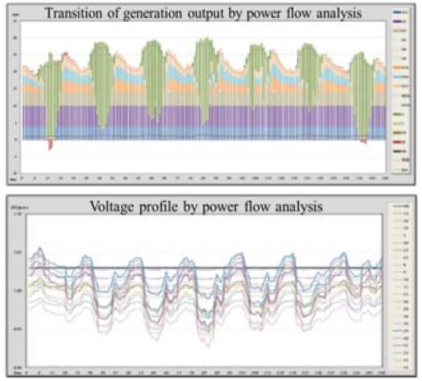
15 nodes



Grid Analysis Model of St. Kitts (example case)



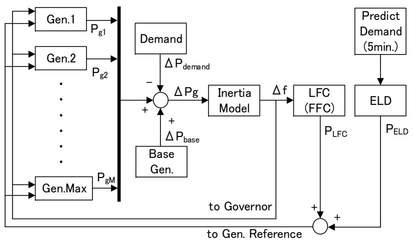
Example of micro-grid model (St. Kitts)



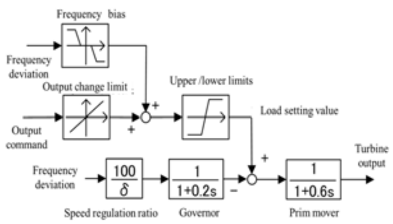
Grid analysis result (generator output, voltage, frequency)

Voltage disturbance at Cayon (Node 29) is large.
Load of transmission line connected to Cayon is heavy.

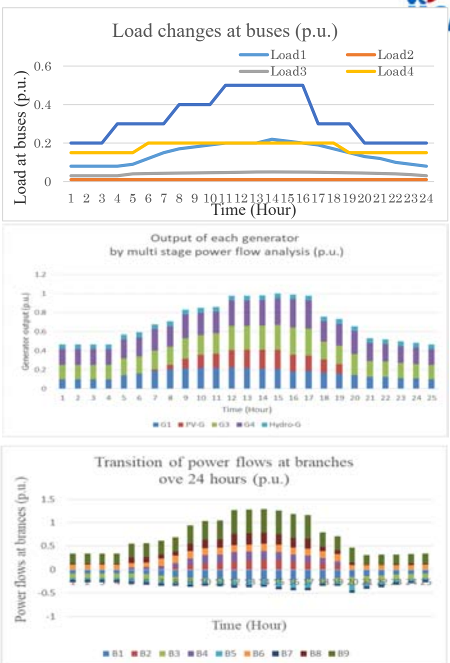
Load-flow Analysis



LFC model using EDC result



Output model of DG



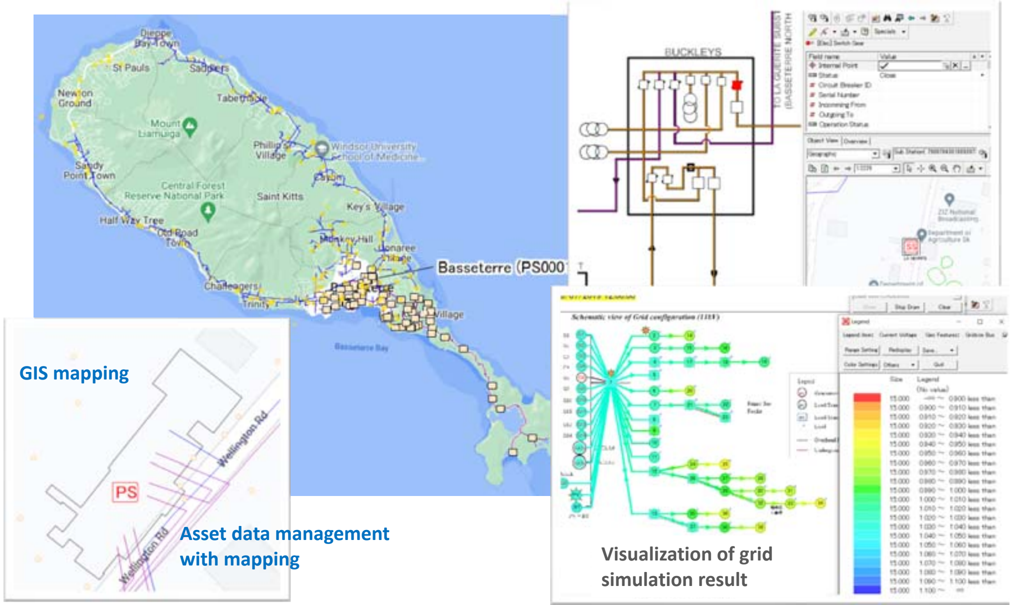
Activity for Grid Stability

- next visit in Sep-Oct 2022-

- Monitoring of Grid
  - Microgrid/VPP Designer (Software)
  - DC Flow Method (Manual calculation)
- Evaluation of Grid Stability
  - Equal Area Criterion (Manual calculation)
- Demand and Supply Control
  - Microgrid/VPP Designer (Software)
  - Plan of LFC and ELD
- Asset Management
  - Smallworld (Software)

VPP: Virtual Power Plant

GIS, Asset Management with Grid Simulation Example of St. Kitts



Requested Data for grid analysis

- NEVLEC
  - Single line diagram of overall network and feeders
  - Demand data (peak and load curve of day, month, year, if any)
  - Distribution line data and transformer of each feeder (feeder length, size, type (ACSR, cable, etc),impedance, resistance, capacitance), and GIS data if possible
  - Location, Capacity and Terminal Voltage of Generation plants including RE and Battery
  - Generator parameters including AVR, PSS(power system stabilizer), turbine and, if any, other control equipment
  - Location, Capacity and Terminal Voltage of Substation with transformer, SVC, STATCOM or Battery, if any
  - Location and amount of consuming power or load in nodes including peak load and minimum load in analysis model, if any
  - Usual operational style about network structure with switch gear operation under heavy load and light load: NA
  - ETAP data and QGIS shapefile of 11 kV network
- SKELEC
  - Same as NEVLEC, if any update from 2019

Appendix 5-3-2 Attendant list of the 1st RE & Grid Stability Seminar (St. Kitts and Nevis)

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE Date: 3 Oct (On-line), 4 Oct, and 5 Oct, 2022

List of Participants from St. Kits and Nevis

Venue: Courtyard by Marriott Bridgetown

List of Participants for Physical Attendance (4 and 5, Oct 2022)

No	Name	Agency	Positionn	Note
1	Bertill Conroy Browne	Ministry of Public Infrastructure	Director	From 1 Oct
2	Denasio Desmond Frank	Ministry of Public Infrastructure	Energy Officer	From 1 Oct
3	Glen Amory	Ministry of Public Infrastructure	Sr. Assist. Secretary	From 1 Oct
4	Haniff Lesroy Woods	SKELEC	Operations Engineer	
5	Curtis Ethan Morton Jr.	Nevis Island Administration	Electrical Inspector	From 1 Oct
7	Greran Majid Javern Liburd	NEVLEC	Lines man	
8	Nelson Horatio Ald Junior Stapleton	NEVLEC	Distribution Manager	
9	Curleane Suzette Karen Liburd	NEVLEC	Human Resource Manager	
	Total Nos of Attendant in Barbados:	**9**		

List of Participants for on-line attendance (all 3-5 Oct, 2022)

No	Name	Agency	Positionn	Note
10	Rhondel Devyn Adlaiv Philip	SKELEC	Renewable Energy and Special Project	
11	Jonathan Kelly	SKELEC	Engineering Manager	
12	Kenrod Roberts	SKELEC	Assistant Engineering Manager	
13	Kevin Bennett	SKELEC	Generation Manager	
14	Collin Brown	SKELEC	Control & Operations Manager	
15	Keane Mark	SKELEC	Generation Maintenance Engineer	
6	Mr. Jesse Hunkins	Nevis Island Administration	Electrical inspector	From 1 Oct replaced from Mr. Deora Pemberton

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

3rd Seminar for Barbados 2nd Seminar for St. Kits and Nevis on Grid Stability and Large RE

6 Dec 2022

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

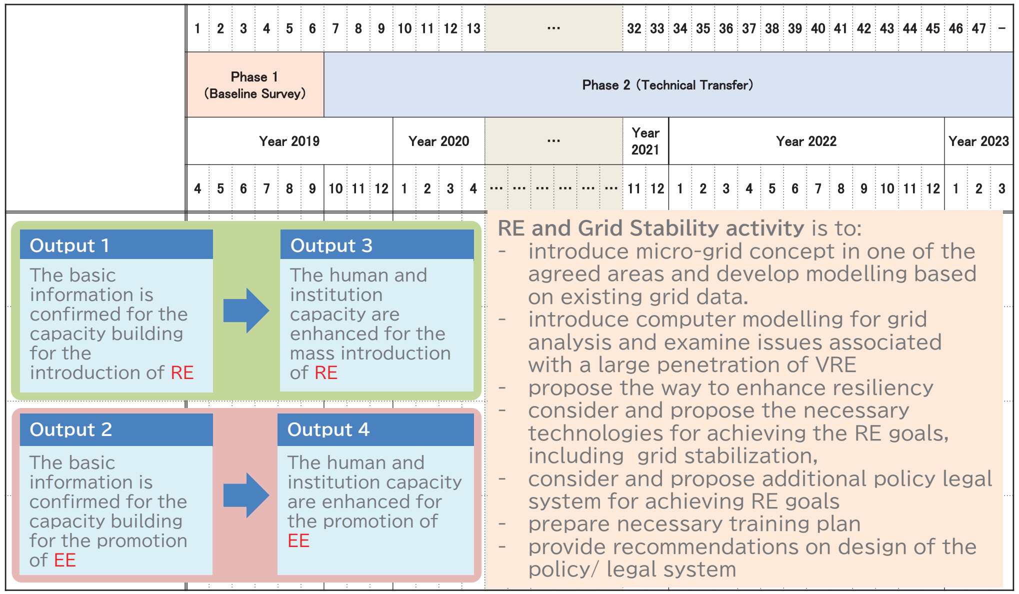
Agenda

- 9:30-9:35 Opening Remarks
- 9:35-10:40 S1 Project Outline, Large RE, Feedback of 2nd seminar, Microgrid Why Grid Stability is necessary
- 10:40-11:30 S2 Grid Modeling
- 11:30-12:30 S3 Basics of Power System Engineering for Grid Stability Simulation
- *12:30-13:30 -- Lunch Break --*
- 13:30-14:20 S4 Load Flow Analysis and its Evaluation
- 14:20-15:20 S5 Transient Stability Analysis and Evaluation of Stability
- 15:20-15:30 S6 Discussion

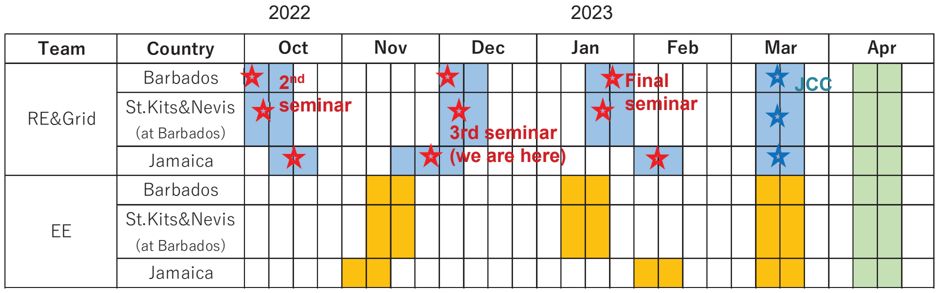
Session No. 1

1. **Project Outline and Large RE**
2. Review and Feedback of 2nd seminar
3. Microgrid Concept
4. Why Grid Stability is necessary

Project Outline and Schedule



Schedule and Key Events for RE&Grid Activity



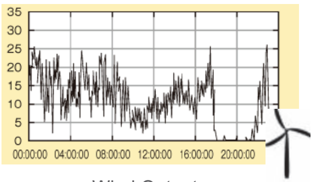
- RE&Grid Team and EE team visit Barbados on spot alternately.
- 1st Seminar on Grid Stability and RE (Introduction, Barbados only) on 27 Jul 2022
- 2nd Seminar on Grid Stability and RE on 3-5 Oct 2022
- **3rd Seminar on Grid Stability and RE on 6-7 Dec 2022**

  Objective: to discuss challenges and solutions for future Barbados/StKN Grid with RE penetration and to share knowledge about grid stability and simulation for future optimum grid planning
- 4th Seminar on Grid Stability and RE in late Jan 2023 (proposed between 23-31 Jan 2021)
- Final Joint Coordinating Committee (JCC) in March 2023

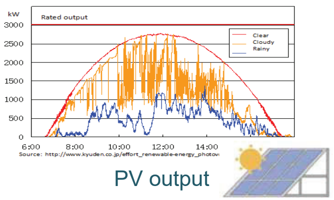
Outline and Agenda for 3rd Seminar on 6-7 Dec 2022

1. Date/Time	**6 Dec 2022 (Tue), 9:30-15:30**	**7 Dec 2022, 9:30-12:00 (Wed)**
2. Venue	**Online by Zoom Platform*1**	**Courtyard by Marriott Bridgetown, Barbados**
3. Agenda	9:30-9:35 Opening Remarks 9:35-9:50 Review & Feedback of 2nd seminar 9:50-10:30 Why Grid Stability is necessary 11:00-11:30 Modelling of Equipment in Grid 11:30-12:30 Microgrid Concept (Coverley Village) 12:30-13:30 -- Lunch Break -- 13:30-15:20 Grid Modelling for Load Flow Analysis (detailed with scenario cases) 15:20-15:30 Discussion and Q&A	9:30-10:20 Load Flow Analysis, Evaluation of Load Flow (Microgrid Designer) 10:20-11:00 Transient Stability Analysis 11:00-11:30 Evaluation of Stability (Comparison between Equal Area Criterion and ETAP) 11:30-11:55 Discussion for 100% RE achievement in Barbados 11:55-12:00 Closing Remarks
4. Participants	Electrical engineers and officers concerning RE and grid planning and analysis from MEB, FTC, BL&P, and UWI. Nos: no limitation * Joint seminar with St. Kitts and Nevis	Electrical engineers and officers concerning RE and grid planning and analysis Nos: 1-2 from MEB, FTC, BL&P, UWI each * Appointment of electrical engineer who has background of power system engineering is welcomed since this session is to conduct grid simulation exercise.

Characteristics of VRE



Wind Output



PV output

Wind
- Unpredictable generation output change
- produce ramps according to weather condition
- Depending on geographic areas, fluctuation comes at once if it installed in the same valley

PV
- No output in night-time and rainy day
- Large fluctuation in tropical climate (likely to change 80% in a minute)

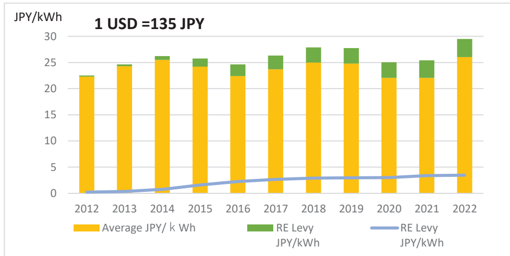
Both (VRE):
- It does not always generate when needed. **Load-supply matching** is an issue
- Time coincidence of VRE, there can be times when there is too much supply. Curtailment of VRE is necessary
  →**energy storage/control cost need to be considered.**

Caribbean Islands:
- Lower cost than tariff →rapid private investment
- Limited area for transmission
- Frequent change of weather condition
- Limited stable RE (hydropower/geothermal)

Challenges for
- **Cost for stability** : who covers?
- Technical and regulatory matters

Power Tariff and RE Levy

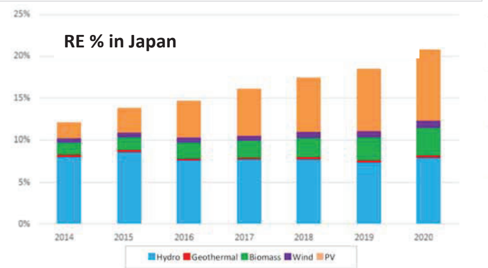
Is the increase in RE penetration so far helping or hurting electricity price?

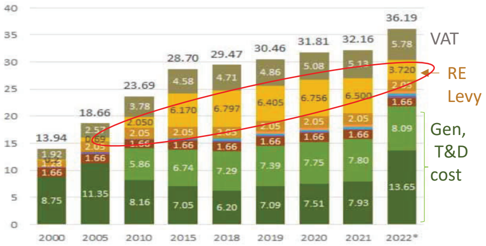


Power Tariff in Japan (JPY/kWh)

In case of Japan…
- **VRE Percentage: approx. 10% in 2021**
- **RE Levy is approx. 10% in 2020-21**
- **10% VRE in kWh base is 20-50 % of VRE capacity base**
- **RE Levy (additional tariff/kWh for RE cost) is likely to be proportional to VRE percentage**
- **Stabilization cost > fuel saving**

→Future ??





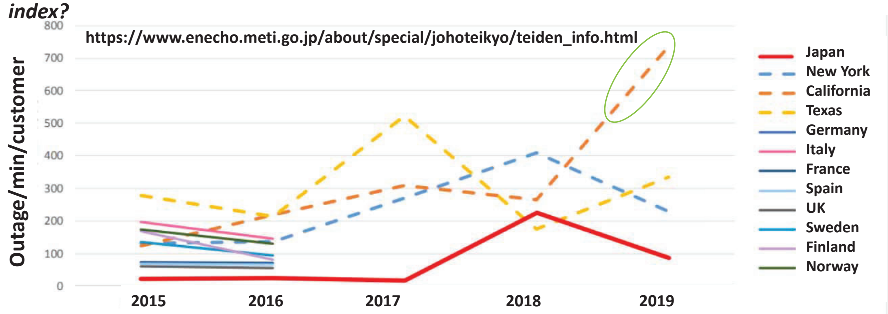
Power Tariff in Germany (Usc/kWh)

Prepared by JET from METI and Enetech data

https://www.de-info.net/

Outage trend and VRE affect on Outage

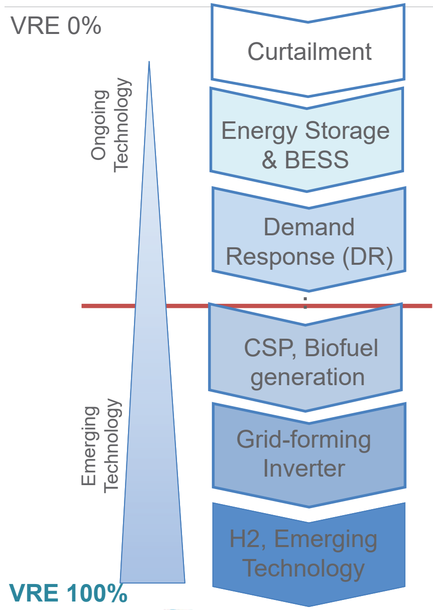
Has the increase in RE penetration begun to affect the momentary interruption(MAIFI) index?



- At present, no momentary interruption is caused from large RE penetration
- In Japan, RE have not yet affect outage but sever weather like typhoon affected
- 28 Sep 2016 South Australia grid with50% Wind . Wind power is disconnected due to thunder and transmission damage → Blackout for 850,000 customer
- California (CAISO): 32%RE in 2019. 14-15 Aug 2020 Load Shedding due to large scale introduction of PV and halt of coal/gas power plant and heat wave in evening

https://ieei.or.jp/2020/09/yamamoto-blog200914/

Arrangement toward 100% RE



Voltage and frequency Stabilization

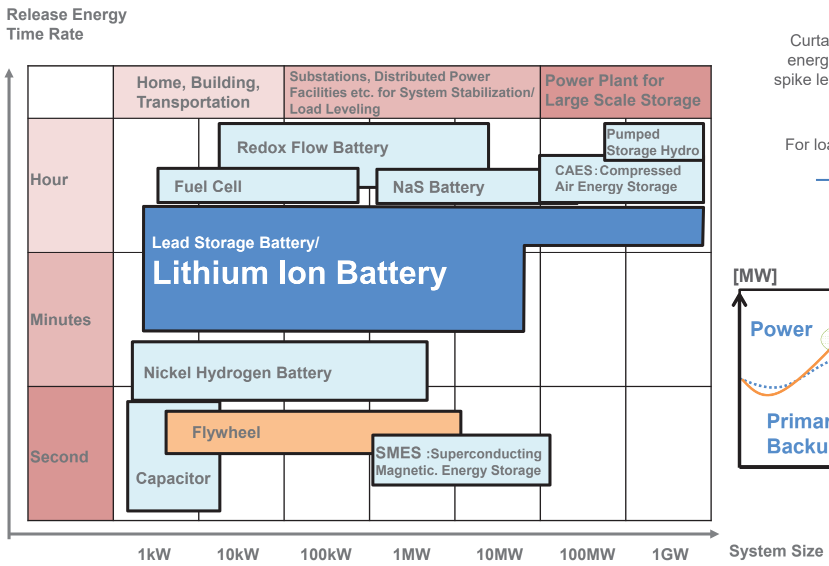
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- **Synchronous condenser, Statcom**
- EV charging time shift
- Demand side management
- Regulatory framework change, **review of grid code**

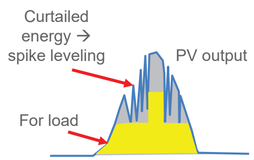
Insufficient Inertia, Synchronizing Force

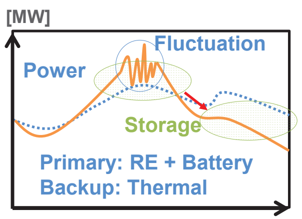
- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale storage

Battery and Energy Storage

Positioning for Energy Storage Technology

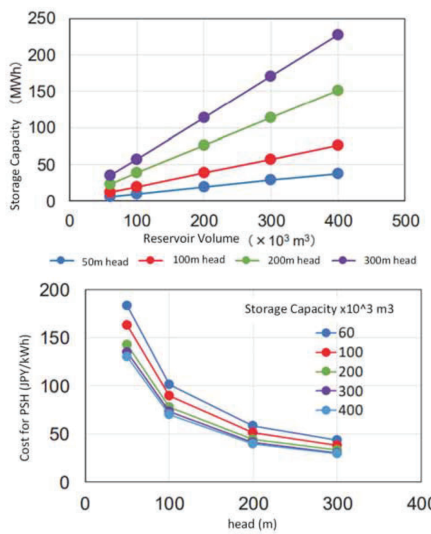






Source: NEDO Renewable Energy Technology White Paper Chapter 9

Pumped Storage vs Li-Battery



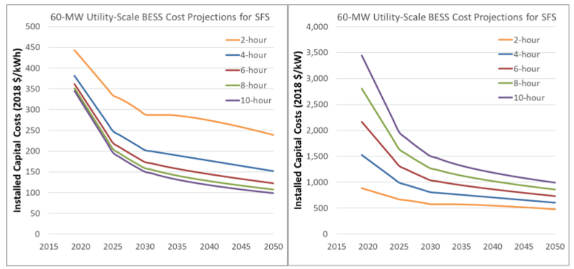
Note: headrace 1500m is assumed for head 200m

Source: Potential Capacity and Cost of Pumped-Storage Power in Japan Strategy for Technology Development Proposal Paper for Policy Making and Governmental Action toward Low Carbon Societies, LCS-FY2018-PP-08, 2019

Is pumped storage considered an economically viable technology option and what are the challenges?

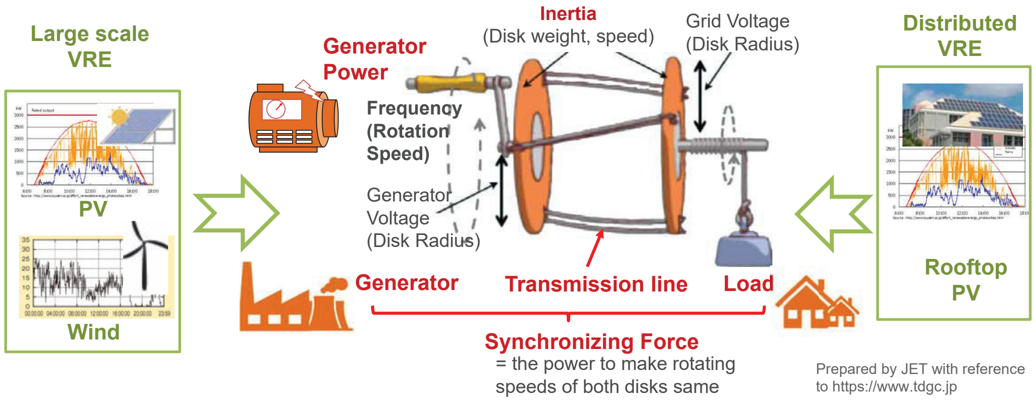
- Challenges: Topology and water. Higher head, lower cost: 700USD/kWh@100m, 350USD/kWh@200m (100,000m3) .
- Long lead time, Environmental Impact Assessment
- Advanta40-50 years life, black start possible
- LiB : 350-450USD/MWh @2022 (for 60MW scale), Cycle: 5000-20,000 @DoD 80-90%

DoD: Depth of Discharge



Source Utility-Scale Battery Storage | Electricity | 2021 | ATB | NREL

Inertia and Synchronizing Force with RE



Prepared by JET with reference to https://www.tdgc.jp

Inertia: The force to keep the rotation of disk when load is changed

Synchronizing Force: The force to keep rotation speed of disks. It keeps back to the same rotation when generation power and load is varied, without entangling.

Fluctuation of large scale VRE affects to generator at generation side and load side

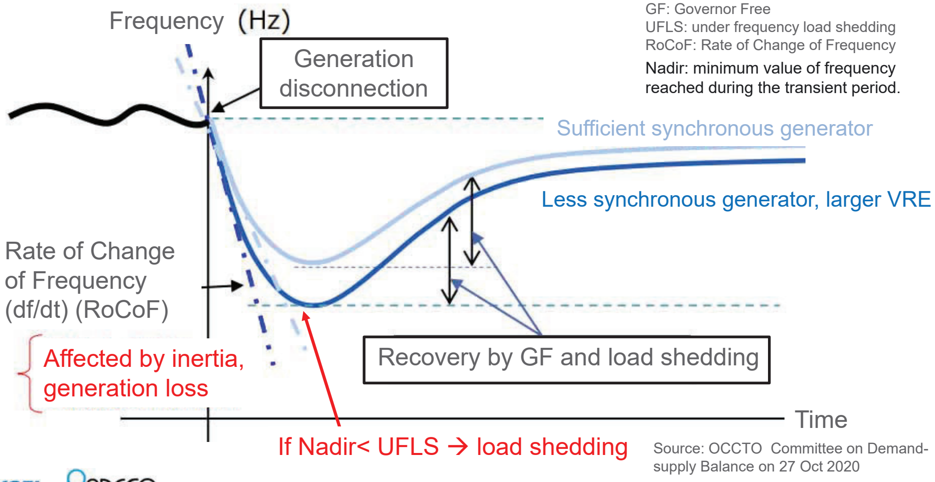
→ Inertia and Synchronizing Force need to be enhanced for grid with large VRE

Inertia and Synchronizing Force with RE

Synchronous generator: The power source establishes voltage and frequency with reactive power, and combines with generators by synchronizing force

VRE/BESS with inverter: DC converted to AC. There is no rotation, no synchronizing force. It monitors grid AC voltage and wave and adjust accordingly → no contribution for stability

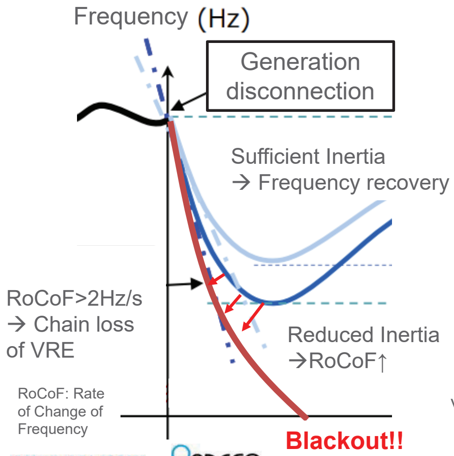
GF: Governor Free
UFLS: under frequency load shedding
RoCoF: Rate of Change of Frequency
Nadir: minimum value of frequency reached during the transient period.

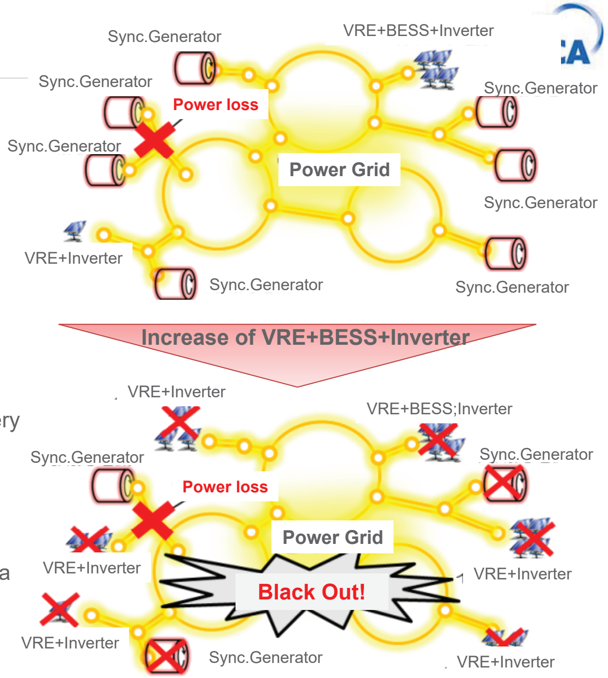


Source: OCCTO Committee on Demand-supply Balance on 27 Oct 2020

Black-out when insufficient Sync. Gen.

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





Source: Transmission and Grid Council, Japan

SCO and STATCOM for Reactive Power

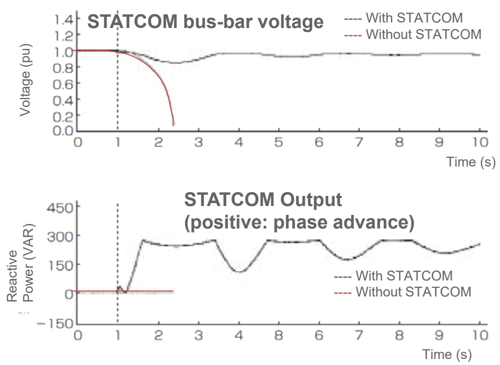
SCO (Synchronous Condenser) :

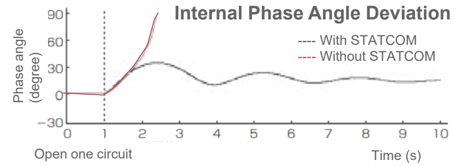
SCO is DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. Though changing field excitation, SCO adjusts reactive power and provides reactive power at the time of voltage drop.

https://energy-shift.com/news/af737655-0462-4655-81ae-b17d86b5784d

STATCOM (STATic Var COMpensator) :

For compensation of reactive power, it generates/absorbs reactive power, and stabilize voltage continuously at high speed by self-commutated inverter.





Source: Enhancement of Steady—State Stability and Suppression of Over—Voltage using 450MVA GCT—STATCOM, Mitsubishi Denki Giho, pp.52-55, Vol.87, No.11, 2013.

https://www.hitachi.co.jp/products/energy/STATCOM/about/index.html

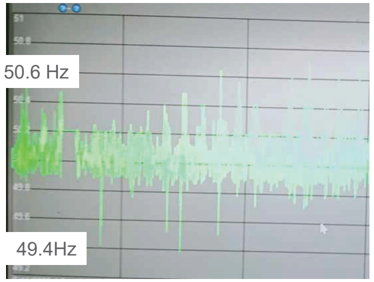
Emerging technology for large RE with Grid stabilization : Generation with Inertia and Synchronous Power

Type of Technology		Advantage	Develop stage
 Source: taiyo-electric	Motor generator (MG)	- Energy in battery provides synchronization and inertia - Small scale supply, for micro grid	- Used as frequency conversion - Commercial operation
 energyvault.com/gravity	Gravity Storage Battery	- Gravity of recycled Concrete block 35ton/nos - Provides inertia - Half cost of Li-ion battery	Pre-commercial, 35 MWh, 4MW per tower η=85% 52.5GW planned in USA
 /www.nedo.go.jp/news/press/AA5_100756.html	CAES (Compressed air energy storage)	- Compressed high pressure air - (Liquid air may be developed) - Provides inertia	-demonstration by NEDO - 900 MW in California - η=70-80%
 electrek.co/	CSP (concentrating solar power) Solar thermal	- With turbine, provides inertia and synchronization - Cost decrease expected, higher efficiency than PV, η=50%	- Commercial operation at Ivanpah392MW 22 bil USD - Heat storage (molten solt, etc) under development
 Source: CIGRE	Grid-forming inverter	- Dynamic active/reactive power, FRT, frequency control, inertia - Applicable to existing PV - (Smart Inv: FRT, VRT, voltage support)	- Under development - (Smart inverter by IEEE1547, Mandatory in Hawai)

Consideration for Larger VRE/BESS Penetration

- Increased application of PV and Wind :
  - Is Battery sufficient measurement?
  - To what extent can utility scale PV and wind be operated without affect on grid power quality?
  - How much can a feeder accommodate distributed PV and BESS?
  - What kind of equipment and measurement is necessary to accommodate VRE without interruption of grid?

- Planning with **grid simulation** is necessary.
  - Load flow analysis
  - Stability analysis
- Grid code needs to be checked for condition of grid connection of VRE and BESS



Example of frequency fluctuation with VRE

Session No. 1

1. Project Outline and Large RE
2. **Review and Feedback of 2nd seminar**
3. Microgrid Concept
4. Why Grid Stability is necessary

Feedbacks for the 2nd seminar in 3-5 Oct 2022

	Question	Feedback
1	What is the challenges to solve to achieve 100%	• No detailed engineering plan. Understanding of grid stability is not linked to penetration of RE sources → Investment for stability is necessary. • Most economical way to compensate fluctuations caused by the intermittent energy from PV Generation. → BESS? Pumped Storage? CASE? Gravity? • Concern: Spinning Reserves still need energy source as the Battery Storage Systems lack inertia, Bio Fuels can work but may cause areas reserved for crops, converted to produce fuels. → GFM may be solution. • The frequency and transmission capacity of the electrical lines will be the challenges. Either with batteries to control the regulation of frequency from electrical output→ Plan with grid simulation • We need a mix of more biomass resources, (liquid or gaseous to provide transition from quick response BESS to solid biomass generation) → Yes.
2	What you would like to know more details in the seminar components	• Where to add storage (On Transmission or Distribution System)? How much storage? → Included in later session. • Load Flow; Frequency Control → Included in later session. • More discussion in distribution circuit challenges- as this is where most of our RE is connected. Understanding of how practically measures to address stability challenges are implemented. → Included in later session. • The effect of hurricanes on small island states that is 100% renewable when everything is destroyed? → Included in later session. • What systems can the customers implement to improve the power fed to the utility to improve grid stability. → Demand response, storage, smart inverter

Feedbacks for the 2nd seminar in 3-5 Oct 2022

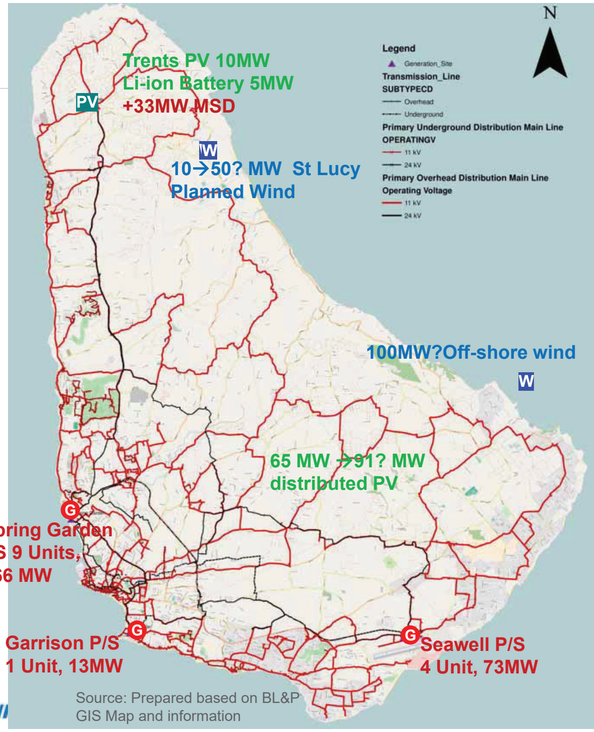
	Question	Feedback
3	Particular topics/challenges of grid stability, RE, and others that you would like JICA Team to include in the next Seminar	• Battery Storage; Use of Grid Modeling Software → Included in later session. • Where to add storage? How much storage? → Included in later session. • applicable technology that can be used for implantation → ditto • More exercises on manual calculations on grid stability. More information about the algorithms that may be implemented in software, including appropriate numerical methods. Development and analysis of microgrid models and scenarios → Included in 2nd day session. • Bus Admittance Matrix and Newton Raphson Method →Please see textbook introduced in 2nd seminar for more in detail • To expand more about grid stability and large scale renewables. Using a model for grid stability and RE penetration → Included in later session • Changes/additions that can be made to existing RE installations to improve the Grid Stability. → discussed in later session. • What can utilities, which are operating a radial power system, do specifically to accept DG from VRE with minimal disruption and negative impact on reliability. • → Investment for stability, update of grid code, securing spinning reserve
4	Advise JICA Team if there is necessary improvement	• it would be good to have practical scenarios for example, the local impact on voltage of adding RE, the best approach to recognizing this before connections and options to address such challenges. → discussed in the later session • more exercises to help reinforce the information supplied. • a qualitative description of possible practical solutions and more focus/hands on practice with using the various models. → to be conducted 2nd day session.

	Question	Feedback
A1	Place, capacity and function of Battery	• For large PV station, battery is effective to decrease the fluctuation caused by uncertain change of sunshine. • For small PV such as roof top home PV, battery had better to be located to neighboring substation with another roof top PV. • Distribution line should be decided as satisfying its capacity, in order not to be over even if maximum output of PV. • State of Charge(SOC) had better to be controlled using Battery Energy Storage System which has advanced function of Battery such as keeping SOC to 80% of maximum capacity to avoid the deterioration of battery.
A2	Benefit of GFM(Grid Forming Inverter), its size and quantity	• GFM(Grid Forming Inverter) is a voltage source inverter. • It controls to keep output voltage and its frequency, and supply virtual inertia to grid. • GFM is better to apply generation resources such as PV, WT(Wind Turbine), EV(Electric Vehicle) and Battery. • Grid forming inverter is still emerging technology, which is under demonstration stage. • It will still take several years that comes into market. Thus no market cost is available yet, but the cost will not be much higher than smart inverter (grid following inverter) once it is developed, according to the research institute who is demonstrating.

	Question	Feedback
A3	Evaluation and Proposal of RE Installation Scenario	• IRRP includes consideration for grid stability with large RE, and proposed SCO (Synchronous Condenser) for grid for reactive power compensation. • Frequency control function is necessary to consider for the large penetration of RE. Synchronous generator type resource is required to control frequency. • PV, wind, BESS can not cope with frequency control. For IRRP, CSP (Concentrated Solar Power) which is synchronous generator is possible. • Meanwhile, grid forming inverter has that function and can provide synchronizing force.
A4	The total PV according to the IRRP (300MW)	• Thermal power or biodiesel (or biojet fuel) will be necessary to sustain spinning reserve for load (150 MW peak). Battery can cover fluctuation for short time. • The battery capacity (MWh) need to be sufficient to sustain fluctuation and peak shift from 300 MW PV. In addition, Battery wilt not be sufficient as permanent operation considering inertia and synchronizing force is not provided from battery. • At the time of severe weather or thunder or any disturbance, battery can not provide power to keep frequency once major power source is disconnected, thus spinning reserve from thermal power is necessary. • How much thermal generator spinning reserve is necessary is depending on the requirement how much grid wants to avoid power cut and blackout.

	Question	Feedback
A5	Do we need to provide spinning reserve for all RE?	• Ideally it is necessary to provide the same amount of spinning reserve as all uncertain RE. • Another way is the combination with SPS(Special Protection System). SPS detects abnormal system conditions and take predetermined, corrective action to preserve system integrity and provide acceptable performance avoiding severe accident. • Predetermined, corrective actions include load shedding and generator tripping.
A6	Can independent generator of large facility like hospital contribute stability?	• It is depending on rule. If reverse flow is allowed as normal operation, it can contribute to keep grid stable. • If the rule for independent generator stipulates, distributed resource must stop after accident. It can not supply to grid.

	Question	Feedback
A7	How is the PV output data included in power flow analysis?	• Injection current from connecter. • To be explained in this seminar
A8	It was unclear about the derivation of the Power Equation for the exercise.	• To be explained in this seminar.
A9	Restoration from Hurricane under 100% RE	• To be discussed in this seminar
A10	Nevis Geothermal Plant evaluation	• To be discussed in this seminar



Grid and Generation of Barbados

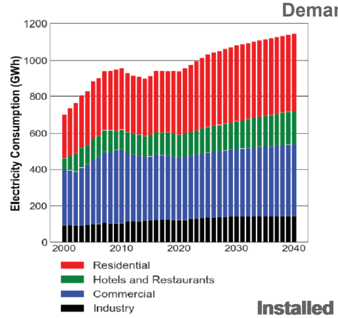
Location		MW/u	Qy	MW	Remark
Existing					
Total thermal power				265	
	Spring Field Total		9	166	LDS, ST, GT
	Garrison	13	1	13	Gas Tubine
	Seawell	13	1	13	Gas Tubine
	Seawell	20	2	40	Gas Tubine
	Trents	8.3	4	33	MSD Engine
Total PV				75.6	
	Trents	10	1	10	PV
	Distributed PV		LS	65.6	PV
Total Battery				5	
	Trents	1	LS	5	BESS
Planned					
Total Planned RE				208.5	
	St Lucy	50	1	10	Wind Planned
	Northeast	100	1	100	Off-shore wind
	St Tomas	30	1	30	Vaucluse Biomass
	PV	13	1	13	PV 52 MW+hydrogen
	Distributed PV		LS	25.5	Licensed yet installed
	PV IPP		LS	30	IPP by 2025

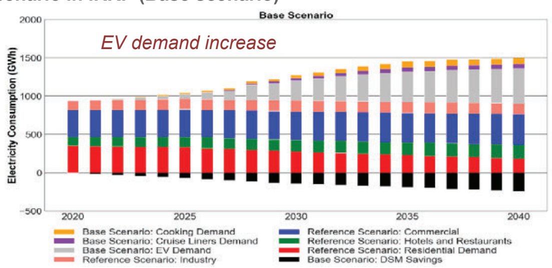
Tentative. Please let us confirm the status and update if any.

Plans of Grid and Generation up to 2030/2040 of Barbados

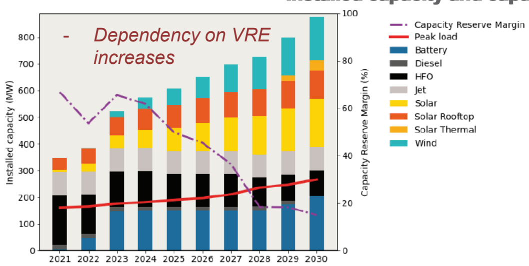
Source: IRRP Draft 2021, MottMacDonald

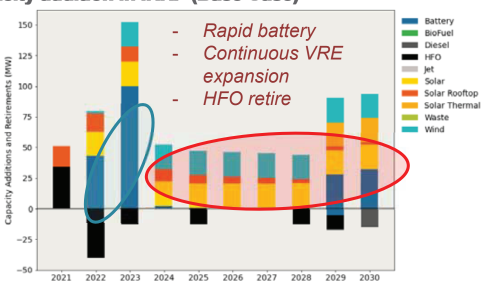
Demand Scenario in IRRP (Base scenario)





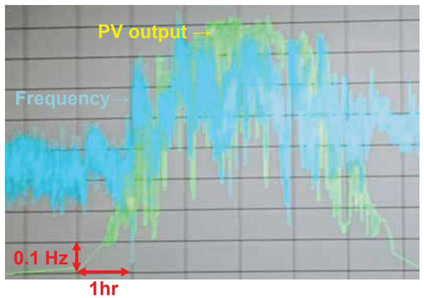
Installed capacity and capacity addition in IRRP (Base Case)

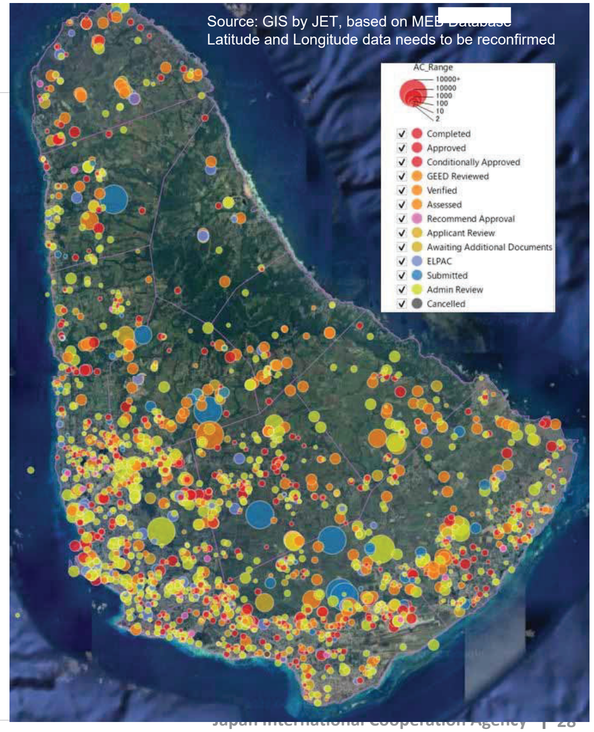




PV and Fluctuation of Frequency in Barbados

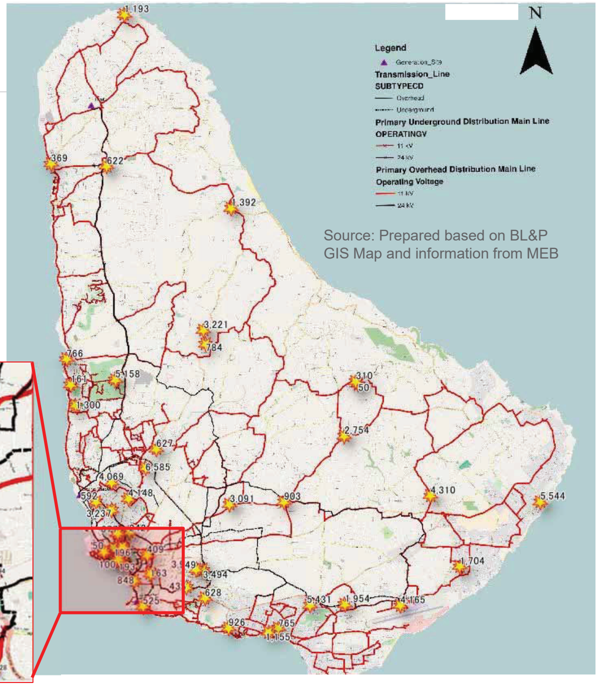
- Currently 65MW distributed PV, to be increased to 91MW.
- Frequency fluctuation
- It needs for confirmation of feeder holding capacity considering fluctuation
- Utility Scale PV is planned for future





PV and Feeder capacity

- Can the feeder accommodate distributed PV
- Distributed PV 65 MW at present , increased to be 91 MW near future
- Feeder-wise capacity assessment is necessary in grid simulation

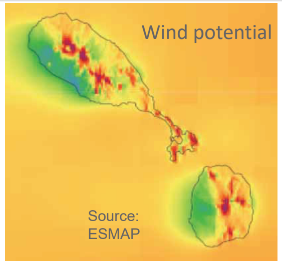


Source: Prepared based on BL&P GIS Map and information from MEB

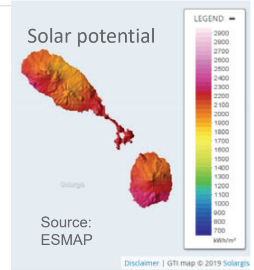
Present Situation and Future Plan of St. Kitts & Nevis

RE Projects in St. Kitts and Navis

Location/Project	Type	Capacity MW	Generation GWh estimated	Year
S: SCASPA	PV	0.7	NA	2013
S: SKELEC	PV	0.5	1	2015
N: Windwatt	Wind	2.2	5.25	2011
N: NREI Geothermal	Geo	**10-30**	NA	**2025**
S: Leclanche	PV	35	43.8	2020
S: Bellevue	Wind	5.7	NA	NA
S: NW Geothermal	Geo	18-36	NA	NA



Source: ESMAP



Source: ESMAP

Necessary consideration for future RE

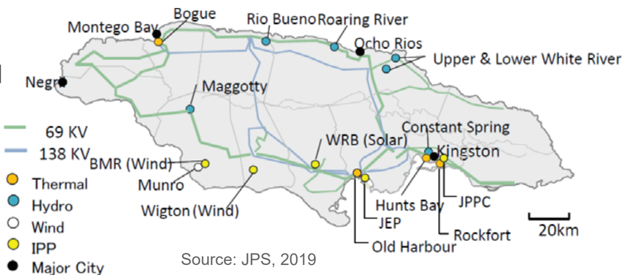
1) Grid stability analysis for new 35MW PV system
2) Update of geothermal development
3) Interconnection (11kV, 66 kV)?

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

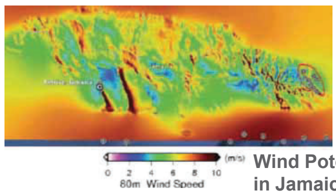
RE Status in Jamaica

Challenges for RE & Grid:

- ✓ Increasing RE capacity >15%. Grid stability and power cut issue
  - ✓ Feeder cut at 49.5 Hz
- ✓ System losses 26.3%(2018) →28.3%(2021)
- ✓ Large number of distributed PV, available database?
- ✓ Wind & PV potential unevenly distributed →less smoothing



Source: JPS, 2019



Wind Potential in Jamaica

Source: Sustainable Energy Roadmap 2013

VRE Projects in Jamaica

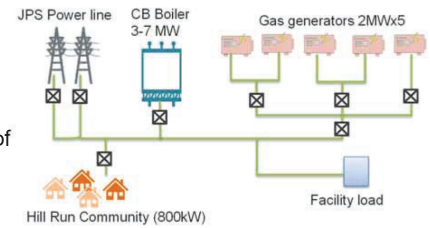
Location/Project		Capacity MW	Generation GWh estimated	Year	Tariff USc/kWh	Investment mil USD
Wigton Ⅰ	Wind	20.7	52	2004	10.21	26
Wigton II	Wind	18	47	2010	10.723	45
Wigton III	Wind	24	63	2016	13.4	46.5
Munro	Wind	3	10.5	2010	(JPS)	
BMR Wind	Wind	36.3	120	2016	12.9	90
Content Solar (WRB)	PV	20	34	2016	18.8	65
Independent roof-top	PV	20?			--	
Eight River (EREC)	PV	33.1		2019	8.5	
Wigton IV	Wind	34		?		
VRE under operation		**142**	**326.5**			

Source: Prepared by JET with several data sources

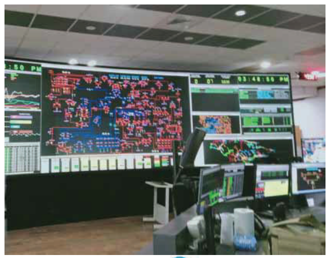
Difficulty due to VRE and Good Practice of Jamaica

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

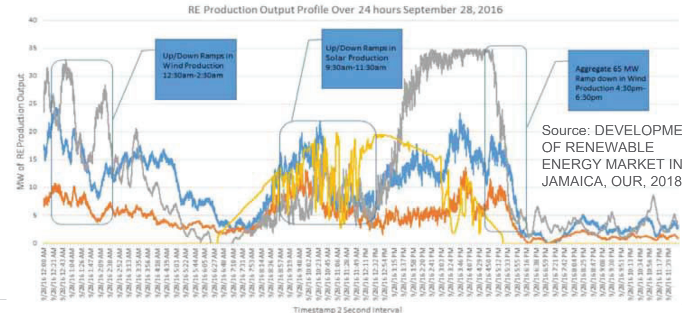
1. Application of 24.5 HESS (next page)
2. Demand projection >99% accuracy → base for efficient operation in System Control Center
3. AWS installed for weather projection and output forecast of PV and wind, utilizing satellite image → 90% accuracy. Remaining 10% is covered by spinning reserve.
4. Microgrid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



Microgrid with CHP for Caribbean Boiler



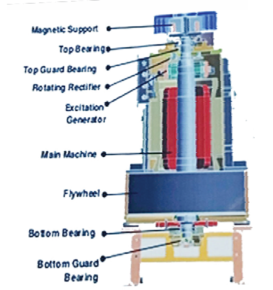
JPS System Control Center

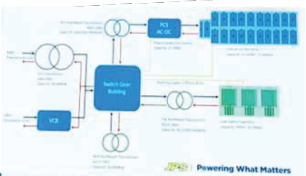


Source: DEVELOPMENT OF RENEWABLE ENERGY MARKET IN JAMAICA, OUR, 2018

JPS Hybrid Energy Storage System (HESS) of JPS in Jamaica

- **24.5 MW HESS (Hybrid Energy Storage System)** installed at Hunts Bay power station
- HESS stabilizes VRE output fluctuation (approx. 175 MW for 650 MW peak load, VRE is 15.2% energy base but capacity is 27.3% average peak, 39.6% at off-peak time)
- Flywheel absorbs small instantaneous fluctuation and prevents battery deuteriation
- Investment cost 27 mil USD





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

Item	BESS
Manufacturer	LG Chem (Korea)
Type	Li-ion
Module	128Ah, 92.3kWh
Capacity	21.5 MW, 16.6 MWh

Example of Grid Code

Country	UK	Ireland	Germany	Japan
Grid Code	The Grid Code	EirGrid Grid Code	Technical Connection Rules fore MV	Grid Code
Regulator	Ofgen (regulator)	TSO	VDE (Association)	OCCTO
Main Items of Grid Code	- Frequency and time for operation continue - Active power increase/ decrease at the time of frequency increase/ decrease - Active power Droop according to frequency change rate - Voltage, harmonic wave, flicker at nodes - FRT requirement at the time of voltage drop - Reactive power supply - Black start and Protection of grid and generators	- Frequency and time for operation continue - Active power decrease/ Increase at the time of frequency increase/ decrease - Governor control rate - FRT requirement at the time of voltage drop - Reactive power supply - Speed of power increase/ decrease with load dispatch order - Lower limit of load - Spinning reserve requirement	-Frequency and voltage that need continuous operation -Active power increase/ decrease at the time of frequency increase/ decrease - FRT requirement at the time of voltage drop - Reactive power supply at the time of voltage change - Active power limit at the time of large voltage change - Protection of grid and generators	(under preparation)

OCCTO: Organization for Cross-regional Coordination of Transmission Operators, Japan
FRT: Fault Ride Through

Recommendation for Future RE and Grid Plan

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

Resilience for RE

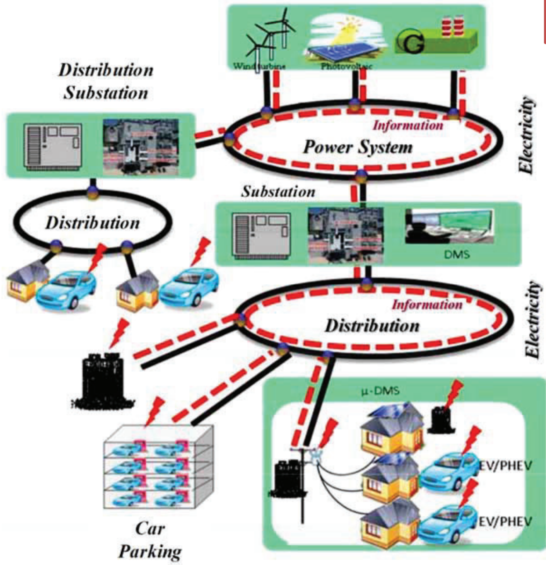
23 Aug 2018 Awaji, Japan
https://www.sankei.com/west/news/180828/wst1808280043-n1.html
600 kW, Fallen at 25.6m/s wind while 60m/s design
- Additional moment due to Excess of high speed
- Missing control power supply

9 Sep 2019 Kanto, Japan
@kadowaki_kozo
Damage of roof-top structure by high speed wind

26 Jul 2019 Himeji, Japan
https://www.dailyshincho.jp/article/2018/07260800/?photo=1
Landslide by a heavy rain

For enhancement of resilience:
- ✓ Design Standard with higher rank hurricane
- ✓ **Autonomous Micro-grid**

Microgrid Concept

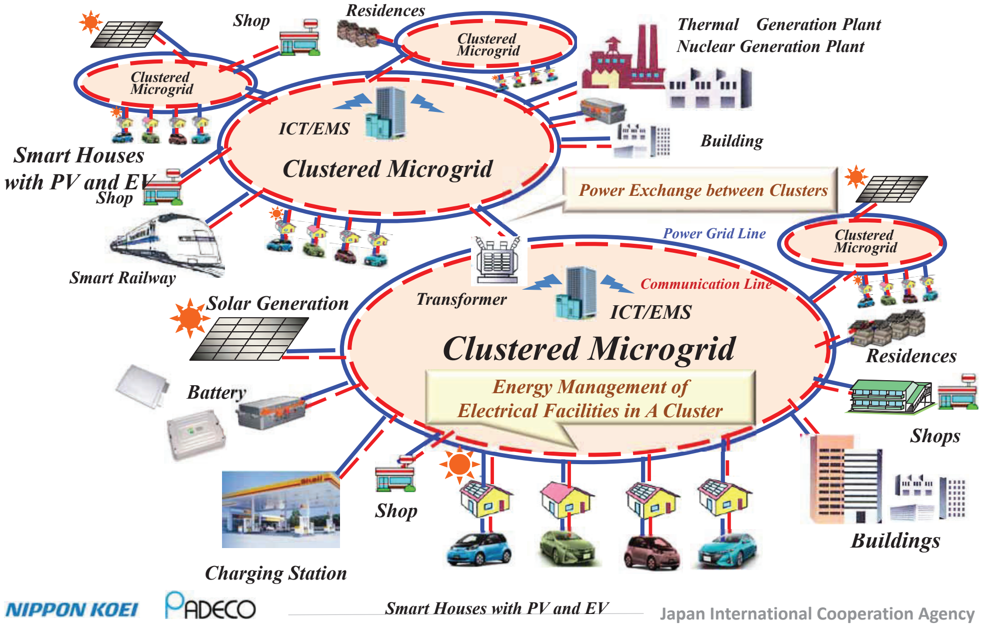


Concept of Micro-grid

- ✓ Respective Micro-grid is connected each other, and each Micro-grid can work independently
- ✓ Local energy production for local consumption
  - ✓ Generation: PV, wind, biomass, DG, GT, battery, etc.
  - ✓ Demand: industry, commercial, home, EV, etc.
- ✓ No transmission → loss saving
- ✓ With IoT, control system, EMS, demand response, smart meters
- ✓ Enhance resiliency

Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

Microgrid for Resilient System
-- Autonomous Micro Grid



Microgrid Planning

1 Study for legal requirement of regulators considering affect on transmission line outside of Microgrid
- Legal requirement for microgrid by the regulatory authority
- Method for emergency recovery, switching from microgrid to master grid, Affect on adjacent areas.

2 Estimation of load and demand at normal and abnormal condition in Microgrid
- Estimate demand of daily curve, total demand of the day/week / year, at normal and abnormal condition,
- data as much as accurate by each feeder.

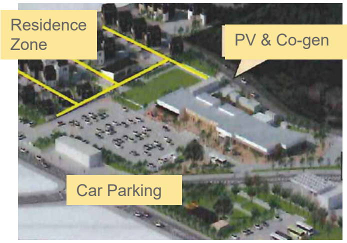
3 Plan for system structure of Microgrid in distribution lines based on demand
- Capacity of generator, and PV, design, selection of equipment.
- Preparation for emergency (load shedding, control, etc.)
- Protection and control method considering supply and demand

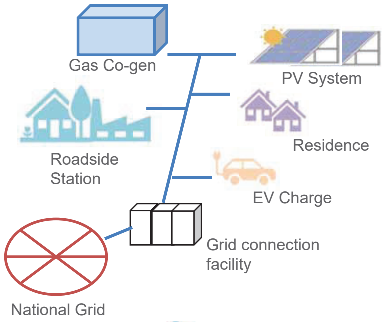
4 New system installation/enhancement for stabilization facility requirement for RE and supply-load balancing
- Plan RE facility with energy storage based on power demand
- Consider necessary stabilization equipment considering fluctuation and output instability.

5 System requirement and legal confirmation for inside and outside Microgrid
- Review regulation and rules including grid code for connection to transmission line
- Operation method at the time of emergency recovery and minimize outage

6 Finalization of system configuration and specification for whole Microgrid
- Based on supply-load balance, finalize system configuration &Spec
- Operation and EMS development, communication system

Microgrid Ex.-1: Mutsuzawa, Chiba, Japan





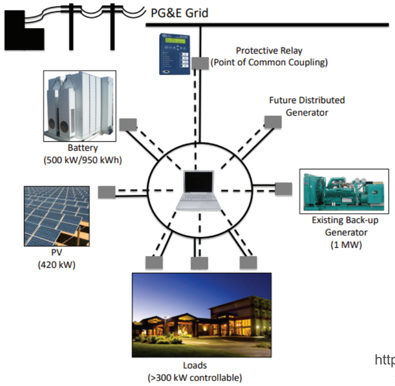
Mutsuzawa Road Side Station

- Gas co-generation (80kWx2), PV system (20kW), Solar heating (37 kW) EV charger,
- Independent power supply for residence zone
- Thermal supply for hot spring by co-gen
- Microgrid area connected with grid
- Continuous supply during Typhoon (large scale regional power cut approx. 1 week) in Sep 2019
  - 1000 utilized power supply, shower, toilet for emergency
  - Regional Disaster-prevention facility
  - All power lines are underground

https://www.env.go.jp/press/files/jp/113284.pdf

Microgrid Ex.-2: Blue Lake Rancheria, CA, USA

- Humboldt County, natural disaster-prone coastal area
- Completed in Mar 2018
- Optimized operation with PV and BESS with back-up DG
- At emergency, independent operation with seamless switching of disconnection/connection of main grid
- Demand response with load shedding for less important load at the time of supply difficulty
- Microgrid controller (EMS) controls independent operation 25%, <u>$170,000 of electricity saving</u> in 2018



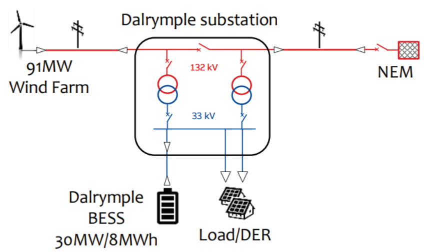
Component	Spec/details
Schedule	July 2015 – March 2018
Utility	PG&E
Generation	PV 420 kW and back up DG 1MW
Inverter	SMA TP30-TL-US10
BESS	500kW/950 kWh Tesla Powerpack
Control (EMS)	Siemens Spectrum Power TM MGMS
Project cost	USD6.32 million

https://bluelakerancheria-nsn.gov/wp-content/uploads/2018/11/BLR_Microgrid_FactSheet.pdf

Microgrid Ex.-3: South Australia Yorke Microgrid

https://www.electranet.com.au/new-battery-charged-and-ready-to-power-lower-yorke-peninsula/

- One circuit 132 kV line is connected to the area, which once had frequent outage and issue on reliability
- Autonomous microgrid, sifted to independent operation without outage, seamless islanding
- <u>91 MW Windfarm</u> provides power
- BESS provides <u>virtual inertia, reactive power compensation, and black start function</u>
- System provides <u>ancillary service</u> with frequency adjustment



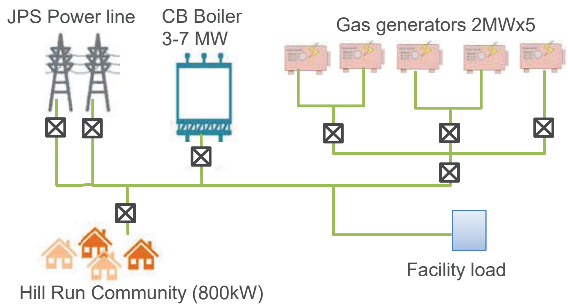
Grid Forming Energy Storage System addresses challenges of grids with high penetration of renewables (A case study), CIGRE, 2020

Items	Description
Utility	Electra Net
Area	Dalrymple, Lower Yorke, SA
Substation	Dairymple S/S 132/33 kV
Generation	91 MW Wind
BESS	30 MW/8MWh ABB
Project cost	30 mil AUD (of which 12 mil AUD is financed by ARENA)

Microgrid Ex.-4: Jamaica Caribbean Boiler-JPS

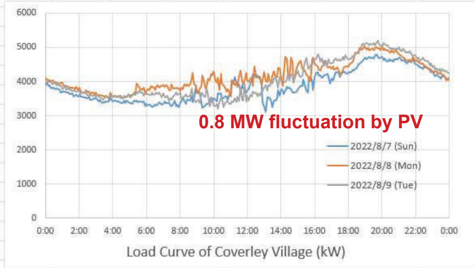
- Microgrid with Combined heat and power (CHP) generation plant and supply to community
- The exhaust heat converted into energy and improve efficiency
- improve its operational efficiency and reliability.
- 5 generators + CB boilers
- Provides power to Hill Run community
- <u>30% CO2 reduction</u> by fuel switch from heavy oil to LNG

https://www.cvmtv.com/news/major-stories/jps-and-cb-group-collaborates-on-new-power-plant/



Microgrid Concept in Barbados: Coverley Village

- 3 kW rooftop PV
- 5-7 MW additional PV BESS and EMS
- Data for load curve, transformer, distribution line information requested
- - Single line diagram
- - distribution line 11 kV (feeder length, size, type (ACRS or cable), impedance, resistance, capacitance, RLC
- Transformer location, kVA
- Interconnection with GAIA



Example of system, to be reviewed

Nos of houses	1026	nos
Roof area for PV	30	m2/house
Commercial/official roof	300	m2 (6 facilities)
Total roof area	31,080	m2
PV Capacity	3108	kWp
Specific PV generation	4.917	kWh/kW/day
PV generation energy	15,282	kWh/day
Peak demand	4,104	kW
Electric energy demand	41,329	kWh/day
External PV	6,622	kWp
BESS capacity	80	MWh
BESS output	4	MWh

3rd Seminar on Grid Stability and Large RE

Session No. 1

1. Project Outline
2. RE and Microgrid Concept
3. Review and Feedback of 1st seminar
4. Why Grid Stability is necessary

Why Grid Stability is necessary

- VRE connected through inverter. Most of PV and Wind Turbine are IBR (Inverter based resources)
- Response of IBR is faster than that of synchronous generator.
- IBR has less or no inertia compared to synchronous generator.
- The output of IBR changes according to the connected power resources such as sunshine or wind.
  - When IBR is connected to grid, IBR can not adjust output according to demand exactly. It requires support from other controllable power for the lack of power.

↓

- Increase or add inertia function to IBR for grid stability
  - Grid Forming Inverter
- Increase generators with large inertia for grid stability
  - Inertia Resources provided by
    Synchronous generators:
    Thermal Power, Hydro Power, Nuclear Power
    Renewable Synchronous generator:
    Biomass, Waste-to-Energy, CSP(Concentrated Solar Power)

Objective of Grid Stability Seminar

- To recognize possible issues and necessary examination items for future grid with large VRE (variable renewable energy) penetration
- To share knowledge of basic of power system analysis to examine future grid challenges
- To discuss about innovation for power system for stable power supply with large VRE

* Data used in the grid stability analysis of this seminar is based on assumption and the result is as an example, not for actual planning purpose.

Role of Us: Power System Engineers

- Supply stable electricity to all the customers without interruption
  - With avoiding power cut, outage or damage on equipment and power appliance
  - With no failures or minimize failures
  - By Minimize the influence of disturbance after faults
- Keep the quality of electricity with
  - Constant voltage
  - Constant frequency
  - Less distortion or harmonics

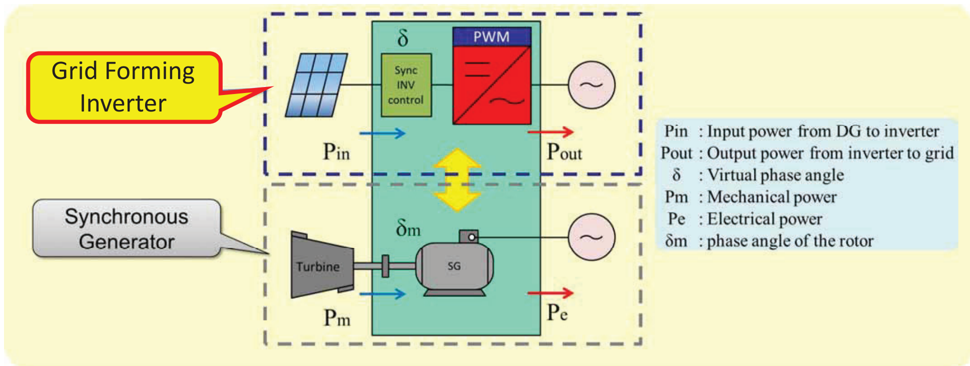
Simple Method of Grid Stability Evaluation

- For steady state stability
  - **Can large amount of RE be installed in the present/planned power system?**
  - Apply Load flow analysis:
    - If we reach at the normal load flow state, actual system is also considered to be stable.
    - From load flow results, adequacy of power flow of transmission line can be assessed. It is evaluated with the maximum capacity of transmission line.
- For transient state stability
  - **Is power system with large amount of RE stable or not, when instantaneous RE fluctuation happens?**
  - Apply Equal Area Criterion:
    - Power system stability under disturbance can be calculated by using acceleration and deceleration energy.
    - Available Transmission Capacity and Spinning Reserve can be calculated briefly.

Base for Evaluation of Grid Stability

- Resource of Virtual Inertia
  - **VRE with Grid Forming Inverter (1)**
  - EV(Electric Vehicle) with Grid Forming Inverter for V2G
  - Virtual Power Plant
- Evaluation Items of Stability
  - **SCR**(Short Circuit Ratio) (2)
  - **ATC**(Available Transmission Capacity) (3)
  - **Spinning Reserve (4)**
- Tools for Analyzing Grid Stability
  - Load Flow Analysis to check available condition
  - Stability Evaluation by EAC(Equal Area Criterion)
- **Microgrid** for Grid Stability
  - Decrease power supply of utility transmission lines
  - Monitor load flow by smart meter accurately
  - Pilferage location may be estimated through State Estimation

(1) Grid Forming Inverter for VRE



Source: M. Kawai, Y. Sakai, H. Sugiyama, H. Taoka "Frequency Improvement of a Power System with a Distributed Generator using Synchronization Inverter," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), CIGRE SC C6 Colloquium, Sep. 2015.

Control Algorithm for Grid Forming Inverter

The control method of Grid Forming Inverter is expressed by the swing equation.
This equation is added damping term and synchronizing power term.

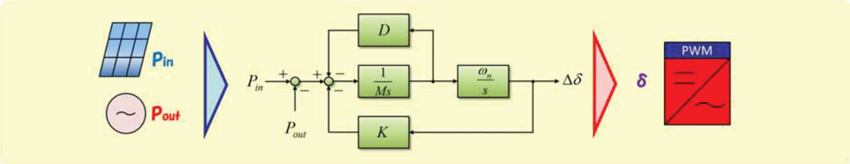
$$\frac{M}{\omega_n}\frac{d^2\delta_m}{dt^2}+\frac{D}{\omega_n}\frac{d\delta_m}{dt}+K\delta_m=P_m-P_e$$

This swing equation of the Grid Forming Inverter is solved for virtual phase angle δ.

The transfer function of voltage value

$$\delta=\frac{\frac{1}{M}\omega_n}{s^2+\frac{D}{M}s+\frac{K}{M}\omega_n}(P_{in}-P_{out})$$

M:Inertia
D:damping Factor
K:synchronizing Factor



Source: M. Kawai, Y. Sakai, H. Sugiyama, H. Taoka "Frequency Improvement of a Power System with a Distributed Generator using Synchronization Inverter," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), CIGRE SC C6 Colloquium, Sep. 2015.

GFL(Grid Following Inverter) & GFM(Grid Forming Inverter)

- GFL(Grid Following Inverter)
  - Current Source Inverter
  - Control output current as adjusting voltage and frequency to grid
  - No supply of synchronizing force.
- GFM(Grid Forming Inverter)
  - Voltage Source Inverter
  - Virtual Synchronous Generator
  - Control output voltage and its frequency as adjusting power to grid's
  - Supply Virtual Inertia to Grid
  - Power resource: PV, WT(Wind Turbine), EV(Electric Vehicle), Battery

ref) "GC0137: Grid Code Modification Proposal Form"
- National Grid, UK, 25 Nov., 2021
- This grid code is the first one in the world that includes the requirement about Grid Forming Inverter.

(2) SCR(Short Circuit Ratio)

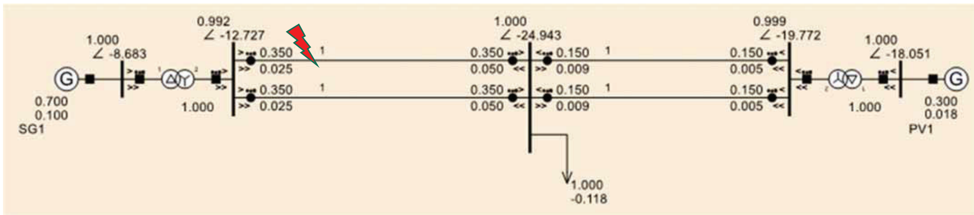
- SCR is the factor to be considered in large RE penetration for grid stability.
- SCR=AC System Capacity/Rated IBR Capacity
  - SCR>3 -------- High SCR, Stable
  - 3>SCR>2 ----- Low SCR
    Small fluctuation continues.
  - 2>SCR -------- Very Low SCR
    Sensitivity of IBR to Grid goes high.
    Grid is unstable that may bring blackout.

ref) "IEEE Std 1204-1997(R2003)", IEEE, 2003
- IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities
- Recognized by ANSI(American National Standards Institute

https://ieeexplore.ieee.org/document/653230

SCR(Short Circuit Ratio) Evaluation Model

- PV: Modelled by virtual low inertia synchronous generator
  - Inertia=0.1 (right side generator)
- SG: high inertia conventional synchronous generator model
  - Inertia=10.0 (left side generator)

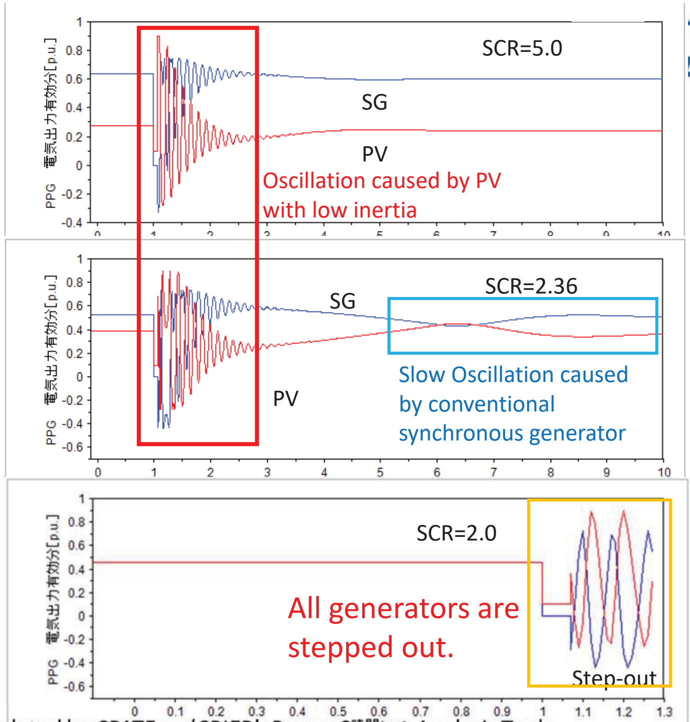


Calculated by CPATFree(CRIEP's Power System Analysis Tools

Difference of SCR value

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

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



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Sources for High SCR Grid

- Following resources can supply inertia to grid.
  - V2G(Vehicle to Grid) of EV(Electric Vehicle) with Grid Forming Inverter
  - BESS(Battery Energy Source System) with Grid Forming Inverter and SOC Control.
    - SOC Control is required to realize Grid Forming Inverter.
  - Biofuel Generator
  - Solar Thermal Generator
  - **Renewable Energy Resources (PV, WT) with Grid Forming Inverter**

(3) ATC(Available Transmission Capacity)

- Transmission capacity needs to be calculated to see whether RE can be transmitted from source location to demand place.
- Available Transmission Capacity from Heat Capacity Limit

$$P_{loss} = R * \left(\frac{V_i}{X}\right)^2 < P_{\mathrm{LOSSMAX}}$$

- Available Transmission Capacity from Transient Stability

$$P = \frac{V_i V_j}{X} \boldsymbol{sin\delta} \quad \rightarrow \quad P_{\mathrm{ATC}} = \frac{V_i V_j}{X} - P_{\mathrm{OP}}$$

R: Transmission line resistance
X: Transmission line inductance
V_i, V_j : Sending Voltage and Receiving voltage, 2)
P_{loss} : Transmission line loss by line Resistance R and line inductance.
$P_{LOSSMAX}$: Capacity Limit of transmission line
P_{ATC} : Available Transmission Capacity
P_{OP} : Operating Power

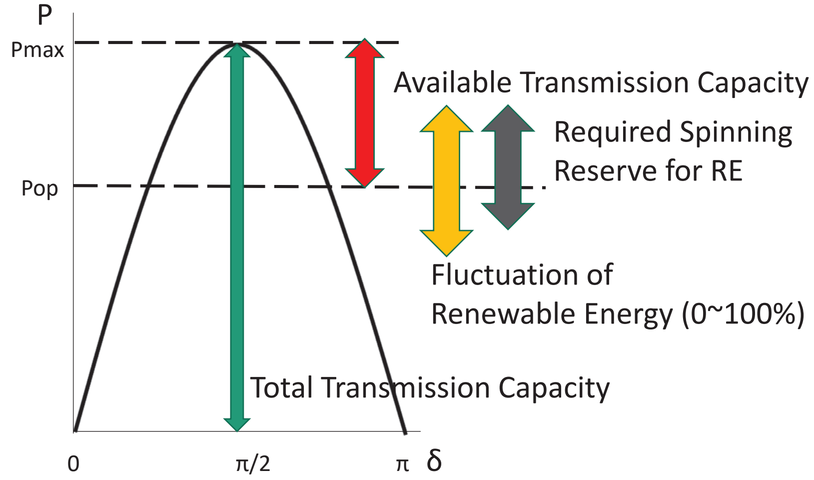
(4) Spinning Reserve

- In order to get electrical power under abnormal condition of grid, spinning reserve should be kept even if VRE is installed.
- Spinning reserve should be more than total fluctuation of load and VRE.

  -> RE, EV and Battery with inertia is required for large RE penetration.
- Best Energy Mix

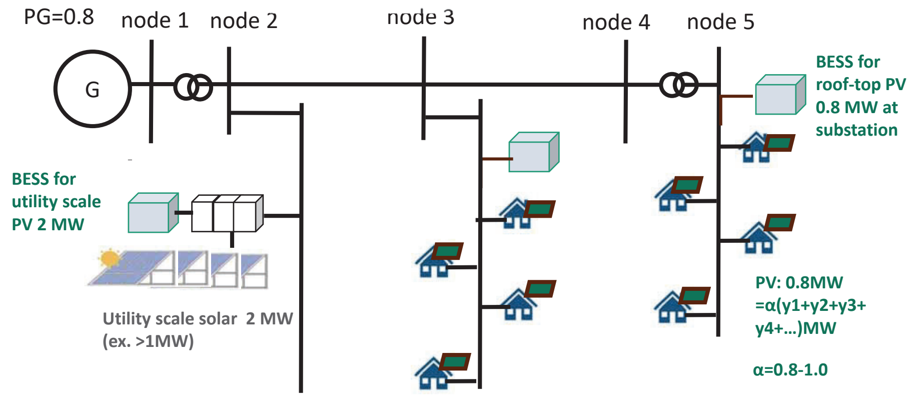
  -> Energy mix of several resources is highly recommended for improving grid stability.
- **RE Sources for Spinning Reserve**
  - **EV, Battery, Fly Wheel -> Short period, Quick response**
  - **Biofuel or Diesel Generator -> Long period, Slow response**

Available Transmission Capacity & Spinning Reserve



Where to add storage? How much storage for VRE?

BESS had better to be set to substations where place BESS at a nearby substation with other PVs.
If the capacity of PV system is large, BESS had better to be set close to PV system.



Evaluation of VRE Installation

- **To know how much we can install PV or WT in a particular power line**
  - **Load Flow Analysis**
  - If you get the answer of load flow such as node voltage and transmission line power, this case is stable.
  - If you cannot get the solution, that case cannot be in real.
- **To know whether RE installed grid is stable**
  - Search operating point through **Equal Area Criterion**
- **To know how much we can install RE**
  - Estimate ATC(Available Transmission Capacity) by **Equal Area Criterion**
- **To know how much spinning reserve is necessary**
  - Maximum capacity of RE

Capacity Guideline for VRE

- The amount of PV output should be under **ATC(Available Transmission Capacity)** in transmission line.
- Maximum PV output should be covered by other generators for the case of its ramping by weather change. The capacity of generators to cope with the ramping in the grid is of **Spinning Reserve**.
- PV fluctuation can be covered by **smoothing effect** if PV systems are installed at different locations among wide area.
- RE with Grid Following Inverter should be **less than 30%** as described in the guideline* about **SCR(Short Circuit Ratio)**.

*IEEE Std 1204-1997(R2003)

Session No. 2
Grid Modelling

<Current if>

- Total Demand: 200MW
- VRE(PV & WT): 46MW
- Distributed PV is 10~20MW

66MW -> 33% of Demand
It is Stability Limit in terms of SCR

- VRE with GFL: Limit is 66MW
- VRE with GFM: VRE over 66MW should be operated by GFM.
- Battery: BESS 1MW*4h / VRE 3MW
  = 4MWh*66/3 = 88MWh (Expected Value)

Cost of RE and Stabilization

PV: US$ 570,000~720,000/MW
SCO(Synchronous Condenser):
US$ 140,000~220,000/MVA（20~30% of PV）
Battery： US$ 400,000/MWh (BESS 1MW*4h / VRE 3MW)

For PV:1MW, SCO(Synchronous Condenser):1MVar, Battery:1.33MWh
PV: US$ 700,000/MW
SCO(Synchronous Condenser): US$ 200,000/MVA
Battery: US$ 400,000/MWh*1.33
(1.33=BESS 1MW*4h / VRE 3MW : Expected Value)
Total: US$ 1,432,000

Cost of RE and Stabilization

PV: US$ 570,000~720,000/MW
SCO(Synchronous Condenser):
US$ 140,000~220,000/MVA（20~30% of PV）
Battery： US$ 400,000/MWh

For PV:66MW(=200*0.33),
SCO(Synchronous Condenser):66MVar, Battery: 88MWh
PV: US$ 700,000/MW*66MW
SCO(Synchronous Condenser): US$ 200,000/MVA*66MW
Battery: US$ 400,000/MWh*1.33*66MW
Total: US$ 1,432,000*66 = 94,500,000

Cost Comparison of Reactive Power Generating Equipment and Sources

Reactive Power Generating Equipment's and Sources	Investment Cost		
	Capital Cost (per kVAR)	*Operating Cost*	*Opportunity Cost*
Capacitors/Reactors	$10-30	Very Low	No
Synchronous Generators	Difficult to separate	High	Yes
STATCOM	$50-100	Moderate	No
Static VAR compensators	$40-100	Moderate	No
Synchronous condensers	$10-40	High	No

Famous O. Igbinovia, Ghaeth Fandi, Zdenek Müller, Jan Švec, Josef Tlusty,
"Cost implication and reactive power generating potential of the synchronous condenser"
2016 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG)

Cost Benefit Comparison between Capacitors and Synchronous Condensers

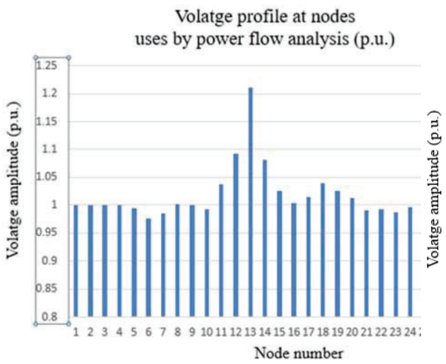
Costs and Benefits ($/year)	Capacitor Banks (5.0 MVAR)	Small Generator Retrofitted to Synchronous Condenser (5.0 MVAR)
Capital Cost	$22,000	$50,000
Technology Life Time	10 years	20 years
Preventive Maintenance Cost	$6,000	$3,500
Cost of Voltage Regulator Maintenance	$6,600	$3,300
Annual Cost in Present Value	$14,800	$9,300

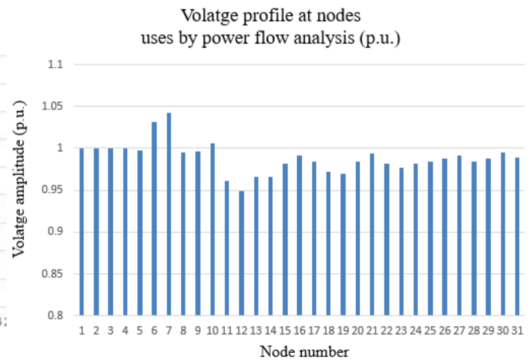
Famous O. Igbinovia, Ghaeth Fandi, Zdenek Müller, Jan Švec, Josef Tlusty,
“Cost implication and reactive power generating potential of the synchronous condenser”
2016 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG)

Location of Batteries

- For WT(Wind Turbine Generator)
  - The capacity of WT is large comparing with other RE.
  - In case utility scale WT is installed in the future, BESS had better to be set close to WT.
- For PV system
  - 1/3~1/2 of total PV capacity are assumed as rooftop PV.
  - The BESS for distributer PV systems should be placed at upstream substation to which those distributed PVs are connected.
  - If the capacity of PV system is large, BESS had better to be set close to PV system.

Load Flow Analysis of Barbados Grid by Microgrid Designer (for Battery)





Effect of Battery

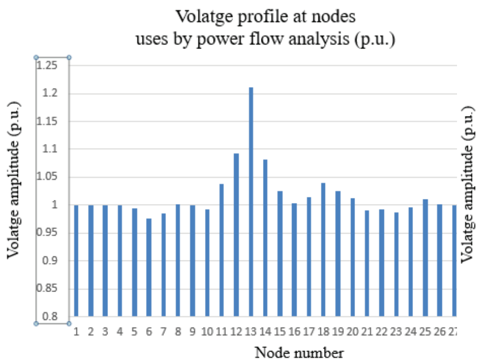
without Battery in end nodes — with Battery in end nodes

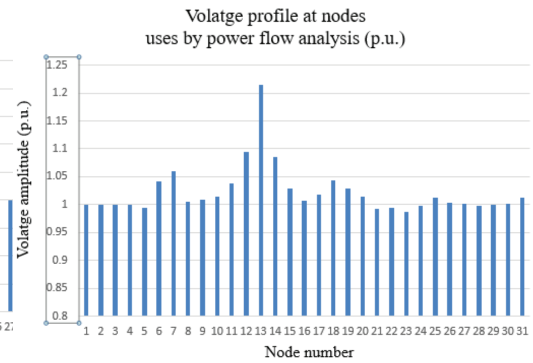
Wind turbine is located at node 13, which is north east area.
Because of no measures in an estimated grid, the voltage is high.
Battery is a good solution to keep grid voltages as appropriate values.

Location of Compensators

- Compensators include SC(Shunt Capacitor), SCO(Synchronous Generator), SVC and STATCOM(Static Var Compensator), and other FACTS(Flexible AC Transmission System) equipment.
- Resources with GFL(Grid Following) Inverter
  - GFL controls node current as current source to follow but does not control node voltage.
  - In order to keep voltage of load node as normal amplitude, a compensator should be installed at substation upstream of the VRE resources connected through GFL in general.
  - The capacity of the compensator should be the same as consuming reactive power of node.
- Resources with GFM(Grid Forming) Inverter
  - It does not require compensators, because GFM inverter is a voltage source inverter and can keep voltage as operation value.

Load Flow Analysis of Barbados Grid by Microgrid Designer (for SC)





Effect of Shunt Capacitor

without SC in end nodes — with SC in end nodes

Wind turbine is located at node 13, which is north east area.
Because of no measures in an estimated grid, the voltage is high.
Shunt capacitor makes no influence to the voltages.

Session No. 3
Basics of Power System Engineering for Grid Stability Simulation

1. Per Unit Method
   Definition, Example
2. Modeling of Power System Equipment
   Transmission line, Transformer, Generator, Load
3. Active Power & Frequency
   Frequency control, Area requirement
4. Reactive Power & Voltage
   P-V Curve, Reactive power source

1. Per Unit Method

- Normalize impedances and quantities across different voltage levels to a common base in a power system
- Simplify calculations without considering voltage levels and capacity of equipment

- Rated capacity of equipment to 1.0
  - Equipment(ex. Generator): Rated Capacity of each equipment
  - Grid: Grid Capacity or Total Generation
    (need not to set to maximum amount of capacity)
- Rated voltage to 1.0
  - Each Transmission Line can be set to 1.0

Per Unit Value & Actual Value

- Normalize a value to one that is based on unit number 1.0
- For each equipment
  - Rated capacity -> 1.0
  - Rated voltage -> 1.0
- For grid
  - Total capacity of grid -> 1.0
  - Rated voltage of transmission line -> 1.0

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

$$\dot{V}_p = \frac{\dot{V}}{V_{base}}, \quad \dot{I}_p = \frac{\dot{I}}{I_{base}}, \quad \dot{Z}_p = \frac{\dot{Z}}{Z_{base}}$$

$$V_{base} = I_{base} Z_{base}$$

$$\frac{\dot{V}}{V_{base}} = \frac{\dot{I}}{I_{base}} \frac{\dot{Z}}{Z_{base}}$$

$$\dot{V}_p = \dot{I}_p \dot{Z}_p$$

$$(VA)_{base} = V_{base} I_{base}$$

$$Y_{base} = \frac{1}{Z_{base}}$$

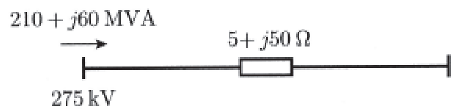
V: Voltage, I: Current, Z: Impedance
Vbase: Base Voltage, Ibase: Base Current
Zbase: Base Impedance, Ybase: Base Admittance
(VA)base: Base Apparent Power
Vp: Per Unit Voltage, Ip: Per Unit Current
Zp: Per Unit Impedance

Example of Conversion to Per Unit

(1) Calculate Base Value

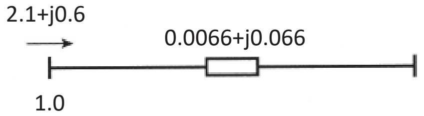
Vbase=275kV

(VA)base=100MVA



$$Z_{\mathrm{Ybase}} = \frac{(275 \times 10^3)^2}{100 \times 10^6} = 756\ \Omega$$

(2) Change Actual Value to Per Unit Value



$$\dot{Z}_{\mathrm{p}} = \frac{5 + j50}{756} = 0.0066 + j0.066$$

$$2.1 + j0.6 = 1.0 I_{\mathrm{p}}^*$$

$$\dot{I}_{\mathrm{p}} = 2.1 - j0.6$$

$$\dot{S}_{\mathrm{sp}} = \dot{V}_{\mathrm{sp}} \dot{I}_{\mathrm{p}}^*$$

$$\dot{V}_{\mathrm{rp}} = \dot{V}_{\mathrm{sp}} - \dot{I}_{\mathrm{p}} \dot{Z}_{\mathrm{p}} = 1.0 - (2.1 - j0.6)(0.0066 + j0.066) = 0.947 - j0.135$$

$$\dot{S}_{\mathrm{rp}} = \dot{V}_{\mathrm{rp}} \dot{I}_{\mathrm{p}}^* = (0.947 - j0.135)(2.1 + j0.6) = 2.07 + j0.285$$

$$\dot{S}_{\mathrm{r}} = (2.07 + j0.285)100\ \mathrm{MVA} = 207 + j28.5\ \mathrm{MVA}$$

$$\dot{V}_{\mathrm{r}} = (0.947 - j0.135)275\ \mathrm{kV} = 260 - j37.1\ \mathrm{kV}$$

$$|\dot{V}_{\mathrm{r}}| = 263\ \mathrm{kV}$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Per Unit Base

- Vbase=11kV
- (VA)base=100MVA
- Ibase=100/11=9.1kA
- Zbase=Vbase^2/(VA)base=11^2/100=1.21Ω
  - R=0.05Ω/km, X=0.1Ω/km
  - Length =10km
  - Rpu=0.05x10/1.21=0.42
  - Xpu=0.1x10/1.21=0.83
  - Zpu=√0.42*0.42+0.83*0.83=0.93 => |Z|=0.93

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rpu: Resistance in Per Unit, Xpu: Reactance in Per Unit

Meaning of Per Unit

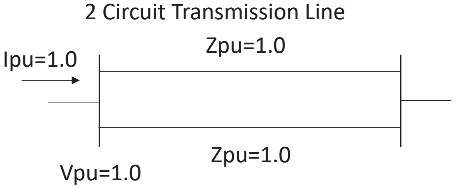
- Meaning of Per Unit:

1pu(|Z|=0.93Ω) impedance transmission line can send 1pu(100MVA) power by 1pu(11kV) voltage. Its current is 1pu(9.1kA).

This will be maximum or rated capacity of transmission line.

If transmission line has 2 circuits, its total impedance will be 0.5pu(0.605Ω), and the maximum capacity will be twice(2pu:200MVA).

Vpu: Voltage in Per Unit
(VA)pu: Base Apparent Power in Per Unit
Ipu: Current in Per Unit
Zpu: Impedance in Per Unit
Rpu: Resistance in Per Unit
Xpu: Reactance in Per Unit

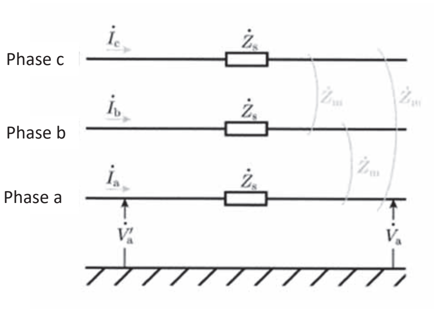


2. Modeling of Power System Equipment

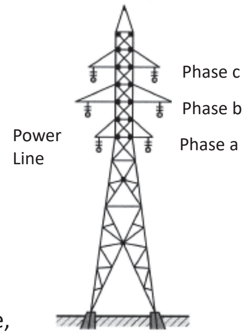
- Make it easy to analyze feature of power system equipment
- Modeling of Components of Power System
  - Transmission Line
  - Synchronous Generator
  - PV(Photovoltaic Generator)
  - WT(Wind Turbine Generator)
  - Load

Transmission Line

- In a 3-Phase balanced system, we may consider only positive phase circuit same as single phase circuit.



Ia, Ib, Ic: Phase Current
Zs: Line Impedance
Va', Va: Phase Voltage
(Sending Terminal Voltage, Receiving Terminal Voltage)

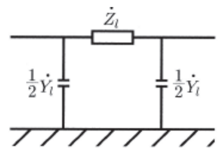


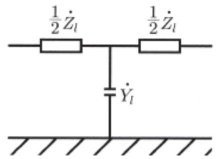
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Equivalent Circuit of Transmission Line

Two types of Equivalent Circuit

- Π (pai) Model
  - Divide line admittance into sending node side and receiving node side
  - No need to add another node
- T (tee) Model
  - Divide line impedance into sending node side and receiving node side
  - Need to add another middle point node
- Π (pai) model is easy to handle in analysis, because it is not necessary to add new node at the middle point of transmission line.





Zl: Impedance of Transmission Line
Yl: Admittance of Transmission Line

Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

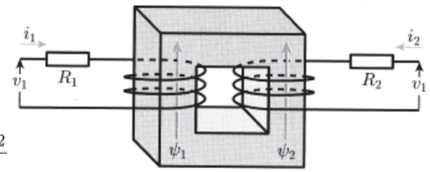
Transformer

- Mathematical equations of transformer

Φ1: primary side flux
Φ2: secondary side flux
L1: primary side self inductance
L2: secondary side self inductance
M1: primary side mutual inductance
M2: secondary side mutual inductance
Ω: angular velocity

$$\begin{cases} v_1 = i_1 R_1 + \dfrac{d\psi_1}{dt} \\ v_2 = i_2 R_2 + \dfrac{d\psi_2}{dt} \end{cases}$$

$$\begin{cases} \psi_1 = L_1 i_1 + M_{12} i_2 \\ \psi_2 = M_{21} i_1 + L_2 i_2 \end{cases} \qquad r = \frac{M_{12}}{L_2}$$



$$\begin{cases} \dot V_1 = \dot I_1 R_1 + j\omega(L_1 \dot I_1 + M_{12}\dot I_2) = (R_1 + j\omega L_1)\dot I_1 + j\omega M_{12}\dot I_2 \\ \dot V_2 = \dot I_2 R_2 + j\omega(M_{21}\dot I_1 + L_2 \dot I_2) = j\omega M_{21}\dot I_1 + (R_2 + j\omega L_2)\dot I_2 \end{cases}$$

Magnetic circuit connects two electrical circuits through a transformer.

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011

Equivalent Circuit of Transformer

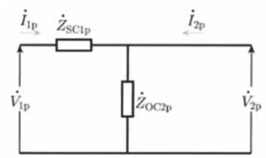
- Relationship of per unit base values

$$\frac{r\dot I_1}{I_{2\mathrm{base}}} = \frac{r\dot I_1}{rI_{1\mathrm{base}}} = \dot I_{1\mathrm{p}} \qquad rI_{1\mathrm{base}} = I_{2\mathrm{base}}, \quad Z_{1\mathrm{base}} = r^2 Z_{2\mathrm{base}}$$

$$\frac{\dot I_2}{rI_{1\mathrm{base}}} = \frac{\dot I_2}{I_{2\mathrm{base}}} = \dot I_{2\mathrm{p}}, \quad \frac{r^2 \dot Z_{\mathrm{OC2}}}{Z_{1\mathrm{base}}} = \frac{\dot Z_{\mathrm{OC2}}}{Z_{2\mathrm{base}}} = \dot Z_{\mathrm{OC2p}}$$

- Equivalent Circuit and Equation

$$\begin{cases} \dot V_{1\mathrm{p}} = \dot I_{1\mathrm{p}} \dot Z_{\mathrm{SC1p}} + (\dot I_{1\mathrm{p}} + \dot I_{2\mathrm{p}})\dot Z_{\mathrm{OC2p}} \\ \dot V_{2\mathrm{p}} = (\dot I_{1\mathrm{p}} + \dot I_{2\mathrm{p}})\dot Z_{\mathrm{OC2p}} \end{cases}$$



I1: Primary side Current, I2 secondary side Current, r: Transformer Ratio
I1base: Primary side Base Current, I2base: Secondary side Base Current
Z1base: Primary side Base Impedance, Z2base: Secondary side Base Impedance
V1p, V2p, I1p, I2p: Per Unit Voltage and Current of Primary, Secondary Circuit
Zsc1, Zsc1p: Short Circuit Impedance from Primary side and its per unit value
Zoc2, Zoc2p: Secondary side Open Circuit Impedance and its per unit value

Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Synchronous Generator (Steady State)

Induced Electromotive Force $\dot{E}_g = E_g e^{j\delta}$

$$
\begin{aligned}
P + jQ &= \dot{V}_t \dot{I}_g^* \\
&= V_t \left(\frac{E_g e^{j\delta} - V_t}{jX_g} \right)^* \\
&= \frac{V_t E_g}{X_g} \sin\delta + j \left(\frac{V_t E_g}{X_g} \cos\delta - \frac{V_t^2}{X_g} \right)
\end{aligned}
$$

$$P = \frac{V_t E_g}{X_g} \sin\delta$$

$$Q = \frac{V_t E_g}{X_g} \cos\delta - \frac{V_t^2}{X_g}$$

Vt: Terminal Voltage, Eg: Induced Electromotive Force
Xg: Armature Impedance, Ig: Armature Current
P: Active Power Output, Q: Reactive Power Output
δ: Internal Electromotive Force Angle
Po: Rated Active Power

Load (Consumer)

- Numerical Model
  - Constant Impedance (**Z**=R+jX)
  - Constant Power (**S**=P+jQ)
  - Constant Current (**I**=a+jb)
  - Easy to include into network equations of power system, because these parameters can be included into Node Admittance Matrix.

How to make a model of Renewable Energy Generator

- PV(Photovoltaic) & WT(Wind Turbine)
  - **Negative load model**
  - Maximum Power Point Control
  - **Follow the Voltage of Grid**
  - Model
    - Constant Current for GFL
    - Constant Voltage for GFM
  - -> similar model of
    Constant Current or Constant Impedance Load model
- Diesel Generator & Biofuel Generator & SCO(Synchronous Condenser)
  - **Synchronous Generator model**
  - Automatic Voltage Regulator -> Constant Voltage
  - Power System Stabilizer -> Control Active Power
  - Governor & Turbine -> Control Frequency
  - -> similar model of **synchronous generator**

3. Active Power & Frequency

- Difference of active power between generator output and load is proportional to frequency.
- Active power of synchronous generators decrease according to frequency.
- Load characteristic is mostly proportion to frequency, because load consists of inductance.
- Crossing point of generator and load characteristics is an operating point.

F0: No-load frequency
FN: Frequency under normal operation
GN: Power of synchronous generators under normal operation

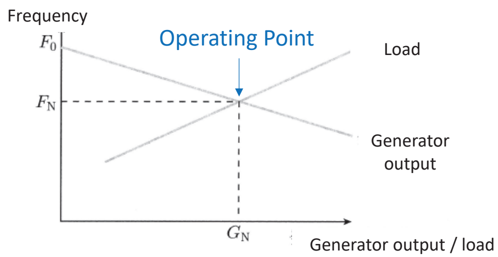


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Frequency Control Scheme

- Frequency Control Scheme is categorized to 4 stages.

(1) Self-control of load

Quick response of Load according to its characteristics.

(2) Turbine Governor control (Governor Free)

Function of synchronous generator

Conventional inverter doesn't have this.

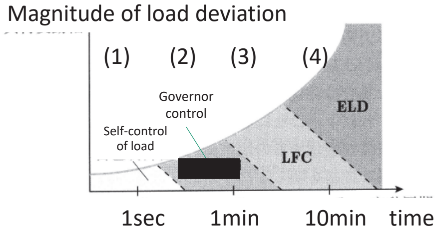
(3) Load Frequency Control

Feedback frequency and change generator outp according to PI (Proportional-Integral) control in EMS as the following equation:

$\Delta PG = (K1+K2/s)\Delta f$

(4) Economic Load Dispatching

Select most cost effective generator among LFC generators



EMS: Energy Management System

-> operated in central control center

ΔPG: Generator Output Change

Δf: Frequency Change

K1: Proportional Gain

K2: Integral Gain

Figures are cited from

M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Power–Frequency Coefficients

- Power-Frequency Coefficients is a constant depending on the governor and load characteristics.

$$\%K_G = \frac{100}{F_0 - F_N}\ \%\mathrm{MW/Hz}$$

$$\%K_G = \frac{100 \times 100}{\varepsilon \times F_N}\ \%\mathrm{MW/Hz}$$

$$\varepsilon = \frac{F_0 - F_N}{F_N} \times 100\,\%$$

$$\Delta P + (\Delta G - \Delta L) = 0$$
$$\Delta P = (K_G + K_L)\Delta F$$

$$K = K_G + K_L\ [\mathrm{MW/Hz}]$$

F0: Rated Frequency

FN: Current Frequency

ΔG: Generator Output Change

ΔL: Load Change

ΔP: Chang of Power

ΔF: Change of Frequency

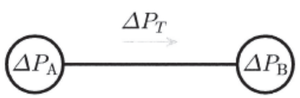
KG: Gain for Generator Output Change

KL: Gain for Load Change

K: Power-Frequency Coefficient

Power Systems Connected by a Tie-Line

- Two interconnected power systems



$$\Delta P_A = \Delta G_A - \Delta L_A$$
$$\Delta P_B = \Delta G_B - \Delta L_B$$

Area Requirement (supply and demand balance and tie line flow)

$$\Delta P_A = K_A \Delta F + \Delta P_T$$
$$\Delta P_B = K_B \Delta F - \Delta P_T$$

Frequency of Interconnected grids are collected as the following equations.

$$\begin{cases} \Delta F = \dfrac{\Delta P_A + \Delta P_B}{K_A + K_B} \\ \Delta P_T = \dfrac{K_B \Delta P_A - K_A \Delta P_B}{K_A + K_B} \end{cases}$$

F0: Rated Frequency

F: Frequency of Interconnected Grid

ΔG: Generator Output Change

ΔL: Load Change

ΔP: Chang of Power

ΔF: Change of Frequency

KG: Gain for Generator Output Change

KL: Gain for Load Change

K: Power-Frequency Coefficient

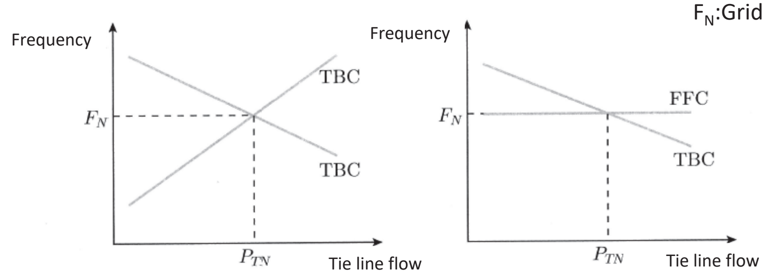
Figure is cited from

M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Relationship between generator, load and frequency

- FFC: Flat Frequency Control
  - To keep frequency constant in a grid
- TBC: Tie Line Load Frequency Bias Control
  - To keep area requirement (supply and demand balance and tie line flow) zero in a grid

F_N:Grid Frequency



Figures are cited from

M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

LFC and ELD

- Load Frequency Control (LFC)
  - LFC control signal, that is output reference of generator, is set every 1 minutes as follows.

$$\Delta P = (-1/R) \times \Delta f$$

ΔP: Resulting Change of Power
R: Speed Regulation
Δf: Change of Frequency

- Economic Load Dispatching (ELD)
  - Equal λ method
  - λ=incremental fuel cost / capacity of generator
  - Comparing each λ of generator, select lowest generator every 5 minutes.

LFC & ELD Model in Microgrid Designer

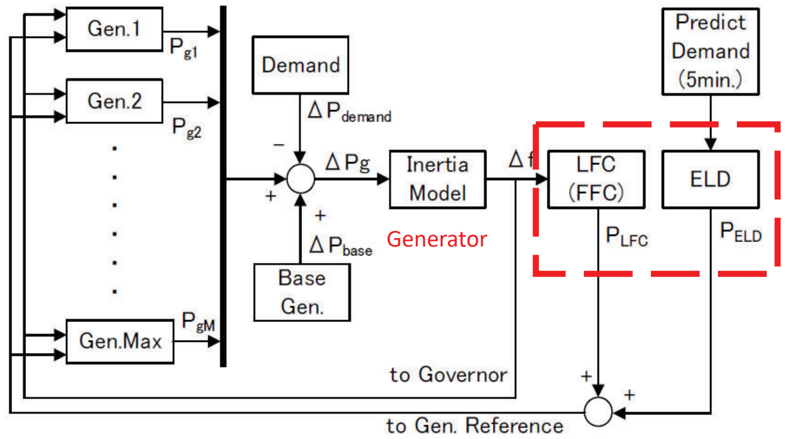
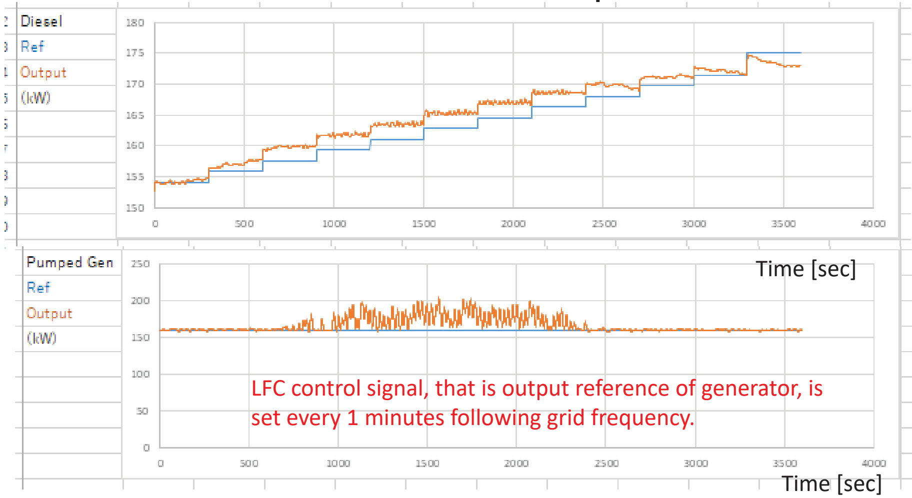


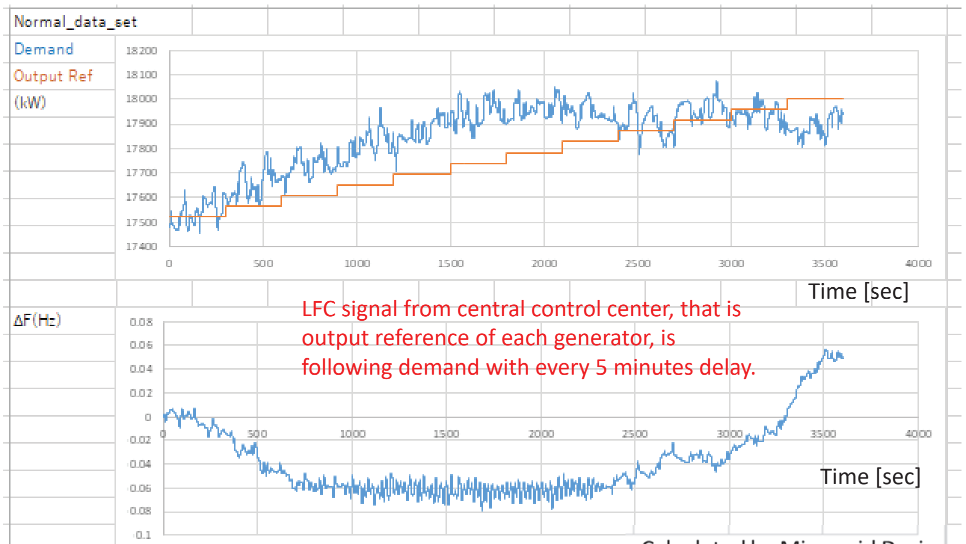
Figure is cited from MicroGrid Designer User and Technical Reference Manual

Example of LFC - Generator Output -



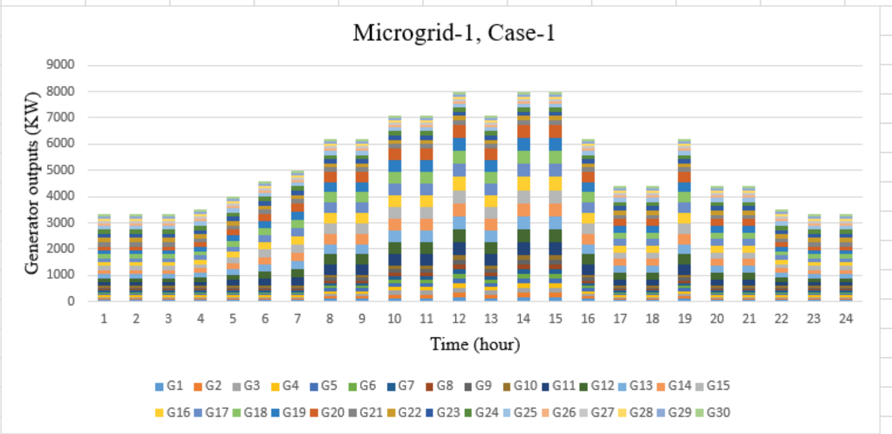
Calculated by Microgrid Designer

Example of LFC - Demand and Frequency -



Calculated by Microgrid Designer

Example of ELD



Calculated by Microgrid Designer

4. Reactive Power & Voltage

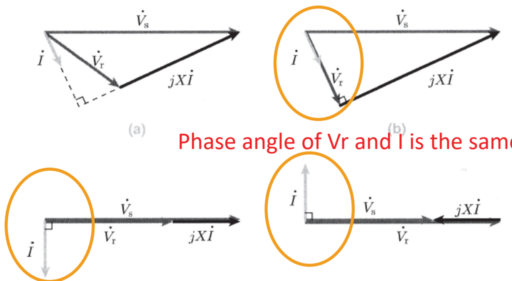
- Most of load consumes reactive power and the voltage of load node will be low.
- Reactive power should be provided or controlled to keep voltage as a set value.
- Providers of reactive power
  - Synchronous generator (SG)
  - Shunt Capacitor (SC)
  - Synchronous Condenser/Capacitor (SCO, RC: Rotary Condenser)
  - Static Var Compensator (SVC) Var means reactive power.
  - Static Var Compensator (STATCOM, Self-commutated Inverter)
  - Voltage Reactive Power Control (VQC)

Reactive Power & Voltage

- Relationship between Reactive Power and Voltage

$$\dot{V}_r = \dot{V}_s - jX\dot{I}$$

(a) Usual load
(b) Power factor=1
(c) Power factor=0,
Lagging load (only inductance)
(d) Power factor=0,
Leading load (only capacitance)

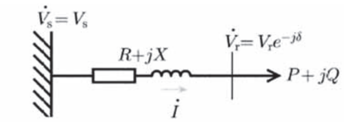


Vs: Sending Terminal Voltage, Vr: Receiving Terminal Voltage
I: Transmission Line Current
X: Transmission Line Impedance

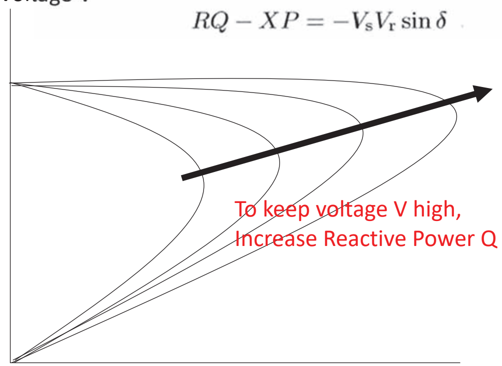
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

P-V Curve & Q(Reactive Power)

- The equations describe a relationship of active power P and Voltage V according to the change of reactive power Q.
- If Reactive Power Q increases, voltage V will be up and active power P of load will increase.
- In order to keep voltage V as around set value, we should increase reactive power Q of load by adding reactive power resources such as Shunt Capacitor, Synchronous Condenser or Static Var Compensator (SVC, STATCOM) to the load node.
- Caution!!: Too much Q decreases node voltage V and causes blackout to grid.



$$RP + XQ + V_r^2 = V_s V_r \cos\delta$$
$$RQ - XP = -V_s V_r \sin\delta$$



Lunch Break

Session No. 4
Load Flow Analysis and its Evaluation

1. Overview of Load Flow Analysis
   Purpose, Methods, Modeling of grid
2. Newton-Raphson Method
   Theory, Characteristics
3. DC Flow Method
   Simple method to solve load flow manually
4. Load Flow Analysis and Evaluation

1. Overview of Load Flow Analysis

- Steady state analysis under small disturbance
- System is explained as linear model.
- Voltage, power, angle are constant at a certain time, and kept as the same value under small disturbance at a certain time.
  -> Load Flow Analysis: Algebraic equations
  -> Eigenvalue Analysis: Differential equations

- Bus & Line, or Node & Branch
  - In actual power system(grid), bus & line(Transmission line & distribution line) are used.
  - In mathematical method, node & branch are used.
  - These words depend on a program.
  - In Microgrid Designer, node & branch are used.
  - In ETAP, bus & line are used.

Load Flow Analysis

- Node Admittance Matrix
  - Relationship between voltage and current for multiple nodes(buses) in a power system
- Power Equation
  - Relationship between active power, reactive power and voltage
- Load Flow Analysis
  - Conduct Steady state analysis of grid, and get the operating state.
  - A set of simultaneous non linear algebraic equations for voltage
  - The output is the voltage and phase angle, active and reactive power (both sides in each line), line losses and slack bus power
- DC Flow Method (manual calculation): Simplified analysis method of power and voltage in grid by setting each voltages as rated value and using scalar value
- Newton Raphson Method (computer calculation): Detailed analysis method of power and voltage using Jacobian matrix which describe sensitivity of power and voltage using vector value

Load Flow Analysis

Necessary items to consider Load flow Analysis

Buses are categorized to the following 3 types.

- Slack (Swing) Node
  - Node with largest capacity generator with constant voltage is generally selected.
  - Only the magnitude and phase angle of the voltage are specified.
  - This node supplements the difference between the scheduled loads and generated power that are caused by the losses in the network.
- P-V Nodes (Generator Nodes)
  - The active power P and voltage magnitude V are specified.
  - The phase angles of the voltages and the reactive power are to be determined.
- P-Q Nodes (Load Nodes or Substation Nodes)
  - The active and reactive powers P, Q are specified.
  - The magnitude and the phase angle of the bus voltages are unknown.

Node Admittance Matrix

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_N \end{bmatrix} = \begin{bmatrix} \dot{Y}_{11} & \dot{Y}_{12} & \cdots & \dot{Y}_{1N} \\ \dot{Y}_{21} & \dot{Y}_{22} & \cdots & \dot{Y}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \dot{Y}_{N1} & \dot{Y}_{N2} & \cdots & \dot{Y}_{NN} \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \vdots \\ \dot{V}_N \end{bmatrix}$$

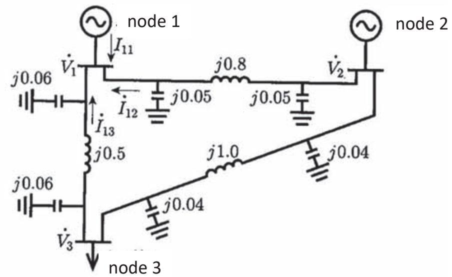
Describe Network Structure

Y= 1/(R+JωL) ＋jωC

R:Resistance

C:Capacitance

L: Inductance



- Calculation example of power flow in 3 nodes network

V1,,,Vn: Node(Bus) Voltage

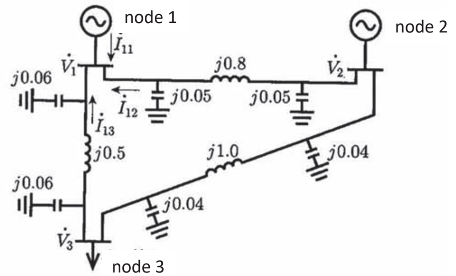
I1,,,In: Branch(Line) Current

Yij: Admittance between each node

Figure is cited from

M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Node Admittance Matrix



$$\dot{Y}_{11} = j0.05 + j0.06 + \frac{1}{j0.8} + \frac{1}{j0.5} = -j3.14$$

$$\dot{Y}_{22} = j0.05 + j0.04 + \frac{1}{j0.8} + \frac{1}{j1.0} = -j2.16$$

$$\dot{Y}_{33} = j0.04 + j0.06 + \frac{1}{j1.0} + \frac{1}{j0.5} = -j2.9$$

$$\dot{Y}_{12} = \dot{Y}_{21} = -\frac{1}{j0.8} = j1.25$$

$$\dot{Y}_{13} = \dot{Y}_{31} = -\frac{1}{j0.5} = j2.0$$

$$\dot{Y}_{23} = \dot{Y}_{32} = -\frac{1}{j1.0} = j1.0$$

- Y_{11}, Y_{22}, Y_{33}:
  - Driving Point Admittance
- $Y_{12}, Y_{21}, Y_{13}, Y_{31}, Y_{23}, Y_{32}$:
  - Transfer Admittance

$$\boldsymbol{Y} = \begin{bmatrix} -j3.14 & j1.25 & j2.0 \\ j1.25 & -j2.16 & j1.0 \\ j2.0 & j1.0 & -j2.9 \end{bmatrix}$$

Figure is cited from

M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Power Equation

- Voltage and current of node k are described as following equations in complex value.
  - $\mathbf{V}_k = e_k + j f_k$, $\mathbf{V}_m = e_m + j f_m$
  - $\mathbf{I}_k = \mathbf{Y}_{km} \mathbf{V}_{km}$
- Power Equation of node k is described using Node Admittance Matrix.

$$P_k + jQ_k = \dot{I}_k^* \dot{V}_k = \sum_{m=1}^{N} \dot{Y}_{km}^* \dot{V}_m^* \dot{V}_k$$

$$P_{ks} = \mathrm{Re}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$

$$Q_{ks} = \mathrm{Im}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$

$$V_{ks}^2 = e_k^2 + f_k^2$$

Vi: Node(Bus) Voltage

Ii: Branch(Line) Current

Yij: Admittance between each node

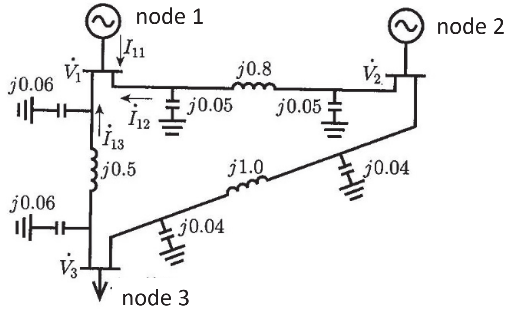
Pi: Node(Bus) Active Power

Qi: Node(Bus) Reactive Power

Power Equation (Example of 3 nodes network)

Power equation describes the way to calculate active power and reactive power using node voltages and node admittance matrix.

Left side value is specified value of power, and right side is a power equation for each node.



$$\begin{aligned} P_{2s} &= \mathrm{Re}\{(j1.25)^*(e_1+jf_1)^*(e_2+jf_2) \\ &\quad + (-j2.16)^*(e_2+jf_2)^*(e_2+jf_2) \\ &\quad + (j1.0)^*(e_3+jf_3)^*(e_2+jf_2)\} \\ &= 1.25e_1f_2 - 1.25e_2f_1 + e_3f_2 - e_2f_3 \end{aligned}$$

$$V_{2s}^2 = e_2^2 + f_2^2$$

$$\begin{aligned} P_{3s} &= \mathrm{Re}\{(j2.0)^*(e_1+jf_1)^*(e_3+jf_3) \\ &\quad + (j1.0)^*(e_2+jf_2)^*(e_3+jf_3) \\ &\quad + (-j2.9)^*(e_3+jf_3)^*(e_3+jf_3)\} \\ &= 2.0e_1f_3 - 2.0e_3f_1 + e_2f_3 - e_3f_2 \end{aligned}$$

$$\begin{aligned} Q_{3s} &= \mathrm{Im}\{(j2.0)^*(e_1+jf_1)^*(e_3+jf_3) \\ &\quad + (j1.0)^*(e_2+jf_2)^*(e_3+jf_3) \\ &\quad + (-j2.9)^*(e_3+jf_3)^*(e_3+jf_3)\} \\ &= 2.9e_3^2 + 2.9f_3^2 - 2.0e_1e_3 - 2.0f_1f_3 - e_2e_3 - f_2f_3 \end{aligned}$$

$$e_1 = V_{1s}, \quad f_1 = 0$$

In this grid, node 1 is set as slack node,
node 2 is set as P-V node,
and node 3 is set as P-Q node.

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

2. Newton Raphson Method

- Newton Raphson Method is appropriate in computer simulation for large grid.
- This method is applied in Microgrid Designer, which is used in the analysis in this seminar.
- We can get the answer, even if load flow is heavy and difficult to get it by another methods.

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Algorithm of Newton Raphson Method

Suppose y=f(x), we solve the value of x which satisfies equation f(x)=0.

1. First(i=0), assume x(i) to a certain value (ex. 1.0).
2. Calculate $$\Delta x^{(i)} = -\frac{f(x^{(i)})}{f'(x^{(i)})}$$
3. Calculate $$x^{(i+1)} = x^{(i)} - \frac{f(x^{(i)})}{f'(x^{(i)})}$$
4. Repeat 2 and 3, until Δx(i)<ε,
   where ε is a accuracy (ex. 0.001).
5. Get answer of x

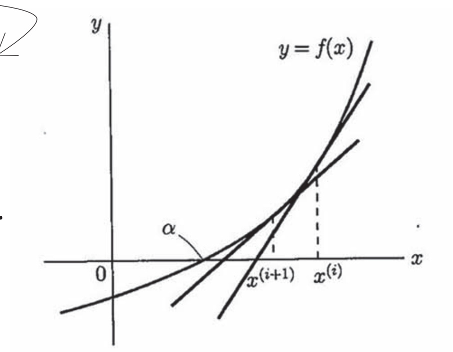


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Newton-Raphson Method

Newton Raphson Method is applied to power equation as follows:

1. Set node voltage to 1.0
2. Calculate Jacobian Matrix using modified voltage (1.0 at first)
3. Calculate ΔP, ΔQ and $\Delta|V|^2$
4. Solve voltage difference ε of each voltage by eq.(1)
5. Calculate new Voltage by eq.(2)
6. Repeat 2-6 until differences of voltage are smaller than a certain value

$$\begin{bmatrix} \Delta P_2 \\ \Delta|\dot{V}_2|^2 \\ \Delta P_3 \\ \Delta Q_3 \end{bmatrix} = -\begin{bmatrix} \frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial e_3} & \frac{\partial P_2}{\partial f_3} \\ \frac{\partial|\dot{V}_2|^2}{\partial e_2} & \frac{\partial|\dot{V}_2|^2}{\partial f_2} & \frac{\partial|\dot{V}_2|^2}{\partial e_3} & \frac{\partial|\dot{V}_2|^2}{\partial f_3} \\ \frac{\partial P_3}{\partial e_2} & \frac{\partial P_3}{\partial f_2} & \frac{\partial P_3}{\partial e_3} & \frac{\partial P_3}{\partial f_3} \\ \frac{\partial Q_3}{\partial e_2} & \frac{\partial Q_3}{\partial f_2} & \frac{\partial Q_3}{\partial e_3} & \frac{\partial Q_3}{\partial f_3} \end{bmatrix} \begin{bmatrix} \varepsilon_1^{(i)} \\ \varepsilon_2^{(i)} \\ \varepsilon_3^{(i)} \\ \varepsilon_4^{(i)} \end{bmatrix} \qquad \text{eq.(1)}$$

$$\begin{bmatrix} e_2^{(i+1)} \\ f_2^{(i+1)} \\ e_3^{(i+1)} \\ f_3^{(i+1)} \end{bmatrix} = \begin{bmatrix} e_2^{(i)} \\ f_2^{(i)} \\ e_3^{(i)} \\ f_3^{(i)} \end{bmatrix} + \begin{bmatrix} \varepsilon_1^{(i)} \\ \varepsilon_2^{(i)} \\ \varepsilon_3^{(i)} \\ \varepsilon_4^{(i)} \end{bmatrix} \qquad \text{eq.(2)}$$

3. DC Flow Method

- Simplified Load Flow Method of Grid
- Set all node voltage to 1.0
- Set all resistance of transmission line to 0.0
- Solve relationship equation below between power and voltage angle for each node

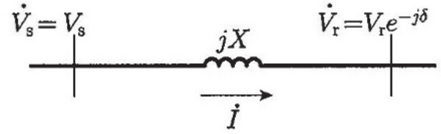
$$P_r = \frac{\delta}{X}$$

δ : Phase Difference of voltages between both side of a transmission line
X : Transmission line inductance
Pr : Active power that flows in a transmission line

DC Flow Method

Manual method to calculate load flow.
Easy to calculate in manual.

δ : Phase Difference of voltages Vs, Vr between both side of a transmission line
X : Transmission line inductance
Pr, Qr : Active power that flows through a transmission line



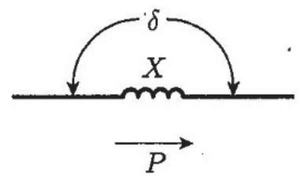
$$P_r + jQ_r = V_r e^{-j\delta} \dot{I}^*$$
$$= V_r e^{-j\delta} \left(\frac{V_s - V_r e^{-j\delta}}{jX} \right)^*$$
$$= \frac{V_s V_r e^{-j\delta} - V_r^2}{-jX}$$
$$= \frac{V_s V_r}{X} \sin\delta + j \frac{V_s V_r \cos\delta - V_r^2}{X}$$

Simplified and Similar to DC circuit solution

$$P_r = \frac{V_s V_r}{X} \sin\delta$$

$$P_r = \frac{\delta}{X}$$

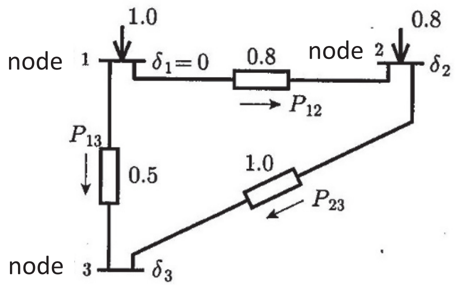
Approximate sinδ by δ



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

DC Flow Method

(Example of 3 nodes network)



Power equation of each node

$$1.0 = \frac{0 - \delta_2}{0.8} + \frac{0 - \delta_3}{0.5}$$

$$0.8 = \frac{\delta_2 - 0}{0.8} + \frac{\delta_2 - \delta_3}{1.0}$$

$$\delta_2 = 0.104$$
$$\delta_3 = -0.565$$

Power flow of transmission line

$$P_{12} = \frac{0 - 0.104}{0.8} = -0.130$$

$$P_{13} = \frac{0 - 0.565}{0.5} = 1.13$$

$$P_{23} = \frac{0.104 + 0.565}{1.0} = 0.669$$

Solution of voltage angle

$$\delta_2 = 0.104$$
$$\delta_3 = -0.565$$

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

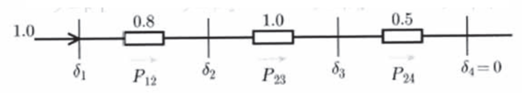
Example of DC Flow method

$$1.0 = \frac{\delta_1 - \delta_2}{0.8}$$

$$0 = \frac{\delta_2 - \delta_1}{0.8} + \frac{\delta_2 - \delta_3}{1.0}$$

$$0 = \frac{\delta_3 - \delta_2}{1.0} + \frac{\delta_3 - 0}{0.5}$$

node 1 node 2 node 3 node 4



$$\delta_1 = 2.3, \quad \delta_2 = 1.5, \quad \delta_3 = 0.5$$

$$P_{12} = 1.0, \quad P_{23} = 1.0, \quad P_{34} = 1.0$$

Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

4. Load Flow Analysis and Evaluation

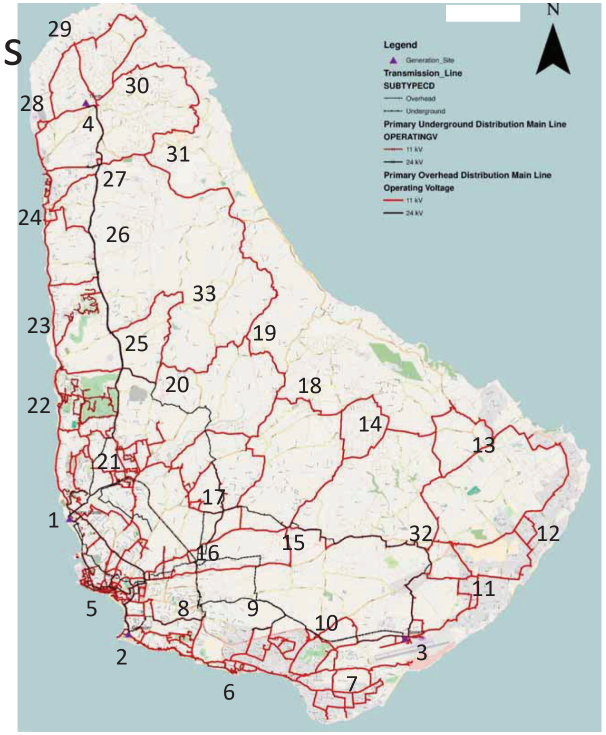
Barbados Grid

33 nodes +24/11kV Substations

=>

50 nodes

Barbados grid model is based on BL&P GIS map opened to public.

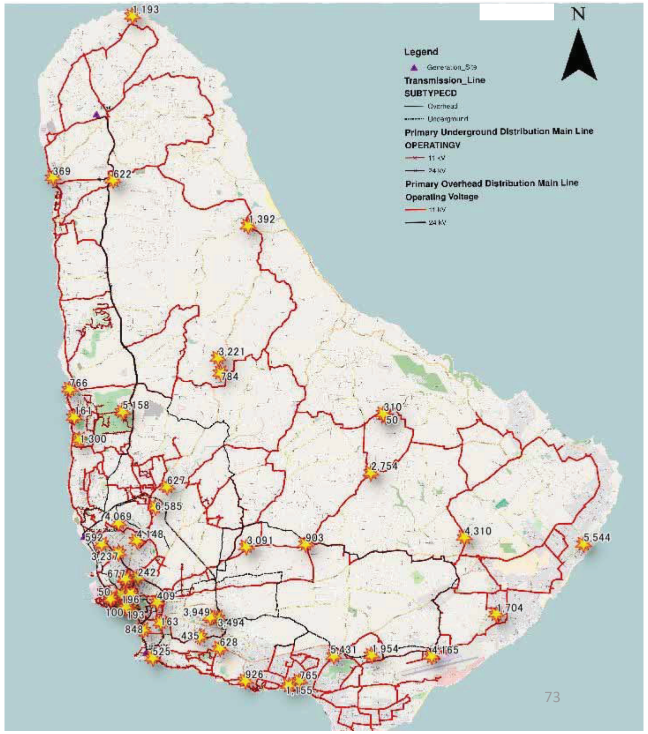


NIPPON KOEI PADECO

PV location to feeder

Total Capacity of PV in our estimated grid is:

Installed PV + Licensed and to be installed PV = 91MW



NIPPON KOEI PADECO

Influence of Total Installed Capacity of PV -Bus Voltages-

The total installed capacity of all PV's connected to feeders is 91MW.

(1) Planned PV(91MW)

(2) No PV(0MW)

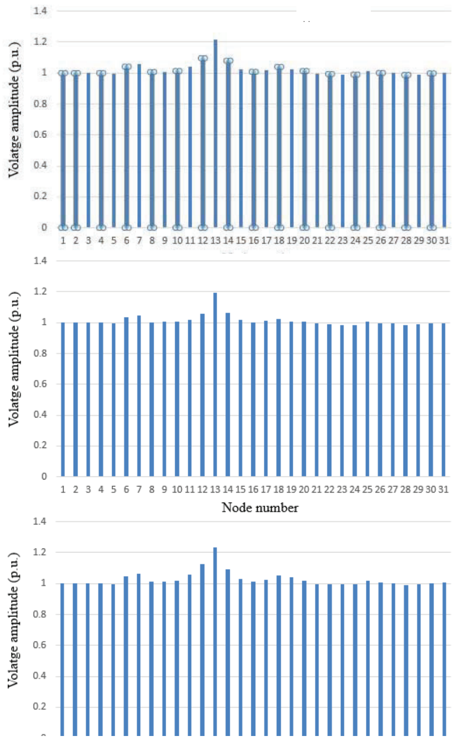
(3) Twice capacity of PV(182MW)

Each PV 's output is twice of rated value.

->

Distributed PV can keep voltage equally in every nodes.

I doesn't give some instability to grid.



NIPPON KOEI PADECO

Influence of Total Installed Capacity of PV –Active and Reactive Power of Lines-

The total installed capacity of all PV's connected to feeders is 91MW.

(1) Planned PV(90MW)

(2) No PV (0MW)

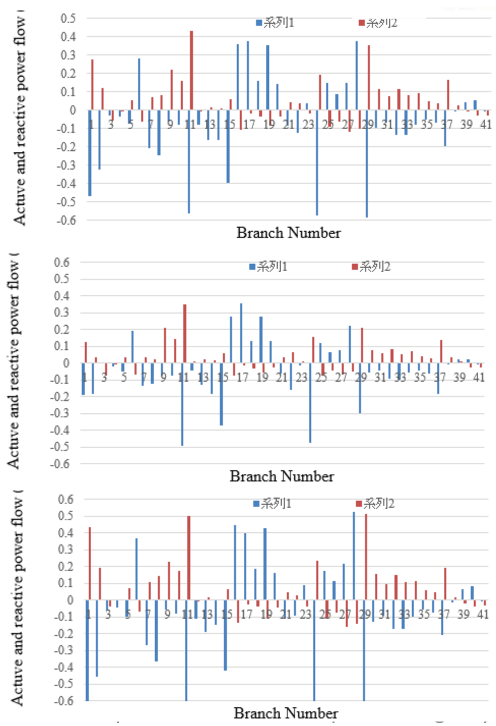
(3) Twice capacity of PV(180MW)

Each PV 's output is twice of rated value.

->

Distributed PV can keep voltage equally in every nodes.

I doesn't give some instability to grid.



NIPPON KOEI PADECO

Between Session 4 and Session 5
--- For Future Grid ----

- Please let us know your idea about Future Grid with RE and grid stability with following form:

https://forms.gle/dJ3e7hswMoq8u6q77

Session No. 5
Transient Stability Analysis and Evaluation of Stability

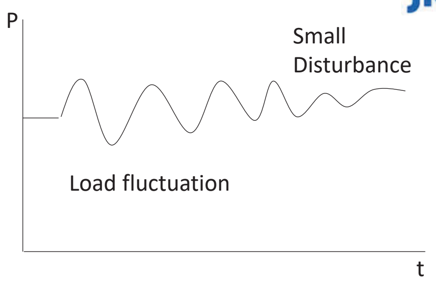
1. Overview of Stability
2. Equal Area Criterion
   Simple method to solve stability manually
3. Exercise of Equal Area Criterion

1. Overview of Stability

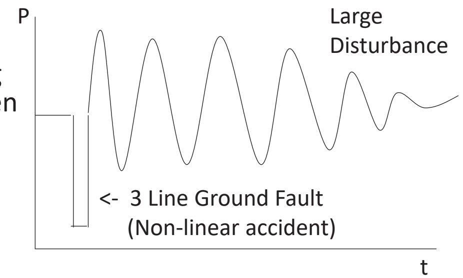
- STABILITY (Definition)
  - If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable.
  - If the system is not stable, it is considered unstable.

Type of Frequency/Voltage Stability

- Small Disturbance Stability (time domain graph)
  - Disturbance with minor fluctuation of load, generator, and other power system components
  - Linear modelled phenomena
  - ->Eigenvalue Analysis, Equal Area Criterion



- Large Disturbance Stability (time domain graph)
  - Disturbance with non-linear accidents such as Switching, setting value change, generator trip, sudden load trip, fault in power system components
  - ->Transient Stability Analysis, Equal Area Criterion



Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Stability Analysis

- Equal Area Criterion (Manual calculation)
  - Active Power Flow Dynamics between one Generator and one Load
    - Simplified Stability Calculation
- Transient Stability Program (Simulation Software)
  - Electro-Mechanical Transient Stability
    - Root Mean Square Value Calculation
    - Dynamics of Power Flow including both Active and Reactive Power
    - PSS/E, ETAP, CYME, DigSILENT,,,
  - Electro-Magnetic Transient Stability
    - Instantaneous Value Calculation
    - Dynamics of Electrical Signal
    - EMTP, EMTDC, PSCAD,,,

Swing Equation

- M $d^2\delta/dt^2 = P_m - P_e = \Delta P$
  - This equation describes relationship between power and frequency.

    f=2πω   ω= dδ/dt
  - Power will swing by disturbances caused by unbalance between generation power and consuming load.
- P_m: Mechanical Generation Power
  - Amount of Synchronous Generators, Renewable Energy and other Power Resources
- P_e: Active Power of Load
  - Customers, Facilities, Industries, etc.

M: Inertia capacity
δ: Rotor Angle
Pm: Mechanical Power
Pe: Electrical Power
AVR: Automatic Voltage Regulator
PSS: Power System Stabilizer

Swing Equation

- Swing equation is a mechanical model of generator rotor movement.

$$\omega = \frac{d\delta}{dt}$$

$$J\frac{d^2\delta}{dt^2} = T_m - T_e$$

$$\omega J\frac{d^2\delta}{dt^2} = P_m - P_e$$

$$M = \omega J$$

$$M\frac{d^2\delta}{dt^2} = P_m - P_e = P_a$$

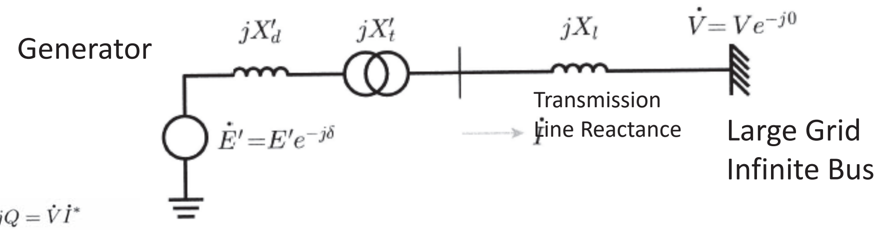
J: Inertia Moment
M: Inertia Capacity
ω: Angle Speed
δ: Rotor Angle
Tm: Mechanical Torque
Te: Electrical Torque
Pm: Mechanical Power
Pe: Electrical Power

2. Equal Area Criterion

- The equal area criterion is a simple graphical method for concluding the transient stability of two-machine systems or a single machine against an infinite bus*.
- This principle does not require the swing equation for the determination of stability conditions.
- The stability conditions are recognized by equating the areas of segments on the power angle diagram between the P-curve and the new power transfer line of the given curve.

* Infinite bus is a constant voltage bus that supplies and consumes any active and reactive power to grid.

Simplified Grid Model



$$P + jQ = \dot{V}\dot{I}^*$$

$$= \dot{V}\left\{\frac{E'e^{-j\delta} - \dot{V}}{j(X'_d + X_t + X_l)}\right\}^*$$

$$= \frac{\dot{V}E'}{X'_d + X_t + X_l}\sin\delta + j\frac{\dot{V}E'\cos\delta - \dot{V}^2}{X'_d + X_t + X_l}$$

$$X = X'_d + X_t + X_l$$

P-δ Equation $P = \frac{\dot{V}E'}{X}\sin\delta$

Synchronizing Force $S = \frac{dP}{d\delta} = \frac{VE'}{X}\cos\delta$

E': Transient Induced Electromotive Force
V: Grid Voltage
Xd': Transient Reactance
Xt': Transformer Reactance
Xl: Transmission Line Reactance
P: Active Power Output
Q: Reactive Power Output

Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Equal Area Criterion for Stability Analysis

A: Acceleration Energy
B: Deceleration Energy
Pm: Power in operation
Pmax: Maximum of Power
δ_0: Phase in operation
δ_a: Minimum Phase in disturbance
δ_b: Maximum Phase under disturbance

Pmax=>ATC

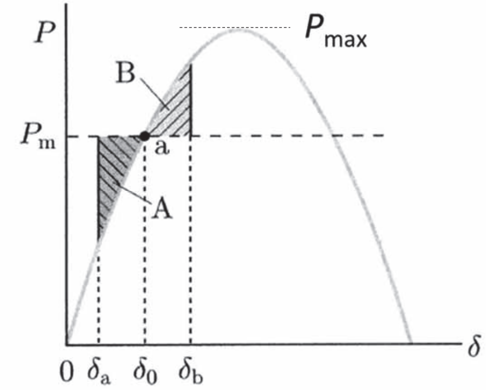


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Equal Area Criterion for Stability Analysis

- $P = \frac{V_i V_j}{X} sin\delta$
- $\frac{dP}{d\delta} = \frac{V_i V_j}{X} cos\delta$

  - Synchronizing Force is differential value of power which is the force return previous operating point.
  - Gradient of Power Curve
  - If Pm reaches to Pmax, synchroniz force will be 0.

A: Acceleration Energy
B: Deceleration Energy

$P = \frac{V_i V_j}{X} sin\delta$

Pmax=>ATC

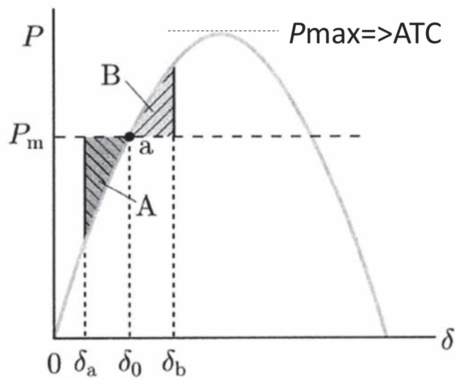


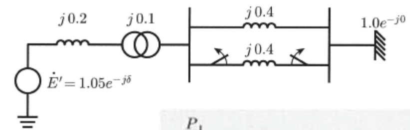
Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

3. Exercise of Equal Area Criterion

- Operation: 3LG(3 Line Ground Fault)-> 1 line Open from 2 line circuit
- Area A is acceleration energy, area B is deceleration energy.
- By opening 1 line circuit, deceleration energy can be provided.

$V = 1.0, \quad E' = 1.05$

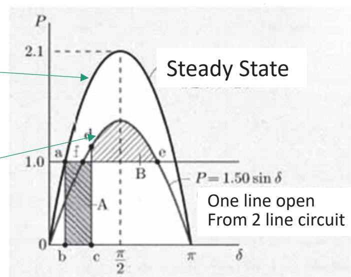
$X = 0.2 + 0.1 + \frac{0.4}{2} = 0.5$



$P = \frac{1.05}{0.5}\sin\delta = 2.10\sin\delta$

$X = 0.2 + 0.1 + 0.4 = 0.7$

$P = \frac{1.05}{0.7}\sin\delta = 1.50\sin\delta$

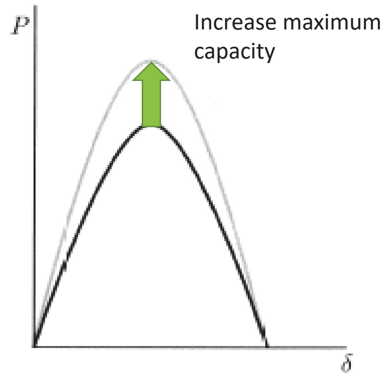


Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

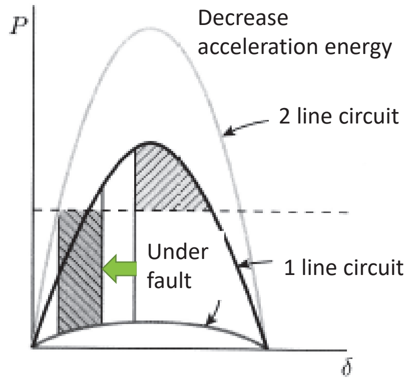
Solution for stability(1) through Equal Area Criterion

$$P = \frac{V_i V_j}{X} \sin\delta$$

(a) To increase Voltage



(b) High Speed Circuit Breaker

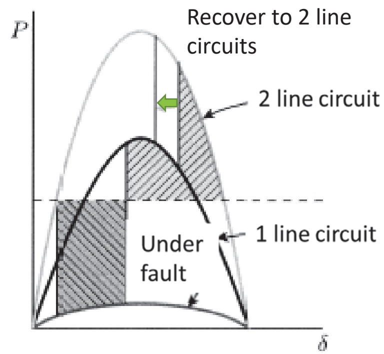


Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

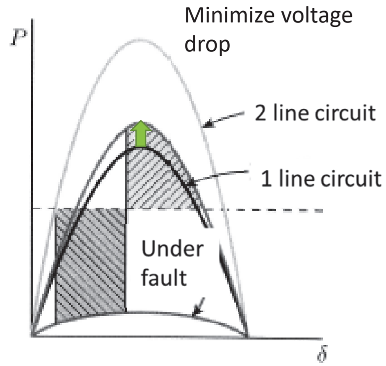
Solution for stability(2) through Equal Area Criterion

$$P = \frac{V_i V_j}{X} \sin\delta$$

(c) High Speed Recloser



(d) High Speed AVR

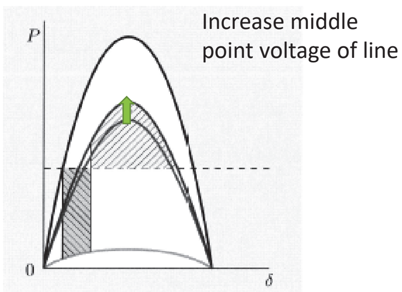


Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

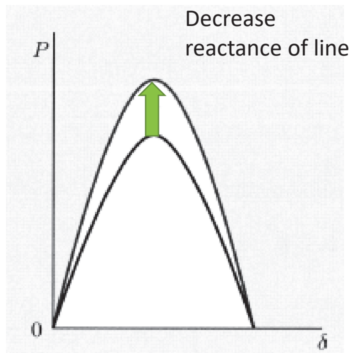
Solution for stability(3) through Equal Area Criterion

$$P = \frac{V_i V_j}{X} \sin\delta$$

(e) Middle Point Switch Gear Station



(f) Series Capacitor



Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Session No. 6
Discussion for future grid and VRE

- Current Grid of Barbados
  - Currently it goes well according to the several measures.
  - Simulation results shows the well controlled grid.
- Assumption of Future Grid (Large amount of RE) in Grid Model and Simulation
  - PVs at east side and west side nodes with/without BESS and Compensators
- Measures
  - BESS , Compensators(SC, SCO, STATCOM)
  - SPS(Special Protection System)

Special Protection System

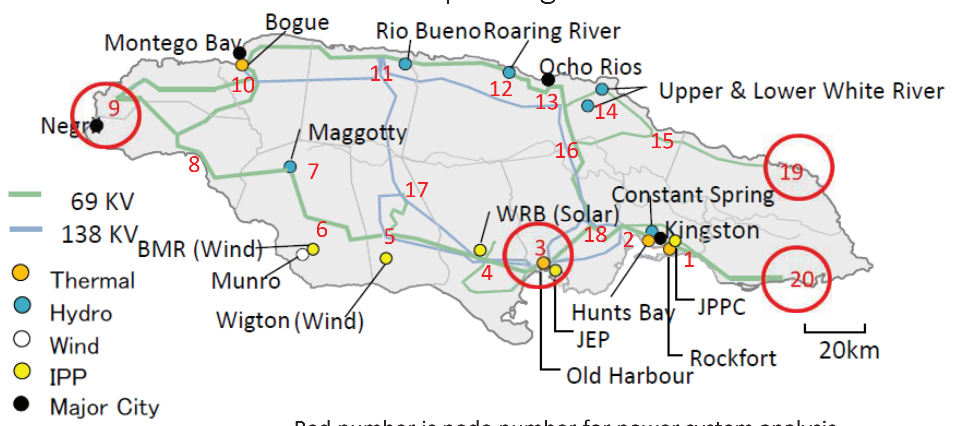
<Definition>

-> Optional functions installed by utility to improve grid protection according to each grid code.

- An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability.
- Such action may include changes in demand, generation (MW and Mvar), or system configuration to maintain system stability, acceptable voltage, or power flows.

Grid of Jamaica

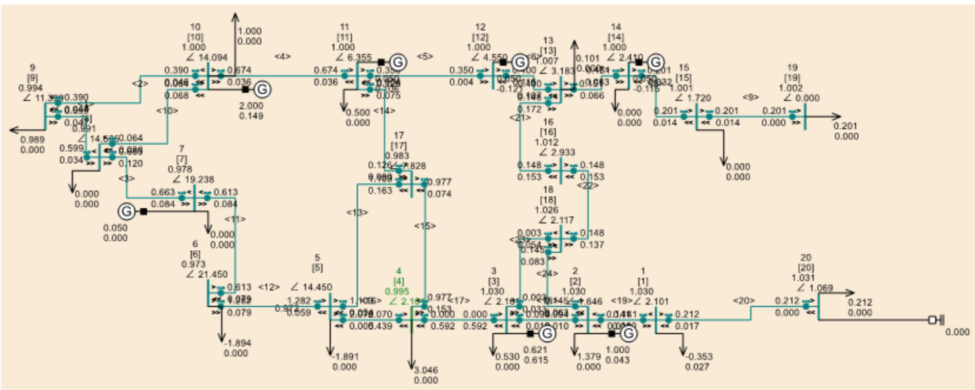
- To Solve Short Term Spinning Reserve Problem -



Red number is node number for power system analysis. Voltages of nodes in red circle became low in the load flow analysis.

* Map is from the presentation document of JPS(Jamaica Power Sector) on May 27, 2019.

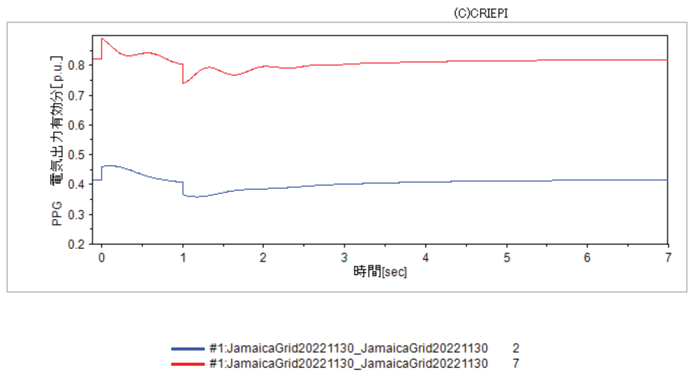
Load Flow Analysis of Jamaica Grid



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Transient Stability Analysis (Case Study)

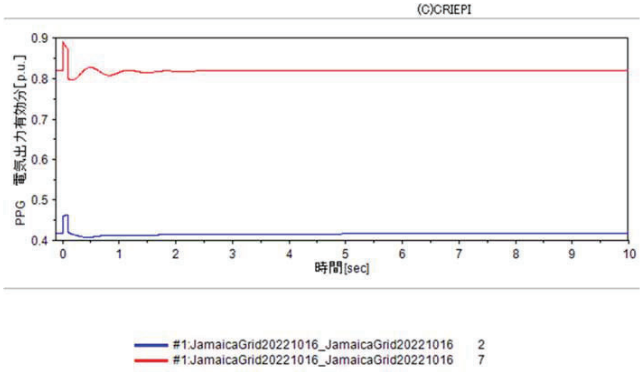
- In case output of PV drops from Max to Zero for 1 second -> Stable



Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Transient Stability Analysis (Case Study)

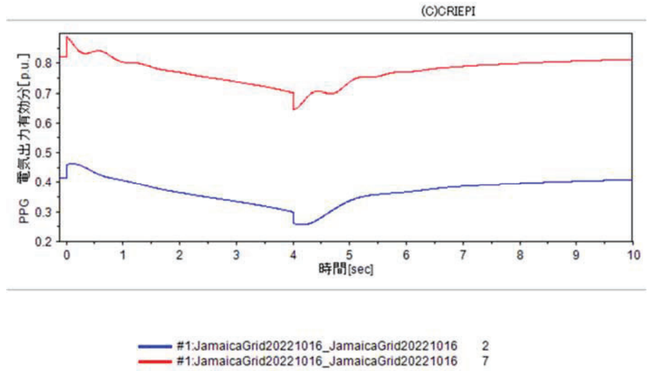
- In case output of PV at node 4 drops from Max to Zero for 1 second -> Stable



Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Transient Stability Analysis (Case Study)

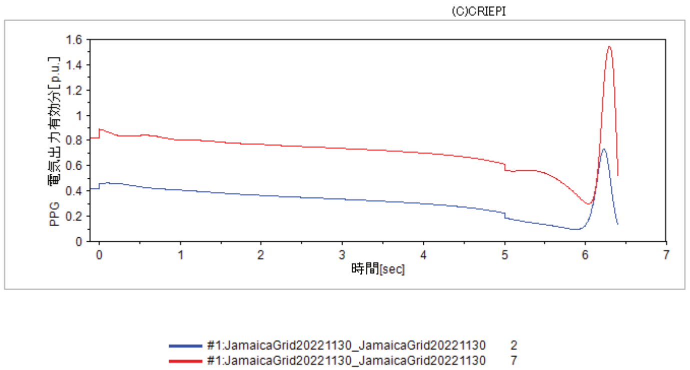
- In case output of PV at node 4 drops from Max to Zero for 4 second -> Stable



Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Transient Stability Analysis (Case Study)

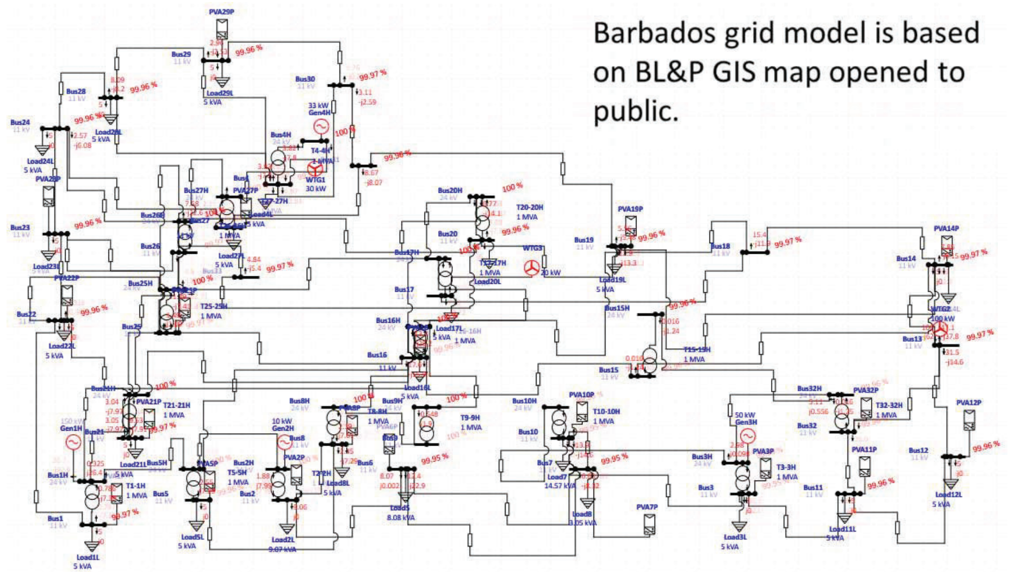
- In case output of PV at node 4 drops from Max to Zero for 5 second -> Unstable



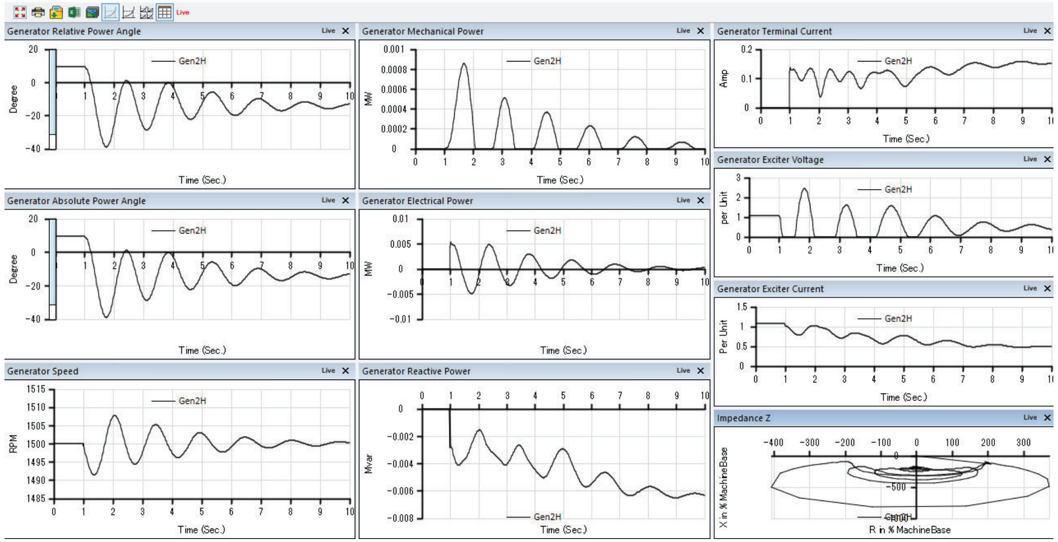
Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Barbados 50 nodes grid map in ETAP

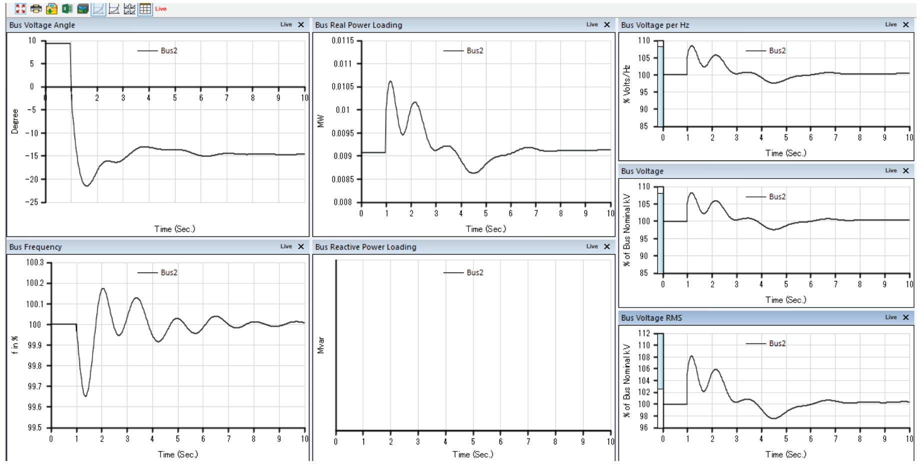
Barbados grid model is based on BL&P GIS map opened to public.



Generator No. 1 Transient after Wind Turbine Trip



Voltage and Power of Bus No. 1 after Wind Turbine Trip



Steps of Stability Analysis and Evaluation

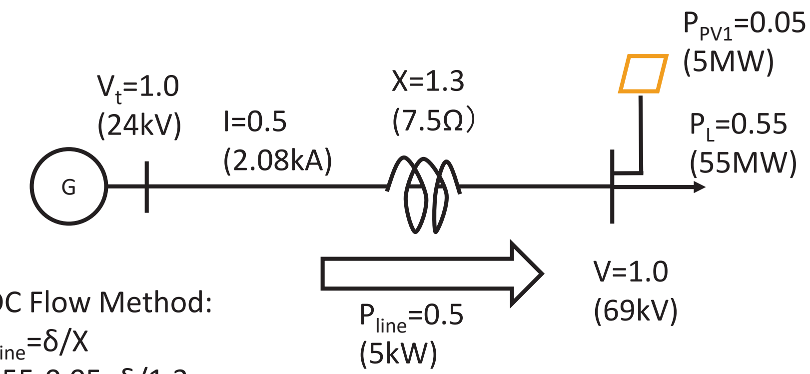
Steps to evaluate stability will be as follows:

1. Load Flow Analysis
2. Equal Area Criterion
3. Short Circuit Ratio
4. Available Transmission Capacity
5. Spinning Reserve

Per Unit Base calculation method for Transmission Network and Distribution Network

- Transmission Network
  - Base VA 100MVA
  - Base Voltage 24kV
  - Base Current 4.16kA (=100/24)
  - Base Impedance 5.76Ω (=24*24/100)
  - Base Admittance 0.174Ω^{-1} (=1/5.76)
- Distribution Network
  - Base VA 100kVA
  - Base Voltage 400V
  - Base Current 250A (=100000/400)
  - Base Impedance 1.6Ω (=400*400/100000)
  - Base Admittance 0.625Ω^{-1} (=1/1.6)

Transmission Network Model



(1) DC Flow Method:

$P_{line}=\delta/X$

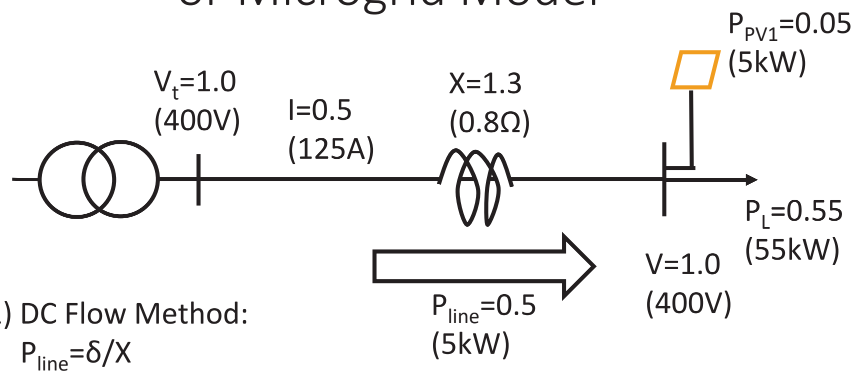
$0.55-0.05=\delta/1.3$

$\delta=0.65$rad=37deg

If $\delta<90$deg, these area is stable.

$I=(P_L-P_{PV1})/V=0.5/1.0=0.5=2.08A$

Distribution Network Model or Microgrid Model



(1) DC Flow Method:

$P_{line}=\delta/X$

$0.55-0.05=\delta/1.3$

$\delta=0.65$rad=37deg

If $\delta<90$deg, these area is stable.

I=(PL-PPV1)/V=0.5/1.0=0.5=125A

P-δ Curve and Stability Evaluation

(2) Pmax=1*1/1.3=0.77

(3) Pop=0.5

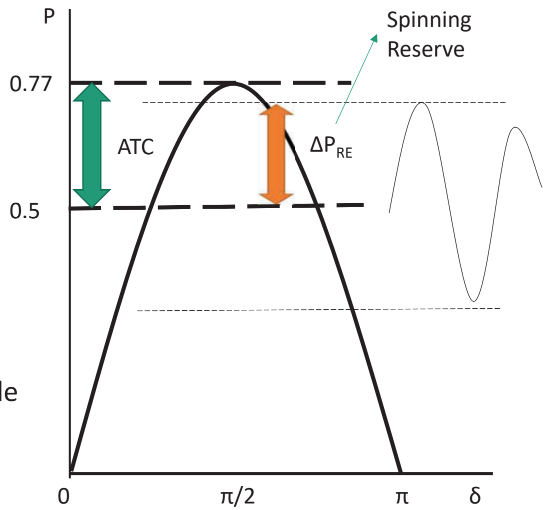
(a) Currently ΔP_{RE}= 0.15
-> Stable

(b) If ΔP_{RE}> 0.27
-> Unstable

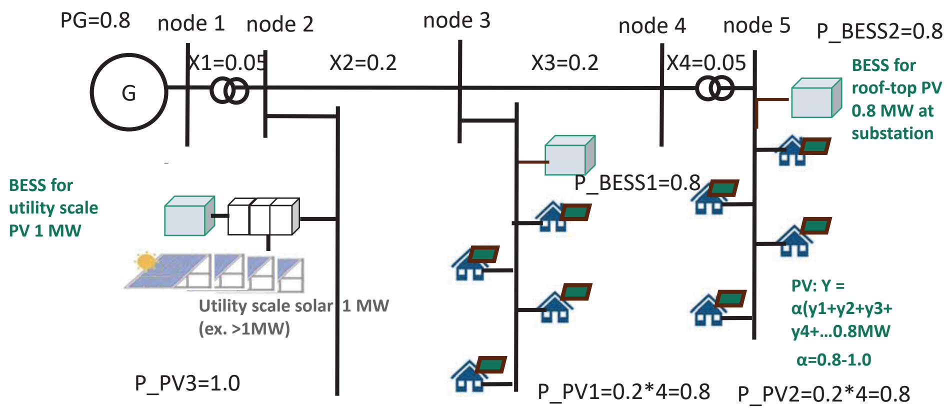
$SCR=Pop/\Delta P_{RE}$
should be over 3
=(a) 3.33 -> Stable
=(b) 1.85 -> Unstable

(4) ATC=0.27 -> If ΔP_{RE}> 0.27
-> Unstable

(5) Spinning Reserve should be more than ΔP_{RE}
=0.15



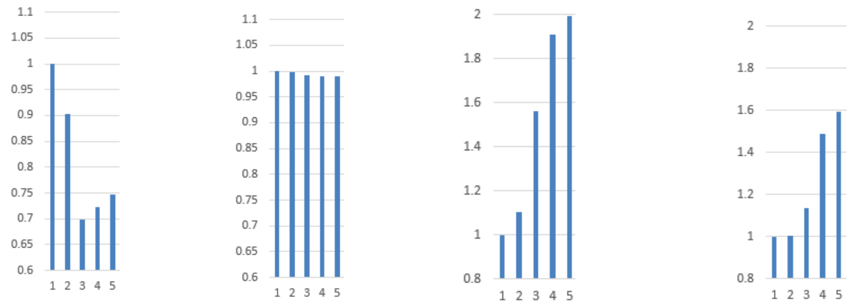
Simple Grid Model for RE



X=X1+X2+X3+X4=0.05+0.2+0.2+0.05=0.5

Load Flow Analysis of Simple Grid -to see the effect of Battery and Large PV-

Y axis : P.U. Voltage



only PV | PV+Battery | PV+Battery+largePV(node2) | PV+Battery+largePV(node5)

- If batteries are connected with no advanced control and output of PV goes zero, node voltage will be high.
- Large PV will cause the increase of node voltages.
- In case PU voltage > 1.1, capacity of distribution line needs to be enhanced.

Suggestion from You

- Do you have any subject to be solved?
- JICA team may conduct grid simulation based on your idea about generation source and other items that will be necessary for future grid.
- Please suggest if any other needs to consider in grid model and simulation.
- Please let us know your request through the following google form, if any additional. (same as the one before session 5)

[redacted]

- We will include your idea or request as a subject in the next Grid Stability Seminar in January, 2023.

Request of Feedback

Please provide your kind feedback with the form below:

[redacted]

Next:If lasted, I will inform tomorrow, after solving and

[redacted]

Thank You!!

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Consideration of Large VRE into Grid

Introduction for Seminar on Grid Stability and Large RE

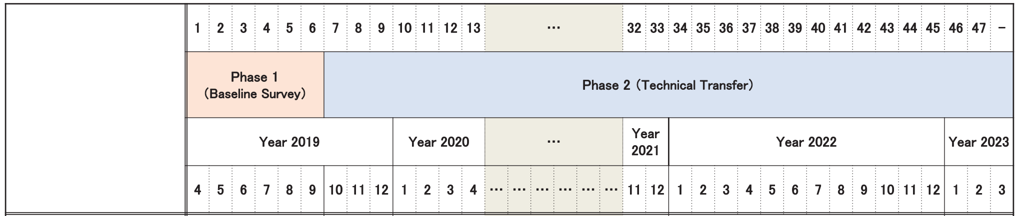
October 2022

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

Agenda

- 9:30-9:40 Introduction and Schedule
- 9:45-10:30 Evaluation of Load Flow Analysis by Microgrid Designer, and Transient Stability Analysis
- 10:30-10:45 Example of LFC and ELD in Microgrid Designer
- 10:45-11:00 Hydrogen and Ammonia concept with Nevis Geothermal
- 11:00-11:30 Draft Program of Training in Japan
- 11:30-12:00 Consideration of Large VRE into Grid, Discussion

Overall Project Schedule



Output 1
The basic information is confirmed for the capacity building for the introduction of RE

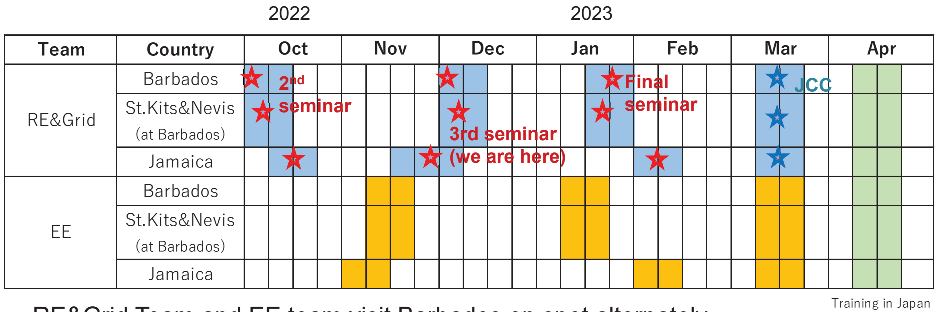
Output 3
The human and institution capacity are enhanced for the mass introduction of RE

Output 2
The basic information is confirmed for the capacity building for the promotion of EE

Output 4
The human and institution capacity are enhanced for the promotion of EE

RE and Grid Stability activity is to:
- introduce computer modelling for grid analysis and examine issues associated with a large penetration of VRE
- introduce micro-grid concept in one of the agreed areas and develop modelling based on existing grid data.
- propose the way to enhance resiliency by use of asset management system.
- consider and propose the necessary technologies for achieving the RE goals, including grid stabilization,
- consider and propose additional policy legal system for achieving RE goals
- Prepare training plan, provide recommendation on policy

Schedule and Key Events for RE&Grid Activity



- RE&Grid Team and EE team visit Barbados on spot alternately.
- 2nd Seminar on Grid Stability and RE on 3-5 Oct 2022
- **3rd Seminar on Grid Stability and RE on 6 and 8 Dec 2022**

  Objective: to discuss challenges and solutions for future Barbados/StKN Grid with RE penetration and to share knowledge about grid stability and simulation for future optimum grid planning
- 4th Seminar on Grid Stability and RE in late Jan 2023 (2 days from 16-20 Jan 2021)
- Final Joint Coordinating Committee (JCC) in March 2023

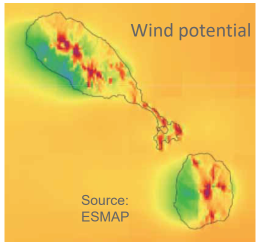
Summary (St Kits and Nevis)

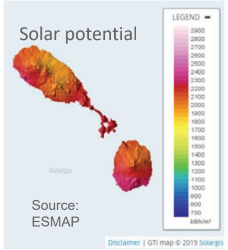
Fields	Findings	Project Activity
Energy Efficiency	• Energy Source: Electricity (63%) , Oil (37%) • Load Curve: Bactrian camel type • Annual Peak Demand: about 25MW (St. Kitts) about 10MW or more (Nevis) • Peak Period: around 11am, 6pm-8pm (St. Kitts) around 12am, 6pm-8pm (Nevis)	Priority 1: Optimized operation with inverter Priority 2: Mini split AC with inverter Priority 3: VRF
Renewable Energy	• 100% RE by 2020 target • 0.7+0.5 MW PV (St.Kitts), damaged • 2MW wind operated at 1.1 MW (Nevis) • Bellevue 5.4 MW wind, Leclanche 35MW PV	Monitoring RE project incl. geothermal Training for grid simulation Introduction of asset management
Grid Stabilization	• 6MW 34 MWh BESS planned for 35MW PV • Output suppression conducted in NEVLEC	
O&M of Thermal Power Generation	• Thermal power plant: total 13 units (St. Kitts), total 8 units (Nevis) • Installed Capacity: total 44.9MW (St. Kitts) total 21.3 MW (Nevis) • Peak demand 24MW (StK), 9.83 MW(Nevis)	-
Human Resources and Capacity Building	• MPI's Energy Division: 4 employees • Most of capacity building is done by OJT • There is no systematic HR development.	JET experts select topics and develop curriculum for technology transfer

RE: Status in St.Kitts & Navis

RE Projects in St. Kitts and Navis

Location/Project	Type	Capacity MW	Generation GWh estimated	Year
S: SCASPA	PV	0.7	NA	2013
S: SKELEC	PV	0.5	1	2015
N: Windwatt	Wind	2.2	5.25	2011
N: NREI Geothermal	Geo	10-30	NA	2026
S: Leclanche	PV	35	43.8	2020
S: Bellevue	Wind	5.7	NA	NA
S: NW Geothermal	Geo	18-36	NA	NA





Necessary consideration for future RE

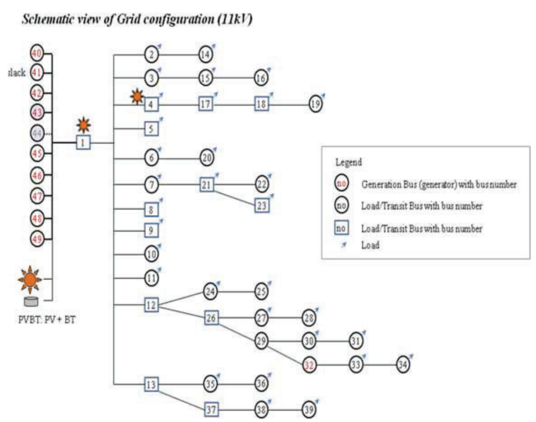
1) Grid stability analysis for new 35MW PV system
2) Update of geothermal development
3) Interconnection (11kV, 66 kV)?

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

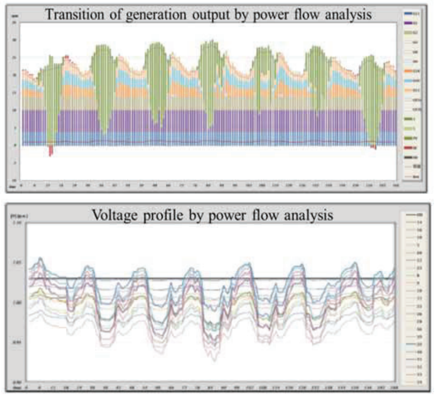
Plan of Install Geothermal Power Plant and Grid Improvement in Nevis

- Phase 1:
  Power Grid Reinforcement from 11KV to 66KV
- Phase 2:
  Expand 66KV transmission, Install 30 MW Geothermal at N3, Connect into St. Kitts Power System
- Phase 3:
  Hydrogen Based Project at Long Point, Install 15 MW Geothermal at N3
- Phase 4:
  66KV from Long Point to Camp (Circular Line complete), Offshore Wind at 50 MW, Additional Geothermal from 15MW to 30MW at N1, Expansion of Hydrogen Based Project

Grid Analysis Model of Microgrid in St. Kitts



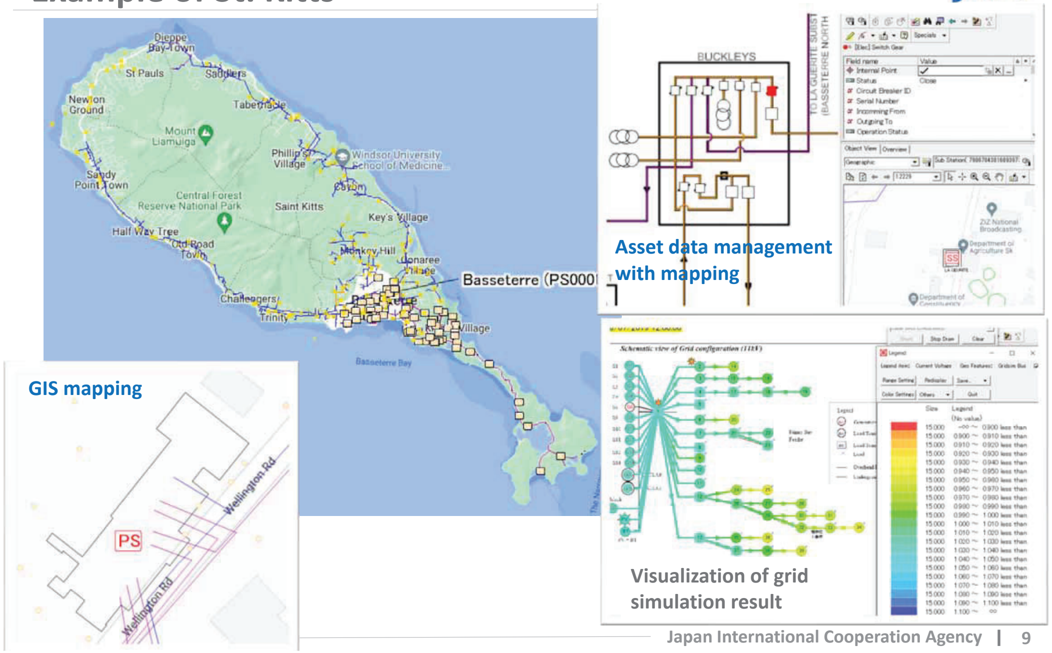
Example of micro-grid model (St. Kitts)



Grid analysis result (generator output, voltage, frequency)

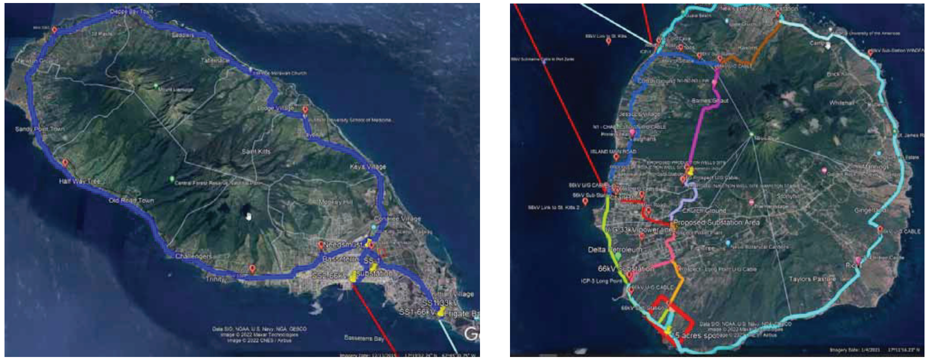
Analysis result is viewed in geographical information system
Smallworld is applied to visualization for investment plan and design

GIS, Asset Management with Grid Simulation Example of St. Kitts



Saint Kitts and Nevis Assumed Grid for Discussion

Plan of assumed 66 kV interconnection



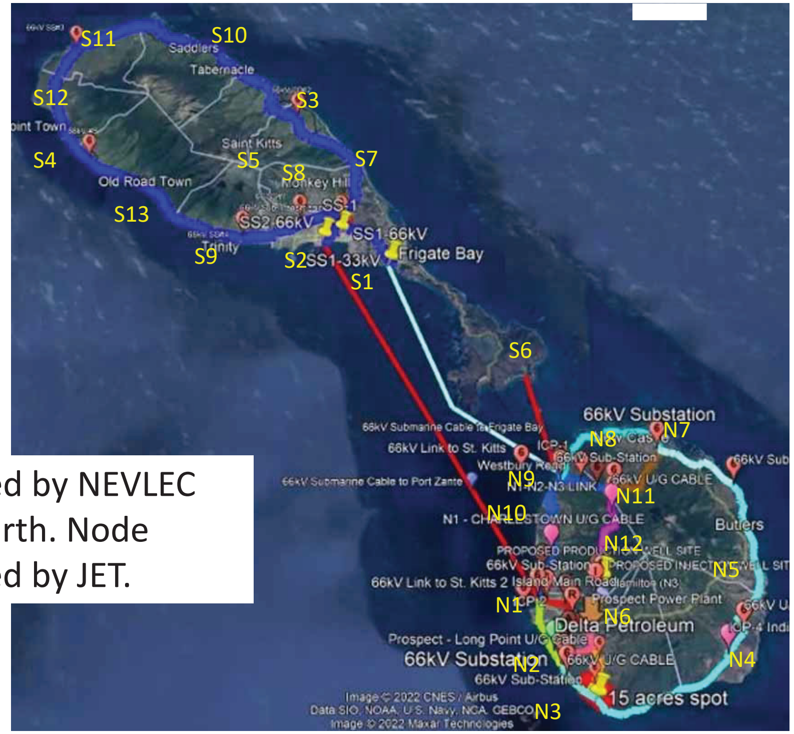
3rd Seminar on Grid Stability and Large RE Day 2

JICA Expert Team, Nippon Koei Co., Ltd.

Objective of Analysis

- In order to get a superior future grid for St. Kitts and Nevis, we have to consider, check, evaluate and make a valuable and acceptable plan for future grid.
- Here we show several processes to do them and try to make some advice for you.
- So the data used in this seminar is only a sample for demonstration.
- Today we introduce and show some tools to evaluate grid.
- If you have some subject to be solved, please let me know it, We will include them and solve the best way in the next seminar.

St. Kitts & Nevis Grid



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

Current and Future Grid of St. Kitts & Nevis

<Current>
- Voltage: 11kV
- Capacity: St.Kitts 25MW, Nevis 10MW
- Installed PV: 35MW in St. Kitts
- Installed WT: 5MW in Nevis
- Installed BESS: 6MW, 44MWh in St. Kitts

<Future Plan>
- Voltage of main transmission line will be up: 66kV
- Capacity of PV: 35MW more
- Capacity of WT: 50MW
- Geothermal Power Plant: First plan is 30MW, Next Plan is upto 90MW

Future Grid Plan of St. Kitts

- Grid Capacity except for VRE: 48.9 MW
- Peak Demand: 26.2MW
- Transmission Line Voltage: 11.2 kV
- Generators: Diesel: 16 Units at Needsmust (S1)
- Wind Turbine: 6.6 MW at Bellevue (Cayon feeder) (S10)
- PV: 0.75MW (not operating) + 0.5MW (some not fully operating) + 1.0MW fully operation (S4, S9)
- Planned PV: 34 MW Leclanche (with 6MW, 44 MWh BESS) under design. Completed in 2024. (S2)

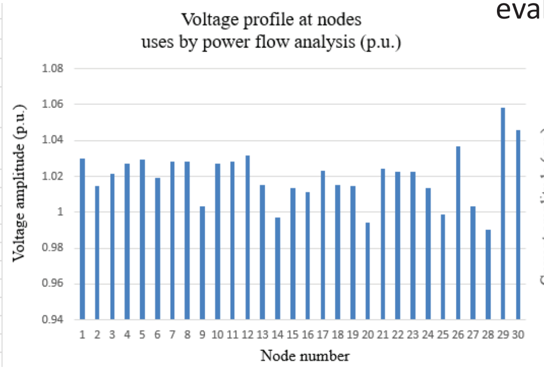
Future Grid Plan of Nevis

- Grid Capacity except for VRE: 18.5 MW (output 16.8MW)
- Peak Demand: 9.83MW
- Transmission Line Voltage: 11.2 kV, Planned to 66kV
- Generators: Diesel 8 Units at Prospect (N1)
- Geothermal Power: 10-30 MW planned (N12)
- Solar Power: 3- 5 MW planned (N3)
- Wind Turbine: 2.2 MW(0.5MW limit) (N7), 50MW (N5)
- BESS: 3-5 MW planned (N3)
- Hydrogen Based Project: 15MW (N2)

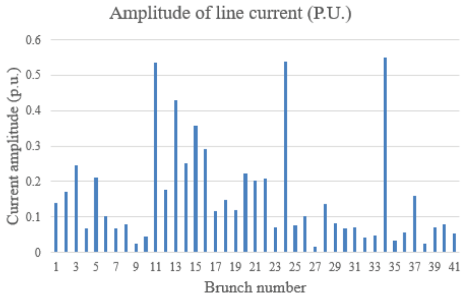
Load Flow Analysis of St. Kitts

Data written as PSS/E format is provided by SKELEC and converted for Microgrid Designer.

Voltages of node no. 29 and 30 are 5~6% over from the rated value. Line currents are within the rated values. Capacity limit of equipment can be evaluated by load flow analysis.



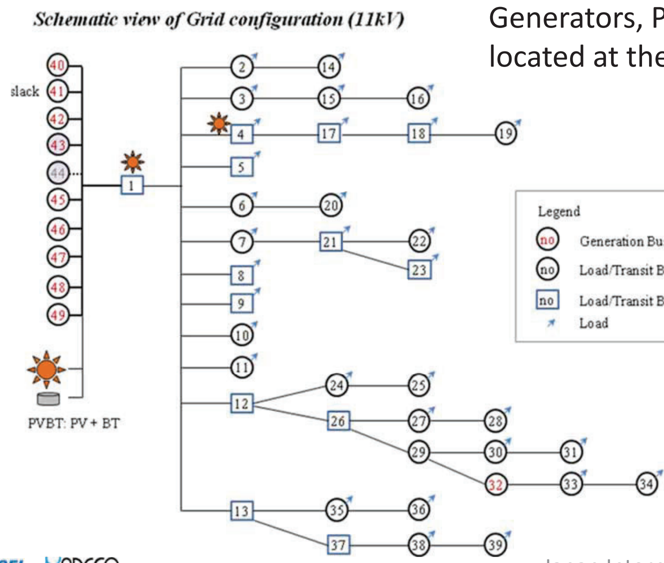
Node Voltage



Line Current

Calculated by Microgrid Designer

St. Kitts Grid



Generators, PV and batteries are located at the same node no.1.

From Microgrid Designer

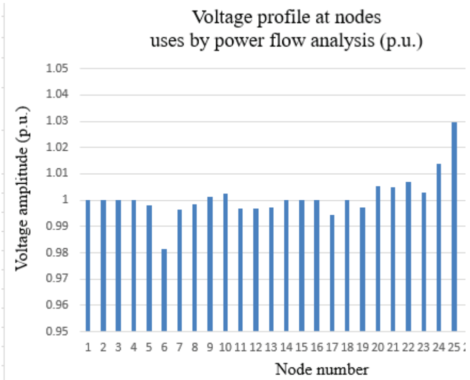
Data for Future Grid of St. Kitts & Nevis

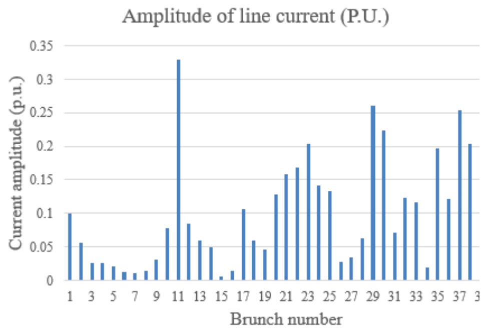
Data is assumed base on Google Map data provided from NEVLEC.
Both network of St. Kitts and Nevis are connected bi 66kV transmission line.

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load			
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	PV	WP	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)
S1	2	1			0.25	0	0.05	0	0.05			
S2	1	1				0	−0.23	0	0.05	0.34		0.06
S3	1	1				0	0	0	0			
S4	1	1				0	0	0	0			
S5	0	1			0	0	0.04	0	0.04			
S6	0	1			0	0	0.03	0	0.03			
S7	0	1			0	0	0.03	0	0.03			
S8	0	1			0	0	0.01	0	0.01			
S9	0	1			0	0	−0.08	0	0.01	0.09		
S10	0	1			0	0	−0.046	0	0.02		0.066	
S11	0	1			0	0	0.02	0	0.02			
S12	0	1			0	0	0.02	0	0.02			
S13	0	1			0	0	0.02	0	0.02			
N1	1	1			0.1	0	0.01	0	0.01			
N2	1	1				0	0.17	0	0.02			0.15
N3	1	1				0	0	0		0.05		0.05
N4	0	1			0	0	0.01	0	0.01			
N5	1	1			0	0	−0.5	0			0.5	
N6	0	1			0	0	0.01	0	0.01			
N7	0	1			0	0	0.005	0	0.01		0.005	
N8	0	1			0	0	0.01	0	0.01			
N9	0	1			0	0	0.01	0	0.01			
N10	0	1			0	0	0.01	0	0.01			
N11	0	1			0	0	0.01	0	0.01			
N12	0	1			0.3	0	0	0	0			

Load Flow Analysis for Future Grid of of St. Kitts & Nevis

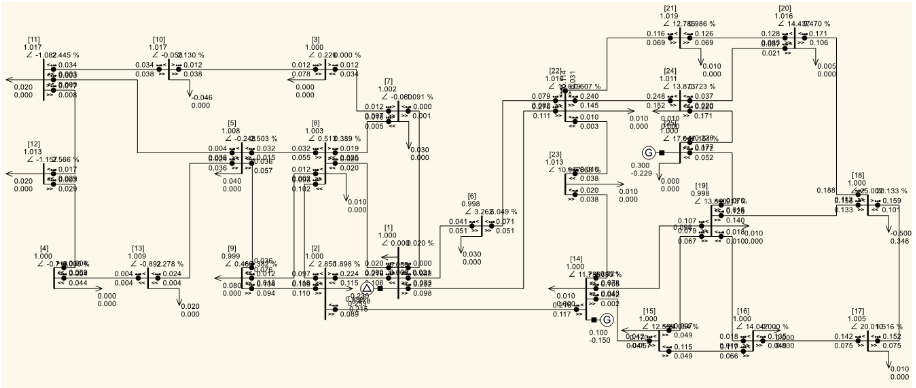
In a case of future grid data of St. Kitts & Nevis, node voltages are within regulation, and line current is under rated value.





Calculated by Microgrid Designer

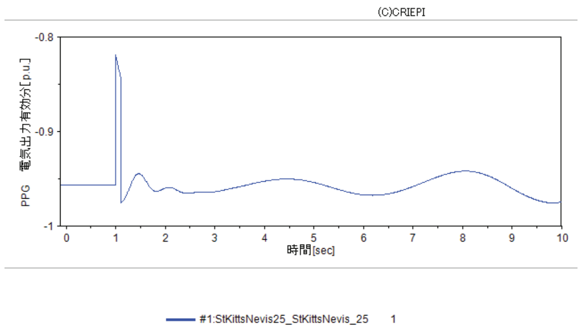
Grid of St. Kitts & Nevis



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Transient Stability Analysis for Future Grid of of St. Kitts & Nevis

After PV in S4 was stopped for 100 mili seconds, the system is going to be stable. Transient stability analysis is necessary to evaluate fluctuation of PV. Transient stability analysis is required to make a plan.



Requested Data for grid analysis

- NEVLEC
  - Single line diagram of overall network and feeders
  - Demand data (peak and load curve of day, month, year, if any)
  - Distribution line data and transformer of each feeder (feeder length, size, type (ACSR, cable, etc),impedance, resistance, capacitance), and GIS data if possible
  - Location, Capacity and Terminal Voltage of Generation plants including RE and Battery
  - Generator parameters including AVR, AVR, PSS, turbine and, if any, other control equipment
  - Location, Capacity and Terminal Voltage of Substation with transformer, SVC, STATCOM or Battery
  - Location and amount of consuming power or load in nodes including peak load and minimum load in analysis model, if any
  - Usual operational style about network structure with switch gear operation under heavy load and light load
  - ETAP data and QGIS shapefile of 11 kV network
- SKELEC
  - Same as NEVLEC, if any update from 2019

Hydrogen and Ammonia concept with Nevis Geothermal: --- Preliminary Study

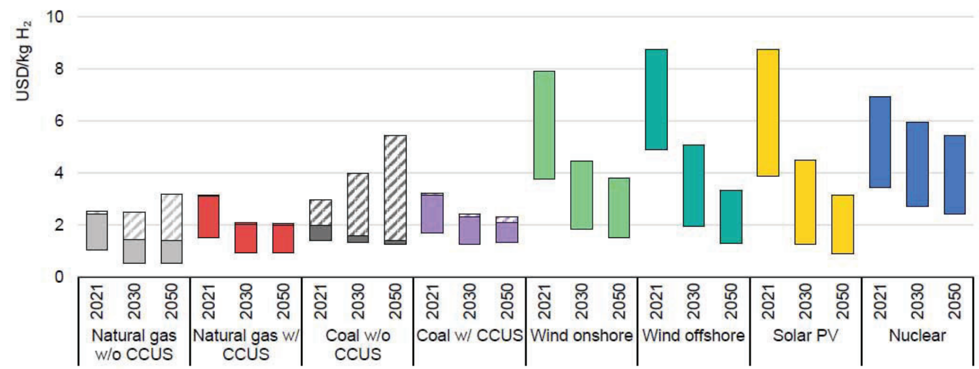
Hydrogen and Ammonia : Preliminary General Cost Study

- Does cost of geothermal 16-17 Usc/kWh with higher capacity factor than PV/Wind for H2 production plant have advantage?
- How does the location of Nevis with tanker transportation affect transportation cost?
- H2 or NH3, which is more feasible in Nevis?

Hydrogen Production Cost by Natural Gas with CCUS, Wind, and Solar

- Natural gas with CCGS is lowest, 1-1.5 USD/kgH2 in 2030 but site is limited.
- Hydrogen production by PV and wind is expected to be 1.5-5 USD/kgH2 in 2030

Levelised cost of hydrogen production by technology in 2021 and in the Net Zero Emissions by 2050 Scenario, 2030 and 2050

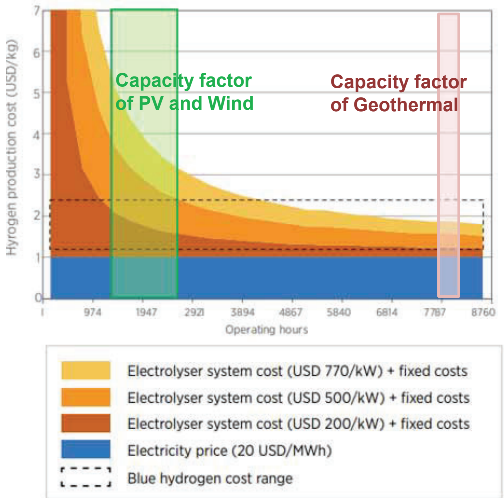


Source : IEA Global Hydrogen Review IEA. All rights reserved.

Notes: Ranges of production cost estimates reflect regional variations in costs and renewable resource conditions. The dashed areas reflect the CO_2 price impact, based on CO_2 prices ranging from USD 15/tonne CO_2 to USD 140/tonne CO_2 between regions in 2030 and USD 55/ tonne CO_2 to USD 250/ tonne CO_2 in 2050.

Sources: Based on data from McKinsey & Company and the Hydrogen Council; Council; IRENA (2020); IEA GHG (2014); IEA GHG (2017); E4Tech (2015); Kawasaki Heavy Industries; Element Energy (2018).

Advantage of Geothermal High Capacity Factor?



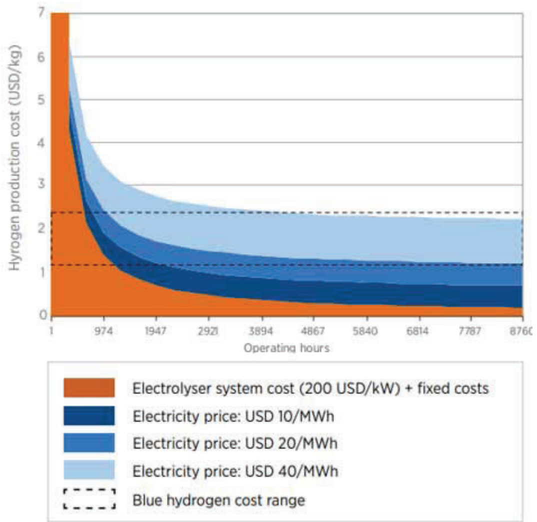
RE Type	Capacity factor	Hour/yr	Electrolyser cost w/o electricity USD/kg*
PV	13-25%	1140-2190	2.8-4.5
Wind	20-30%	1752-2752	2.3-3.3
Geothermal	90-95%	7784-8322	0.8-0.9

*Electrolyser system cost (770USD/kW)

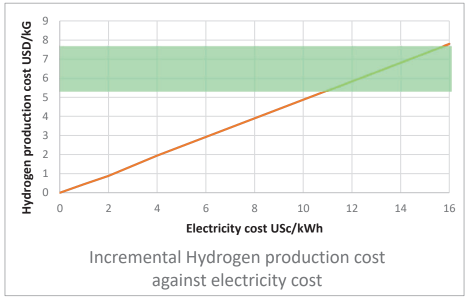
- Advantage of high capacity factor of Geothermal:
  2.0-2.8 USD/kgH2 (@ 770 USD/kW)
- System cost/kW become lower, the advantage will be smaller

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

Hydrogen Production Cost by Geothermal vs PV/Wind



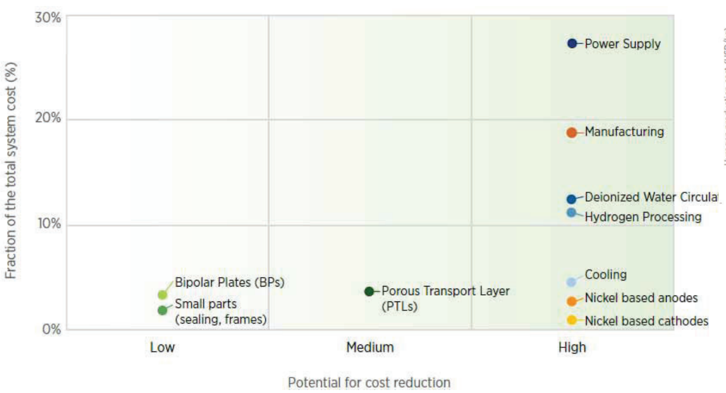
Source: IRENA Green Hydrogen Cost Reduction
Note: Efficiency at nominal capacity is 65% (with an LHV of 51.2 kWh/kg H2), the discount rate 8% and the stack lifetime 80 000 hours

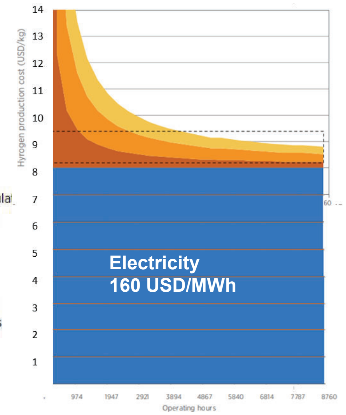


Source: Prepared by JET referring to IRENA Green Hydrogen Cost Reduction

- Advantage of high capacity factor of Geothermal: **2.0-2.8 USD/kgH2**
- → in case geothermal cost is 16USc/kWh, it will have advantage by capacity factor if PV and Wind (13-30%) and is more than 10.2-12 USc/kWh (102-120 USD/MWh)

for future cost reduction of H2





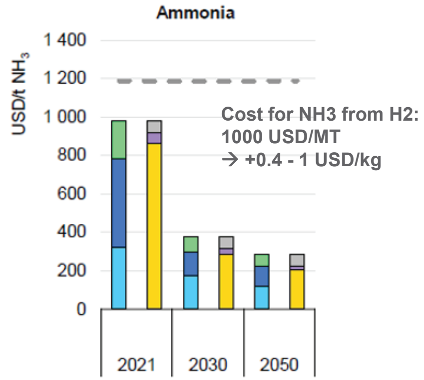
Source: IRENA

- Electricity cost is affect cost highest
- Manufacturing cost (plant for electrolysis) is about 19%, which is related to scale merit

Current cost and projected cost of NH3

Current Cost for NH3 300-650 USD/MT depending on fossil fuel price
Cost for NH3 from H2 is depending on H2 production cost

https://www.procurementresource.com/resource-center/ammonia-price-trends



Source : IEA Global Hydrogen Review

Hydrogen and Ammonia energy content

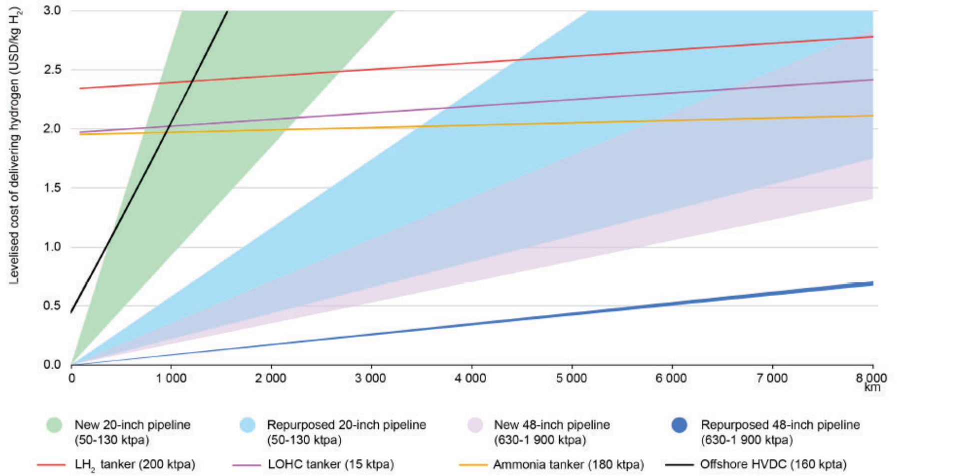
Type	Energy content (LHV) [MJ/Kg]	Energy content (LHV) [MJ/L]	Density [kg/m3]
Cooled Ammonia (Liquefied)	18.6	12.69 (1 atm, -33℃)	682
Compressed Ammonia (Liquefied)	18.6	11.65 (300 bar ,25℃)	626
Cooled Hydrogen (Liquefied)	120	8.5 (1atm, -253℃)	70.85
Compressed Hydrogen (gaseous)	120	2.46 (300 bar, 25℃)	20.54
Diesel (n-dodecane)	44.11	32.89 (1 atm, 25℃)	745.7
Gasoline (iso-octane)	44.34	(n-octane) 30.93 (1 atm,25℃)	(n-octane) 697.6

Source: prepared from https://www.iea-amf.org/content/fuel_information/ammonia

- Energy content per kg : H2 is 10 times than NH2
- To liquify for transportation by tanker, H2 requires -253 ℃
- 1ton LHOC (liquid hydrogen organic career) can transport 62 kg H2 →7440 MJ/ton
- Liquified NH3 18,600 MJ/ton

Cost of Transportation of Hydrogen and Ammonia

Levelised costs of delivering hydrogen by pipeline and by ship as LH2, LOHC and ammonia carriers, and electricity transmission, 2030



Source : IEA Global Hydrogen Review

IEA. All rights reserved.

Notes: ktpa = kilotonnes per year; LH2 = liquefied hydrogen; LOHC = liquid organic hydrogen carrier. Includes conversion, export terminal, shipping, import terminal and reconversion costs for each carrier system (LH2, LOHC and ammonia). The import and export terminals include storage costs at the port. Pipelines refer to onshore transmission pipelines operating at ranges between 25% and 75% of their design capacity during 5 000 full load hours. Electricity transmission reflects the transmission of the electricity required to obtain 1 kg H2 in an electrolyser with a 69% efficiency located at the distance represented by the x-axis.
Source: IEA analysis based on data from Guidehouse (2021) and IAE (2016).

LOHC : Liquid Organic Hydrogen Carrier

Cost of Transportation of LOHC

Cost of Hydrogen, LOHC, NH3 tanker

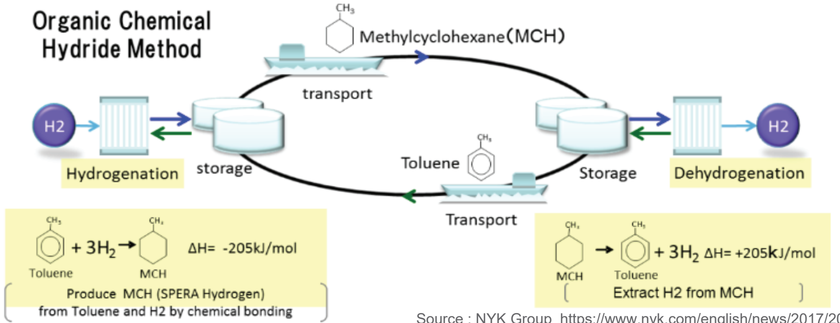
Geothermal capacity	10	MW
Operation hr	8000	hr/year
Power Production	80,000	MWh/year
Hydrogen efficiency	48.95	MWh/ton
Hydrogen production	1,634	ton/year
LOHC carriage	62	kgH2/t_LOHC
LOHC tanker	15,000	ton/year
H2 by LOHC tanker	930	tonH2/year
nos of tanker	2	tankers/yr

NH3/ LOHC Career cost (USD/kg)

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

Source : Prepared by JET IEA Global Hydrogen Review

*** Ammonia Production cost: +0.4-1 USD/kg**



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

For the next step

- If PV/Wind cost is more than10.2-12 USc/kWh, 16 Usc/kWh Geothermal has advantage in hydrogen production in terms of market competitiveness
- For smaller transportation, LOHC may be the appropriate considering tanker transportation and 10-30 MW scale
- Difference of H2 and NH3 production cost: For larger scale, NH3 may have advantage
- F/S considering site specific cost and future details is necessary

Appendix 5-4-2 Attendant list, and Q&A, of the 2nd RE & Grid Stability Seminar (St. Kitts and Nevis)

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE in Dec 6-8 2022 (Barbados and St.Kitts&Nevis): Q&A

No	Item	Content	Name	Answer	Further Notes
1	Question	How current is the data that is been shown on the Barbados maps?	Stephen Worme, BREA	The base map with 11 & 24.9 kV feeder line is from Web page of BL&PC. The data of transmission lines, generator, transformer and load are assumed by JET. The PV location is based on MEB solar database. Information of PV capacity on feeder lines is as of Oct 2022 based on MEB.	Issues with the different format of input of coordinate system may cause inaccuracy of map. Those are being rectified to ensure standardization. Mapping only started recently.
2	Question	What about Hydrogen potential as an Emerging Technology?	Stephen Worme, BREA	Hydrogen is alternative way for energy storage. When hydrogen is stored in Fuel Cell, it can be converted to electricity. Cost is still much higher than BESS.	
3	Question	Would you propose that the Microgrid be owned by the Utility or have a separate owner?	Stephen Worme, BREA	It depends on regulation. In some countries, only transmission operator can own and operate microgrid. In Japan, private local utility JV with local government operates Microgrid. It may be an idea that government of a central utility owns or manage the micro grid.	
4	Question	Can these examples of microgrids on the large systems indicated in the examples be easily extrapolated to the smaller grids of Jamaica, Barbados and St Kitts?	Stephen Worme	Yes. Australia can be used in terms of a scalable example as seen in the presentation.	California etc. can be used as examples but they can import energy unlike us here in the region as SIDS. Barbados is small and unlike Jamacia it has size challenges
5	Question	Are Grid Forming Inverters commercially available? Can you provide examples you are familiar with/ How does the cost compare with Grid Following Inverters?	Robert Goodridge	Microgrid Ex.-3: South Australia Yorke already applies a kind of Grid Forming Inverter for BESS. It is demonstration. In Japan, 5 inverter manufacturer demonstrates. Hopefully it will be available in the market for 5 years. Since the difference of GFM with conventional inverter is software, not material, the cost will not be very higher than other inverter, although development cost need to be considered. We will inform and discuss current states of the development of Grid Forming Inverter in the next seminar.	
6	Question	Grid forming Inverters look like they could be a very valuable solution to address some of the grid stability challenges. Would they still continue supplying power to the grid when the grid power goes off and, if they do wouldn't, they introduce a potential safety issue for the utility?	Stephen Worme, BREA	From recovery of black-out, generator with permanent magnetic motor is necessary. Grid Forming Inverter converts provided energy resources to electricity, however, it can not operate solely from black start condition. In order to continue to supply electricity, energy resources should be available continuously.	
7	Question	Has JICA conducted any analysis of the current state of the Grid in Barbados? Has any specific projections/recommendations been made to address current/expected stability issues in Barbados?	Robert Goodridge	We conducted some analysis based on current grid assumptions and some PV/Wind additional scenario for trial, which will be presented in afternoon session and tomorrow session.	
8	Question	Slide 20: (1) Why 66/3? (2) Is the 3MW VRE directly connected to be battery?	Felicia Cox	(1) 66MW is 33% of total capacity of 200MW in a sample grid. Japanese utilities consider that the capacity of PV is about 1/3 of its rated capacity when they make daily operation plan. This should be different in case of Barbados when 100% RE is targeted and should be higher like 66/0.8. (2) VRE is connected to battery through DC filter.	
9	Question	Do you recommend 4 hours of storage for PV and what size PV systems should have storage ?	William Hinds	4 hours is just an example. It is half of day time. We will discuss the way to calculate the optimal size of battery in the next seminar.	
10	Question	(3) Is the recommendation that peak battery be 1/3 peak VRE? (4) Why 4h battery?	Felicia Cox	For Barbados, it will be necessary to to be a higher percentage. IRRP should already study the optimal size. For the case of Japanese utilities, they consider that the capacity of PV is about 1/3 of its rated capacity when they make daily operation plan. (4) 4 hours are an example. It is half of day time, as stated above.	
11	Question	Is there an international standard for sizing storage ?	William Hinds	We'd think there is no international standards, and the applicable standards depends on design philosophy with situation and conditions.	

No	Item	Content	Name	Answer	Further Notes
12	Question	We will have variable RE up to 100 MW. Query the approach for analysis of the Bar system give we will have a very large share of RE. Related to dynamic and transient stability. Sorry 100 % RE	Rohan Seale, BLPC	Thank you for your information about future plan of RE. It is challenging.	
13	Comment	All these examples assumes that you have other generation that are not VRE. Remember that VREs don't contribute to SC. There is no standard for battery storage. It depends on the length of time the probability of not having VRE available reserves.	Chandrabhan Sharma	That is right. Our tested cases are examples to evaluate several measurements to solve the problem on grid stability.	
14	Comment	Can it model current and ongoing grid RE integration	Rohan Seale, BLPC	That is the core of our technical capacity building project. We have created a 91 MW RE scenario in which we will share today for example. Tomorrow we would like to exercise what you are having as current situation. If you could provide the current or ongoing or planned RE situation, we will simulate.	
15	Question	Can we reduced the need for overnight storage by use biodiesel in a limited number of fossil fuel generators ?	William Hinds, MEB	Biodiesel can be used as a base load generator. However, fuel cost will be high. Cost comparison with BESS considering deterioration should be discussed.	
16	Question	Would there be a significant problem if the solar on the grid is as much as 60% ?	William Hinds, MEB	Without spinning reserve, it will be a problem with possibility of high grid instability. High PV grid penetration will cause instability if the ramp rate of the spinning reserve cannot manage the fluctuation of instantaneous PV output. For example, if 100 MW peak, 60MW is PV with 40% spinning reserve 40MW, and if 80% of PV output fluctuates instantaneously, 48MW will fall suddenly. Apparently, 40MW spinning reserve can not cover this, and black out will occur.	We have to take some measurements to keep suitable inertia in the grid. One of solutions will be an install of Grid Forming Inverter with Battery.
17	Question	Light & Power has a load shedding system which traditionally trips feeders when the frequency drops to a certain level. This is now complicated by the connection of PV systems on the feeders as, when feeders are tripped due to load shedding, they will not be only disconnecting load but also disconnecting generation if done during the period of operation of the RE system. What will be the impact of this instability? Have you modelled this and what were the impacts?	Stephen Worme	Usually the RE is stopped by load shedding and can not supply during load shedding of the feeder to which the RE is connected. If a grid forming inverter is installed, the inertia for the grid will not be lost, which can increase grid instability. Correct planning should be employed when determining the effects of load shedding using energy modeling software. We will introduce an example of special protection system with RE which has been installed to the Chubu Electric Company in Japan in the next seminar.	
18	Question	How much MW of storage is reduced by 1 MW of biodiesel generation ?	William Hinds, MEB	If Biodiesel 1MW generation is applied, same output of battery can be saved. Biodiesel is expensive compared to conventional comparable fuels. Comparison of biodiesel and battery cost need to be done. It may be discussed in the next seminar.	
19	Question	How does Microgrid Designer program differ from ETAP?	Stephen Worme, BREA	Microgrid Designer is a excel macro base software, in which main part is for load flow analysis. It can calculate steady state power flow and voltage in a grid, but it cannot calculate dynamic phenomena and transient stability of grid. ETAP includes static and transient stability analysis.	
20	Question	These inputs are based on maximum capacities given the static inputs?	Stephen Worme, BREA	Yes. We are doing steady state load flow analysis to determine the typical case scenario.	
21	Question	Why is the PV desegregated?	Stephen Worme, BREA	Currently PV is available for across the island and rapidly spreader. Wind need specific terrain condition.	
22	Question	What is the cut off point for failure tolerance in the designed grid? And what is the cut off time in terms of days disconnected?	Stephen Worme, BREA	There are some parameters such as frequency, voltage, current, etc. according to transmission line specification and grid code. Such parameters are considered .	
23	Question	BLPC has provided all the data necessary?	Stephen Worme, BREA	Load flow data by second is ideal for our microgrid simulation. We have used the information of BLPC opened to public with some assumption simulate data. Some data is provided by BLPC. Some is assumed by JET.	

No	Item	Content	Name	Answer	Further Notes
24	Question	In ELD, does the simulator show PV and all the generators?	Stephen Worme, BREA	This program shows the economic load dispatch of thermal generators, and it doesn't show PV as it doesn't consume fuel. The PV output assumed to be used always with 1st priority since it does not have marginal cost. Is deducted from the generator output.	We consider the fuel costs and the heat rate of generators as parameter. Lower load than rated output decrease the efficiency of generators
25	Question	100 MW off-shore wind will require 60 kV line, not 24.9 kV as conducted in power flow analysis.	Stephen Worme, BREA	The power flow analysis can solve even transmission capacity is not sufficient. It provides value of p.u. and we need to assess from the result of the value for transmission line upgrade according to result. You are right. Transmission line should be upgrade to higher voltage.	100 MW off-shore wind is not included in IRRP and we have to add an additional scenario for what is envisioned by Barbados and the Government.
26	Question	Our IRRP shows installed capacity and not output. How can we remedy this?	Stephen Worme, BREA	For system planning, we will assume the most severe (maximum) case of power flow, which is installed capacity, not average output.	
27	Question	We have 600MW of capacity in our model, while real-time peak is 150MW	Stephen Worme, BREA	To provide sufficient MWh with low capacity factor of PV and wind, much larger MW installation capacity with energy storage is necessary. We have to always consider the inrush current and demand flows in our grid to create the best fit grid model for Barbados.	Biofuels are the best option in Barbados in the short to medium term
28	Question	What is the load flow calculation based on	Stephen Worme	Generator capacity is based on IRRP scenario-1. Network structure and impedance are assumed from a google map and opened data of BLPC Web page.	The government will apply IRRP scenario-3 as the base. Scenario-3 need to be incorporated in simulation.
29	Question	Guyana has standard for battery safety.	NEVLEC	Thank you for the information. In Japan, NITE also covers standard for battery.	
30	Request	We would like to test the Microgrid Designer and input Nevis model.	NEVLEC	We have sent the software. Please try and contact us if any.	

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE: Attendant Day-1 (6 Dec 2022)

Total (except JET)	**45**
Total (including JET)	**50**

No.	Name Resistered	Position	Organization	Country	Confirmed
1	Alex Harewood		JET	Barbados	OK
2	Allison Davis		MEB	Barbados	
3	Alton Best				OK
4	Andrew Gittens	PS	MEB	Barbados	
5	Andy Williams		SKELEC	Barbados	OK
6	Bertill Conroy Browne	Director	MPI	St. Kitts and Nevis	OK
7	Bryan Haynes				OK
8	Clement Williams		SKELEC	St. Kitts and Nevis	
9	Collin Brown	Control & Operations Manager	SKELEC	St. Kitts and Nevis	
10	Collin Williams		SKELEC	St. Kitts and Nevis	OK
11	Curleane Liburd		NEVLEC	St. Kitts and Nevis	
12	Curtis Morton		NIA	St. Kitts and Nevis	OK
13	Cyprian Moore		BLPC	Barbados	OK
14	Dara Haynes Fergusson		MEB	Barbados	
15	Debra Dowridge	DPS	MEB	Barbados	
16	Denasio Frank		MPI	St. Kitts and Nevis	OK
17	Felicia Cox	Director	Adaptive Intelligence Solutions	Barbados	OK
18	Frances Scantlebury		MEB	Barbados	
19	Frank Branch	Technical Officer	MEB	Barbados	OK
20	Gaston Dixon		SKELEC	St. Kitts and Nevis	OK
21	Giovanni Buckle		CCREEE	Barbados	OK
22	Glen Amory	Sr. Assist. Secretary	MPI	St. Kitts and Nevis	OK
23	Haniff Woods	Operations Engineer	SKELEC	St. Kitts and Nevis	OK
24	Heather Sealy	Deputy Chief Electrical Offic	GEED	Barbados	OK
26	Horace Archer		MEB	Barbados	OK
27	Ian Ward		NEVLEC	St. Kitts and Nevis	
28	I-Ronn Audin		JET	St. Kitts and Nevis	OK
29	Jason Andalcio		CCREEE	Barbados	OK
30	Jervan Swanston		NEVLEC	St. Kitts and Nevis	OK
31	Jesse Hunkis		NIA	St. Kitts and Nevis	OK
32	Jonathan Brathwaite		BLPC	Barbados	OK
33	Jonathan Kelly	Engineering Manager	SKELEC	St. Kitts and Nevis	OK
34	Joy Cox	Director	Adaptive Intelligence Solutions	Barbados	OK
35	Justin Taylor		CCREEE	Barbados	OK
36	Karl Nembhard		BREA	Barbados	OK
37	Keane Mark	Generation Maintenance Engin	SKELEC	St. Kitts and Nevis	
38	Kenrod Roberts	Assistant Engineering Manager	SKELEC	St. Kitts and Nevis	OK
39	Kevin Bennett	Generation Manager	SKELEC	St. Kitts and Nevis	OK
40	Mick Pascal		SKELEC	St. Kitts and Nevis	
41	Morland Williams	Inc.Mechanic Engineer	GAIA	Barbados	
42	Naftalie Errar	Planning Engineer	NEVLEC	St. Kitts and Nevis	OK
43	Natasha Corbin		UWI	Barbados	OK
44	Natasha Davis				OK
45	Nelson Horatio Ald Junior S	Distribution Manager	NEVLEC	St. Kitts and Nevis	OK
46	NEVLEC		NEVLEC	St. Kitts and Nevis	OK
47	Nidia Reader		WCC	Barbados	OK
48	Raoul Pemberton		NIA	St. Kitts and Nevis	OK
49	Rhondel Philip		SKELEC	St. Kitts and Nevis	OK
50	Robert Goodridge		BREA	Barbados	OK

51	Robert Harewood		BLPC	Barbados	OK
52	Roger Beckles		BLPC	Barbados	OK
53	Rohan Seale		BLPC	Barbados	OK
54	Ron Farley	Managing Director	BREA	Barbados	OK
55	Ronell Pemberton		NEVLEC	St. Kitts and Nevis	OK
56	Starett France		NEVLEC	St. Kitts and Nevis	OK
57	Stephen Worme		BREA	Barbados	OK
58	Terrance Straughn	Chief Operations Engineer Renewable Energy Officer	BNTCL	Barbados	OK
59	Terry Neblett		MEB	Barbados	OK
61	Tyrone White	Chief Electrical Officer	GEED	Barbados	
62	William Hinds		MEB	Barbados	OK
63	Yuka Nakagwa		JET	Japan	OK
60	Tomoaki Tsuji		JET	Japan	OK
25	Hisao Taoka		JET	Japan	OK

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE: Attendant Day-2 (7 Dec 2022)

No.	Name	Position	Org.
1	Frank Branch		MEB
2	Horace Archer		MEB
3	William Hinds		MEB
4	Terry Neblett		MEB
5	Stephen Worme		BREA
6	Robert Goodridge		BREA
7	Giovanni Buckle		CCREEE
8	Justin Taylor		CCREEE
9	Jonathan Brathwaite		BLPC
10	Yuka Nakagwa		JET
11	Taoka Hisao		JET
12	Alex Harewood		JET
13	Natasha Davis	Operations Manager	Williams Solar
14	Felicia Cox	CEO	Adaptative Intelligent Solutions

Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-1)

18-19 Jan 2023

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

Agenda (Day-1)

1 Introduction for the Seminar, Review and feedback
2. RE and Microgrid Planning
3. Development Status of Grid Forming Inverter and its Safety
   - Current Status, Blackout with GFM & Black Start using BESS
4. Battery & Hydrogen as an Electricity Storage, cost comparison
5. Special Protection System including Load Shedding, PV/WT Trip
6. Inter-connection, Simulation Cases for future grid of St.Kitts &Nevis
7. Harmonics and filtering
8. Measurement Function of Inverter, Grid Code
9. Sample of Other Countries Situations of Grid and RE
10. Demonstration of Asset Management System
11. Presentation from SKELEC and NEVLEC about current status and challenges

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-1)

1 **Introduction for the Seminar, Review and feedback**
2. Microgrid Planning with Large RE
3. Development Status of Grid Forming Inverter and its Safety
   - Current Status, Blackout with GFM & Black Start using BESS
4. Battery & Hydrogen as an Electricity Storage, cost comparison
5. Special Protection System including Load Shedding, PV/WT Trip
6. Inter-connection, Simulation Cases for future grid of St.Kitts &Nevis
7. Harmonics and filtering
8. Measurement Function of Inverter, Grid Code
9. Sample of Other Countries Situations of Grid and RE
10. Demonstration of Asset Management System
11. Presentation from SKELEC and NEVLEC about current status and challenges

Introduction

Project Outline and Schedule

1 2 3 4 5 6 7 8 9 10 11 12 13 … 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 –

Phase 1 (Baseline Survey) | Phase 2 (Technical Transfer)

Year 2019 | Year 2020 | … | Year 2021 | Year 2022 | Year 2023

4 5 6 7 8 9 10 11 12 1 2 3 4 … … … … … … 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3

Output 1
The basic information is confirmed for the capacity building for the introduction of RE

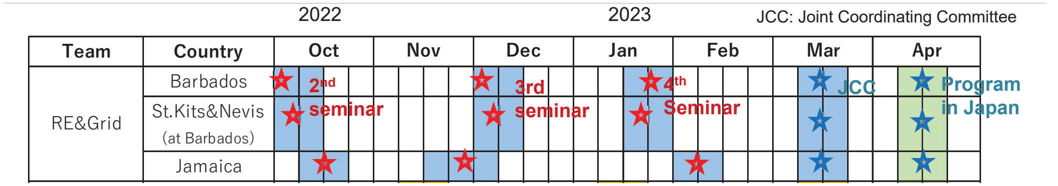
Output 3
The human and institution capacity are enhanced for the mass introduction of RE

Output 2
The basic information is confirmed for the capacity building for the promotion of EE

Output 4
The human and institution capacity are enhanced for the promotion of EE

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

Schedule and Key Events for RE&Grid Activity



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

Feedback at the 3rd Seminar

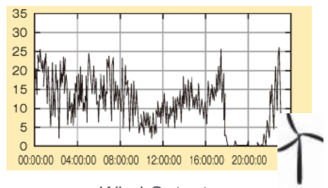
SCO: Synchrono
BESS: Battery Energy Storage System
GFM: Grid Forming Inverter
T&D: Transmission and Distribution

Items	Feedback	4th Seminars
To achieve 100% RE, what generation source do you want to try for the grid stability	Nevis 100 % RE will be achieved by Geothermal. Other mix can be (50% geothermal energy, 25% PV, 25% Wind)	In Day-2, the scenario will be in the grid model. 35 MW PV case for St. Kitts is also tested.
What is necessary for grid stability in your country?	1)BESS with 4hrs storage, redesign of the Nevis grid. Add a transmission system 2) SCO by Utility company. Grid forming inverter can be part of the solution once commercially available.	1) 4hrs storage case will be considered in grid model 2) GFM updated situation is provided in no. 3 of Day1
Other requests to consider in grid model and simulation.	1) Nevis have 11kV distribution system. Addition of a transmission system will enable separation of T&D. 2) Short circuit analysis.	1) Included in Day-1, no,6 2) Included in Day-1, no.5
Please provide Additional suggestion for seminar	- incentive/tariffs for other types of grid improvement beyond storage - Weather prediction (15 min. ahead) required with microgrids	-Demand side management -Weather prediction system included in no. 2, Day-1

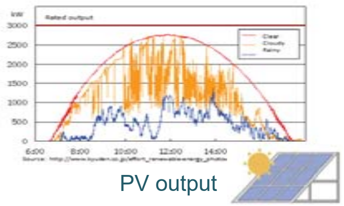
Feedback at the 3rd Seminar (2)

Items	Feedback	4th Seminar
Questions that you would like to know more details in the seminar	1) Cost of grid stability based on various RE, overall cost impacts of technology mixes as PV penetration increases. 2) The approach to building the model. What do you consider when using lumped parameters? In ETAP? 3) Hormonics or less distortion 4) The impact of load shedding at various times of day of feeders which have PV penetration and complications that result when tripping occurs. 5) Safety considerations of GFM, which seem to be able to continue operating when power is lost from the grid. 6) Calculations or model development in open source software e.g. Octave, Python, etc. 7) Shallow geothermal wells compare to deep wells 8) Combine RE source of energy, Geothermal and hydro	1) Included in Day-1, no.3 2) Included in Day-2 3) Included in Day-1, no.7 4) Let's try in Day-2 (most severe case) 5) Included in Day-3 6) Sorry. We can not since opensource is not recommended. 7) May discuss in Program in Japan 8) It is same as RE with thermal
Particular challenges of grid stability, RE, others	1) Solar without storage 2) more specific discussion of SCO, more worked examples 3) using BESS for black start 4) Using a BESS for frequent discharge on the system :effect in battery degradation and the life of the battery. 5) Harmonic distortion and frequency stabilization	1) Brings stability issue 2) discussed in Day-2 3) Included Day-1,no3 4) Included Day-1, no2 5) Included Day-1, no.7

Characteristics of VRE



Wind Output



PV output

Wind
- Unpredictable generation output change
- produce ramps according to weather condition
- Depending on geographic areas, fluctuation comes at once if it installed in the same valley

PV
- No output in night-time and rainy day
- Large fluctuation in tropical climate (likely to change 80% in a minute)

Both (VRE):
- It does not always generate when needed. **Load-supply matching** is an issue
- Time coincidence of VRE, there can be times when there is too much supply. Curtailment of VRE is necessary →**energy storage/control cost need to be considered.**

Challenges in Caribbean Islands:
- Lower cost than tariff →rapid private investment
- Frequent change of weather
- Limited area for transmission and smoothing
- Limited stable RE (hydropower/geothermal)

Challenges for
- **Cost for stability** : who covers?
- Technical and regulatory matters

Arrangement toward 100% RE

VRE 0%

Ongoing Technology

Emerging Technology

VRE 100%

- Curtailment
- Energy Storage & BESS
- Demand Response (DR)
- CSP, Biofuel generation
- Grid-forming Inverter
- H2, Emerging Technology

Voltage and frequency Stabilization

- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- **Reactive power supply: SCO, Statcom**
- EV charging time shift
- Demand side management
- Regulatory framework change, **review of grid code**

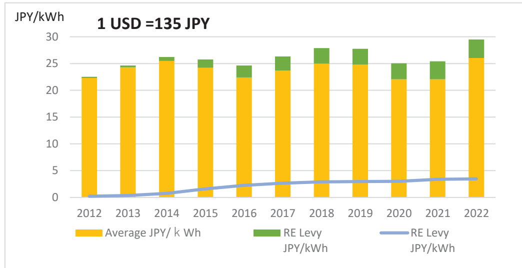
Insufficient Inertia, Synchronizing Force

- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale storage

SCO: Syncronous Condensor

Power Tariff and RE Levy

Is the increase in RE penetration so far helping or hurting electricity price?

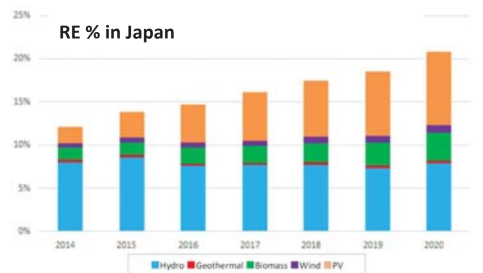


Power Tariff in Japan (JPY/kWh)

In case of Japan…

- **VRE Percentage: approx. 10% in 2021**
- **RE Levy is approx. 10% in 2020-21**
- **10% VRE in kWh base is 20-50 % of VRE capacity base**
- **RE Levy (additional tariff/kWh for RE cost) is likely to be proportional to VRE percentage**
- **Stabilization cost > fuel saving**

→Future ??



Power Tariff in Germany (Usc/kWh)

https://www.de-info.net/

Prepared by JET from METI and Enetech data

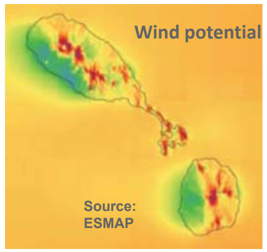
Introduction

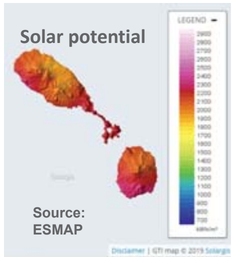
Summary of Status (St. Kitts and Nevis)

Fields	Status	Project Activity
Energy Efficiency	• Energy Source: Electricity (63%) , Oil (37%) • Load Curve: Bactrian camel type • Annual Peak Demand: about 25MW (St. Kitts) about 10MW or more (Nevis) • Peak Period: around 11am, 6pm-8pm (St. Kitts) around 12am, 6pm-8pm (Nevis)	Priority 1: Optimized operation with inverter Priority 2: Mini split AC with inverter Priority 3: VRF
Renewable Energy	• 100% RE by 2020 target • 0.7+0.5 MW PV (St.Kitts), damaged • 2MW wind operated at 1.1 MW (Nevis) • Bellevue 5.4 MW wind, Leclanche 35MW PV	Monitoring RE project incl. geothermal Training for grid simulation Introduction of asset management
Grid Stabilization	• 6MW 34 MWh BESS planned for 35MW PV • Output suppression of wind conducted in NEVLEC	
Thermal Power Generation	• Thermal power plant: total 13 units (St. Kitts), total 8 units (Nevis) • Installed Capacity: total 44.9MW (St. Kitts) total 21.3 MW (Nevis) • Peak demand 24MW (StK), 9.83 MW(Nevis)	-

Introduction

RE Status and Plan in St. Kitts & Nevis





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

Necessary consideration for future RE

1) **Grid stability analysis for new 35MW PV system**
2) **Update of geothermal development**
3) **Nevis plan with Interconnection (11kV, 66 kV)?**

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

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-1)

1 Introduction for the Seminar, Review and feedback
2. **RE and Microgrid Planning**
3. Development Status of Grid Forming Inverter and its Safety
   - Current Status, Blackout with GFM & Black Start using BESS
4. Battery & Hydrogen as an Electricity Storage, cost comparison
5. Special Protection System including Load Shedding, PV/WT Trip
6. Inter-connection, Simulation Cases for future grid of St.Kitts &Nevis
7. Harmonics and filtering
8. Measurement Function of Inverter, Grid Code
9. Sample of Other Countries Situations of Grid and RE
10. Demonstration of Asset Management System
11. Presentation from SKELEC and NEVLEC about current status and challenges

Feedback: What is Cost of grid stability based on various RE?

Cost of comparison of Grid Stability for various RE

Cost of stability is depending on plant factor and fluctuation of VRE
- lower plant factor requires large battery storage size (inverse proportion)
- larger and more rapid fluctuation requires larger ramp rate of spinning reserve and battery discharge speed
- Smaller cost of kW output requires larger cost of grid stability
- Total cost of RE and grid stability needs to be considered in planning

→ RE cost is site specific. F/S for respective project is necessary.

	Total installed costs (2021 USD/kW)			Capacity factor (%)			Levelised cost of electricity (2021 USD/kWh)		
	2010	2021	Percent change	2010	2021	Percent change	2010	2021	Percent change
Bioenergy	2 714	2 353	-13%	72	68	-6%	0.078	0.067	-14%
Geothermal	2 714	3 991	47%	87	77	-11%	0.050	0.068	34%
Hydropower	1 315	2 135	62%	44	45	2%	0.039	0.048	24%
Solar PV	4 808	857	-82%	14	17	25%	0.417	0.048	-88%
CSP	9 422	9 091	-4%	30	80	167%	0.358	0.114	-68%
Onshore wind	2 042	1 325	-35%	27	39	44%	0.102	0.033	-68%
Offshore wind	4 876	2 858	-41%	38	39	3%	0.188	0.075	-60%

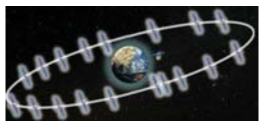
Source: RENEWABLE POWER GENERATION COSTS IN 2021 (IRENA)

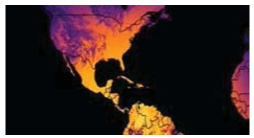
Cost of comparison of Grid Stability for various RE

RE Source	Capacity factor	Fluctuation	USc/kWh	Availability	Cost for stability	Remark
PV	13-18%	High	4-10	Everywhere	Highest. Need spinning reserve and battery for rain day/night time	Lowest generation cost, Highest stability cost
CSP	30-80%	No	15-40	Limited	Zero	Emerging technology
Wind	25-50%	High	5-15	Limited potential area	Need spinning reserve/battery	Cost can be reduced by smoothing in wide area installation
Geothermal	- 95%	No	15-20	Quite limited	Zero or negative, as base load. Ramp rate : 20%/min of output	Ideal
Hydro	10-90%	No	4-20	Very limited	Negative, as spinning reserve . Ramp rate: 10-30%/min	Seasonal fluctuation of water availability
Biomass	20-80%	No	8-20	Limited by Feedstock	Zero. Ramp rate: 1-4%/min	Depends on feedstock availability
Biofuel	0-80%	No	20-40	Need import .	Negative. It can be used as spinning reserve. Ramp rate: 20%min	Fuel cost is high
Biogas	20-90%	No	10-20	Limited	Negative. Best as spinning reserve. Ramp rate: 50%/min of output	Depends on tank size and feedstock

Feedback: Weather prediction (LIDAR/satellite/etc; 15 min. ahead)

Weather prediction system for VRE





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

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

% errors of Intraday & Day-Ahead PV Power Forecast

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

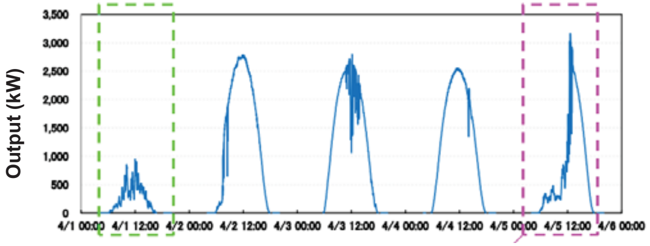
https://solcast.com/forecast-accuracy

Feedback: Weather prediction (LIDAR/satellite/etc; 15 min. ahead)

Weather prediction system by Sky Camera for VRE

For short time advance prediction, whole-sky camera system will do.

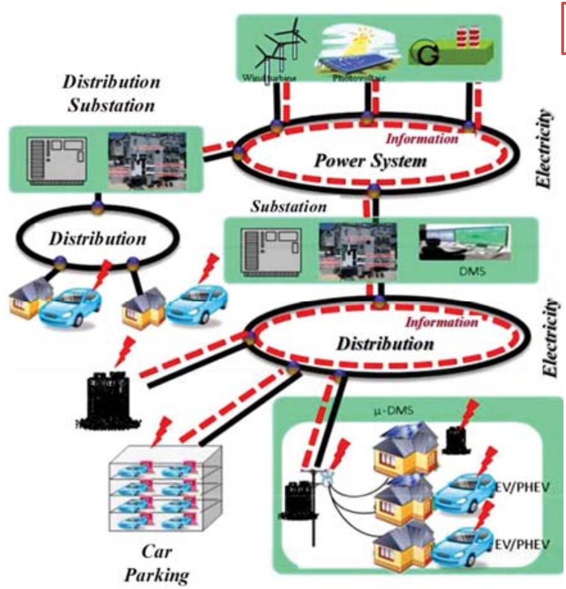
- Weather prediction for 5-30 minutes advance by detection of cloud movement with Whole-Sky Camera
- AI reads image and predict short-term irradiation (ex. SolarMi by Skyperfect JSAT)



PV output time series variation (1 Apr to 4 Apr9)

https://www.data.jma.go.jp/sat_info/himawari/kondan/kai3/shiryou3_2-2.pdf

Microgrid Concept

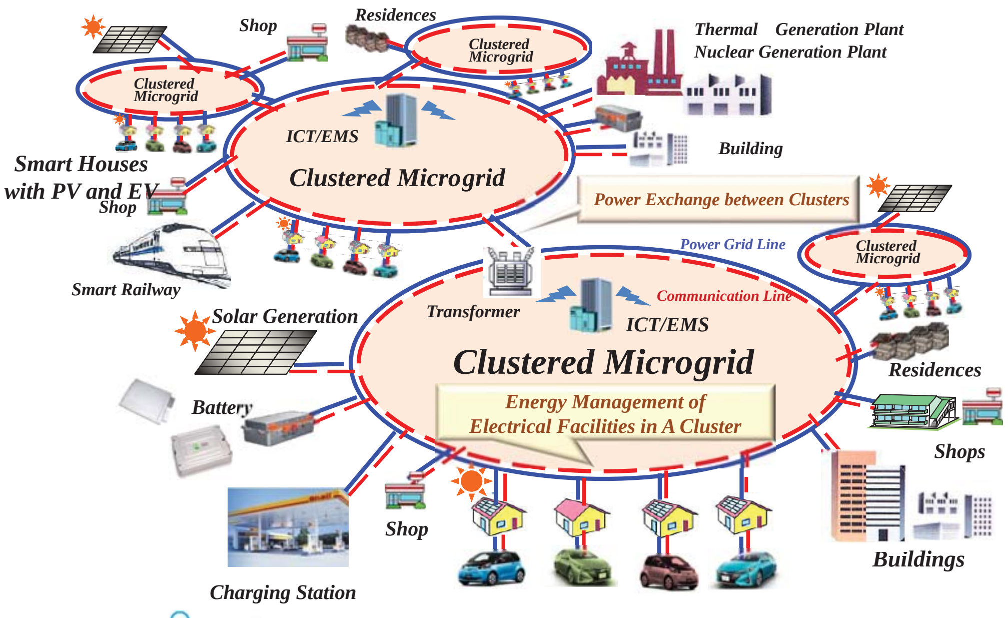


Concept of Micro-grid

- ✓ Respective Micro-grid is connected each other, and each Micro-grid can work independently
- ✓ Local energy production for local consumption
  - ✓ Generation: PV, wind, biomass, DG, GT, battery, etc.
  - ✓ Demand: industry, commercial, home, EV, etc.
- ✓ No transmission → loss saving
- ✓ With IoT, control system, EMS, demand response, smart meters
- ✓ Enhance resiliency

Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

Microgrid for Resilient System
-- Autonomous Micro Grid



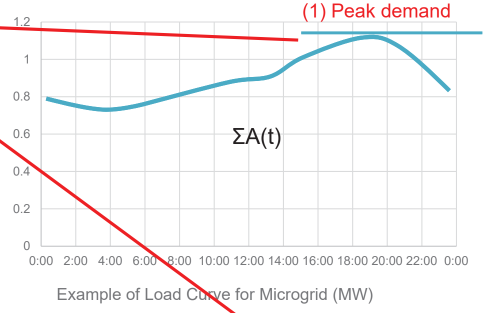
Microgrid Planning

1	Study for legal requirement of regulators considering affect on transmission line outside of Microgrid	- Legal requirement for microgrid by the regulatory authority - Method for emergency recovery, switching from microgrid to master grid, Affect on adjacent areas.
2	Estimation of load and demand at peak condition in Microgrid	- Estimate demand of daily curve, total demand of the day/week / year, at peak condition, abnormal condition
3	Plan for system structure of Microgrid in distribution lines based on demand	- Determination of capacity of generation system, design, selection of equipment. - Preparation for emergency (load shedding, control, etc.) - Protection and control method considering supply and demand
4	New system installation/enhancement for stabilization facility requirement for RE and supply-load balancing	- Plan RE facility with energy storage based on demand - Consider necessary stabilization equipment considering fluctuation and output instability. - Grid plan: Load flow analysis and transient analysis
5	System requirement and legal confirmation for inside and outside Microgrid	- Review regulation and rules including grid code for connection to transmission line - Operation method at the time of emergency recovery and minimize outage
6	Finalization of system configuration and specification for whole Microgrid	- Based on supply-load balance, finalize system configuration &Spec - Operation and EMS development, communication system

Microgrid Planning
Determination of generation output (in case of PV)

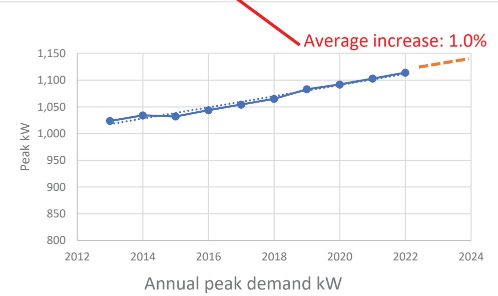
(1)	Max kW of peak day	1,114
(2)	Demand consideration yr	10
(3)	Demand increase %/yr	1%
(4)	Final peak demand kW	1,230
(5)	Reserver rate	10%
(6)	Design capacity kW	1,353
(7)	Present energy demand kWh/d	20,962
(8)	Design energy kWh/d	23,155
(9)	Specific PV generation kWh/kW/day	4,764
(10)	Design PV Output kW	4,400

(1) Peak demand



Example of Load Curve for Microgrid (MW)

Average increase: 1.0%



Annual peak demand kW

(9) Calculated from
- Irradiation: I kWh/m2
- PV output: P kW/m2
- Design coefficient K

Solar Atlas provides typical kWh/kW/day

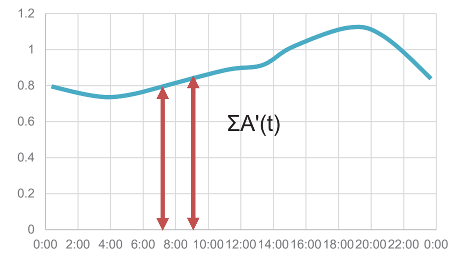
Microgrid Planning: Determination of Battery Capacity

(7)	Present energy demand kWh/d	20,962
(11)	BESS PCS output kW	1,353
(12)	Efficiency of PCS	95%
(13)	Battery Capacity kW	1,425
(14)	Capacity rate after cycle life K	0.8
(15)	Depth of Discharge D	0.8
(16)	Charge-discharge efficiency η	0.9
(17)	Nos of days to store energy n	1
(18)	Design Battery Energy kWh	36,292

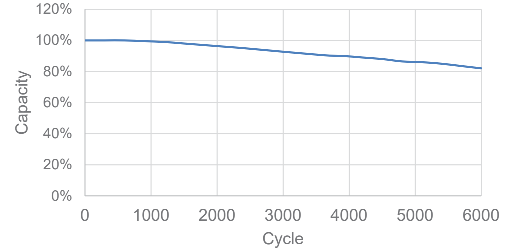
Quite large to store all 24h energy!

$$S = n\frac{\sum_{t=0}^{24} A'(t)}{L \cdot \eta}$$

Where,
S : Energy Capacity of Battery (kWh)
n : nos of days to store energy
A'(t) : Hourly demand of battery coverage (kWh)
L: Maintenance factor = K x D
K: Capacity after cycle of life, generally 0.8 for LiB battery
D: Depth of discharge , generally 0.8 -1.0 for LiB battery
η: Charge-discharge efficiency of battery



Example of Load Curve for Microgrid (MW)



Capacity of Battery against Year

Prepared by JET

Microgrid Planning: Analysis for Stability

Grid Investment plan:
(Capacity of grid with planned RE)
→ Power Flow Analysis

Additional RE power to grid :
Is current grid capacity enough to accommodate planned RE?
→ **Power Flow Analysis** is necessary to confirm :
- if grid capacity can accommodate RE
- to check active power & reactive power, voltage
- the steady state with most severe case (maximum power) is applied → grid modification plan to be prepared

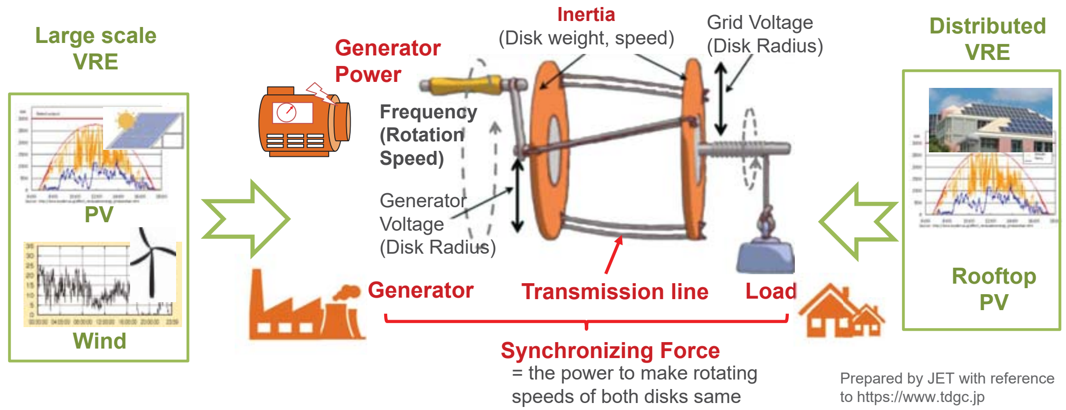
Grid Operation plan:
(stable operation avoiding disturbance, accident, power cut, black out)
→ Transient Analysis

Voltage and frequency will fluctuate according to VRE
→ **Transient Analysis** is necessary :
- Power system stability with VRE fluctuation need to be calculated by using acceleration and deceleration of energy
- Necessity of Available Transmission Capacity and Spinning Reserve can be analyzed
- Requirement for Stabilizing equipment to be assessed

Optimum operation
→Economic Load Dispatch / LFC

Operation of generators based on merit order to minimize fuel cost for generators (especially with thermal spinning reserve)
→ **Economic Load Dispatch** provides operation mode for optimized operation
- ex. Cost of Battery vs Cost of biodiesel

Inertia and Synchronizing Force with RE



Prepared by JET with reference to https://www.tdgc.jp

Inertia: The force to keep the rotation of disk when load is changed
Synchronizing Force: The force to keep rotation speed of disks. It keeps back to the same rotation when generation power and load is varied, without entangling.

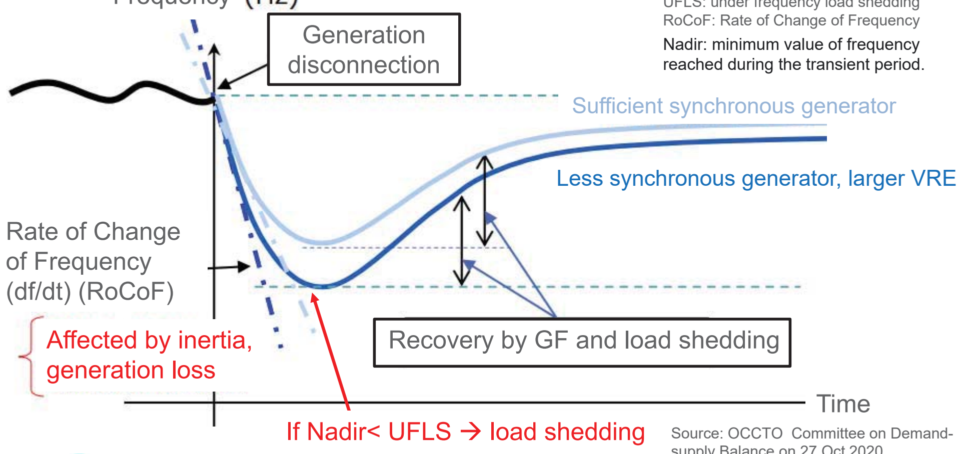
Fluctuation of large scale VRE affects to generator at generation side and load side
→ Inertia and Synchronizing Force need to be enhanced for grid with large VRE

Synchronous generator and VRE

Output fluctuation by inverter connected VRE may cause black out

Synchronous generator: The power source establishes and maintain voltage and frequency with reactive power. It combines with other generators by synchronizing force

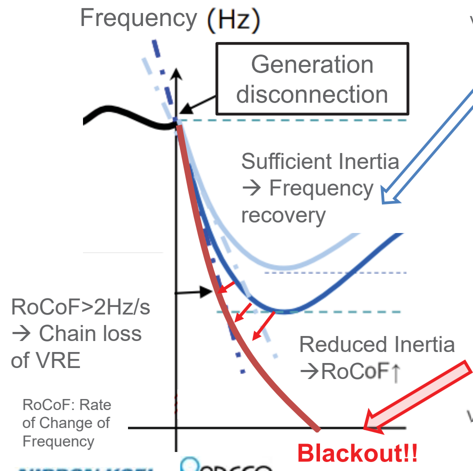
VRE/BESS with inverter: DC is converted to AC. There is no rotation, no synchronizing force. It monitors grid AC voltage and wave and adjust accordingly → no contribution for stability

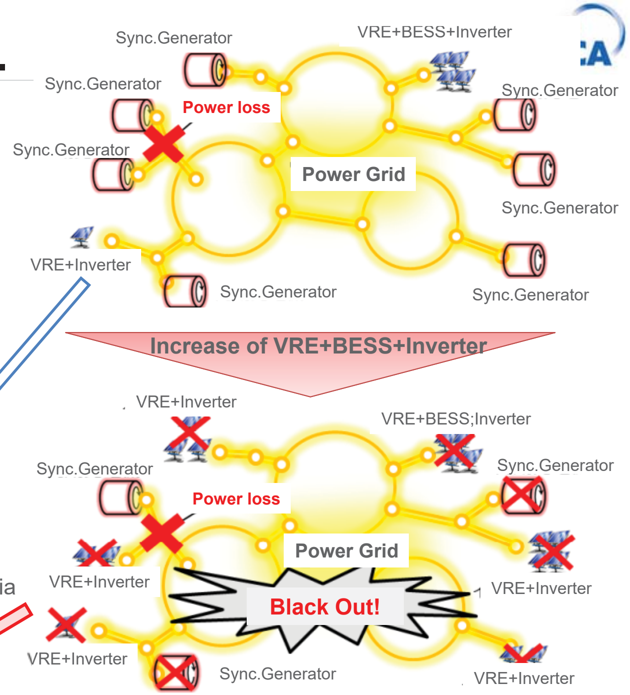


Source: OCCTO Committee on Demand-supply Balance on 27 Oct 2020

Black-out when insufficient Sync. Gen.

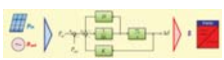
If synchronous generator is reduced and inertial is not sufficient
→ Frequency drop, with no recovery
→ Chain reaction of loss of VRE
→ **Black out**





Source: Transmission and Grid Council, Japan

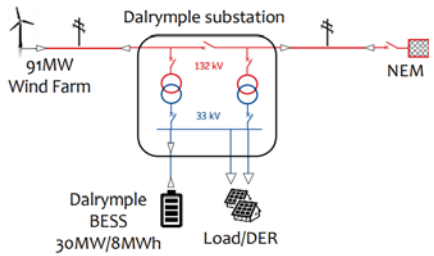
Emerging technology for large RE with Grid stabilization : Generation with Inertia and Synchronous Power

Type of Technology		Advantage	Develop stage
 Source: taiyo-electric	Motor generator (MG)	- Energy in battery provides synchronization and inertia - Small scale supply, for micro grid	- Used as frequency conversion - Commercial operation
 energyvault.com/gravity	Gravity Storage Battery	- Gravity of recycled Concrete block 35ton/nos - Provides inertia - Half cost of Li-ion battery	Pre-commercial, 35 MWh, 4MW per tower η=85% 52.5GW planned in USA
 /www.nedo.go.jp/news/press/AA5_100756.html	CAES (Compressed air energy storage)	- Compressed high pressure air - (Liquid air may be developed) - Provides inertia	-demonstration by NEDO - 900 MW in California - η=70-80%
 electrek.co/	CSP (concentrating solar power) Solar thermal	- With turbine, provides inertia and synchronization - Cost decrease expected, higher efficiency than PV, η=50%	- Commercial operation at Ivanpah392MW 22 bil USD - Heat storage (molten solt, etc) under development
 Source: CIGRE	Grid-forming inverter	- Dynamic active/reactive power, FRT, frequency control, inertia - Applicable to existing PV - (Smart Inv: FRT, VRT, voltage support)	- Under development - (Smart inverter by IEEE1547, Mandatory in Hawai)

Microgrid Ex.-3: South Australia Yorke Microgrid

https://www.electranet.com.au/new-battery-charged-and-ready-to-power-lower-yorke-peninsula/

- One circuit 132 kV line is connected to the area, which once had frequent outage and issue on reliability
- Autonomous microgrid, sifted to independent operation without outage, seamless islanding
- 91 MW Windfarm provides power
- BESS provides virtual inertia, reactive power compensation, and black start function
- System provides ancillary service with frequency adjustment



Grid Forming Energy Storage System addresses challenges of grids with high penetration of renewables (A case study), CIGRE, 2020

Items	Description
Utility	Electra Net
Area	Dalrymple, Lower Yorke, SA
Substation	Dairymple S/S 132/33 kV
Generation	91 MW Wind
BESS	30 MW/8MWh ABB
Project cost	30 mil AUD (of which 12 mil AUD is financed by ARENA)

4th Seminar on Grid Stability and Large RE
Day-1 Session

3. Development Status of Grid Forming Inverter(GFM) and its Safety
   - Current Status
   - Blackout with GFM & Black Start using Battery Energy Storage System(BESS)

5. Special Protection System including Load Shedding, Photovoltaic(PV)/Wind Turbine(WT) Generator Trip

6. Inter-connection, Simulation Cases future grid of St. Kitts & Nevis

8. Measurement Function of Inverter, Grid Code

Feedback from 3rd Seminar on Grid Stability and Large RE

i. Current states of the development of Grid Forming Inverter (GFM) and safety condition of GFM
   i. Describe in Day-1 Session 3

ii. Example of special protection system (SPS) with RE and impact of load shedding of feeders with PV penetration
   i. Describe in Day-1 Session 5

iii. Optimizing size of battery & BESS for black start
   i. Describe in Day-2 Session 2

iv. Hydrogen
   i. Describe in Day-1 Session 4

v. Harmonics or less distortion
   i. Describe in Day-1 Session 7

This section is a feedback and request of current states of the development of Grid Forming Inverter (GFM) and safety condition of GFM

3. Development Status of Grid Forming Inverter and its Safety

<Current project for the development of GFM>

- GFM Projects in Japan
  - New Energy and Industrial Technology Development Organization(NEDO) project with Tokyo Electric Power Co. (TEPCO), National Institute of Advanced Industrial Science and Technology(AIST)

- GFM projects in the world
  - Europe Union(EU): OSMOSE, MIGRATE, Smart Net
  - USA: Grid Forming Research Consortium, Department of Energy(DOE) program

National R&D project in 2019-2021 in Japan

Next-Generation Power Network Stabilization Technology Development for Large-Scale Integration of Renewable Energies

Project of NEDO (New Energy and Industrial Technology Development Organization)
2019-2021 (Partially last to 2023)

The development of Grid Forming Inverter is one of the subject of Item 3 in the following 4 items of this project.

Item1: Development of control units for Japanese connect and manage grid (last to 2023)

Item2: Development of control method to cope with decrease in inertia using phasor measurement unit

Item3: Development of optimal method to control voltage and power flow in distribution system with IBR

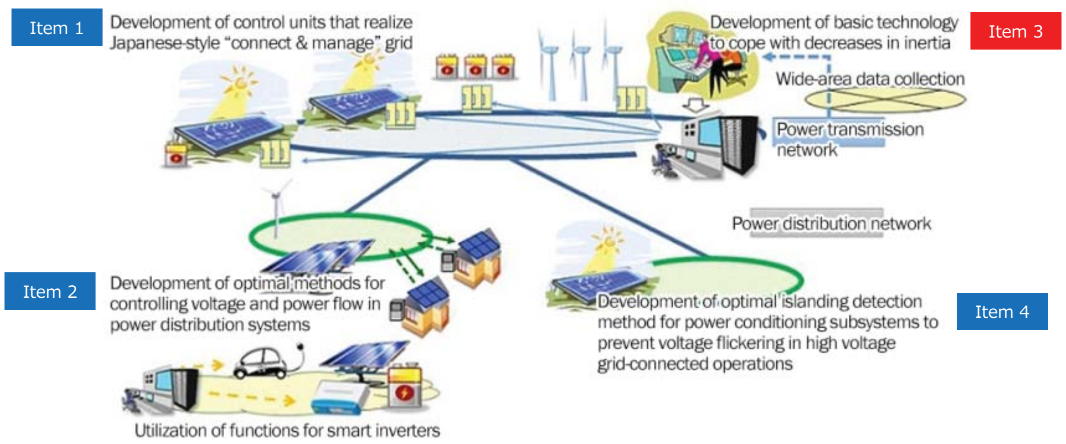
Item4: Development of optimal standing detection method in high voltage distribution system

https://www.nedo.go.jp/english/activities/activities_ZZJP_100150.html

National R&D project in 2019-2021 in Japan

Next-Generation Power Network Stabilization Technology Development for Large-Scale Integration of Renewable Energies (Birds-eye view)

This is the graphical image and relationship of each item of this project.

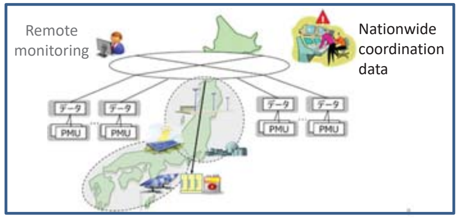


https://www.nedo.go.jp/english/activities/activities_ZZJP_100150.html

National R&D project in 2019-2021 in Japan

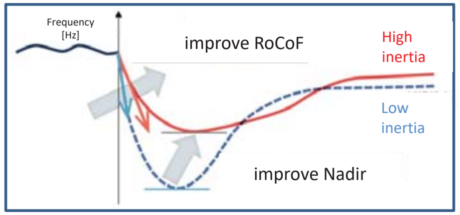
Item 3: Development of basic technology to cope with decreases in inertia (Scope)

① R&D for real-time inertial estimation



Develop the inertia monitoring system

② R&D for inverter-based synthetic inertia



Develop countermeasure for low inertia

Cf. TEPCO report

■ **Scope:**

- R&D for the inverter-based synthetic inertia.
  - ✓ Option 1: Add a new function to the legacy **Grid-following Inverter (GFL)**
  - ✓ Option 2: Develop the novel **Grid-Forming Inverter (GFM)**
- Development of simulation model and evaluation of inverter-based synthetic inertia capability.

https://www.nedo.go.jp/english/activities/activities_ZZJP_100150.html

National R&D project in 2022-2026 in Japan

STREAM Project

Future-generation power network Stabilization Technology development for utilization of Renewable Energy As the Major power source

Project of NEDO (New Energy and Industrial Technology Development Organization)

- Development of Inverter Based Resources(IBR) as Measure against Low Inertia Grid (Group1-3)
  - Test Grid Forming Inverters Produced by 4 models and 5 functions
  - Show the revised proposal of grid code for Grid Forming Inverter(GFM) to Organization for Cross-regional Coordination of Transmission Operators(OCCTO)
- Development of Grid Forming Inverter(GFM) for Microgrid with Renewable Energy for major power source

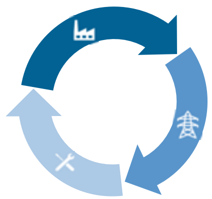
STREAM Project overview of Group1 and Group2

Group1 Development of Inverter-based Countermeasures for low system inertia (TEPCO Holding(HD), TEPCO Power Grid(PG), AIST)

- Requirement and specification study.
- Design & development of Prototype.
- 3 venders for battery storage inverter and 1 institute with vender for PV inverter.

Group2 Validation and testing (TEPCO HD, TEPCO PG, CRIEPI, AIST, JET)

- Study for Key Performance Indicator(KPI), Lab/Field testing, and certification of grid forming inverter.



Laboratory testing
- Development of test procedure achieving certification.
- Impact assessment of new function with Virtual(HIL) testing technologies

Demo field testing
- Testing on full-scale distribution systems
- Remaining test that lab testing do not cover

Prototype improvement
- Grid interconnection testing and conformance to requirements
- Revision of inverter requirements

Lab testing: Smart System Research Facility, AIST

Demo field testing: Akagi testing Center, CRIEPI

Output
- The standard for equipment specifications
- Data/report for revision of Grid Code

TEPCO:Tokyo Electric Power Co.
CRIEPI:Central Research Institute of Electric Power Industry
AIST: Advanced Industrial Science and Technology
JET:Japan Electric Safety & Environment Technology Laboratory

STREAM Project overview of Group3

Group3 Simulation based impact assessment study

•This study will share and/or reflect to Group1 and Group2.

Phasor-based simulation (Hiroshima Univ., Kure tech.)

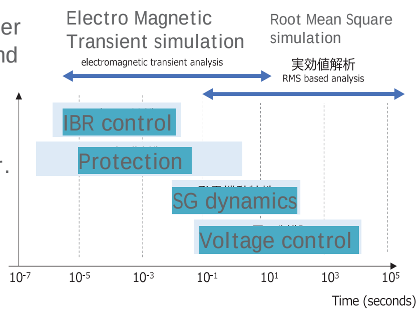
- Development of control algorithm for Grid forming inverter
- Development for Phasor-based simulation technologies and analysis study for grid system stabilities.

EMT-based simulation (AIST)

- Study for rotating angle stability.
- The parametric sensitive analysis of grid-forming inverter.

Model aggregation (Hokkaido Univ.)

- Development for combination analysis with aggregation model.
- Impact analysis for the main transmission line with grid-forming inverter



Impact assessment study of inverter-based countermeasure for future power system (Tokyo Univ., Waseda Univ.)

- Planning and simulation for demand and supply.
  - Development of Unit Commitment (UC) model
  - Making a plan/Analysis of multiple scenarios for a type of power unit.
  - Study for integration of synthetics inertia GFL/GFM inverter.
  - Simulation analysis based on the IEEE-EAST10 model.

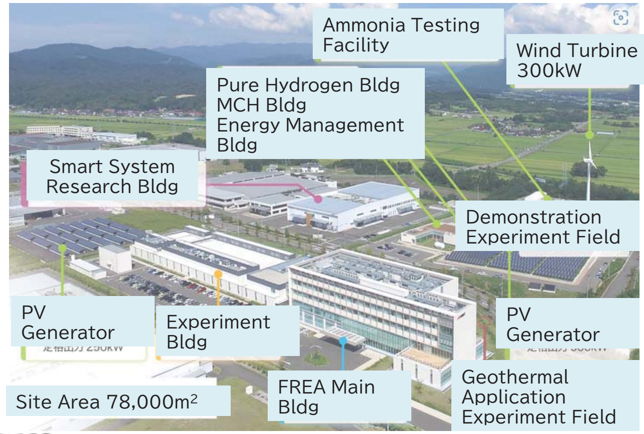
The Fukushima Renewable Energy Institu (FREA)

National Institute of Advanced Industrial Science and Technology(AIST) established the Fukushima Renewable Energy Institute in Koriyama, Fukushima Prefecture in April 2014, to promote R&D into renewable energy.

The Fukushima Renewable Energy Institute, AIST (FREA) has two basic missions:

(1) Promotion of R&D into renewable energy, which is open to the world as a novel research base to develop innovative technologies in collaboration with domestic and international partners.

(2) To make a contribution to industrial clusters and reconstruction



Smart System R&D Test Platform (FREA-G)

One of the world largest testing facility for Smart Grid

Grid Forming Inverter is tested for development worldwide here.

A. Grid Connection Test Bed

- Compatible with worldwide interconnection test for DER (Fault-Ride-Through, anti-islanding, etc.) with grid simulator.
- Grid simulator is a programmable AC source that emulates grid characteristics to evaluate performance and reliability of grid-connected equipment.
  - Maximum capacity of Grid simulator: 5 MVA
  - PV and Battery emulator: 3.3 MW up to 2000V
  - Inverter testing capability: up to 3 MW

B. Safety Test Bed

- Emulate realistic temperature and humidity environment to evaluate safety and long-term reliability of grid-connected equipment. e.g., thermal cycle and humidity freeze test, surge voltage test, etc.
- Other safety testing e.g., surge voltage test

C. EMC Test Bed

- Testing for electromagnetic radiation from/to grid-connected equipment.

D. System Performance Test Bed

- Evaluate multiple system level DER capabilities e.g., microgrid lab-based demonstration, energy management system (EMS) testing such as DERMS, VPP, etc.

Feedback from 3rd Seminar on Grid Stability and Large RE

Black Start using BESS

This is a feedback about question of the way to supply power to the grid when the grid power goes off.

In order to continue to supply electricity, Grid Forming Inverter(GFM) can be a kick starter, when black start will be applied after blackout. if energy resources is available continuously.

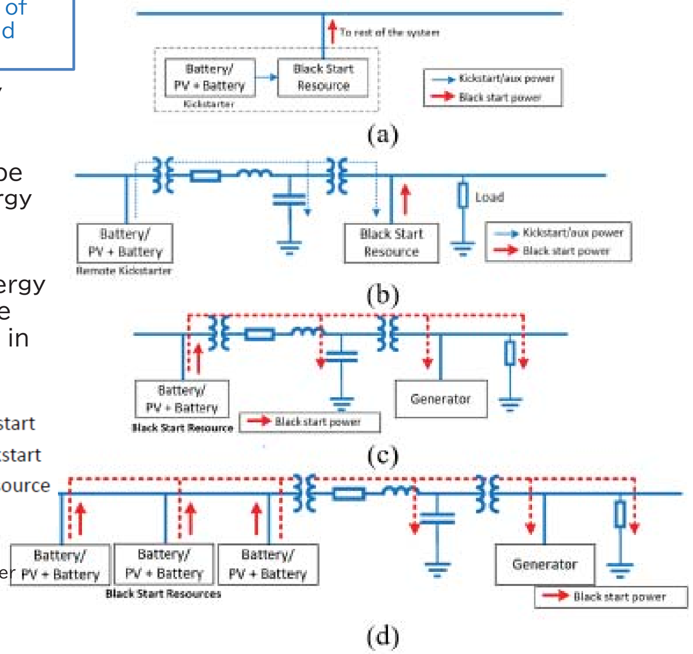
NREL(National Renewable Energy Laboratory), USA proposes the way for black start using GFM in 4 ways.

(a). Config. 1: On-site Kick-Starter for a Blackstart

(b). Config. 2: Remote Kick-Starter for a Blackstart

(c). Config. 3: Fully Functional Black-Start Resource

(d). Config. 4: Collective Blackstart



BlackstartH. Jain, G. Seo, E. Lockhart, V. Gevogian and B. Kroposki, "Blackstart of Power Grids with Inverter-Based Resources, IEEE 20PESGM1199

Battery VS Hydrogen Storage

Jan-18, 2023
JET (JICA Expert Team)
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Contents

Prerequisites of contents

Battery

Source: Solar Thermal Energy Promotion Inc.

VS

Hydrogen

Source: Macrovector / Freepik

Please note …

- Technologies related to batteries and hydrogen storage are still developing.
- Presentation material include examples of a sort of study.

Battery VS Hydrogen Storage (1)

What are the strengths of Battey and Hydrogen storage?

	Power to Gas (Hydrogen)	Lead battery	Lithium-ion battery	NAS battery	Redox flow battery
Energy Density	1,290 Wh/L *1	40 – 80 Wh/L	200 – 300 Wh/L	140 Wh/L	10 Wh/L
Energy Conversion Efficiency	75 – 80% *2	75 – 85%	95%	90%	70%
Response Time	10 seconds *3	Max. tens of milliseconds	Max. tens of milliseconds	Max. tens of milliseconds	Max. tens of milliseconds

*1 In case of 70 MPa Compressed H2
*2 Efficiency of water electrolyzer
*3 Response time of water electrolyzer

Source: JET created this table based on the report of CO2 Free Hydrogen Working Group, Ministry of Economic, Technology and Industry, Japan, 2017

Battery VS Hydrogen Storage (2)

What are the strengths of Battey and Hydrogen storage?

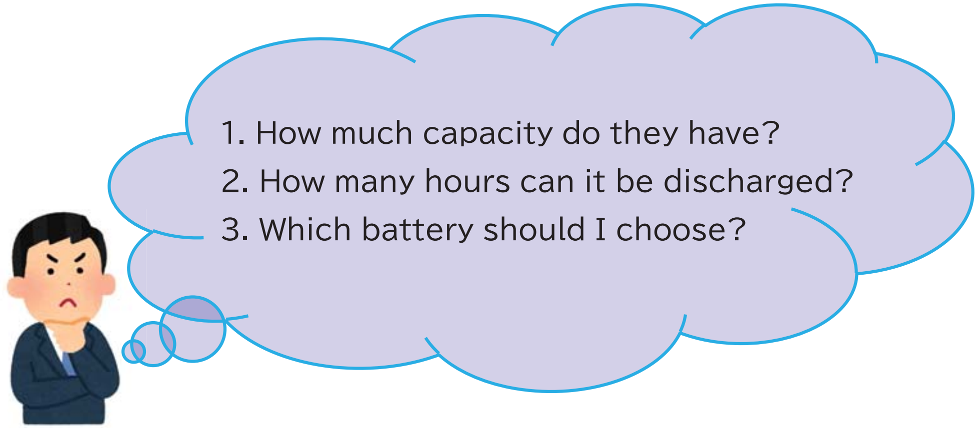
1. Battery
Fast response speed
⇒ Superior ability to follow output fluctuations of renewable energy

2. Hydrogen Storage
High energy density
⇒ Suitable for large-volume and long-term energy storage

Before discussing costs, let's first look at the different characteristics of each

Batteries Energy Storage System

1. Battery
Fast response speed
⇒ Superior ability to follow output fluctuations of renewable energy



Characteristics of Batteries (1)

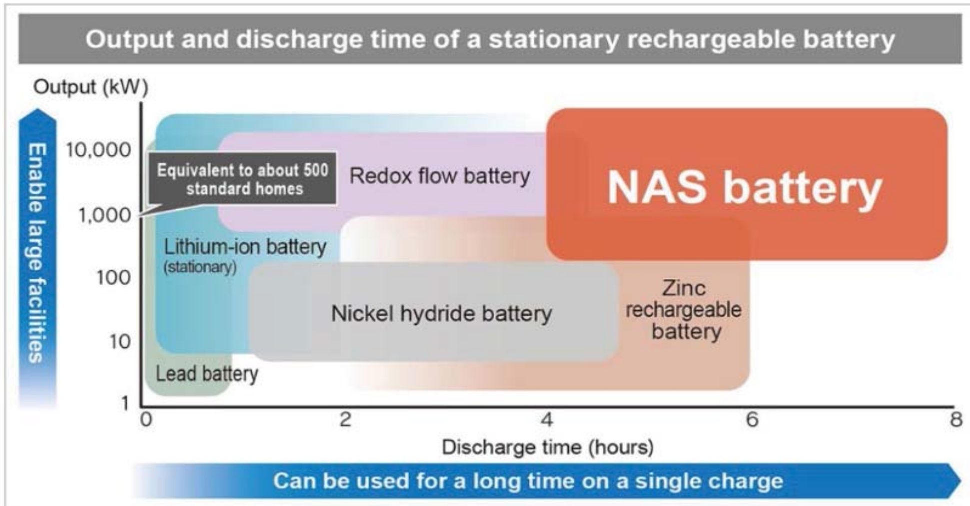
The characteristics of each typical battery are shown below.

	Advantage	Disadvantage
Lead-Acid battery	➢ Low manufacturing costs result in lower unit power costs ➢ Easy maintenance	□ Faster deterioration as the number of charge/discharge cycles increases □ Physically large
Lithium-Ion battery	➢ Compact size and large capacity ➢ High-current charging and discharging	□ Fire hazard □ Extreme degradation after around 500 charge-discharge cycles
NaS battery	➢ Durability ➢ High energy density ➢ Low cost	□ Requires about 300 Celsius degrees to operate □ Handling and disposal of hazardous materials such as sodium and sulfur
Redox-flow battery	➢ Easy to scale up and suitable for large-capacity facilities ➢ Long cycle life, can be used for more than 10 years	□ Relatively low energy density □ Long installation period for large facilities □ Requires a large site

Source: JET created this table based on the report of CO2 Free Hydrogen Working Group, Ministry of Economic, Technology and Industry, Japan, 2017

Characteristics of Batteries (2)

Storage batteries depend on capacity and discharge time.



Source: https://www.mynewsdesk.com/ngk-insulators/news/sodium-sulfur-battery-technology-nas-battery-enables-megawatt-hour-energy-storage-realizes-a-stable-supply-of-renewable-energy-410813

Hydrogen Storage(1)

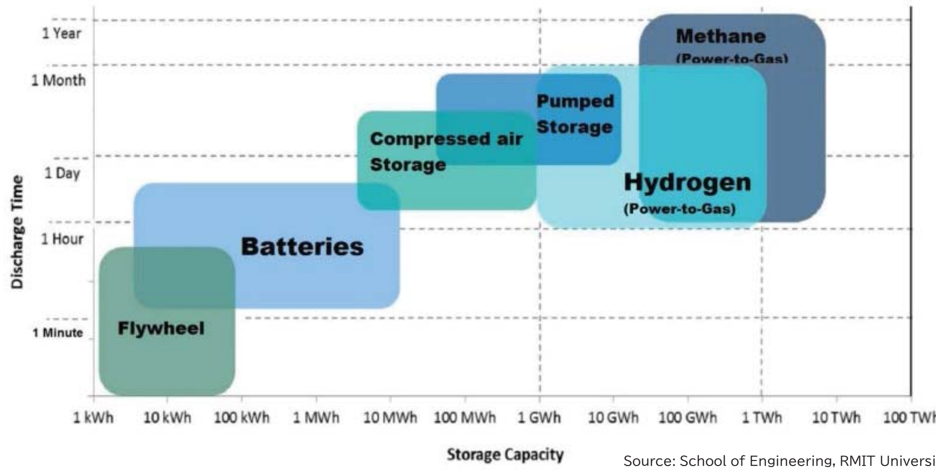
2. Hydrogen Storage

High energy density

⇒ Suitable for large-volume and long-term energy storage

1. How long is "long term storage"?
2. How large is "large-volume"?
3. In what cases is hydrogen storage advantageous over batteries?

Hydrogen Storage(2)

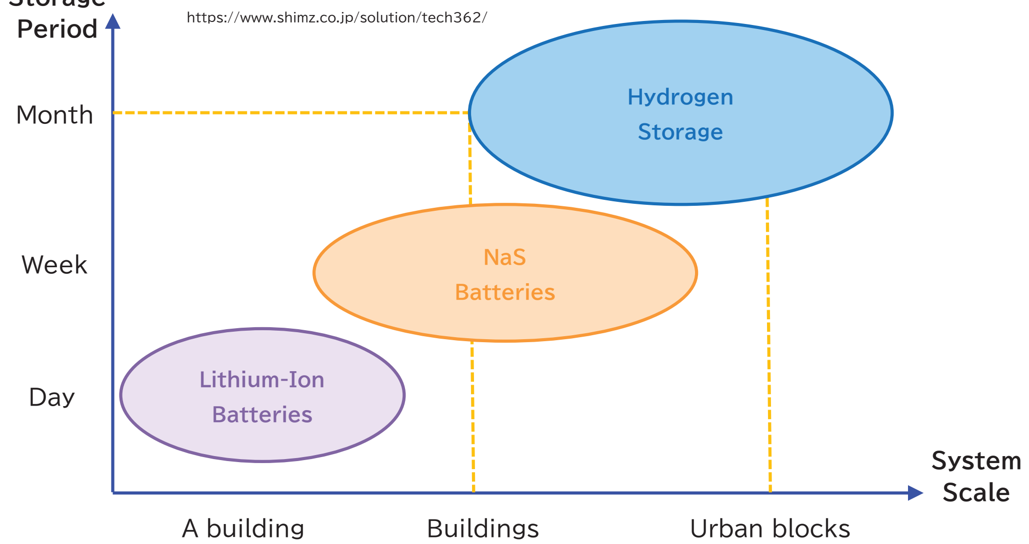


Source: School of Engineering, RMIT University (2015)

It is difficult to compare the cost of hydrogen with that of batteries. The areas of expertise are totally different.

Case Studies in Japan (1)

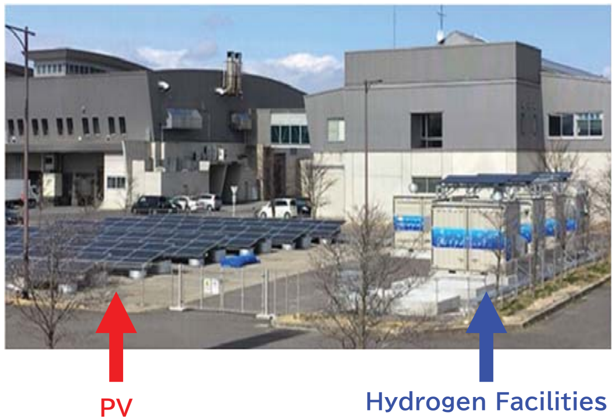
Source: JET created this image based on Hydro Q-BiC, Shimizu Corporation, Japan https://www.shimz.co.jp/solution/tech362/



⇒ See a case study of hydrogen storage.

Case Studies in Japan (2)

Buildings of wholesales market



Specifications	
Location	Wholesales Market
Power Demand	100 kW
PV	64 kW
Water Electrolyzer	5 Nm3/h
Hydrogen absorbing alloy tank	(1) 80 Nm3 (2) 100 Nm3
Fuel cell	14 kW
Batteries	20 kW - 20 kWh Lithium-Ion

Source: Hydro Q-BiC, Shimizu Corporation, Japan, https://www.shimz.co.jp/solution/tech362/

Case Studies in Japan (3)

Office Building (Zero Emission Building)

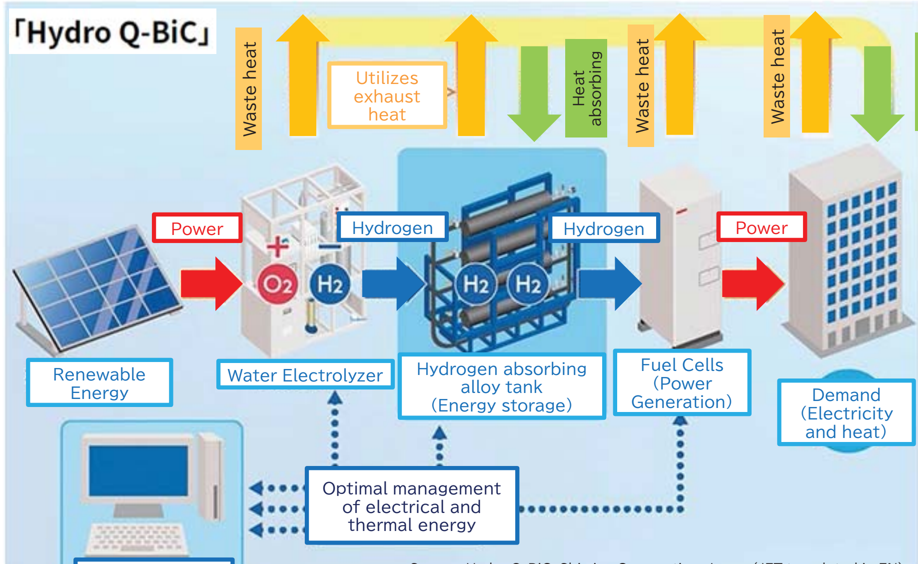
Specifications	
Location	Office building
PV	140 kW
Hydrogen absorbing alloy tank	2,000 kWh

Hydrogen Facilities Basement

- Various energy-saving technologies
- PV system
- Hydrogen production and storage with PV surplus power

Source: Hydro Q-BiC, Shimizu Corporation, Japan,
https://www.shimz.co.jp/company/about/news-release/2021/2021006.html

Hydrogen Storage System

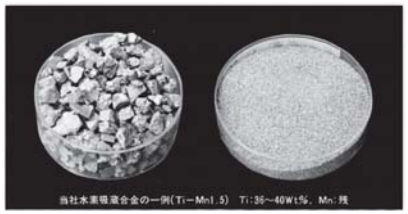


Source: Hydro Q-BiC, Shimizu Corporation, Japan (JET translated in EN)
https://www.shimz.co.jp/solution/tech362/

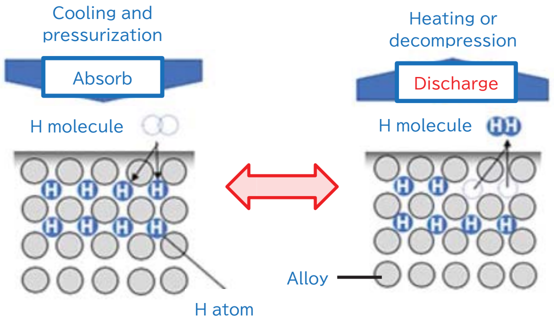
What is "Hydrogen absorbing alloy"?

Alloy that absorbs hydrogen and releases.

- ➢ Compact storage of large volumes of hydrogen: compressed to about 1/1000th of its original volume
- ➢ Low cylinder pressure reduces the possibility of leakage (Less than 1 MPa)



Source: http://www.daido-100th.com/topics/327/

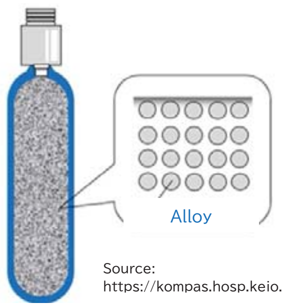


Source:
https://kompas.hosp.keio.ac.jp/sp/contents/medical info/science/201912.html

What is "Hydrogen absorbing alloy"?

The issue with hydrogen storage alloy tanks

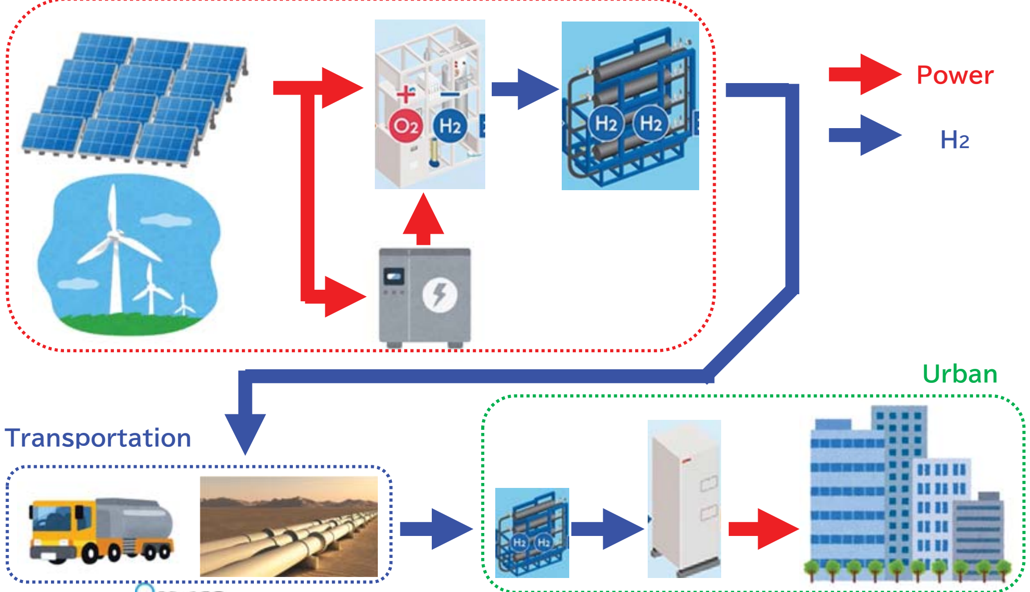
- ◻ The tanks will be made of alloy, so they are heavier than cylinders such as compressed hydrogen
- ◻ Alloy prices are expensive as of 2022.



Source:
https://kompas.hosp.keio.ac.jp/sp/contents/medical info/science/201912.html

Image of Hydrogen Utilization

Source: Hydro Q-BiC, Shimizu Corporation, Japan
https://www.shimz.co.jp/solution/tech362/

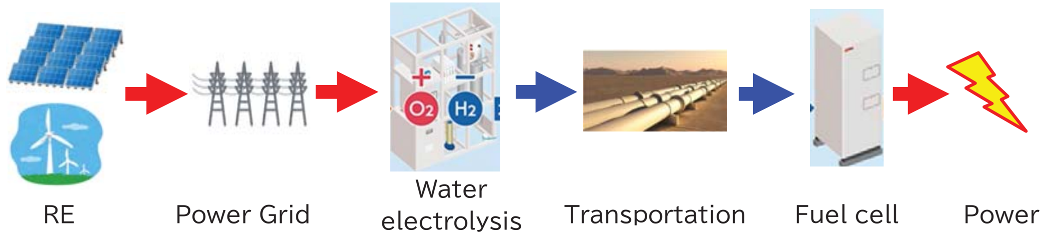


Cost of Hydrogen Production

Systems using hydrogen storage alloy tanks are not yet at the commercial stage.

An example calculation of hydrogen production using RE through grid in one study and its generation costs as applied to the CARICOM region is presented below.

[Equipment configuration]



Cost estimation of H_2 Production (1)

This trial calculation based on purchasing electricity produced from renewable energy sources via the grid and using that electricity to produce green hydrogen.

Cost Estimation		
Water electrolyzer rated capacity (Rated input power)	17.5	MW
Annual hydrogen production (ton)	2,936	ton/year
Annual hydrogen production (Nm3)	264,462	Nm3/year
Amount of electricity required per year	151,620	MWh/year
Variable-OPEX(Water)	67,714	USD/year
Variable-OPEX(Electricity)	24,115,195	USD/year
LCOH (price of equalized hydrogen)	9.89	USD/kg-H2

Source: Created by JET

Cost estimation of H_2 Production (2)

Green hydrogen price in 2022 is 5.5 - 9.5 USD/kg-H2,
* Depending on location and conditions.

Source: S&P Global Commodity Insights, USA
https://www.spglobal.com/commodityinsights/en/our-methodology/price-assessments/energy-transition/hydrogen-price-assessments

⇨ In the CARICOM region, it is impractical to purchase electricity from renewable energy sources via the grid to produce green hydrogen.

If they can get the electricity needed for water electrolysis from their own renewable energy generation facilities

⇨ The cost of hydrogen production can be reduced.

Conclusion

◆ **Battery Storage**
Batteries and hydrogen storage have different areas of expertise, so choose based on features, not cost.

◆ **Method of Hydrogen Storage**
In addition to compressed hydrogen and liquefied hydrogen, there are also storage methods using hydrogen storage alloys.

◆ **Cost of Green Hydrogen**
The unit cost of producing green hydrogen is high, but the cost can be reduced to some extent by direct using of renewable energy.

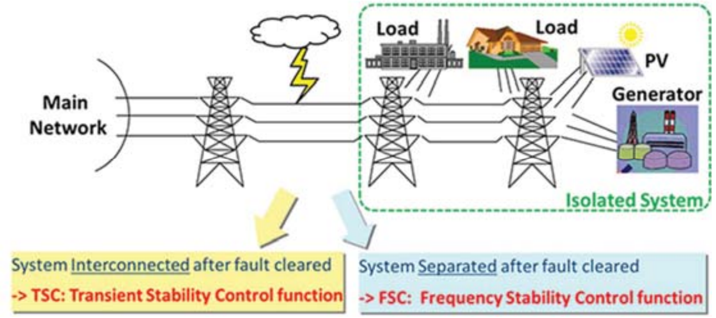
This section is a feedback and request of example of special protection system (SPS) with RE and impact of load shedding of feeders with PV penetration

5. Special Protection System(SPS) including Load Shedding, PV/WT Trip

- Actions in SPS
  - Actions for Generator
    - Trip of Synchronous Generator
    - Control of Connection and Output of PV and Wind Turbine
  - Actions for Load
    - Shedding of Load
  - Actions for Transmission Line
    - Operation of Circuit Switch or Closer
- Examples
  - Chubu Electric: ISC (Integrated Stability Control System)
  - Kansai Electric: BSS (Block System Stabilizer)

Trunk Transmission Integrated Stability Control System (ISC) -Overview-

- When a fault occurs in the power system, the ISC system trips the unstable generators and control switch gear instantly according to the results of calculated transient stability analysis of the system.
- When a grid separation is detected in the power system, the ISC system trips the surplus generators or sheds the surplus demand according to the solution of frequency stability analysis.
- The ISC system recognizes the power system configuration in real time and automatically change several operation settings.



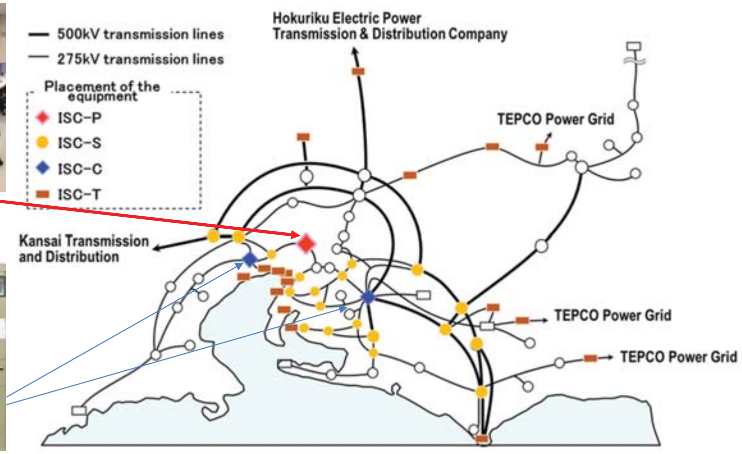
https://powergrid.chuden.co.jp/english/technical/operation/isc/

Trunk Transmission Integrated Stability Control System (ISC) -Allocation of control stations-

Control stations and terminals are located in wide area of the grid.

ISC-P

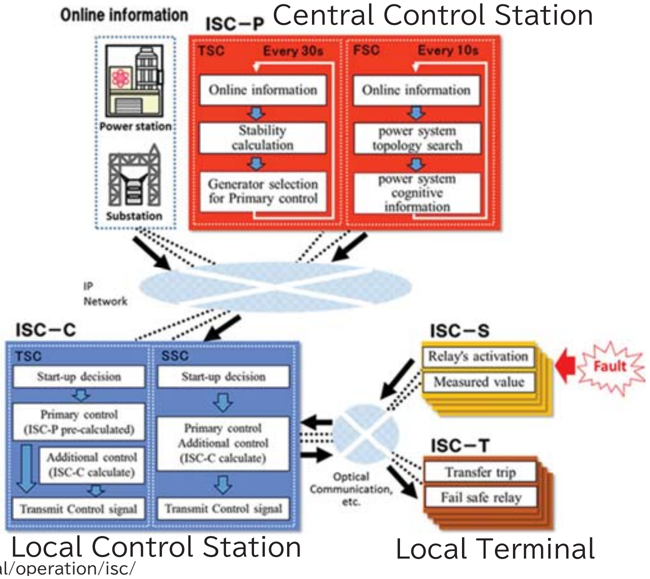
ISC-C



https://powergrid.chuden.co.jp/english/technical/operation/isc/

Trunk Transmission Integrated Stability Control System (ISC) -Function of control stations-

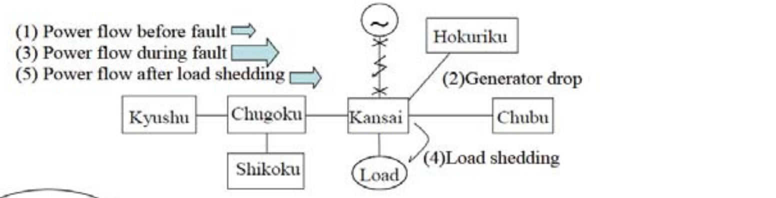
- **Master control station (ISC-P) : for Precalculation**
  - The system will conduct grid transient stability calculation every 30 seconds for more than 1000 N-1 fault cases, and inform operators within a certain minutes in case significant accident is likely to occur.
- **Local control station (ISC-C) : for Postcalculation**
  - The system calculates the transient stability of present grid condition. In case unstable case is occurred, countermeasure is directed that can minimize affect of fault.



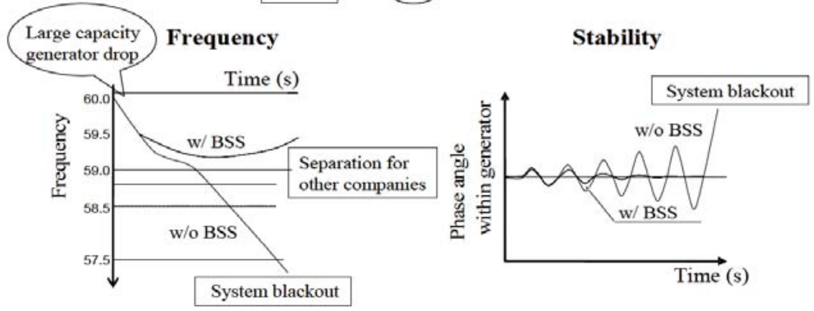
https://powergrid.chuden.co.jp/english/technical/operation/isc/

Block System Stabilizer : Advanced Wide-area Special Protection System –Outline of Control-

Outline of stabilizer control



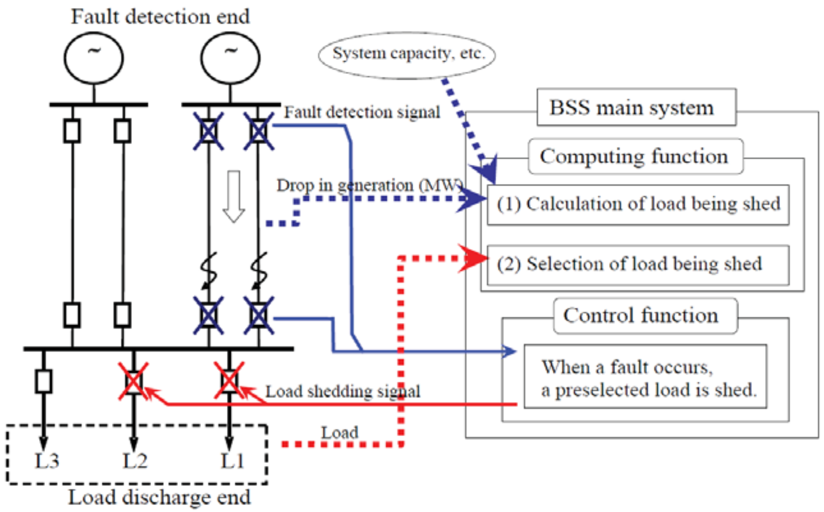
The flow of Control Sequence is:
(1)Before fault
(2)Generator drops
(3)Fault occurs
(4)Load is shedded
(5)After load shedding, grid will be stable.



A. Nakajima, m. Morita, T. Hayashi, T. takeyasu, K. Kurose, T. Aramaki & A. kadokami., "Development of an Advanced Wide-area Special Protection System," Journal of International Council on Electrical Engineering, Vol.3, No.4, pp.334-339, 2013.

Block System Stabilizer : Advanced Wide-area Special Protection System - Control Scheme -

Control Scheme of Block system Stabilizer

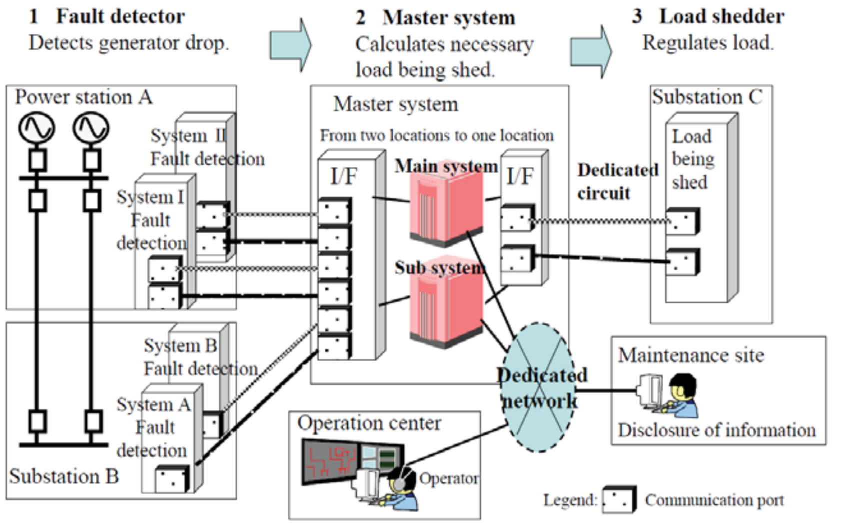


A. Nakajima, m. Morita, T. Hayashi, T. takeyasu, K. Kurose, T. Aramaki & A. kadokami., "Development of an Advanced Wide-area Special Protection System," Journal of International Council on Electrical Engineering, Vol.3, No.4, pp.334-339, 2013.

Block System Stabilizer : Advanced Wide-area Special Protection System –System Configuration-

System Composition

Relationship of stations and terminals are described.
(1)Fault Detector (ISC-S)
(2)Master System (ISC-P, ISC-C)
(3)Load Shedder (ISC-T)



A. Nakajima, m. Morita, T. Hayashi, T. takeyasu, K. Kurose, T. Aramaki & A. kadokami., "Development of an Advanced Wide-area Special Protection System," Journal of International Council on Electrical Engineering, Vol.3, No.4, pp.334-339, 2013.

Special Protection System in Kansai Electric Power

Block System Stabilizer : Advanced Wide-area Special Protection System –Control Panels-

Local Control Station (ISC-C) | Fault Detection Terminal (ISC-S) | Local Control Station (ISC-T)

A. Nakajima, m. Morita, T. Hayashi, T. takeyasu, K. Kurose, T. Aramaki & A. kadokami., "Development of an Advanced Wide-area Special Protection System," Journal of International Council on Electrical Engineering, Vol.3, No.4, pp.334-339, 2013.

6. Inter-connection, Simulation Cases future grid of St. Kitts & Nevis

- Current Grid in St. Kitts & Nevis
- Future Grid Plan in St. Kitts & Nevis

- **Evaluation Process of Grid Stability**
  - Calculate base value of capacity, voltage, impedance and admittance
  - Calculate line impedance and admittance
  - Convert physical value of impedance and admittance to PU value
  - Calculate generation & load capacity from actual value to PU
  - Run Load Flow Analysis program

Plan of Exercise in Day-2

- Current data of St. Kitts and modification
- Current data of Nevis and modification
- Combined Grid of St. Kitts & Nevis and modification

- Future data of St. Kitts (66kV, assumed by JET)
- Future data of Nevis (66kV, assumed by JET)
- Combined Future Grid of St. Kitts & Nevis (66kV, assumed by JET)

- Other exercises from your proposal

Preparation of Data in St. Kitts & Nevis

	Actual Data	Planned Data	Assumed Data	
Current Grid of St. Kitts	Line Impedance	Generation capacity	Load Battery	
Current data of Nevis	Line Impedance	Generation capacity	Load Battery	
Combined Grid of St. Kitts & Nevis	Line Impedance	Generation capacity	Load Battery	
Future data of St. Kitts		Generation Capacity	Line Impedance Load, Battery	
Future data of St. Kitts		Generation Capacity	Line Impedance Load, Battery	
Combined Future Grid of St. Kitts & Nevis		Generation Capacity	Line Impedance Load, Battery	

Preparation of data for analysis

(1) Calculate base value of capacity, voltage, current, impedance and admittance
(2) Calculate distribution line impedance and node admittance
  (1) {Runit[ohm/km] +jXunit[ohm/km]}*Length of line[km]=R[ohm]+jX[ohm]
  (2) Rpu+jXpu=(R[ohm]+jX[ohm])/Zbase[ohm]
  (3) {Gunit[1/ohm/km]+jBunit[1/ohm/km]}+Length of line[km]~G+jB
  (4) Gpu+jBpu=(G[1/ohm]+jB[1/ohm])/Ybase[1/ohm]
(3) Calculate generation capacity and load capacity
  (1) Ppu+Qpu=(P[W]+jQ[var])/(VA)base[VA]
(4) Decide Swing node, P-V node and P-Q node
(5) Set Ppu to 0 for substation.
(6) Set Qpu to the value of capacitance in PU for substation.
(7) Run Load Flow Analysis Program(Microgrid Designer)

Calculation Per Unit Value In the case of 100MVA, 11kV

(1) Calculate base value of capacity, voltage, current, impedance and admittance
  (1) Vbase=11kV
  (2) (VA)base=100MVA
  (3) Ibase=100/11=9.1kA
  (4) Zbase=Vbase2/(VA)base=112/100=1.2 ohm
  (5) Ybase=1/Zbase=1/1.21=0.83 1/ohm
(2) Calculate distribution line impedance and node admittance
  (1) {0.05[ohm/km] +j0.1[ohm/km]}*5[km]=0.25[ohm]+j0.5[ohm]
  (2) Rpu+jXpu=(0.25[ohm]+j0.5[ohm])/1.2[ohm]=0.20+j0.42
  (3) {0[1/ohm/km]+j0.00001[1/ohm/km]}+5[km]~0+j0.00005
  (4) Gpu+jBpu=(0[1/ohm]+j0.00005[1/ohm])/0.83[1/ohm]=0+j0.000012
(3) Calculate generation capacity and load capacity
  (1) Ppu+Qpu=(10[MW]+j5[Mvar])/100 [MVA]=0.1+j0.05

Please prepare to change your data to PU value.

Rule of Setting Value

- Capacity of RE is set as minus P load
- Capacity of Battery is set as minus P
- Load capacity is set as minus P load
- For Var Compensator
  - Set capacity data to node admittance or reactive power
- For node which can keep voltage constant
  - Set voltage as constant value and node should be set as P-V node.

Grid Stability Analysis and Evaluation

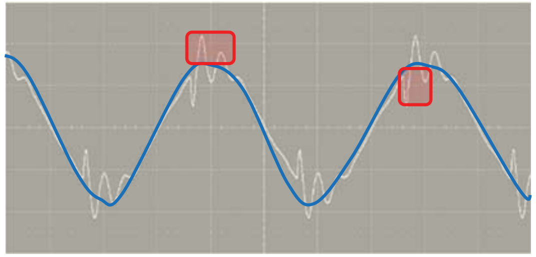
Evaluation steps of grid stability are as follows:

1. Load Flow Analysis
   1. Check voltage magnitude and angle of nodes
      1. Within acceptable value
   2. Check power flow of line
      1. Within TTC
   3. Check Consuming and Generating power in nodes
      1. Within rated capacity
2. Equal Area Criterion
   1. Check operating point
3. Short Circuit Ratio
   1. Check inverter output
4. Available Transmission Capacity
   1. Check current ATC
5. Spinning Reserve
   1. Check capacity of generators and batteries

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-1)

Harmonics

Increase of inverter source VRE may bring harmonics problem in the grid



https://www.denkenseiki.co.jp/products_noize/harmonic/

- A harmonic is a wave with a frequency that is a positive integer multiple of the fundamental frequency, the frequency of the original periodic signal.
- The original signal is also called the 1st harmonic, the other harmonics are known as higher harmonics. All harmonics are periodic at the fundamental frequency.
- for 50 Hz, 150Hz･250Hz･350Hz･450Hz… , Up to 2000 Hz is generally measured

Harmonic :

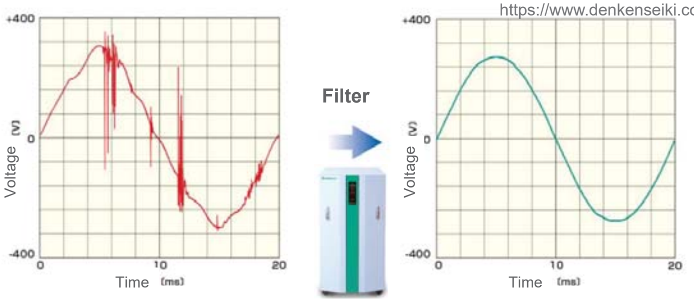
- A harmonic is noise of wave, caused by inverter converting from DC (from PV, wind) to AC (for grid) and user side from AC to DC (air conditioner, etc)
- Harmonic has affect on power equipment and appliance and causes of malfunction and failure of equipment, melt and cut of fuse, etc.
- Accident may be caused by harmonic
  - ex. Over-heat of a reactor due to harmonic current, lubricant is vaporized, ignited, and exploded
- **Filtering** is necessary to remove harmonics

Countermeasure for Harminoics

- Generally, Grid Code stipulate acceptable harmonic in %
  ex. Jamaica: <6.5% total & <5% individual for 69kV, <2% total& <1.5% individual for 138kV
  Japan: <5% for 6.6 kV and <3% for above 66 kV)
- Over heat, unusual noise, expansion are reported as accident

"If harmonics that exceed above listed standards result from the operation of the VRE producer's electrical equipment which are verified by testing, the system shall be disconnected until the harmonics are mitigated by the producer in accordance with standards" (Grid code, Jamaica)

https://www.denkenseiki.co.jp/products_noize/harmonic/



Filter such as noise-cut automatic voltage regulator is applied:

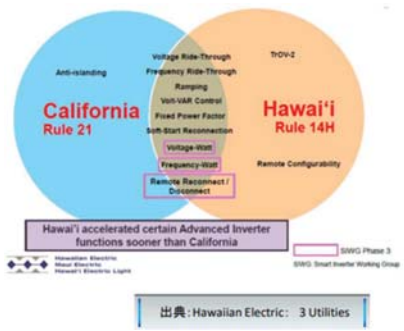
- To supply power with stabilization for harmonic, noise, voltage fluctuation
- To adjust the wave shape to suitable sign curve
- To control instantaneous fluctuation (serge, flicker, etc.)

Feedback from 3rd Seminar on Grid Stability and Large RE

8. Measurement Function of Inverter (Smart Inverter and its Grid Code) and effect of Battery

This section is a feedback and request of Harmonics or less distortion.

- Grid Code for Smart inverter
  - California Rule21, Hawaii Rule14
  -> Merged to IEEE 1547-2018 Standard
- Smart Inverter functions
  - Stabilization of Voltage and Frequency
  - Active filtering for harmonics
  - Keep Power conditioning to create near-pure sine wave
  - Control active power, power factor and reactive power output
  - Remote control capabilities including remote curtailment of output
  - Bi-directional communications capabilities
  - Remote monitoring
  - Smooth connect/disconnect
  - Low/high voltage and frequency ride-through



Harmonics, Over Voltage and Voltage Regulation

Harmonics is caused by load as the fluctuation of current.
- It will be appeared as the fluctuation of terminal voltage which is caused by voltage drop in distribution line.
- The impedance of distribution line is constant.
- But if the frequency of grid changes, the impedance of distribution line will change.
- Voltage fluctuation is calculated by multiplying impedance and line current.

Over Voltage is caused by fault or harmonics.
- Over voltage relay is set to 138% or other values in IEEE 1547-2018 Standard.

Voltage regulation
- Voltage regulation is influenced by the fluctuation of current and the change of impedance.

Grid Code
- Voltage regulation is defined as 5% of rated voltage for low voltage and 3% of rated voltage for high voltage grid in Japan and the most of countries.

Grid Code of Harmonics defined in IEEE 1547-2018 Standard

Harmonic current distortion, inter-harmonic current distortion, and total rated-current distortion (TRD) at the *reference point of applicability* (RPA) shall not exceed the limits stated in the following paragraph and in Table 26 and Table 27.

Table 26—Maximum odd harmonic current distortion in percent of rated current (I_{rated})[a]

Individual odd harmonic order h	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$[109]	Total rated current distortion (TRD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Table 27—Maximum even harmonic current distortion in percent of rated current (I_{rated})[a]

Individual even harmonic order h	$h = 2$	$h = 4$	$h = 6$	$8 \le h < 50$
Percent (%)	1.0	2.0	3.0	Associated range specified in Table 26

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

$$\%TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}} \times 100\%$$

I_1 is the fundamental current as measured at the RPA
I_{rated} is the DER rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA)
I_{rms} is the root-mean-square of the DER current, inclusive of all frequency components, as measured at the RPA

Grid Code of Over Voltage defined in IEEE 1547-2018 Standard

The limitation of **over voltage** is 138% for fundamental frequency voltage and the following figure for instantaneous voltage.

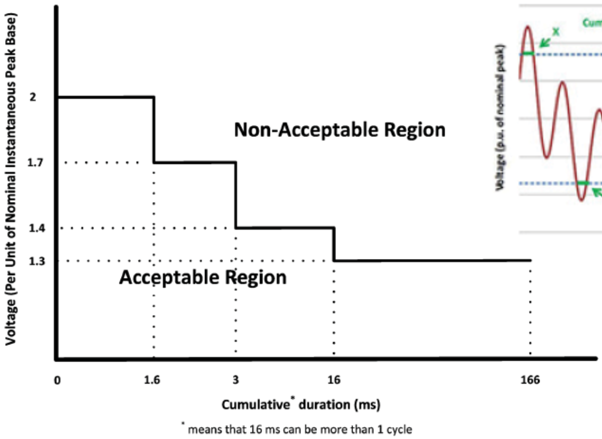
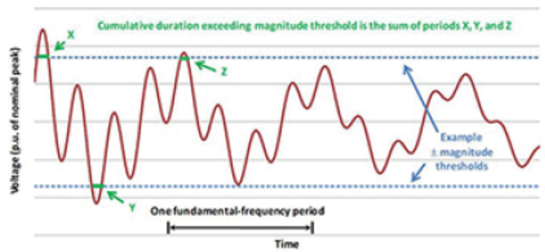


Figure 3 —Transient overvoltage limits

110 Cumulative duration is illustrated as follows:



Overview of Advanced Smart Inverter Capabilities

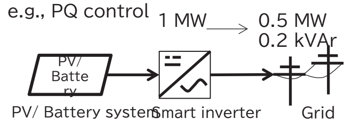
Smart Inverter includes several functions including grid forming control.

- More comprehensive planning and communications with DER systems
- Smart inverters can mitigate impact on power quality and reliability in response to local voltage and frequency issues as well as modify generation and storage actions based on communicated requests.
- To help manage increasing penetration of variable renewable energy generation

Advanced function for Grid stability

① Active/ Reactive power control

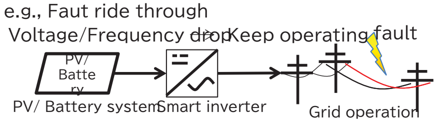
e.g., PQ control



Voltage and Frequency support function

② Grid protection

e.g., Faut ride through

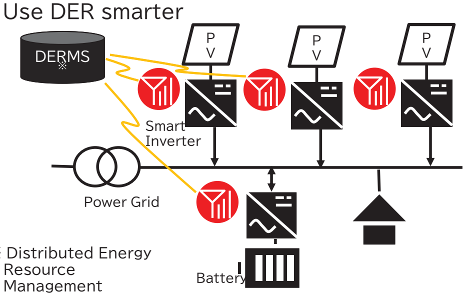


Recovering functionality in contingency

DER/smart inverter operation

③ Remote control and setting

Communication capability
Use DER smarter



※ Distributed Energy Resource Management Systems

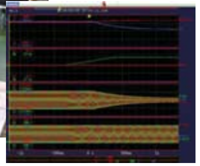
NEDO Project:FY2016–FY2018

Smart inverter testing – NEDO project

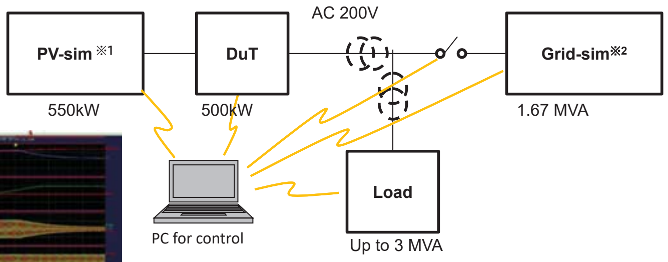
※AIST assist this project by testing only

- In this project, a smart inverter prototype was developed. Total 15 grid support functions has been implemented to the inverter.
- Testing method was developed and demonstrated for power system in Japan.
- Total 120 test cases were evaluated and defined the requirement for future grid code have been identified.

Device under Test (DuT)



e.g., Frequency droop function test

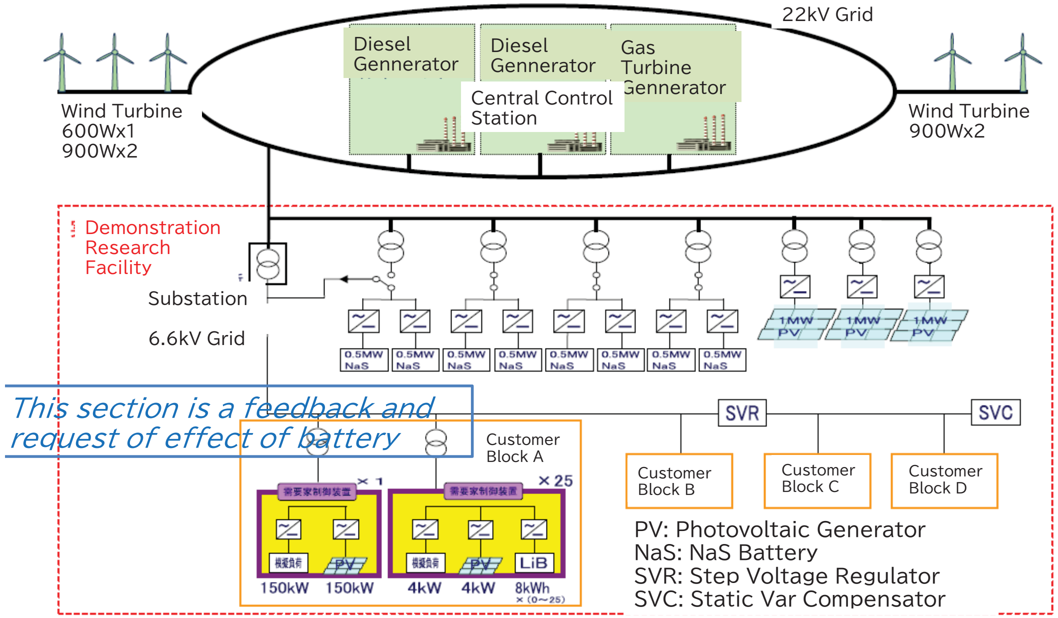


※1 Solar PV simulator
※2 Grid simulator

33

Feedback from 3rd Seminar on Grid Stability and Large RE

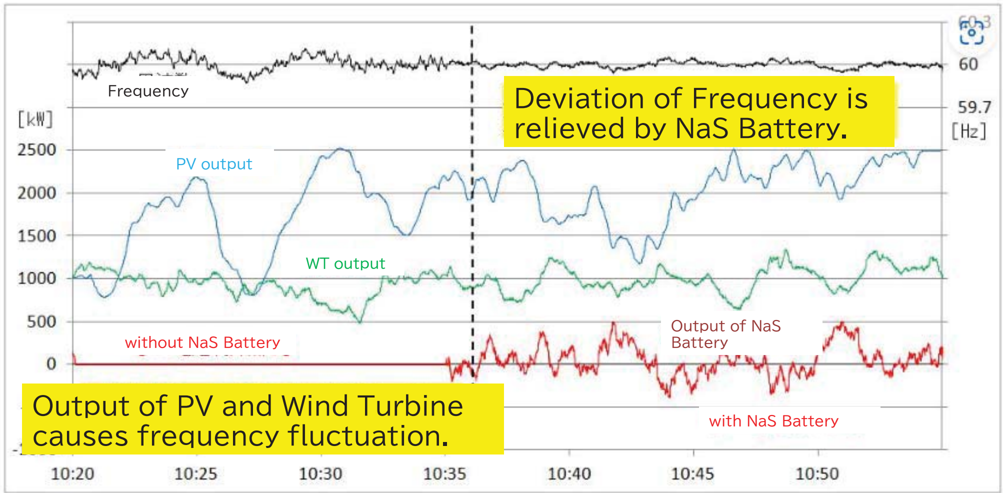
Miyakojima Island Mega Solar Demonstration Experimental Facility



https://www.okiden.co.jp/active/r_and_d/miyako/index.html

PV, Wind Turbine, NaS Battery and Frequency

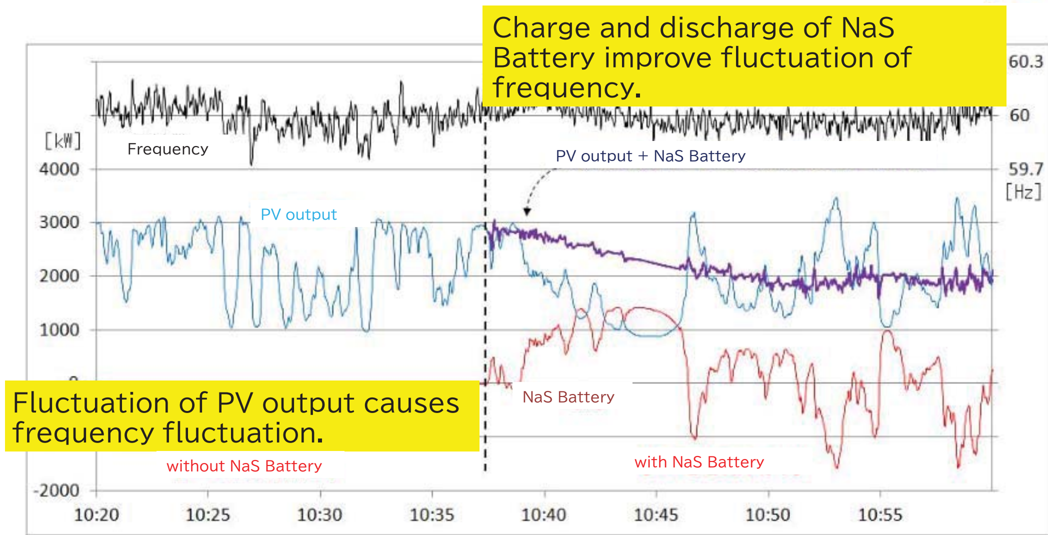
in Miyakojima Island Mega Solar Demonstration Experimental Facility



https://www.okiden.co.jp/active/r_and_d/miyako/index.html

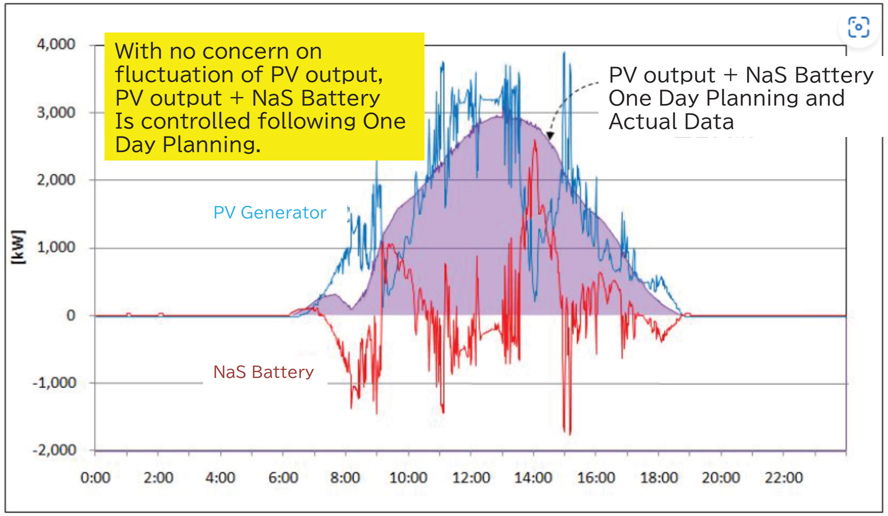
PV, NaS Battery and Frequency

in Miyakojima Island Mega Solar Demonstration Experimental Facility



https://www.okiden.co.jp/active/r_and_d/miyako/index.html

Demand and Supply of one day
in Miyakojima Mega Solar Demonstration Experimental Facility



https://www.okiden.co.jp/active/r_and_d/miyako/index.html

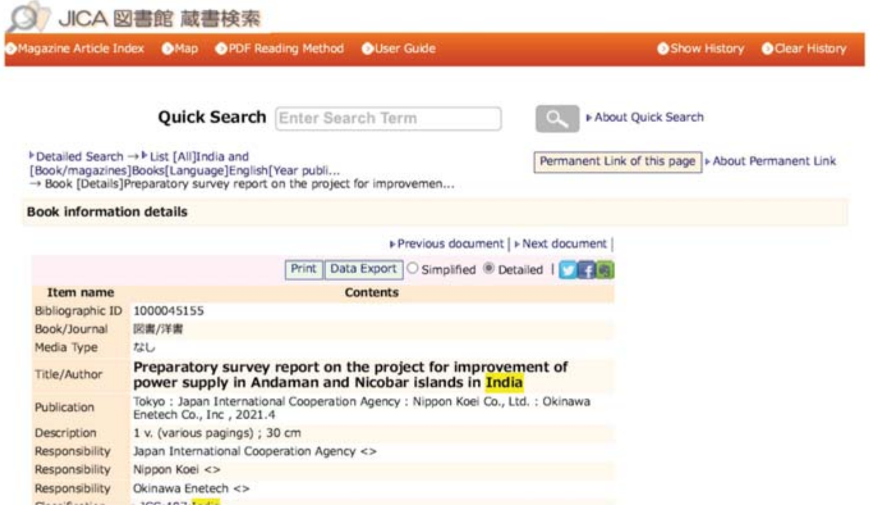
A Sample of Other Countries Situation of Grid and Renewable Energy

(A Sample from JICA Study Reports)

Study Name:

Preparatory Survey for the Project for Improvement of Power Supply in Andaman and Nicobar Islands in India

Data Source: JICA Library Portal Site
You can download JICA reports.



https://libopac.jica.go.jp/search/detail?rowIndex=12&method=detail&bibId=1000045155

Study Team Member

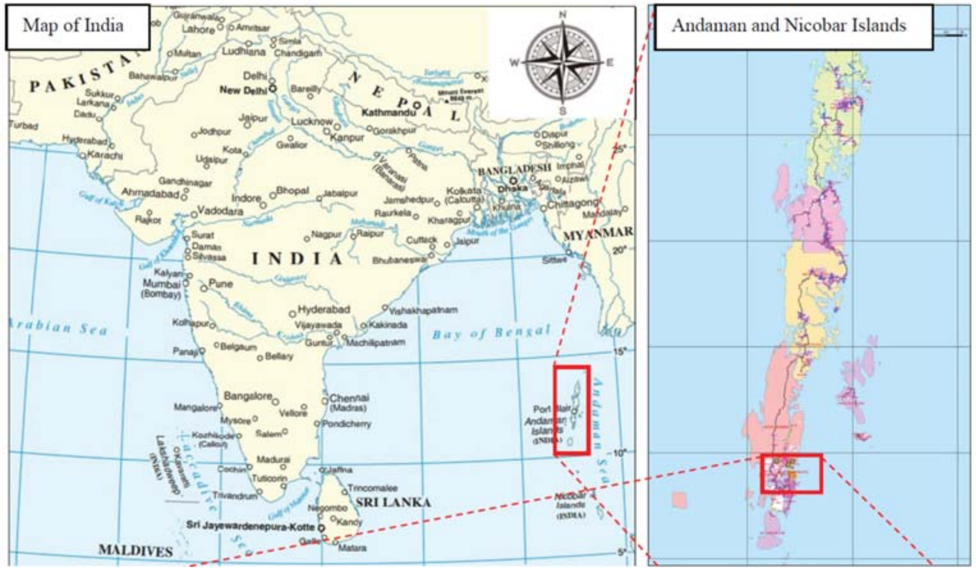
Member List of the JICA Survey Team

1. 1st Field Survey

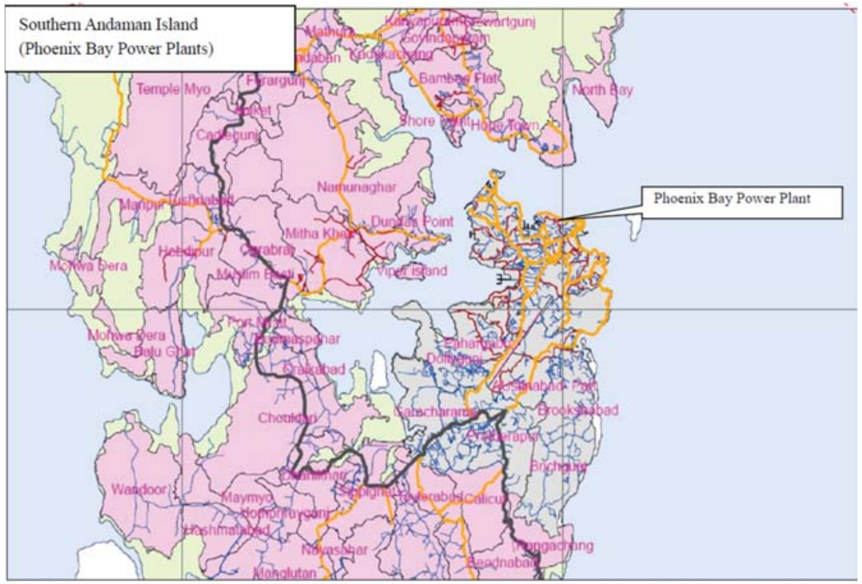
No.	Name	Designation	Company / Organization
1	Mr. Tomoyasu FUKUCHI	Team Leader of Consultant Team and Power Planning	Nippon Koei Co., Ltd.
2	Mr. Luis KAKEFUKU	Diesel Power Generation Facility Planning	OKINAWA ENETECH CO.,INC
3	Mr. Ryosuke OGAWA	Power Grid Planning	Nippon Koei Co., Ltd.
4	Mr. Akinari ISHIMURA	Equipment Planning (1)	Nippon Koei Co., Ltd.
5	Mr. CHOWDHURY TANVIR AHMED	Equipment Planning (2)	Nippon Koei Co., Ltd.

and the other 13 members

Location of the Study Site (1/2)



Location of the Study Site (2/2)



Features of the Study Site

Site Name: South Andaman Island

Site Latitude: N11°40’

Ground Area: 1,262 km²

Rainy Season: from May to October

Dry season: from November to April

Average Annual Rainfall: exceeds 3,000 mm

Population: 238,142 (Census of India 2011)

Major Industries: Tourism (mainly domestic tourists)

Power Supply in South Andaman Island as of November 2020

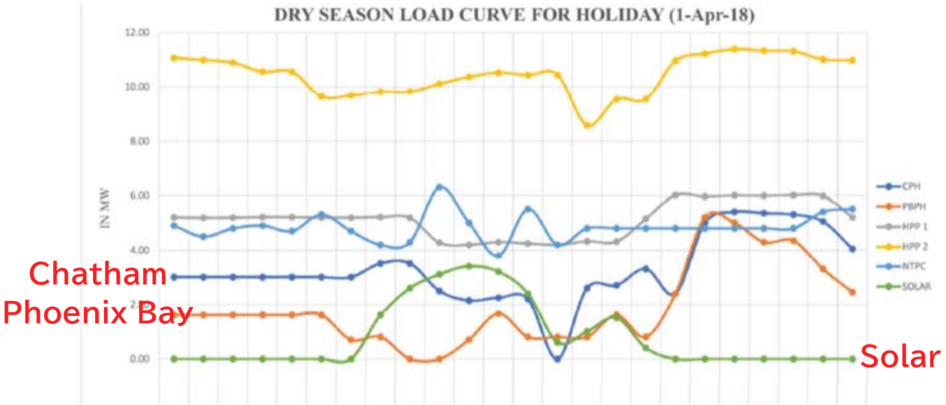
Power Source: diesel engine power plants (42.0 MW)
solar power plants (29 MW)

Power Source Ownership and Operation: mainly by
Independent Power Producer (IPP)

Peak Demand: about 40 MW (in the evening)

Grid Voltage: 33 kV as transmission
11 kV, 400/230 V as distribution

Daily Load Curve on 1 April 2018



	Hrs 0:30	Hrs 1:30	Hrs 2:30	Hrs 3:30	Hrs 4:30	Hrs 5:30	Hrs 6:30	Hrs 7:30	Hrs 8:30	Hrs 9:30	Hrs 10:30	Hrs 11:30
CPH	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.50	3.50	2.50	2.15	2.25
PBPH	1.60	1.60	1.60	1.60	1.60	1.60	0.70	0.80	0.00	0.00	0.70	1.65
HPP 1	5.20	5.18	5.19	5.21	5.21	5.19	5.19	5.21	5.18	4.28	4.20	4.30
HPP 2	11.05	10.98	10.88	10.55	10.55	9.64	9.67	9.81	9.82	10.11	10.36	10.52
NTPC	4.90	4.50	4.80	4.90	4.70	5.30	4.70	4.20	4.30	6.30	5.00	3.80
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	2.60	3.10	3.40	3.20

	Hrs 12:30	Hrs 13:30	Hrs 14:30	Hrs 15:30	Hrs 16:30	Hrs 17:30	Hrs 18:30	Hrs 19:30	Hrs 20:30	Hrs 21:30	Hrs 22:30	Hrs 23:30
CPH	2.20	0.00	2.60	2.70	3.30	2.40	5.00	5.40	5.35	5.30	5.05	4.05
PBPH	0.80	0.80	0.80	1.60	0.80	2.40	5.20	5.00	4.30	4.35	3.30	2.45
HPP 1	4.25	4.20	4.33	4.32	5.15	6.02	5.97	6.01	6.00	6.02	5.99	5.20
HPP 2	10.43	10.44	8.58	9.53	9.54	10.95	11.2	11.37	11.32	11.30	11.00	10.97
NTPC	5.50	4.20	4.80	4.80	4.80	4.80	4.80	4.80	4.80	4.80	5.40	5.50
SOLAR	2.40	0.60	1.00	1.50	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Min:26.29MW

Max:32.58MW

Challenging for Power Supply in South Andaman Islands

- To increase power supply capacity to meet the growing demand,
- To ensure the stability of the grid operation under the solar power connection to the grid

Power Development Plan

India Government Policy:
Switching from diesel engine generators to Liquefied Natural Gas (LNG) engine generators and renewable energy to reduce carbon emission

LNG: to introduce LNG engine power plant of 50 MW in 2022 in South Andaman Island : progress (?)

Solar Power : to introduce 100 MW in South Andaman and other Andaman and Nicobar Islands

The Government of India' s Request

The Government of India requested to the Government of Japan for grant aid to improve the power supply of South Andaman Island in 2015.

The Study Output

■Based on the request, JICA dispatched the study team to South Andaman Island

■ The Study formulated the project to install storage batteries and related facilities to contribute to effectively utilizing renewable energy and stabilizing the grid operation.

■Grant Agreement of the project was signed on 30 March 2022.

Project Outline

- Storage battery
- SCADA system (Local SCADA system to control management of storage battery, system stabilizer equipment, and invertor/convertor)
- Building (for installation of the above mentioned components)
- Grid connecting equipment

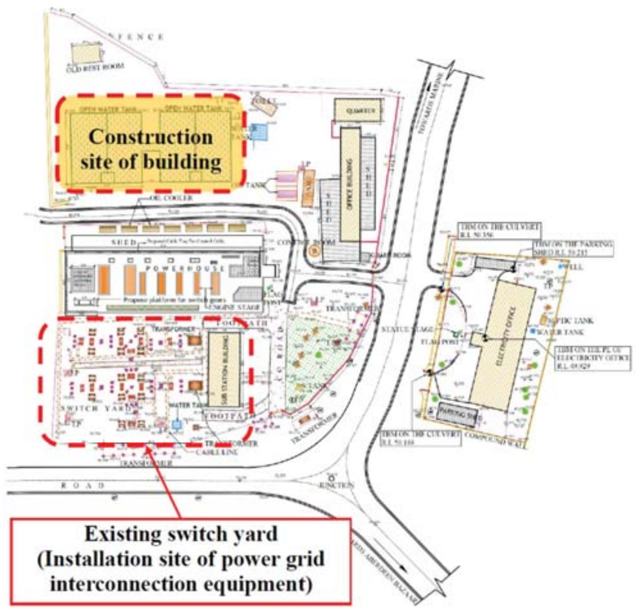
Project Outline: Battery Specification

Table 1 Design Overview

Item	Contains
Storage battery type	Lithium-ion battery
Power	30 MW
Capacity	15 MWh

Source: Prepared by the JICA Survey Team

Project Outline: Project Site



Source: Prepared by the JICA Survey Team
Figure 1-3-1 Project Site

Project Outline: Image: Building

Project Outline: Image: Storage Battery

Project Outline: Image: SCADA Room

Evaluation of the Project

Table 2 Quantitative Evaluation of the Project

	Indicator	Standard Value (year 2020)	Target Value (year 2026)
1	Maximum battery power (MW)	-	30
2	Maximum battery capacity (MWh)	-	14.25
3	Discharge power* (MWh/year)	-	2,971
4	System frequency fluctuation range (Hz)	49.08 ～ 51.83	50 ± 0.5
5	Reduction of greenhouse gas (tCO_2 /year)	-	2,683

(Note) * : This is the assumed amount of annual surplus power discharged from solar power generation.

Source: Prepared by the JICA Survey Team

Study History: Discussion Paper in 2016 (1/2)

Option1 (Original Component)
Diesel Engine Generator 15 MW

Component	Quantity/Size	Remarks
Diesel Engine Generator	15 MW	3 sets x 5 MW
Power House Building	1 building	
Power System Stabilizer	1 set	
Batteries	1 MWh	
SCADA	1 set	

Option 2
Dual Fuel Engine Generator 9 MW (without LNG storage tank and LNG handling facilities)

Component	Quantity/Size	Remarks
Dual Fuel Engine Generator	9 MW	3 sets x 3 MW
Power House Building	1 building	
Power System Stabilizer	1 set	
Batteries	4 MWh	
SCADA	1 set	

Study History: Discussion Paper in 2016 (2/2)

Option 3
Dual Fuel Engine Generator 4.5 MW (without LNG storage tank and LNG handling facilities)

Component	Quantity/Size	Remarks
Dual Fuel Engine Generator	4.5 MW	1.5 sets x 3 MW
Power House Building	1 building	
Power System Stabilizer	1 set	
Batteries	9 MWh	
SCADA	1 set	

Option 4
Without Engine Generator

Component	Quantity/Size	Remarks
Control House Building	1 building	
Power System Stabilizer	1 set	
Batteries	15 MWh	
SCADA	1 set	

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-1)

1 Introduction for the Seminar, Review and feedback
2. Microgrid Planning with Large RE
3. Development Status of Grid Forming Inverter and its Safety
   - Current Status, Blackout with GFM & Black Start using BESS
4. Battery & Hydrogen as an Electricity Storage, cost comparison
5. Special Protection System including Load Shedding, PV/WT Trip
6. Inter-connection, Simulation Cases for future grid of St.Kitts &Nevis
7. Harmonics and filtering
8. Measurement Function of Inverter, Grid Code
9. Sample of Other Countries Situations of Grid and RE
10. **Demonstration of Asset Management System**
11. Presentation from SKELEC and NEVLEC about current status and challenges

Asset Management for Power System Resilience

Why Asset Management is important for resiliency?

- Increasing hurricane risks → risks for large scale damage on asset
- **Digital Twin** with precise mapping and database for all equipment enables followings:
  - Fast fault location finding
  - Speedy dispatch of maintenance engineer for recovery
  - Alternative route finding with connectivity analysis
    - The system will be a platform for simulator, SCADA, field real time data, maps, etc

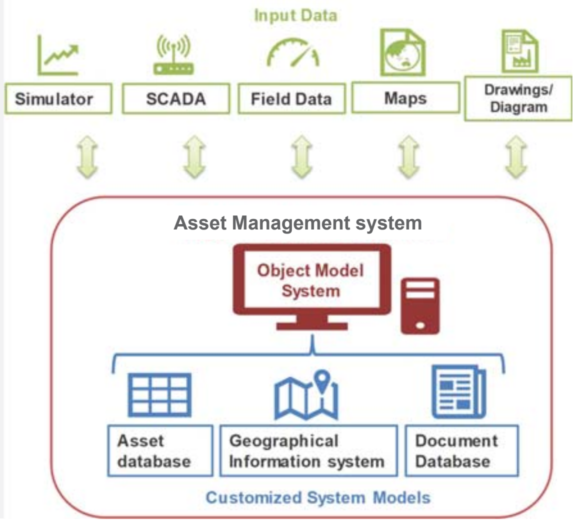
23 Aug 2018 Awaji, Japan
https://www.sankei.com/west/news/180828/wst1808280043-n1.html

26 Jul 2019 Himeji, Japan
https://www.dailyshincho.jp/article/2018/07260800/?photo=1
Landslide by a heavy rain

Asset Management for Resilience: as system platform

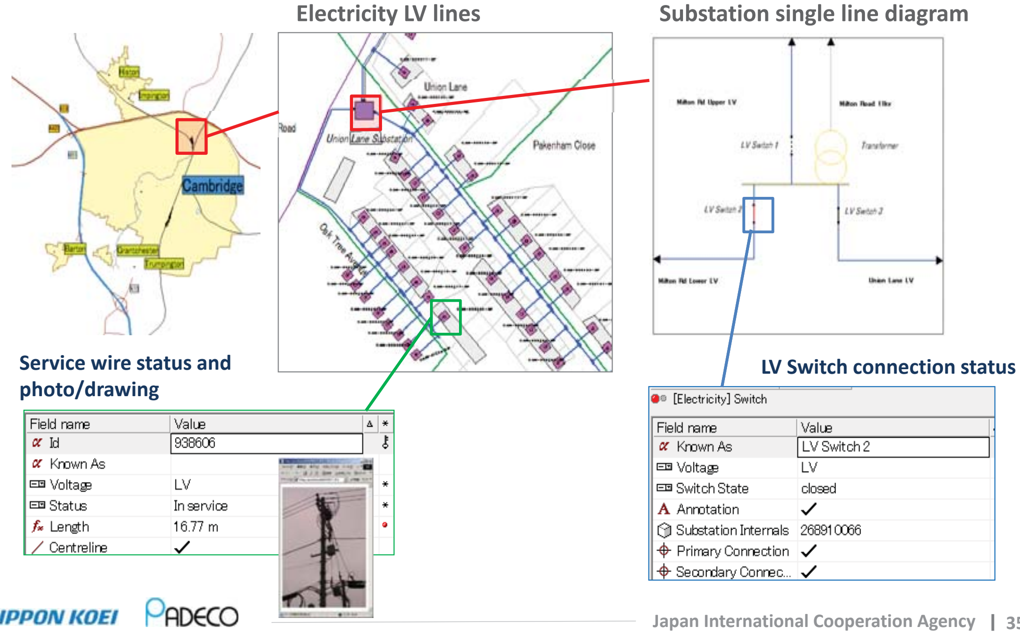
- To Optimize planning
- To Minimize time for recovery from failure with system integration

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



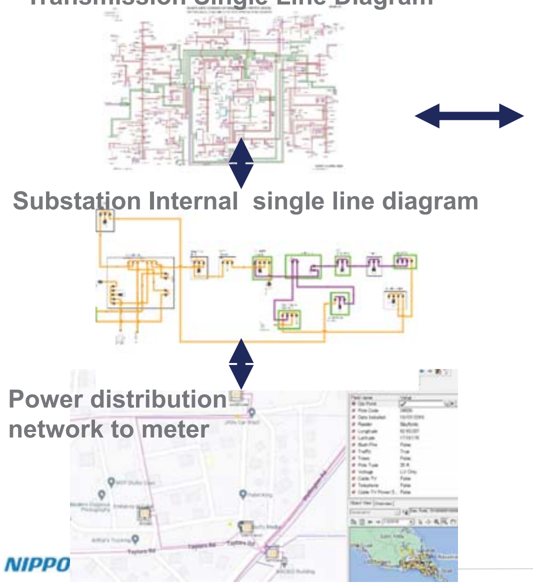
Asset Management for Power System Resilience

Asset data of equipment status in PS and SS, network trace, fault finding



Asset Management for Resiliency

Linking all asset data on to one data platform

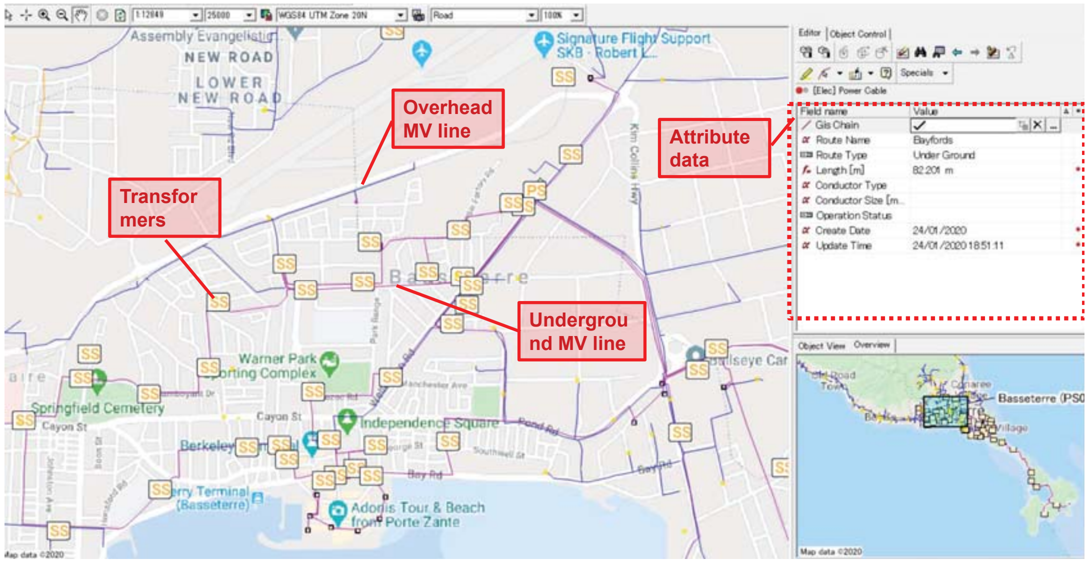


Power Network Mapping Data

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

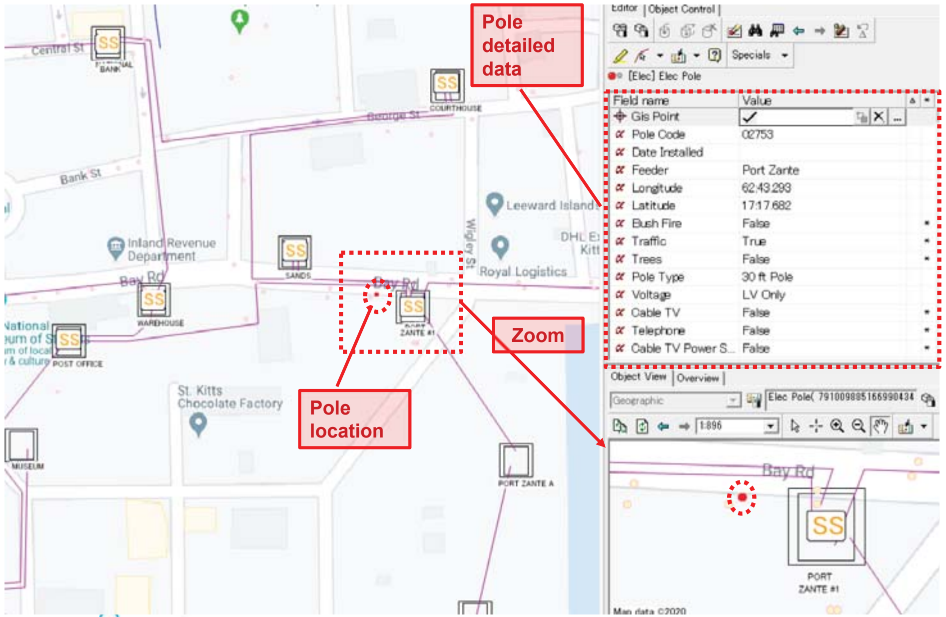
Asset Management System example: St.Kitts

Network infrastructure mapping with database → easy to obtain precise location



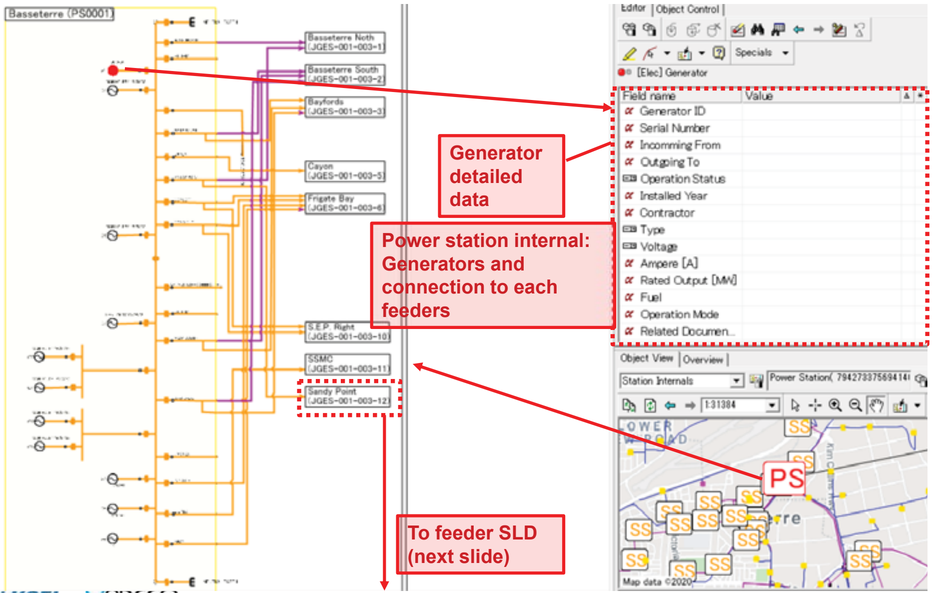
Asset Management System example: St.Kitts

Big data up to pole and consumer meters can be incorporated.



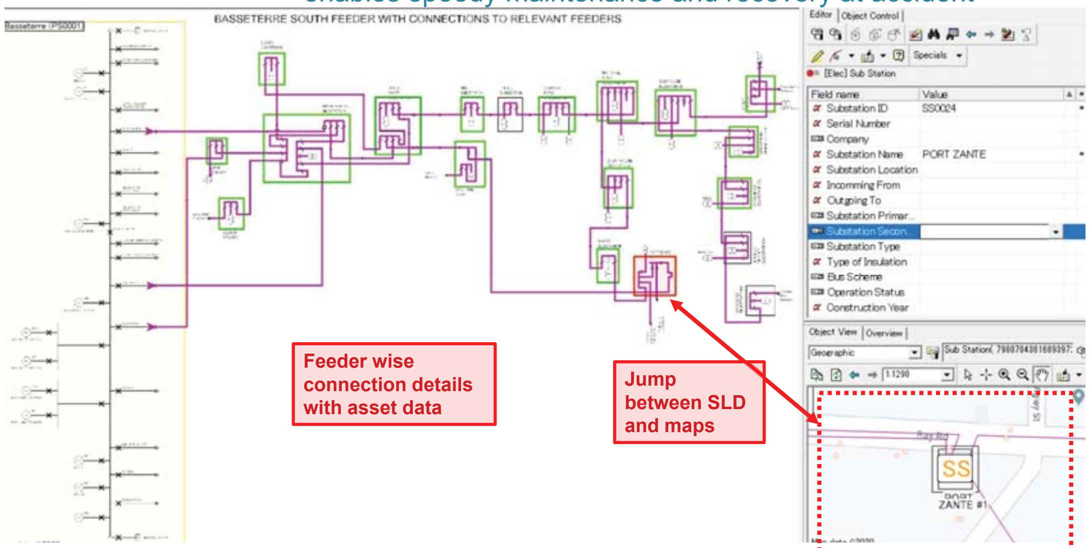
Asset Management System example: St.Kitts

Single Line Diagram with mapping data → easy connection tracing & network analysis



Asset Management System example: St.Kitts

Feeder wise detailed asset data and link with map enables speedy maintenance and recovery at accident



Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-2)

18-19 Jan 2023

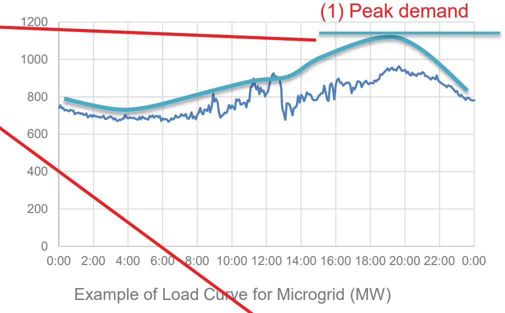
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Agenda (Day-2)

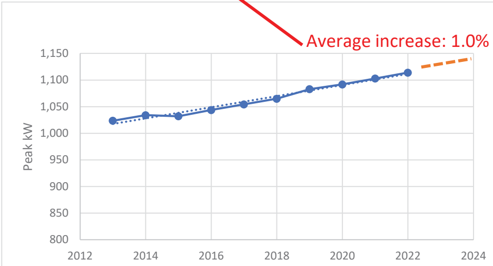
1. Introduction of Microgrid Designer and Transient Analysis
   - Role of Tools for Power System Analysis, - Load Flow Analysis
   - Transient Stability Analysis for Operation and Control
2. Investment of MW and MWh of Energy Storage for VRE
3. Exercise on simple grid example and Microgrid
   - Load Flow Analysis, - Transient Stability Analysis
4. Exercise on Future Grid
   - Design and Operation Planning
   - Load Flow Analysis, - Transient Stability Analysis
5. Analysis Result and Countermeasure of Grid Stability
6. Discussion, policy recommendation, and Way Forward
7. Conclusion and Closing Remarks

Microgrid Planning
Determination of generation output (in case of PV)

(1)	Max kW of peak day	1,114
(2)	Demand consideration yr	10
(3)	Demand increase %/yr	1%
(4)	Final peak demand kW	1,230
(5)	Reserver rate	0%
(6)	Design capacity kW	1,230
(7)	Present energy demand kWh/d	20,962
(8)	Design energy kWh/d	23,155
(9)	Specific PV generation kWh/kW/day	4.764



Example of Load Curve for Microgrid (MW)



Annual peak demand kW

(9) Calculated from
- Irradiation: I kWh/m2
- PV output: P kW/m2
- Design coefficient K

Solar Atlas provides typical kWh/kW/day

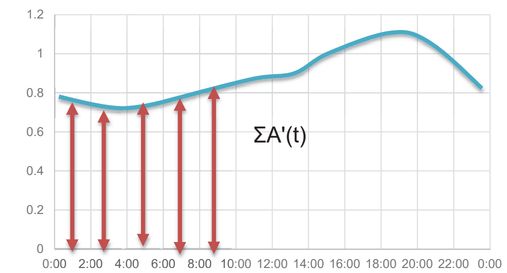
Microgrid Planning: Determination of Battery Capacity

In case 1 day energy need to be stored….

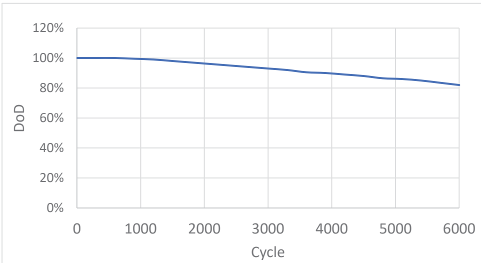
(11)	BESS PCS output kW	1,230
(12)	Efficiency of PCS	97%
(13)	Battery Capacity kW	1,268
(14)	Capacity rate after cycle life K	0.9
(15)	Depth of Discharge D	0.9
(16)	Charge-discharge efficiency η	0.9
(17)	Nos of days to store energy n	1
(18)	Design Battery Energy kWh	29,562
(19)	Required PV Output for batetery	6,205

$$S = n\frac{\sum_{t=0}^{24} A'(t)}{L \cdot \eta}$$

Where,
S : Energy Capacity of Battery (kWh)
n : nos of days to store energy
A'(t) : Hourly demand of battery coverage (kWh)
L: Maintenance factor = K x D
K: Capacity after cycle of life, generally 0.8 for LiB battery
D: Depth of discharge , generally 0.8 -1.0 for LiB battery
η: Charge-discharge efficiency of battery



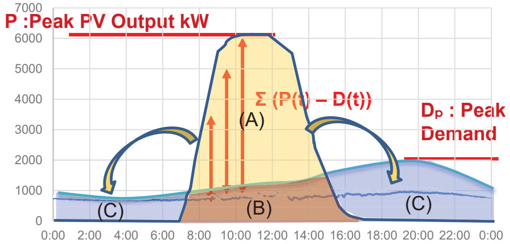
Example of Load Curve for Microgrid (MW)



Change of Depth of Discharge (DoD) against Year

Prepared by JET

Microgrid Planning: Determination of Battery Capacity
In case of peak shift



Load Curve and PV Output (kW)

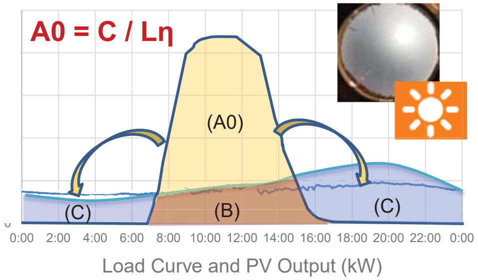
(A): Energy to be stored in Battery
(B): Day demand directly covered by PV
(C): Night demand need to be covered by battery
D_p = 1230 kW
P = 6205 kWp
PV generated E kWh = (A) + (B)
Demand D kWh = (B) + (C)
(A) > (C) / L・η

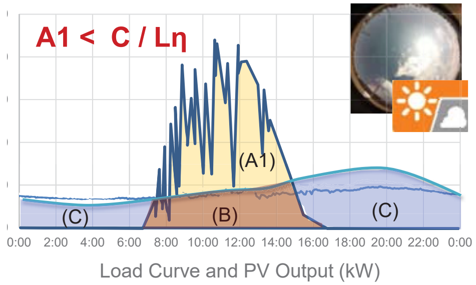
L: Maintenance factor
η: Charge-discharge efficiency of battery

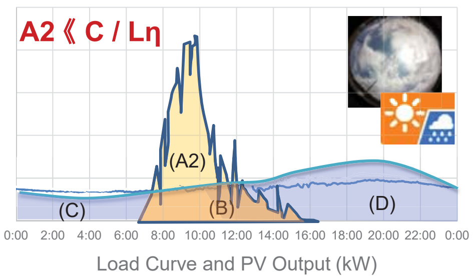
In case battery covers night load :
P_{PV} = 6206 kW
PV generated E kWh = (A) + (B)
Demand D kWh = (B) + (C)
Σ (P(t) – D(t)) = (A) > (C) / L・η

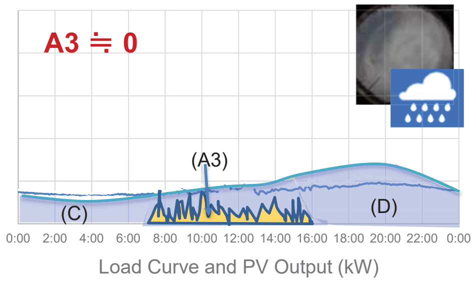
Dp: Peak Demand
Ppv: PV Peak Output
P(t): PV output at the time (t)
D(t): Demand at the time (t)

Pattern of Weather: If 100% PV, how much Battery capacity should be to cover cloudy and rainy days?



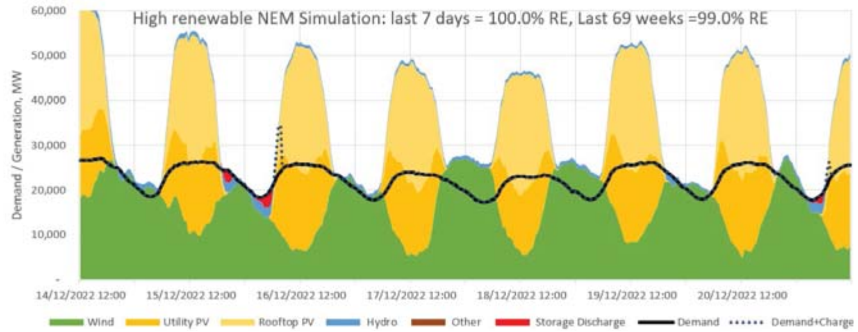






Sample ideal operation with 100% RE

Sample case of 100% RE in Australia : (idea, with wind, hydro, 5 hrs storage
- Large curtailment of utility scale to feed rooftop PV
- Good resource of wind



Australian grid get very close to 100% renewable electricity with just 5 hrs of storage (24 GW / 120 GWh)
Results: Dec 2022, 100% RE

4th Seminar on Grid Stability and Large RE

Day-2 Session

1. Introduction of Microgrid Designer & Transient Analysis
   - Role of Tools for Power System Analysis
   - Load Flow Analysis
   - Transient Stability Analysis for Operation and Control
2. Investment of MW and MWh of Energy Storage for Variable Renewable Energy(VRE)
3. Exercise on simple grid example and Microgrid
   - Design and Operation Planning
   - Load Flow Analysis, Transient Stability Analysis
4. Exercise on Future Grid
   - Design and Operation Planning
   - Load Flow Analysis
   - Transient Stability Analysis
5. Analysis Result and Countermeasure of Grid Stability

1. Introduction of Microgrid Designer & Transient Analysis

We show the role of power system analysis for introducing RE.

- Requirements for RE
  - Steady State Stability for Grid Planning
    - -> Load Flow Analysis
      - Node Voltage: within a margin of error 10%
      - Line Current under an available capacity
      - Total Line Capacity under rated value of power
  - Transient State Stability for Grid Operation
    - -> Transient Stability Analysis
      - Nadir caused by output change of RE
      - RoCoF(Rate of Change of Frequency) after fault
- Microgrid Designer is a simple application for
  - Load Flow Analysis
  - Extended Application
    - Load Frequency Control
    - Economic Load Dispatching

Tools for Power System Analysis

We describe relationship of application and tools.

Application	Load Flow Analysis	Transient Stability Analysis	Electro Magnetic Transient Analysis
Design and Test of Equipment	O	O	O
Generation Planning for SG, RE, Battery and other resources	O		
Planning of Transmission Line, Distribution Line and Substation	O		
Operation and Control for Frequency Stability and Security Assessment	O	O	
Training of operator in Control Center	O	O	
Protection and Control for Fault or Emergency		O	O

Steps of Load Flow Analysis by Microgrid Designer

Please download and install Microgrid Designer and conduct followings:

1. Preparation of data (detail is in the next page)
   1. Capacity of generator and load including RE and battery
   2. Impedance and admittance of transmission line and distribution line
   3. Admittance of Equipment for Var Compensator
2. Set Per Unit Base Value from grid capacity and voltage
3. Calculate Per Unit data from prepared data
4. Prepare an new excel file by copying a sample file
5. Input prepared data to the new excel file
6. Start to calculate

Preparation of data for load flow analysis

(1) Calculate base value of capacity, voltage, current, impedance and admittance

(2) Calculate distribution line impedance and node admittance

- (1) {R_unit[ohm/km] +jX_unit[ohm/km]}*Length of line[km]=R[ohm]+jX[ohm]
- (2) R_pu+jX_pu=(R[ohm]+jX[ohm])/Zbase[ohm]
- (3) {G_unit[1/ohm/km]+jB_unit[1/ohm/km]}+Length of line[km]=G+jB
- (4) G_pu+jB_pu=(G[1/ohm]+jB[1/ohm])/Ybase[1/ohm]

(3) Calculate generation capacity and load capacity

- (1) P_pu+Q_pu=(P[W]+jQ[var])/(VA)base[VA]

(4) Decide Slack node, P-V node and P-Q node

(5) Set P_pu to 0 for substation.

(6) Set Q_pu to the value of capacitance in Per Unit for substation.

(7) Run Load Flow Analysis Program(Microgrid Designer)

R_unit, X_unit, Z_unit, G_unit, B_unit, Y_unit : resistance, reactance, impedance, conductance, susceptance and admittance per unit length(1km) in ohm or siemens(1/ohm)
R, X, Z, G, B, Y : resistance, reactance, reactance, conductance, susceptance and admittance in ohm or siemens(1/ohm)
R_pu, X_pu, Z_pu, G_pu, B_pu, Y_pu : resistance, reactance, reactance, conductance, susceptance and admittance in per unit

Rule of Setting Value for Load Flow Analysis

- Capacity of RE is set as negative load P
- Capacity of Battery is set as negative load P
- For Var Compensator
  - Set node admittance or negative reactive power of load
- For node which can keep voltage constant such as synchronous generator or STATCOM
  - Set voltage as constant value and node should be set as P-V node

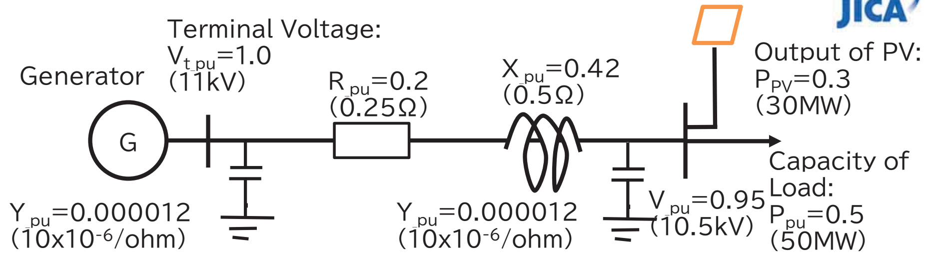
Grid Stability Analysis and Evaluation

Evaluation steps of grid stability are as follows:

1. Load Flow Analysis
   1. Check voltage magnitude and angle of nodes
      Within acceptable value
   2. Check power flow of line
      Within Total Transfer Capacity (TTC)
   3. Check Consuming and Generating power in nodes
      Within rated capacity
2. Equal Area Criterion
   Check operating point
3. Short Circuit Ratio
   Check inverter output
4. Available Transmission Capacity
   Check current Available Transfer Capacity (ATC)
5. Spinning Reserve
   Check capacity of generators and batteries

Exercise 1

Per Unit & Load Flow Analy



(1) Calculate base value of capacity, voltage, current, impedance and admittance
  (1) Vbase=11kV
  (2) (VA)base=100MVA
  (3) Ibase=100/11=9.1kA
  (4) Zbase=Vbase2/(VA)base=112/100=1.2 ohm
  (5) Ybase=1/Zbase=1/1.21=0.83 1/ohm
(2) Calculate distribution line impedance and node admittance
  (1) {0.05[ohm/km] +j0.1[ohm/km]}*5[km]=0.25[ohm]+j0.5[ohm]
  (2) R_{pu}+jX_{pu}=(0.25[ohm]+j0.55[ohm])/1.2[ohm]=0.20+j0.42
  (3) {0[1/ohm/km]+j0.00001[1/ohm/km]}+5[km]~0+j0.00005
  (4) G_{pu}+jB_{pu}=(0[1/ohm]+j0.00005[1/ohm])/0.83[1/ohm]=0+j0.000012
(3) Calculate generation capacity and load capacity
  (1) P_{pu}=50[MW]/100 [MVA]=0.5, P_{PV}=30[MW]/100 [MVA]=0.3

Please prepare to change your data to Per Unit value.

Exercise 1 4thREGS_Ex01.xlsm

NodeData

Load Flow Analysis of 4thREGS_Ex01

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load			
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	PV	WP	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)
1	2	1					0		0			
2	0	1					0.2		0.5	0.3		

BranchData

Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	1	2		0.2	0.42	0.000012	

Results_Node

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)
1	2	1	1	0	0	0	0.2087	0.01824	0.20949	−4.99
2	0	1	0.9543	−5.05	−0.2	0	−0.19992	0.00017	0.20949	175

Results_Branch

Output Form of Obtained Results for Buses by Singel Stage Power Flow Anlysis									
Branch ID	Connected nodes		Power flow from node-M		Power flow from node-N		Line current		Tap
(Number)	M	N	P (p.u.)	Q(pu)	P(pu)	Q(pu)	I (pu)	Phase aqngel (Degree)	
1	1	2	0.2087	0.01824	−0.19992	0.00017	0.20949	−4.99	

Setting sheet of Node Data for Load Flow Analysis in Microgrid Designer

Node ID
Up to 4 characters

Type of node (2:Slack node, 1:P-V node, 0:P-Q node)

Magnitude of node voltage in PU

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.)	(x.)
1		1.03					0	0
2		1			0.07842	0	0.0643	0.0386
3		1			0.00422	0	0.047	0.0315

Capacity of synchronous generators (Pg and Qg) in PU

Capacity of load (Pl and Ql) in PU

Setting sheet of Branch Data for Load Flow Analysis for Microgrid Designer

Branch ID
Integer up to 5 digits

Sending Node and Receiving Node

Tap of Transformer

Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	1	2		0.09024	0.08624	0	0
2	1	3		0.03319	0.04143	0	0
3	1	4		0.00887	0.00815	0	0

Line Resistance, Reactance and Admittance(half value)

Setting sheet of Capacity of Renewable Energy and Battery for Microgrid Designer

Load can be calculated by setting data in the yellow cell.
Please input capacity of
Load,
Utility PV, Distributed PV,
Wind Turbine and BESS,
Then the total capacity of each node is calculated and input Pl automatically.

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load				
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	Utility PV	Distributed PV	Wind Turbine	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)	(pu)
1	2	1			0.434	0	−0.26184	0			0.131837		0.13
2	1	1			0.197	0	0.055154	0	0.1		0.024846		0.02
3	1	1			0.53	0	−1.38559	0	0.1	0.7	0.045587		0.74

Notes for Load Flow Analysis in Microgrid Designer

Followings are the notes to use Microgrid Designer.

1. This program is composed of an excel file and execution file.
2. Your set of excel file and execution file should be in the same folder as a set.
3. Calculated data is overwritten. In order to save the results, you should move the excel file to another place.
4. Edge node should have some load or generator.
5. Total number of branch should be less than 100.
6. The excel file includes a sheet of input data format both node data and branch data for Microgrid Designer.
7. Node name is set by 4digit character.
8. Node types are categorized into 3 types: P-V node, P-Q node and Slack node. Those numbers (0, 1, 2) should be put in the column. 0 as P-Q node, 1 as P-V node, and 2 as Slack node. Data of generator output (Pg and Qg) and terminal voltage(V) should be node type of P-V node.
9. RE output is set to P-Q node, and input it as Load (Pl and Ql) in yellow cells. RE output is set by positive value.
10. Pl is automatically calculated based on load, PV, WT, BESS data input in yellow cells.

Feedback from 3rd Seminar on Grid Stability and Large RE

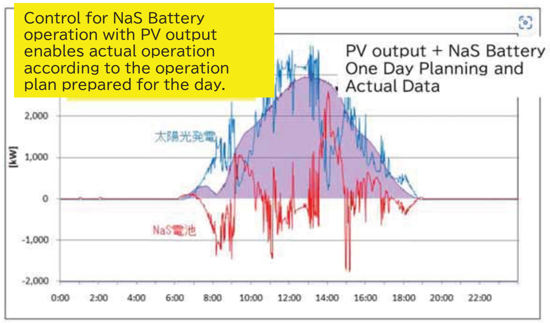
2. Investment of MW and MWh of Energy Storage for VRE

This section is a feedback and request of optimal capacity of battery.

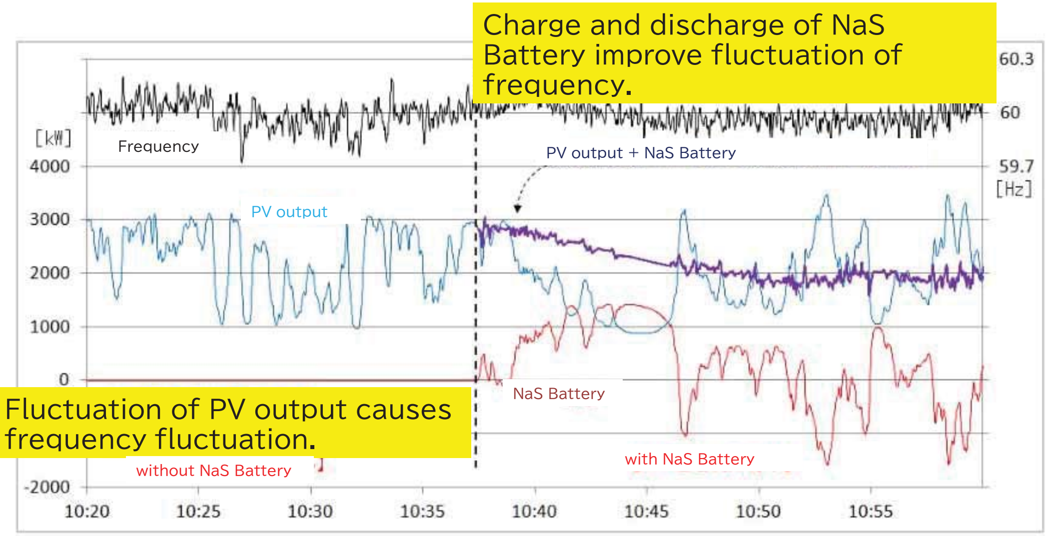
MWh of battery can be less than MWh of PV output.
The following equation can calculate only fluctuation capacity of PV.

(MWh) of battery = (MWh) of PV output – (MWh) of planed average PV output as shown in Miyakojima Mega Solar Demonstration Experimental Facility as shown in the right figure.

- Assume capacity of PV
- Estimate maximum capacity in MW of PV in a fine day
- Estimate maximum total capacity in MWh per day of PV
- MWh had better to be at least 1day capacity.



PV, Wind Turbine, NaS Battery and Frequency
in Miyakojima Island Mega Solar Demonstration Experimental Facility

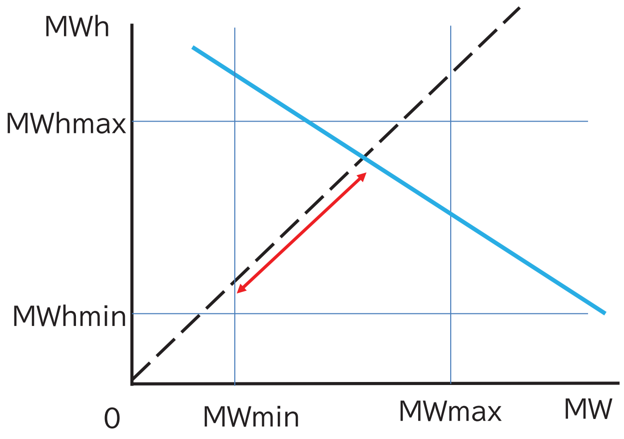


https://www.okiden.co.jp/active/r_and_d/miyako/index.html

Linear Programming Method to determine Battery Capacity

(1) Definition of Capacity
MWh=MW x hour
(2) Range of MW PV output
MWmax>MW>MWmin
(3) Range of MWh PV output
Mwhmax>MWh>Mwhmin
(4) Characteristic of Battery
MWh=-k x MW + a

-> Red Line is available Battery Capacity Area

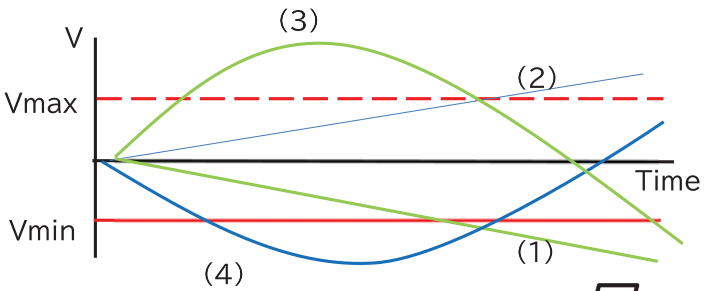


3. Exercise on simple model and Microgrid

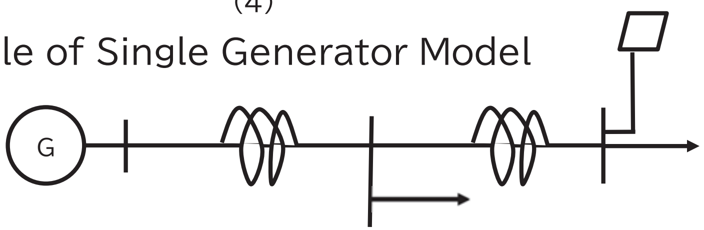
Single Generator with Infinite Bus Model is popular for research and development, and it is used for several application or evaluation.

(1)Fall evenly
(2)Rise evenly
(3)Rise and fall
(4)Fall and rise

Let's exercise!



This is the example of Single Generator Model



Calculation of Per Unit Base Value

This is an example.

<Distribution Grid>

- Vbase=11kV
- (VA)base=100MVA
- Ibase=100/11=9.1kA
- Zbase=Vbase^2/(VA)base=11^2/100=1.21Ω
  - R=0.05Ω/km, X=0.1Ω/km
  - Length =10km
  - Rpu=0.05x10/1.21=0.42
  - Xpu=0.1x10/1.21=0.83
  - Zpu=$\sqrt{0.42*0.42+0.83*0.83}$=0.93 => |Z|=0.93

Calculate impedance in PU from line length, resistance and reactance

Calculate voltage and capacity in PU from base value

Vbase: Base Voltage
(VA)base: Base Apparent Power
Ibase: Base Current
Zbase: Base Impedance
Rbase: Base Resistance, Xbase: Base Reactance
Rpu: Resistance in Per Unit, Xpu: Reactance in Per Unit

Meaning of Per Unit for Power System Analysis

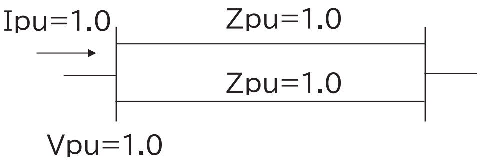
<Meaning of Per Unit>

1pu(|Z|=0.93Ω) impedance transmission line can send 1pu(100MVA) power by 1pu(11kV) voltage. Its current is 1pu(9.1kA).

This will be maximum or rated capacity of transmission line.

If transmission line has 2 circuits, its total impedance will be 0.5pu(0.605Ω), and the maximum capacity will be twice(2pu:200MVA).

Vpu: Voltage in Per Unit
(VA)pu: Base Apparent Power in Per Unit
Ipu: Current in Per Unit
Zpu: Impedance in Per Unit
Rpu: Resistance in Per Unit
Xpu: Reactance in Per Unit



2 Circuit Transmission Line

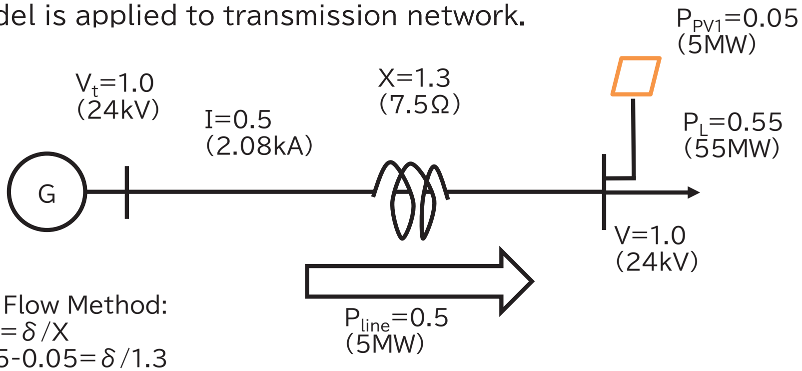
Per Unit Base calculation

- Case A
  - Base VA 100MVA
  - Base Voltage 24kV
  - Base Current 4.16kA (=100/24)
  - Base Impedance 5.76[ohm](=24*24/100)
  - Base Admittance 0.174[1/ohm](=1/5.76)
- Case B
  - Base VA 100kVA
  - Base Voltage 400V
  - Base Current 250A (=100000/400)
  - Base Impedance 1.6[ohm] (=400*400/100000)
  - Base Admittance 0.625[1/ohm](=1/1.6)

Exercise 2 4thREGS_Ex02.xlsm

Case A Grid Model

PU based model is applied to transmission network.



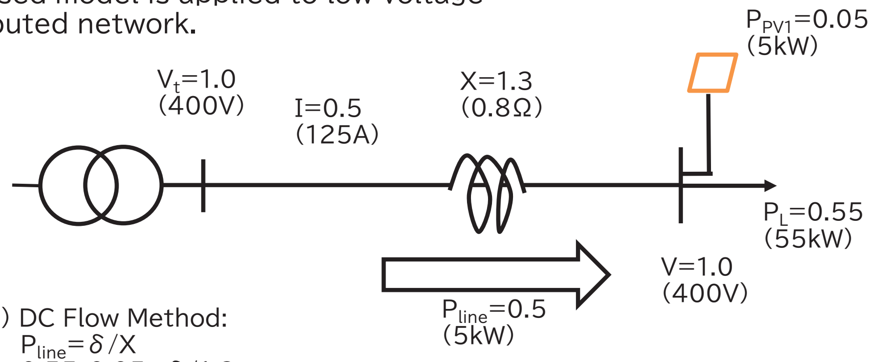
(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
$I=(P_L-P_{PV1})/V=0.5/1.0=0.5=2.08A$

This model can be applied to extend transmission network.

Exercise 2 4thREGS_Ex02.xlsm

Case B Grid Model

PU based model is applied to low voltage distributed network.



(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
I=(PL-PPV1)/V=0.5/1.0=0.5=125A

Exercise 2 4thREGS_Ex02.xlsm

Load Flow Analysis of 4thREGS_Ex02

NodeData

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load			
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	PV	WP	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)
1	2	1					0		0			
2	1	1					0.5		0.55	0.05		

BranchData

Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	1	2			1.3		

Results_Node

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)
1	2	1	1	0	0	0	0.5	0.18467	0.53301	−20.27
2	1	1	1	−40.54	−0.5	0	−0.5	0.18467	0.53301	159.73

Results_Branch

Output Form of Obtained Results for Buses by Singel Stage Power Flow Anlysis									
Branch ID	Connected nodes		Power flow from node-M		Power flow from node-N		Line current		Tap
(Number)	M	N	P (p.u.)	Q(pu)	P(pu)	Q(pu)	I (pu)	Phase aqngel (Degree)	
1	1	2	0.5	0.18467	−0.5	0.18467	0.53301	−20.27	

P-δ Curve and Stability Evaluation

Evaluation step (2)-(5)

(2) Pmax=1*1/1.3=0.77

(3) Pop=0.5

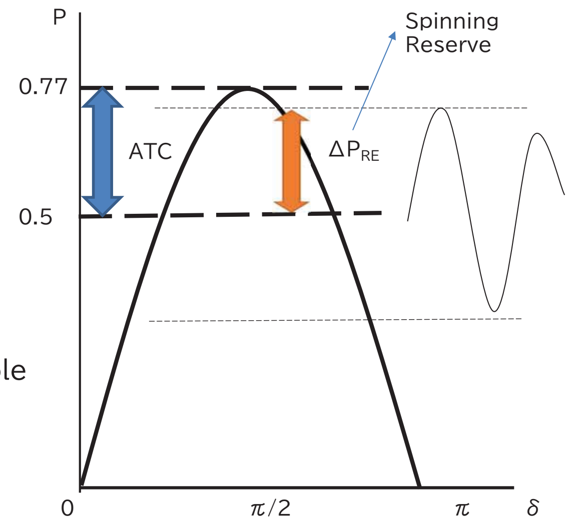
(a) Currently ΔP_{RE}= 0.15
-> Stable

(b) If ΔP_{RE}> 0.27
-> Unstable

SCR=Pop/ΔP_{RE}
should be over 3
=(a) 3.33 -> Stable
=(b) 1.85 -> Unstable

(4) ATC=0.27 -> If ΔP_{RE}> 0.27
-> Unstable

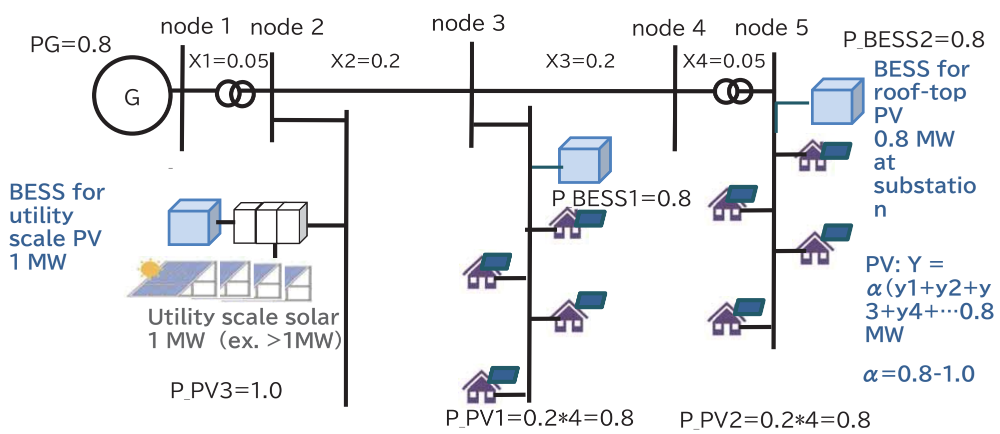
(5) Spinning Reserve should be more than ΔP_{RE}
=0.15



Exercise 3 4thREGS_Ex03.xlsm

Simple Grid Model for RE

To see the effect of Battery and Large PV



X=X1+X2+X3+X4=0.05+0.2+0.2+0.05=0.5

Exercise 3 4thREGS_Ex03.xlsm

Load Flow Analysis of 4thREGS_Ex03

NodeData

Ex03-1

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load			
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	PV	WP	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)
1	2	1			2		0		0			
2		1					0		0			
3		1					1		1			
4		1					0					
5		1					1		1			

Ex03-5

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load			
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	PV	WP	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)
1	2	1			2		0		0			
2		1					0		0	1		1
3		1					1		1	0.8		0.8
4		1					0					
5		1					−3.2		1	5		0.8

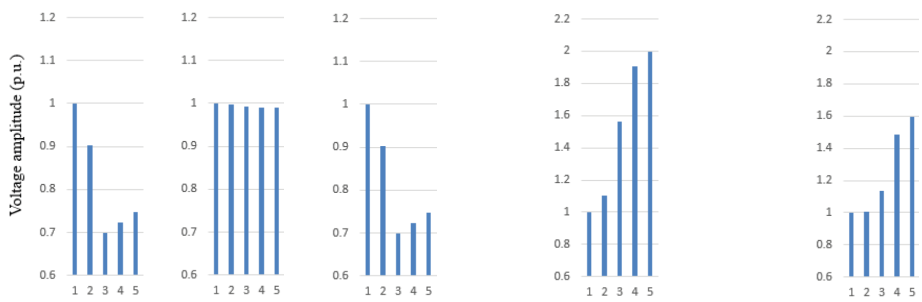
BranchData

Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	1	2			0.05		
2	2	3			0.2		
3	3	4			0.2		
4	4	5			0.05		

Exercise 3 4thREGS_Ex03.xlsm

Load Flow Analysis of Simple Grid -Effect of Battery and Large PV-

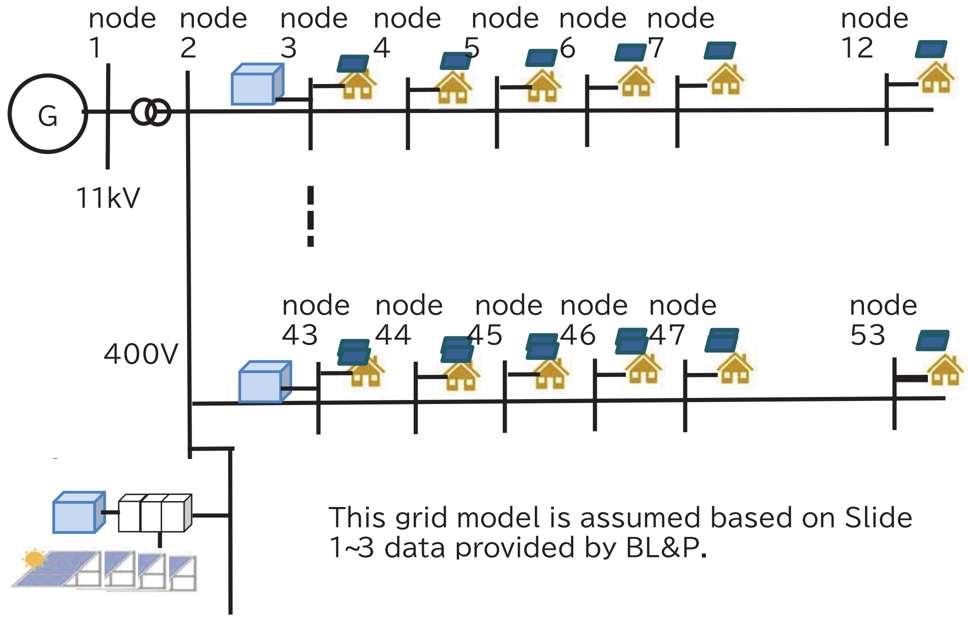
Y axis : P.U. Voltage



- If batteries are connected with no advanced control and output of PV goes zero, node voltage does not change.
- Large PV will cause the increase of node voltages.
- In case PU voltage > 1.1, capacity of distribution line needs to be enhanced.

Exercise 4 4thREGS_Ex04.xlsm

Microgrid Model



This grid model is assumed based on Slide 1~3 data provided by BL&P.

Exercise 4 4thREGS_Ex04.xlsm

Modeling Guide of Microgrid

- Base capacity: 1MW
- Base voltage: 11kV/400V
- Base current: 90A/2.5kA
- Base impedance:122ohm/0.16ohm
- Total load capacity of houses is set to 40.8kW.
- Total PV capacity is set to 30.6kW.
- Node 1 is a distribution substation connected to utility grid by 11kV.
- Node 2 is a power receiving equipment to Coverley Village, where voltage is converted from 11kV to 400V and distributed to houses through 400kV feeder.
- 5 Feeders connect node 2 and every houses.
- A feeder has 10-11 nodes. Each node is connected to 20 houses.
- Maximum load capacity in a house is 4kW/house, and PV capacity is 3kW/house.
- Node 2 has 6MW PV and 6MW BESS.
- BESS is operated as charging mode usually.
- Each house has the same capacity of BESS as PV.

Exercise 4 4thREGS_Ex04.xlsm

Load Flow Analysis of 4thREGS_Ex04

NodeData

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load				
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	Utility PV	Distributed PV	Wind Turbine	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)	(pu)
1	2	1			1		0	0					
2	1	1					−7	0			7		
3	0	1					0.04	0	0.08		0.04		
4	0	1					0.04	0	0.08		0.04		
5	0	1					0.04	0	0.08		0.04		
6	0	1					0.04	0	0.08		0.04		
7	0	1					0.04	0	0.08		0.04		
8	0	1					0.04	0	0.08		0.04		
9	0	1					0.04	0	0.08		0.04		
10	0	1					0.04	0	0.08		0.04		
11	0	1					0.04	0	0.08		0.04		

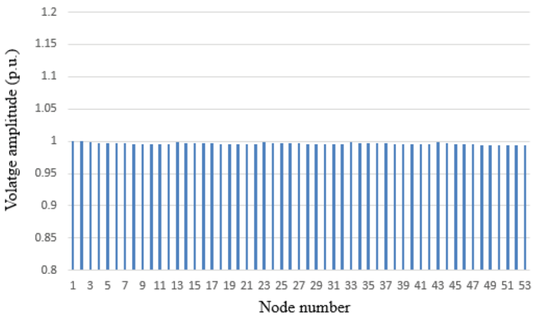
BranchData

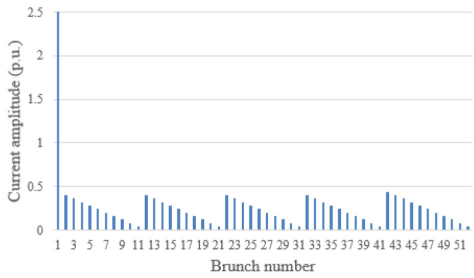
Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
1	1	2	1		0.001		0
2	2	3	1		0.05		0
3	3	4	1		0.05		0
4	4	5	1		0.05		0
5	5	6	1		0.05		0
6	6	7	1		0.05		0
7	7	8	1		0.05		0
8	8	9	1		0.05		0
9	9	10	1		0.05		0
10	10	11	1		0.05		0
11	11	12	1		0.05		0
12	2	13	1		0.05		0
13	13	14	1		0.05		0

Exercise 4 4thREGS_Ex04.xlsm

Load Flow Analysis of Microgrid Model

- Node voltage decrease a little gradually to the end of feeder.
- Line current of feeder is within the rated value except for the distribution line from substation.





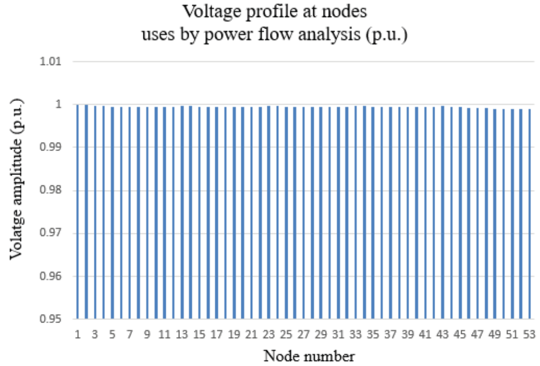
Node Voltage

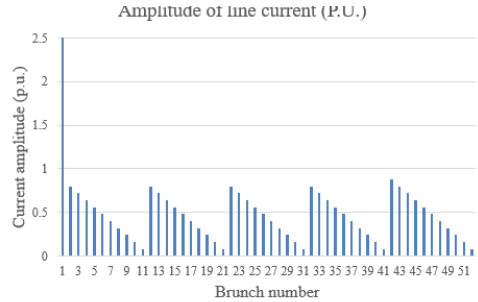
Line Current

Exercise 4 4thREGS_Ex04.xlsm

Load Flow Analysis with charging mode of BESS

- Node voltage decrease a little gradually to the end of feeder.
- Line current of feeder is within the rated value.





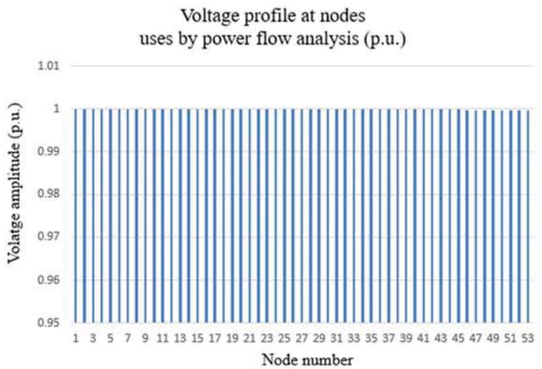
Node Voltage

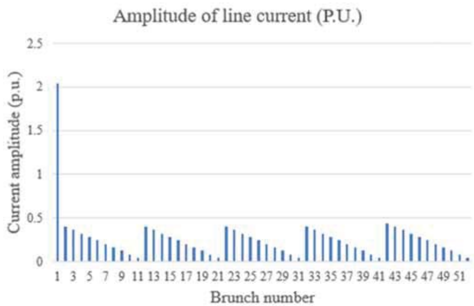
Line Current

Exercise 4 4thREGS_Ex04.xlsm

Load Flow Analysis with discharging mode of BESS

- Node voltage are kept as the rated value and stable.
- Line current of feeder is under its rated value.
- Battery for houses is very effective to keep voltage normal.





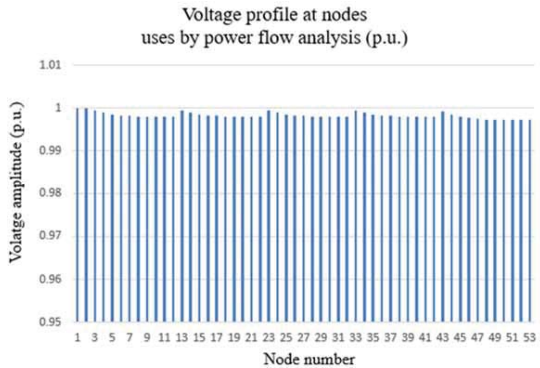
Node Voltage

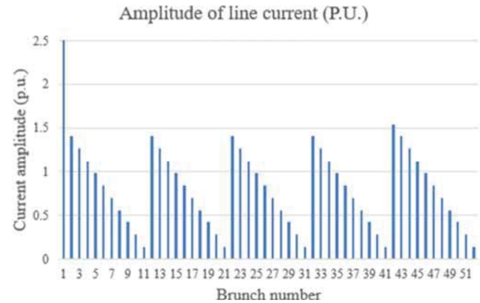
Line Current

Exercise 4 4thREGS_Ex04.xlsm

Load Flow Analysis with no PV and charging mode of BESS

- Node voltage decrease gradually to the end of feeder.
- Line current of feeder exceeds its rated capacity.





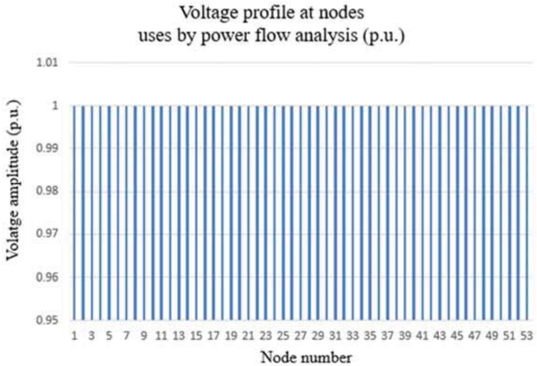
Node Voltage

Line Current

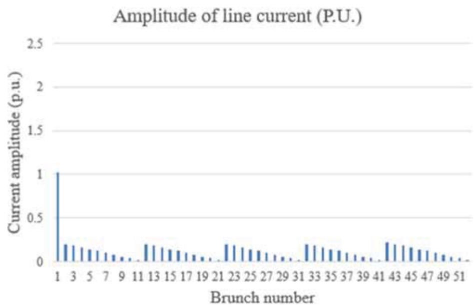
Exercise 4 4thREGS_Ex04.xlsm

Load Flow Analysis with no PV and discharging mode of BESS

- Node voltage are kept as the rated value and stable.
- Line current of feeder is very low.
- Battery for houses is very effective to keep voltage normal even if PV has dropped out.



Node Voltage



Line Current

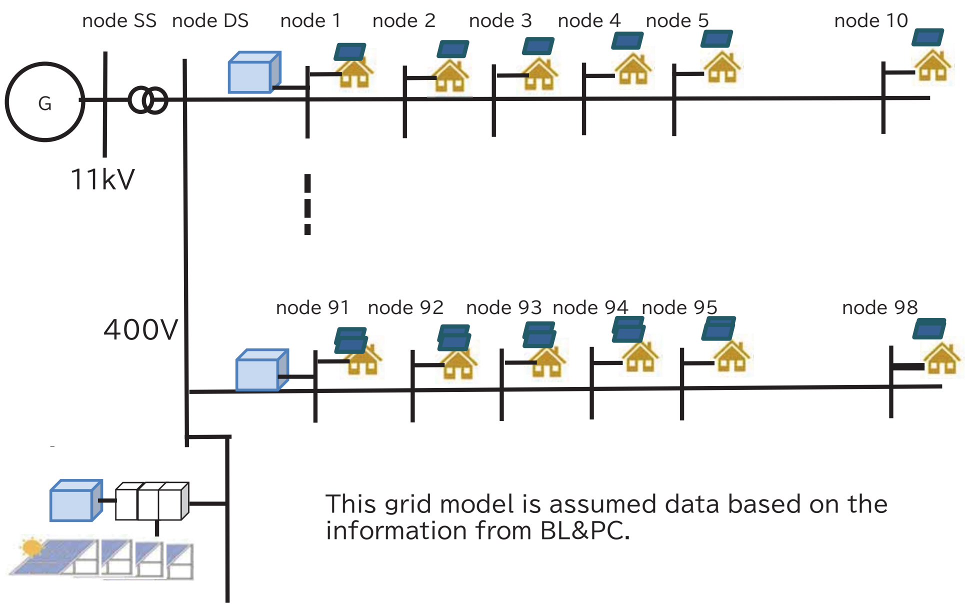
Exercise 4 4thREGS_Ex04.xlsm

Evaluation of Microgrid

- Node voltage decrease at the end of feeder gradually.
- Line current of feeder exceeds its rated capacity, when PV drops out and battery has to charge.
- Battery for houses is very effective to keep voltage normal.

Exercise 5 4thREGS_Ex05.xlsm

100 node Microgrid Model



This grid model is assumed data based on the information from BL&PC.

Exercise 5 4thREGS_Ex05.xlsm

Load Flow Analysis of 4thREGS_Ex04

NodeData

Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load				
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	Utility PV	Distributed PV	Wind Turbine	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(pu)	(pu)	(pu)	(pu)	(pu)
SS	2	1			1		0	0					
DS	1	1					0	0					
1	0	1					0.1	0	0.4		0.3		
2	0	1					0.1	0	0.4		0.3		
3	0	1					0.1	0	0.4		0.3		
4	0	1					0.1	0	0.4		0.3		
5	0	1					0.1	0	0.4		0.3		
6	0	1					0.1	0	0.4		0.3		
7	0	1					0.1	0	0.4		0.3		
8	0	1					0.1	0	0.4		0.3		
9	0	1					0.1	0	0.4		0.3		
10	0	1					0.1	0	0.4		0.3		

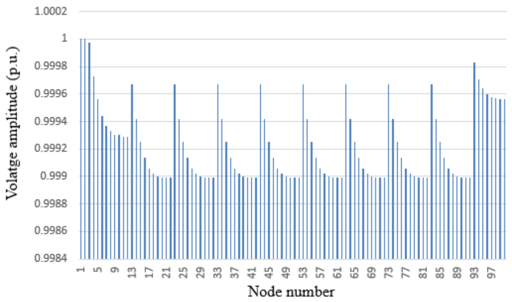
BranchData

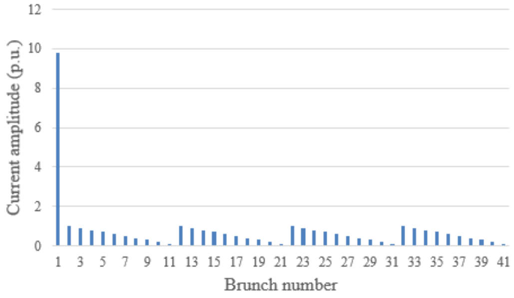
Branch data Input Form for Single Stage Power Flow Analysis							
Branch ID	Sending node	Receiving node	No. of circuits	Resistance R	Reactance X	Admittance Y/2	Tap ratio
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)	default =1	(p.u.)	(p.u.)	(p.u.)	default = 1.0
200	SS	DS	1		0.001		0
201	DS	1	1		0.001		
1	1	2	1		0.01		
2	2	3	1		0.01		0
3	3	4	1		0.01		0
4	4	5	1		0.01		0
5	5	6	1		0.01		0
6	6	7	1		0.01		0
7	7	8	1		0.01		0
8	8	9	1		0.01		0
9	9	10	1		0.01		0
10	DS	11	1		0.01		0
11	11	12	1		0.01		0

Exercise 5 4thREGS_Ex05.xlsm

Load Flow Analysis of Microgrid Model

- Node voltage decrease a little gradually to the end of feeder.
- Line current of feeder is within the rated value except for the distribution line from substation.





Node Voltage

Line Current

4. Exercise on Future Grid

- In order to achieve sustainable future grid for St. Kitts and Nevis, it needs to consider, check, evaluate and prepare the plan with sufficient stability with renewable energy for future grid.
- The data used in this seminar is a sample for demonstration for training purpose, not prepared for actual implementation plan.
- The objective of the Day-2 is to introduce and show some tools to evaluate the grid.
- If you have any case scenarios to be solved, please try to input and solve load flow analysis program.

Plan of Exercise in Day-2

- Current data of St. Kitts and modification
- Current data of Nevis and modification
- Interconnection of grid between St. Kitts and Nevis, and its modification

- Data for future upgrade of St. Kitts (66kV, assumed by JET)
- Data for future upgrade of Nevis (66kV, assumed by JET)
- Interconnection data of grid between St. Kitts and Nevis (66kV, assumed by JET)

- Other exercises based on your suggestion

Preparation of Load Flow Data in St. Kitts & Nevis

	Actual Data	Planned Data	Assumed Data
Current Grid of St. Kitts	Line Impedance	Generation capacity	Load Battery
Current data of Nevis	Line Impedance	Generation capacity	Load Battery
Combined Grid of St. Kitts & Nevis	Line Impedance	Generation capacity	Load Battery
Future data of St. Kitts	Google Map	Generation Capacity	Line Impedance Load, Battery
Future data of St. Kitts	Google Map	Generation Capacity	Line Impedance Load, Battery
Combined Future Grid of St. Kitts & Nevis	Google Map	Generation Capacity	Line Impedance Load, Battery

Current and Future Grid of St. Kitts & Nevis considered in Load Flow Analysis

Name in ( ) shows the node name in Grid Map of PSS/E base data for St. Kitts and ETAP data for Nevis.

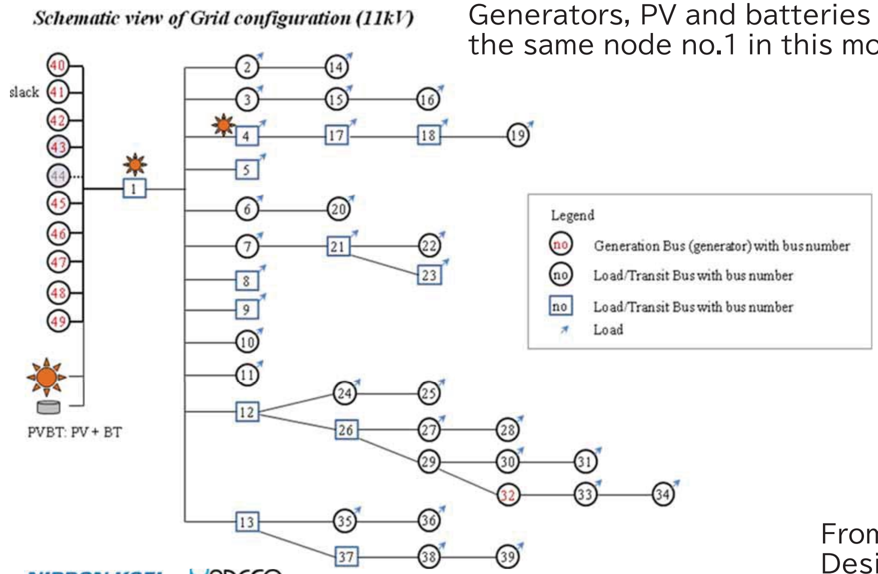
<Current>
- Voltage: 11kV
- Capacity: St.Kitts 25MW, Nevis 10MW
- Installed PV: 0.7+0.5MW in St. Kitts (1)
- Installed WT: 2.2MW in Nevis (CG06)

<Future Plan>
- Voltage of main transmission line will be up: 66kV
- Capacity of PV: 35MW in St. Kitts (16, 25)
- Capacity of WT: 5.7MW in St. Kitts (34), 50MW in Nevis (GG04)
- Geothermal Power Plant: 30MW -> 45MW -> 60-75MW (CG05)

Exercise 6 4thREGS_Ex06_StKitts_44_2020.xlsm
Exercise 7 4thREGS_Ex07_StKitts_44_2022_RE.xlsm

Modeling of St. Kitts Grid

Generators, PV and batteries are located at the same node no.1 in this model.



From Microgrid Designer

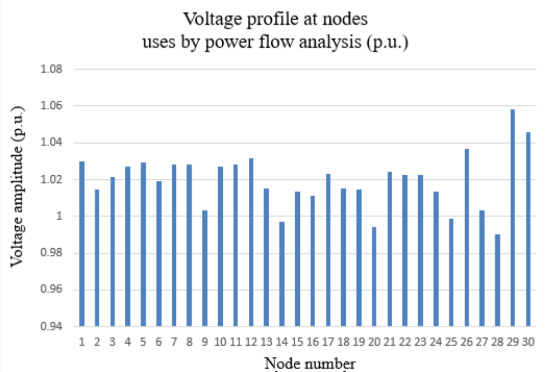
Exercise 6 4thREGS_Ex06_StKitts_44_2020.xlsm

Result of Load Flow Analysis of St. Kitts using Microgrid Designer

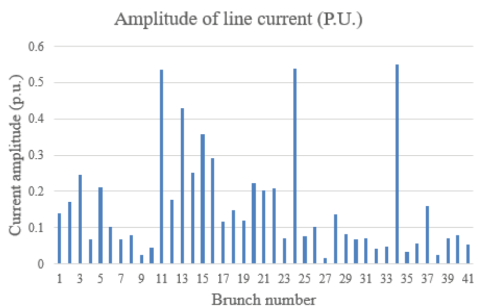
Capacity limit of equipment can be evaluated by load flow analysis.

Data prepared in PSS/E format was provided from SKELEC in and converted to input Microgrid Designer.

→ Voltages of node no. 29 and 30 are 5~6% over from the rated value. This is not a problem.
→ Line currents result fall within the rated values.



Node Voltage



Line Current

Calculated by Microgrid Designer

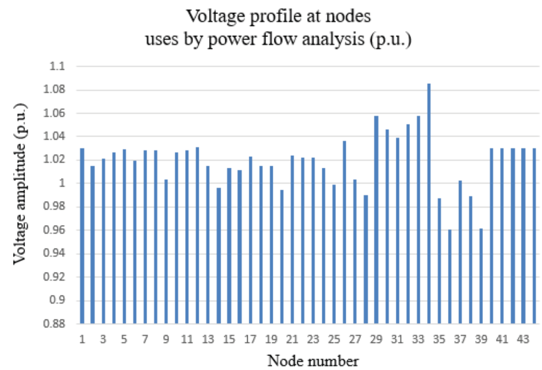
Exercise 7 4thREGS_Ex07_StKitts_44_2022_RE.xlsm

Result of Load Flow Analysis of St. Kitts with Wind Power using Microgrid Designer

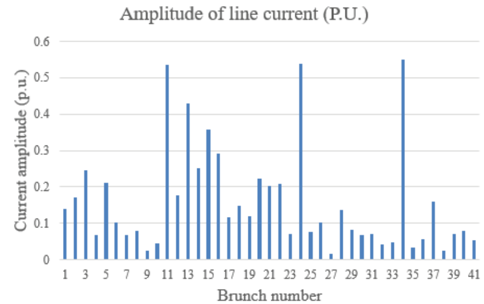
Capacity limit of equipment can be evaluated by load flow analysis.

Data prepared in PSS/E format was provided from SKELEC in and converted to input Microgrid Designer.

→ Line currents result fall within the rated values.

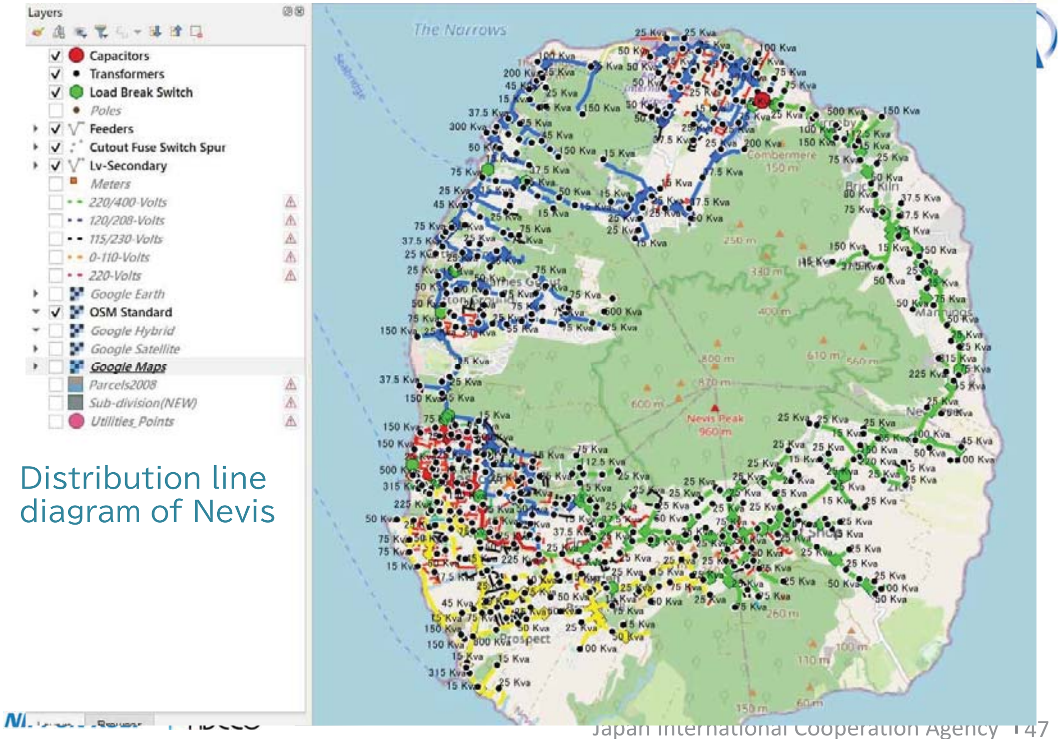


Node Voltage



Line Current

Calculated by Microgrid Designer

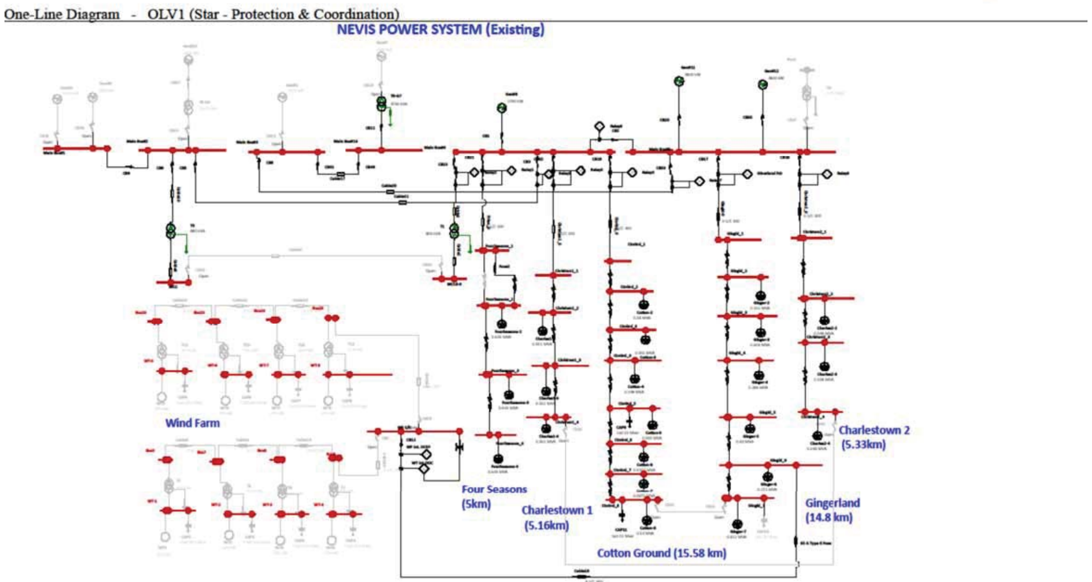


Distribution line diagram of Nevis

Distribution line diagram of Nevis

Exercise 8 4thREGS_Ex08_Nevis_29_2022.xlsm

Grid Model of Nevis



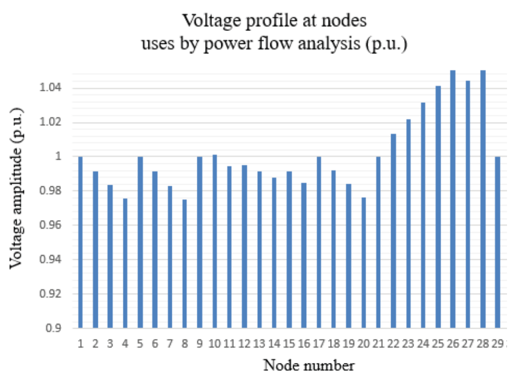
Exercise 8 4thREGS_Ex08_Nevis_29_2022.xlsm

Result of Load Flow Analysis of Nevis using Microgrid Designer

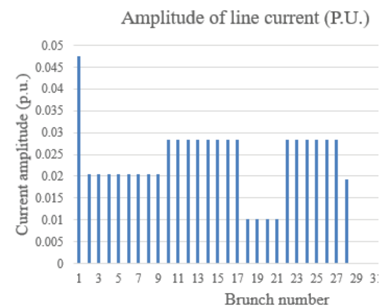
Capacity limit of equipment can be evaluated by load flow analysis.

Data prepared in ETAP format was provided from NEVLEC in and converted to input Microgrid Designer.

→ Line currents result fall within the rated values.



Node Voltage



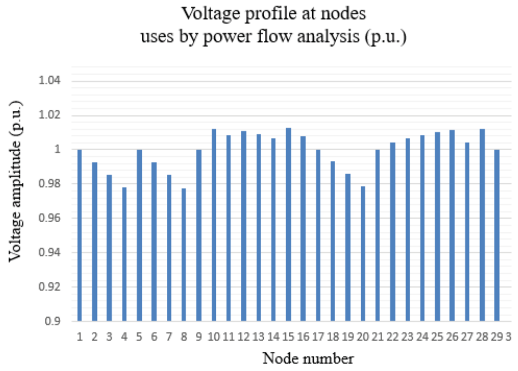
Line Current

Calculated by Microgrid Designer

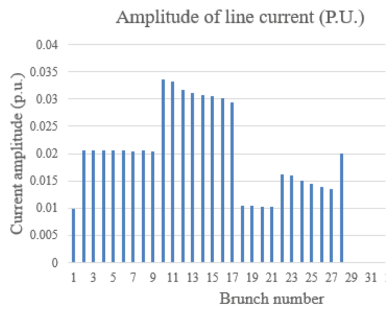
Exercise 8 4thREGS_Ex08_Nevis_29_2022.xlsm

Result of Load Flow Analysis of Nevis using Microgrid Designer

Data prepared in ETAP format was provided from NEVLEC in and converted to input Microgrid Designer.



Node Voltage



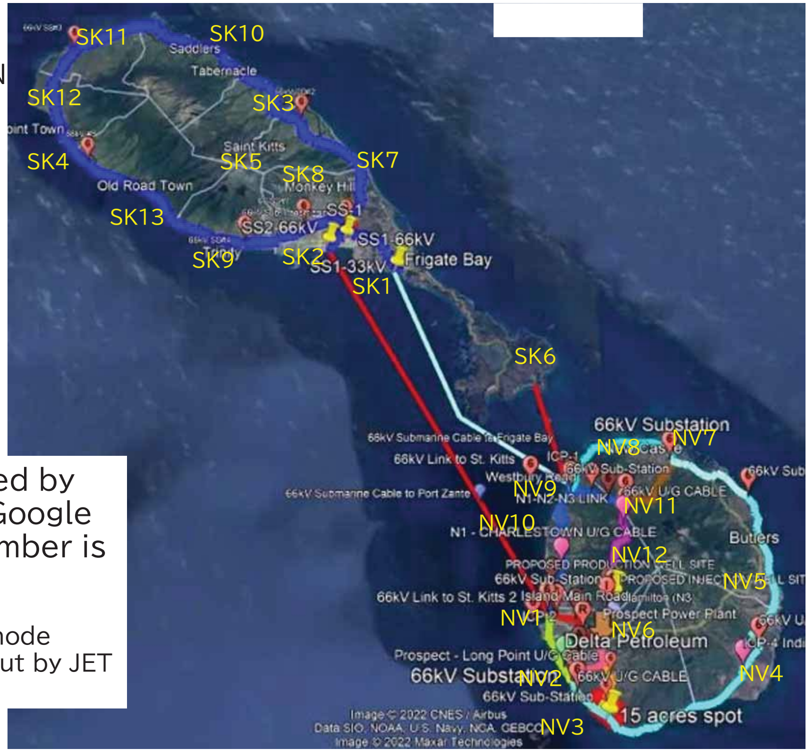
Line Current

Exercise 9

4thREGS_Ex09_StKN_25_Future.xlsm

St. Kitts & Nevis Future Grid

Data is assumed from Google Earth KML file provided from NEVLEC. Both network of St. Kitts and Nevis are connected by 11kV and 66kV transmission line.



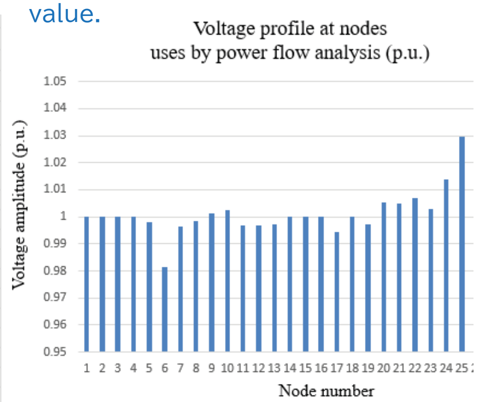
Source: Prepared by NEVLEC using Google Earth. Node Number is added by JET.

"SK" and "NV" are node number randomly put by JET for grid analysis.

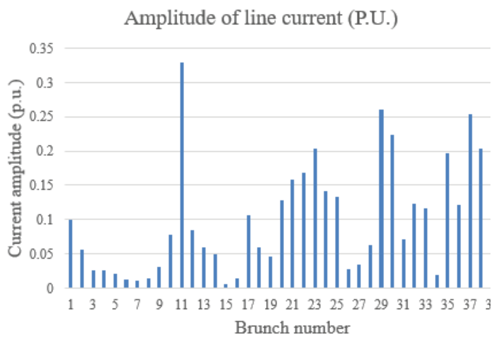
Exercise 9 4thREGS_Ex09_StKN_25_Future.xlsm

Load Flow Analysis in Microgrid Designer for Future Grid of St. Kitts & Nevis based on assumed Future Plan

With the scenario case of future grid plan of St. Kitts & Nevis, the results show that node voltages are within appropriate range, and line current is under rated value.



Node Voltages

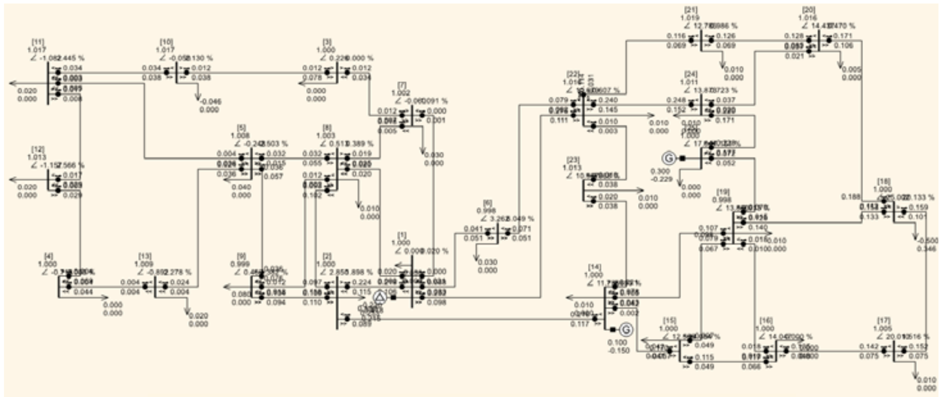


Line Current

Calculated by Microgrid Designer

Example of Modeling of Grid of St. Kitts & Nevis in CPAT Software

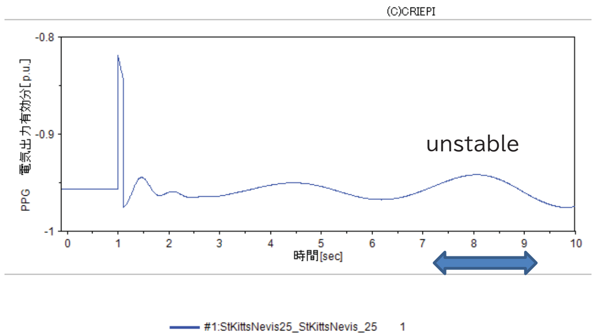
The Load flow analysis and transient analysis is conducted for trial to confirm the stability of the future St. Kitts and Nevis grid using a software "CPATFree"



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Result of Transient Stability Analysis with CPAT for Future Grid of St. Kitts & Nevis

Transient stability analysis is necessary to evaluate fluctuation of PV.
Transient stability analysis is required to prepare plan and design of transmission line.



The transient stability in the case that PV in SK4 in St. Kitts is disconnected for 100 milliseconds was simulated.
As the result, the system seems to be stable at first. But the oscillation is going to be larger, which is considered to be unstable. Some measurement is required to make system stable. By transient stability analysis, you can find a stability problem.

5. Result of Load Flow Analysis and Countermeasure of Grid Stability

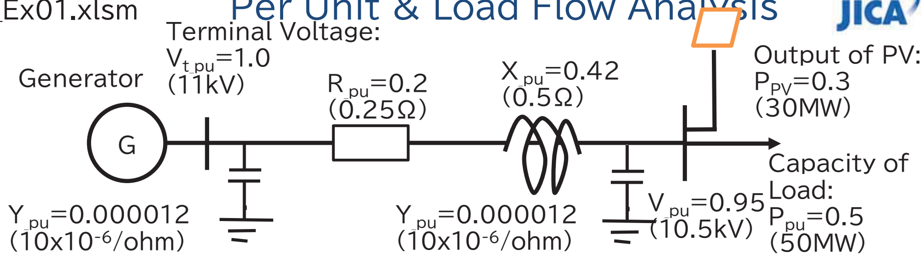
- In St. Kitts and Nevis, conventional generator plants are concentrated at one or a few areas.
- PV and WT are located or planned to suburbs.
- Voltage of distribution lines which are connected to PV or WT should be higher voltage, because of less capacity and fluctuation of voltage.
- If load in the middle of line is large, its voltage will be low. Measurement such as hunt capacitor or var compensator is necessary.
- Installation of Grid Forming Inverter for PV and WT is useful.
- At lease smart inverter shich has dynamic Voltage Support function will be required for keeping grid stable.
- The voltage level should be increased to 66kV earlier.

Exercise 1

4th Seminar on Grid Stability and Large RE Day-2

4thREGS_Ex01.xlsm

Per Unit & Load Flow Analysis



(1) Calculate base value of capacity, voltage, current, impedance and admittance
- (1) Vbase=11kV
- (2) (VA)base=100MVA
- (3) Ibase=100/11=9.1kA
- (4) Zbase=Vbase2/(VA)base=112/100=1.2 ohm
- (5) Ybase=1/Zbase=1/1.21=0.83 1/ohm

(2) Calculate distribution line impedance and node admittance
- (1) {0.05[ohm/km] +j0.1[ohm/km]}*5[km]=0.25[ohm]+j0.5[ohm]
- (2) $R_{pu}+jX_{pu}$=(0.25[ohm]+j0.55[ohm])/1.2[ohm]=0.20+j0.42
- (3) {0[1/ohm/km]+j0.00001[1/ohm/km]}+5[km]~0+j0.00005
- (4) $G_{pu}+jB_{pu}$=(0[1/ohm]+j0.00005[1/ohm])/0.83[1/ohm]=0+j0.000012

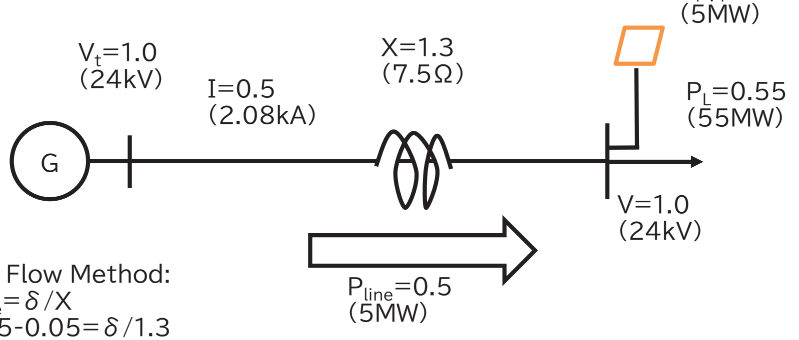
(3) Calculate generation capacity and load capacity
- (1) P_{pu}=50[MW]/100 [MVA]=0.5, P_{PV}=30[MW]/100 [MVA]=0.3

Please prepare to change your data to Per Unit value.

Exercise 2 4thREGS_Ex02.xlsm

Case A Grid Model

PU based model is applied to transmission network.



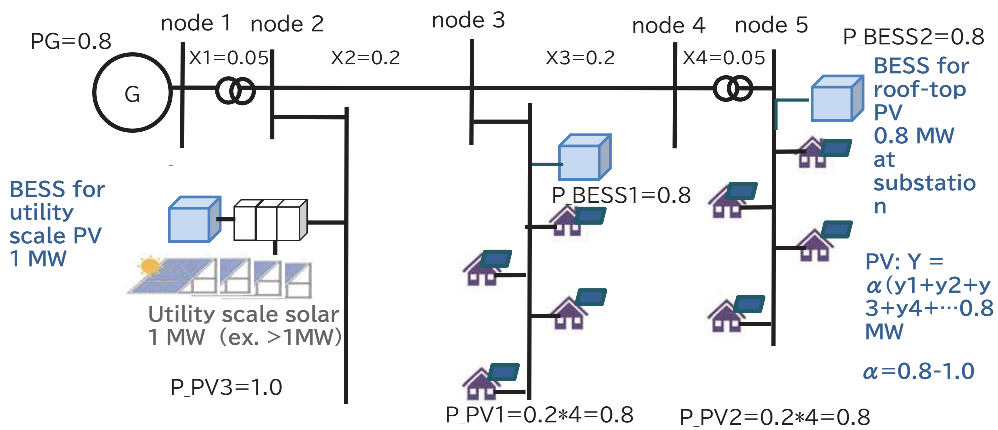
(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
$I=(P_L-P_{PV1})/V$=0.5/1.0=0.5=2.08A

This model can be applied to extend transmission network.

Exercise 3 4thREGS_Ex03.xlsm

Simple Grid Model for RE

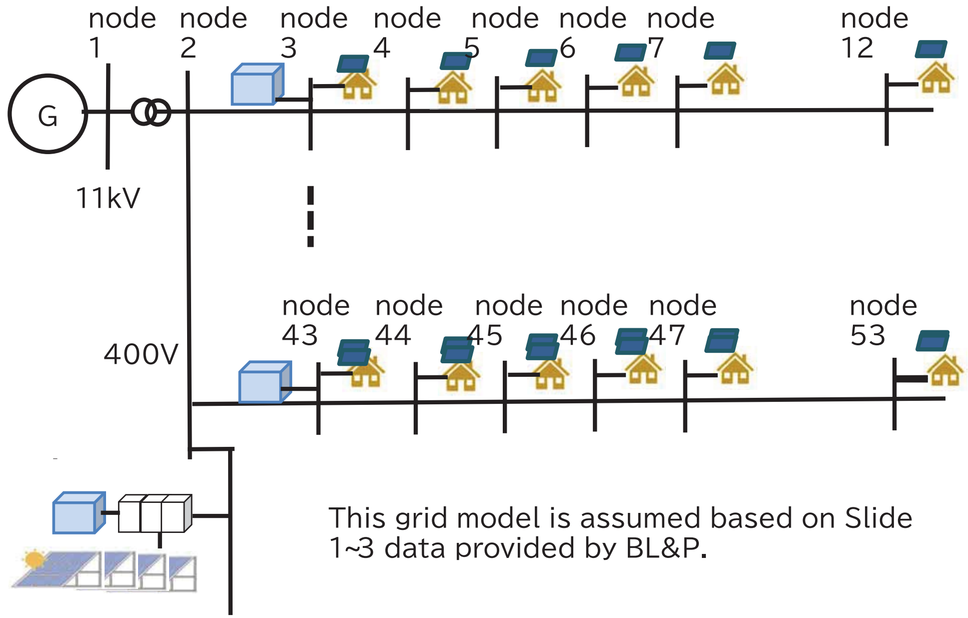
To see the effect of Battery and Large PV



X=X1+X2+X3+X4=0.05+0.2+0.2+0.05=0.5

Exercise 4 4thREGS_Ex04.xlsm

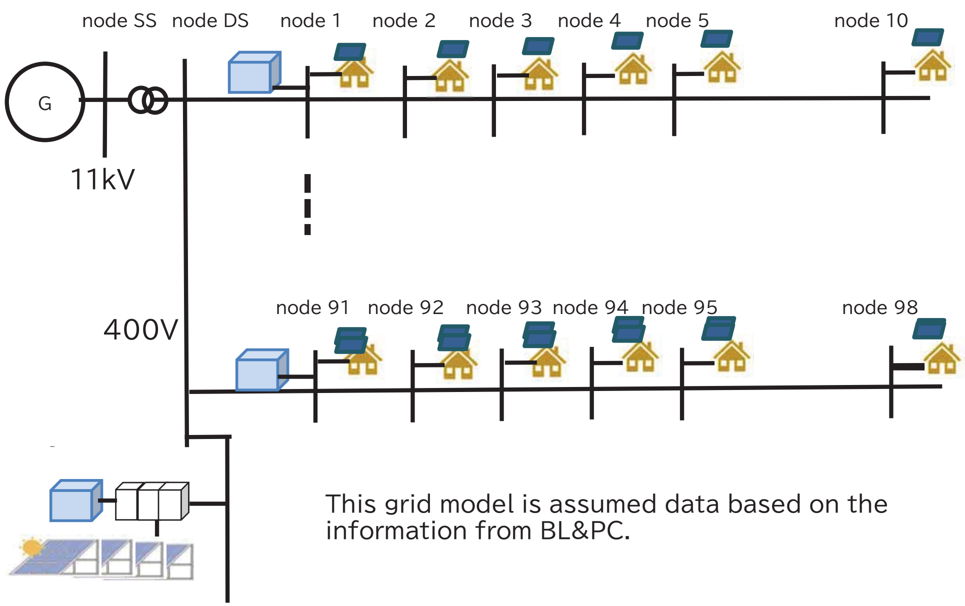
Microgrid Model



This grid model is assumed based on Slide 1~3 data provided by BL&P.

Exercise 5 4thREGS_Ex05.xlsm

100 node Microgrid Model



This grid model is assumed data based on the information from BL&PC.

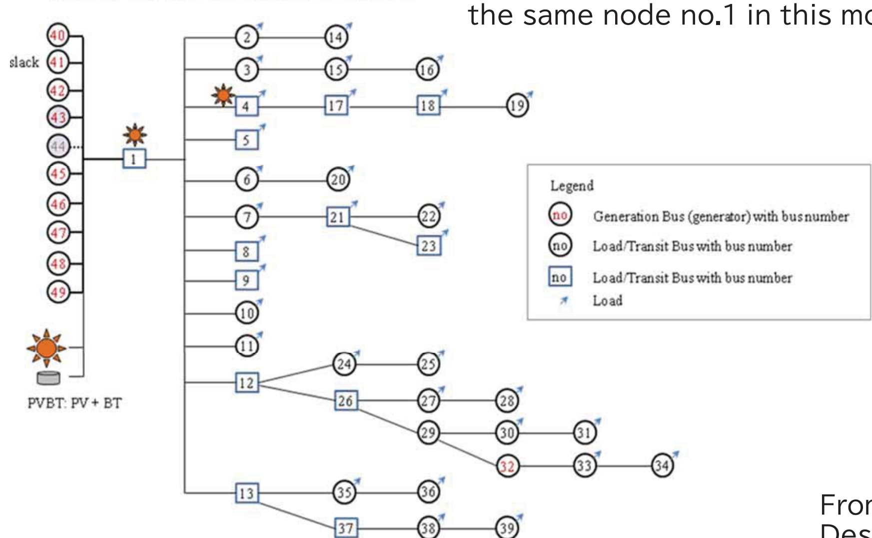
Exercise 6 4thREGS_Ex06_StKitts_44_2020.xlsm

Exercise 7 4thREGS_Ex07_StKitts_44_2022_RE.xlsm

Modeling of St. Kitts Grid

Generators, PV and batteries are located at the same node no.1 in this model.

Schematic view of Grid configuration (11kV)

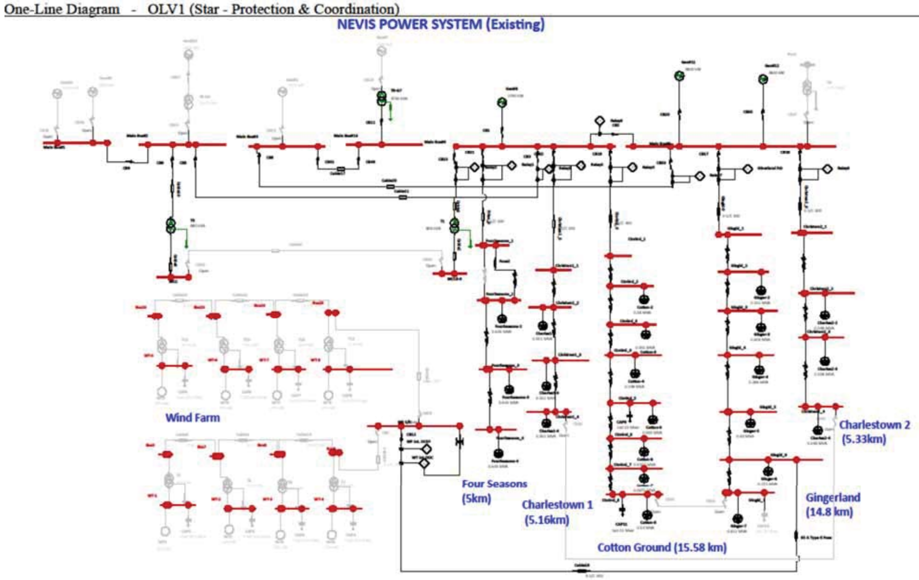


From Microgrid Designer

Exercise 8 4thREGS_Ex08_Nevis_29_2022.xlsm

Grid Model of Nevis

One-Line Diagram - OLV1 (Star - Protection & Coordination)

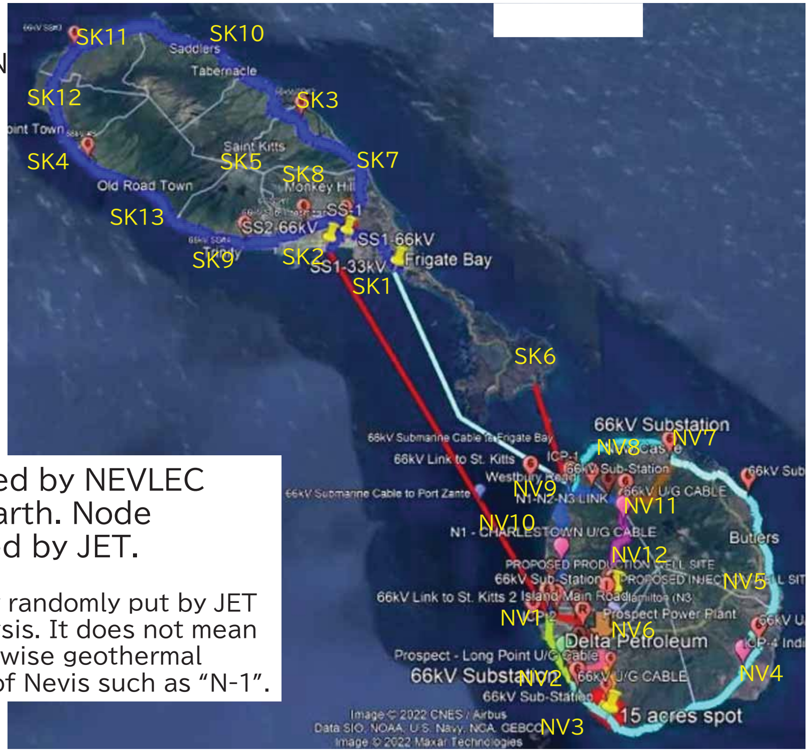


Exercise 9

4thREGS_Ex09_StKN_25_Future.xlsm

St. Kitts & Nevis Future Grid

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



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

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

NIPPON KOEI PADECO

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-2)

1. Introduction of Microgrid Designer and Transient Analysis - Role of Tools for Power System Analysis, - Load Flow Analysis
   - Transient Stability Analysis for Operation and Control
2. Investment of MW and MWh of Energy Storage for VRE
3. Exercise on simple grid example and Microgrid
   - Load Flow Analysis, - Transient Stability Analysis
4. Exercise on Future Grid
   - Design and Operation Planning
   - Load Flow Analysis, - Transient Stability Analysis
5. Analysis Result and Countermeasure of Grid Stability
6. **Discussion, policy recommendation, and Way Forward**
7. Conclusion and Closing Remarks

NIPPON KOEI PADECO

Discussion for policy

Q from JET	Feedback	Remark
What is the most challenging for achieving 100% RE?	- Grid stability by storage and spinning reserves - Technology availability at appropriate cost, Cost of implementation. - The use of IPP result in an increase cost of energy to the consumers. - Control of grid voltages &frequencies - Who will bear the responsibility for grid stability	- GFM with appropriate amount of BESS might be lease cost once it becomes available. - Cost sharing by Grid stability will be needed
What is necessary for grid stability?	- Batteries, grid forming inverters, SCO, demand response, microgrid integration, bi-directional relays and control - Inverters that provide reactive power. - Wind and solar forecasting based on measurement of solar and wind - Include pumped storage, Hydrogen - SCO by utility. GFM can be part of the solution once it become commercially available. - to create multiple micro grids which can interconnect	
How much sec/min/hrs of interruption per day or per year do you assume it is acceptable when 100%RE is established?	- The standards should be kept, 2 interruptions/yr, 1hr per year (Barbados) - 1 to 1.5 hours per year - better than 24 hours per year. - Interruptions should not exceed 1 week (168hrs) per year.	- RE mix of PV and wind will increase outages - To decrease outage, investment cost such as battery for longer days will be necessary

Discussion for policy (2)

Q from JET	Feedback	Remark
For achieving RE target 100% with grid stability, who and how to cover the cost?	- IPP producer should install stability measurement and should have the responsibility of minimizing the impact - Special selling rates should be given IPPs who invest in RE with control & stabilizing - It will be picked up by the consumers, as whoever pays it will need to pass it on to consumers. Incentive to minimize is necessary. - The feed in tariff rate has to be increased - Subsidy by government - The cost of grid stability will have to be shared between the utility, IPPs &customers.	It will be needed to be shared by IPP, utility, consumer, and government. For government, external financing opportunity can be considered
Please provide Additional suggestion for seminar	- incentive/tariffs for other types of grid improvement beyond the storage - Weather prediction (LIDAR/satellite/etc; 15 min. ahead) required, along with microgrids,	- Demand side management - Weather prediction system installation

Recommendation for Future RE and Grid Plan

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