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

	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 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

Jul-22 Aug Sep Oct Nov Dec Jan-23 Feb Mar

Month	7	7	7	7	8	8	8	8	8	9	9	9	9	10	10	10	10	10	11
Date	4	11	18	25	1	8	15	22	29	5	12	19	26	3	10	17	24	31	7
EE Team										KN	B							B	KN
RE Team				B										B	KN	J			
											*1								
Note	Hurricane Season																		

Month	11	11	11	12	12	12	12	1	1	1	1	1	2	2	2	2	3	3	3
Date	14	21	28	5	12	19	26	2	9	16	23	30	6	13	20	27	6	13	20
EE Team	J								B	KN	J					*	*		
RE Team		J	B	KN					J	B	KN					*	*		
Note				Christmas Season								Training in Japan							

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]

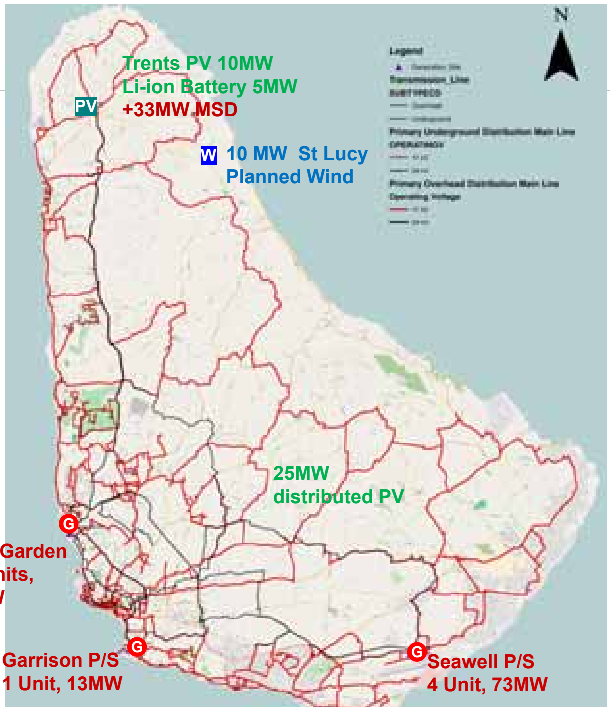
Possibility of training in Japan depends on COVID-19 situation. It might be shifted to Apr 2023.

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



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

Barbados Grid and PS

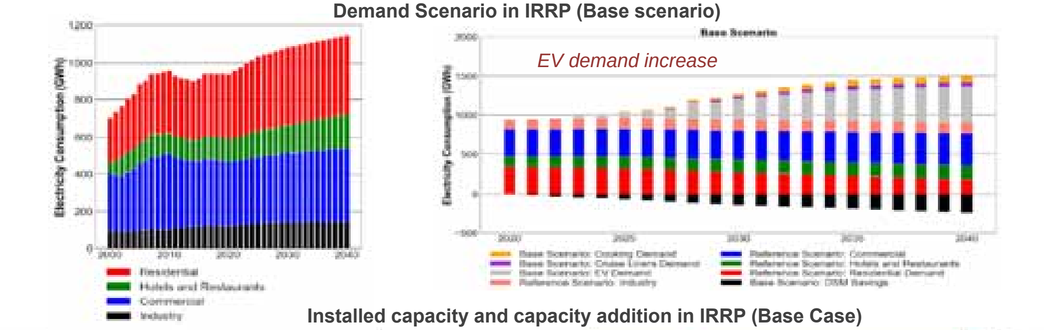
Location	MW/u	Qy	MW	Remark
Existing				
Total thermal power			232	
Spring Field	12	3	36	LSD Engine
Spring Field	12.5	1	12.5	LSD Engine
Spring Field	30	2	60	LSD Engine
Spring Field	20	2	40	Steam Turbine
Spring Field	17.5	1	17.5	Gas Tubine
Spring Field Total		9	166	
Garrison	13	1	13	Gas Tubine
Seawell	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.

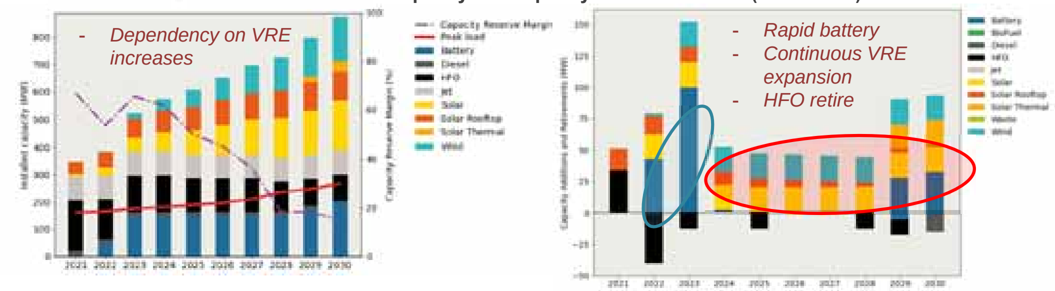
Barbados Demand&Installed capacity in IRRP

Source: IRRP Draft 2021, MottMacDonald

Demand Scenario in IRRP (Base scenario)



Installed capacity and capacity addition in IRRP (Base Case)



2. Baseline Survey Report- Summary

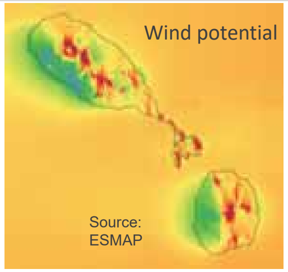
Summary (St Kits and Nevis)

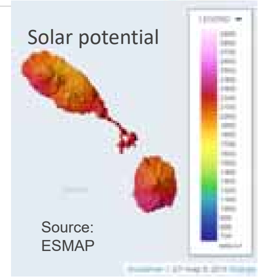
Fields	Findings	Project Activity
Energy Efficiency	• Energy Source: Electricity (63%) , Oil (37%) • Load Curve: Bactrian camel type • Annual Peak Demand: about 25MW (St. Kitts) about 10MW or more (Nevis) • Peak Period: around 11am, 6pm-8pm (St. Kitts) around 12am, 6pm-8pm (Nevis)	Priority 1: Optimized 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

2. Baseline Survey Report- Summary

Summary: Jamaica

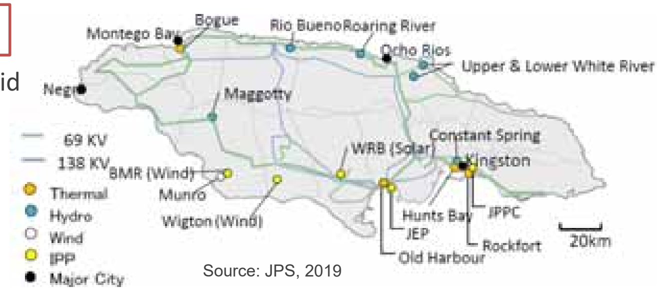
*1 JPS Annual Report 2021 *2 IRP Feb 2020
*3 Interview to JPS *4 Transmission Code

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

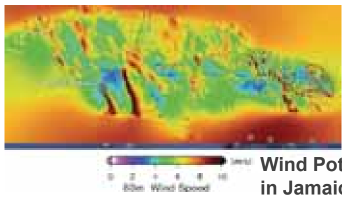
RE Status in Jamaica

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



Wind Potential in Jamaica

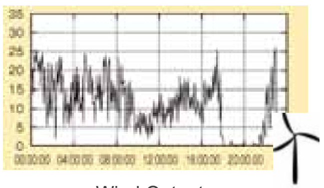
Source: Sustainable Energy Roadmap 2013

VRE Projects in Jamica

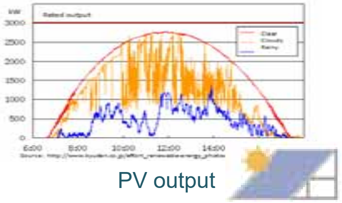
Location/Project		Capacity MW	Generation GWh estimated	Year	Tariff USc/kWh	Investment mil USD
Wigton I	Wind	20.7	52	2004	10.21	26
Wigton II	Wind	18	47	2010	10.723	45
Wigton III	Wind	24	63	2016	13.4	46.5
Munro	Wind	3	10.5	2010	(JPS)	
BMR Wind	Wind	36.3	120	2016	12.9	90
Content Solar (WRB)	PV	20	34	2016	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: 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

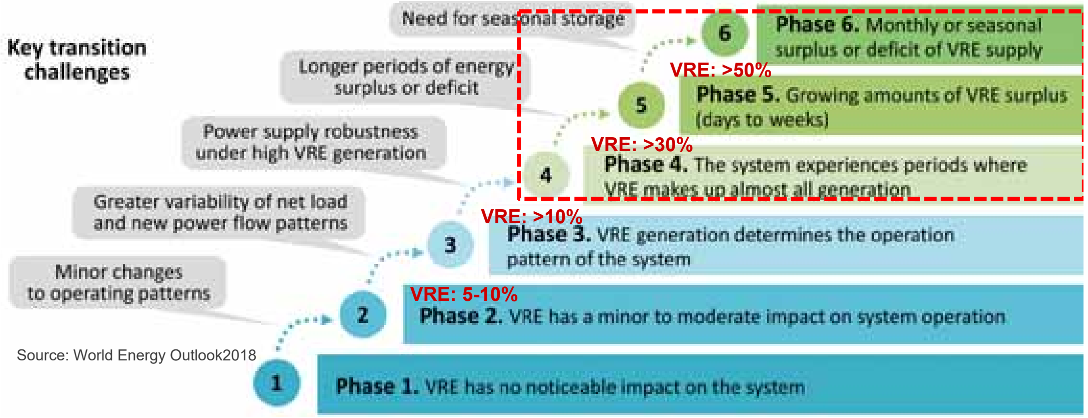
PV
- No output in night-time and rainy day
- Large fluctuation in tropical climate (likely to change 80% in a minute)

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

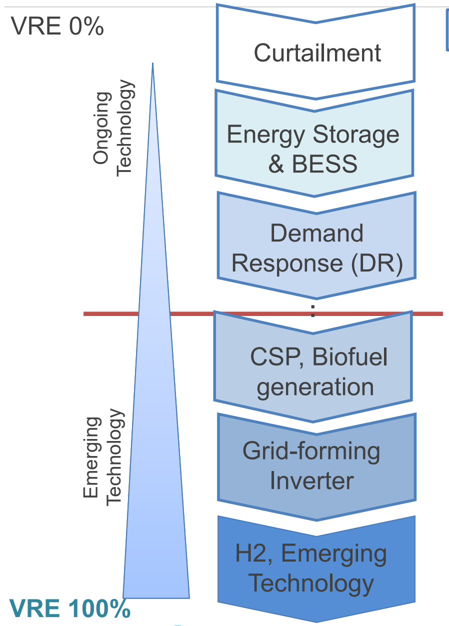
Transition Changes of RE Penetration



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

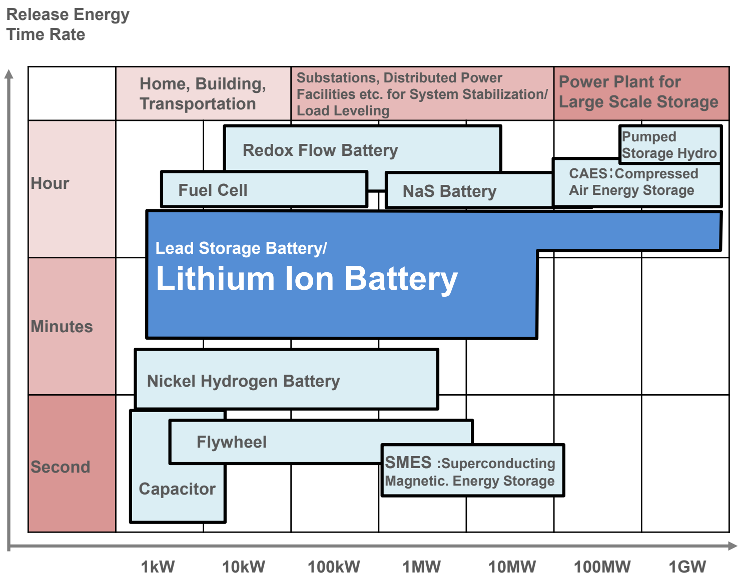


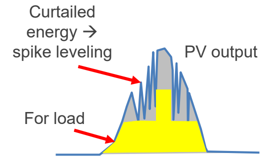
Voltage and frequency Stabilization
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- EV charging time shift
- Demand side management
- Regulatory framework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

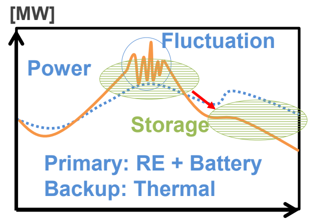
Insufficient Inertia, Synchronizing Force
- **Synchronous condenser, Statcom**
- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale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

Battery and Energy Storage

Positioning for Energy Storage Technology



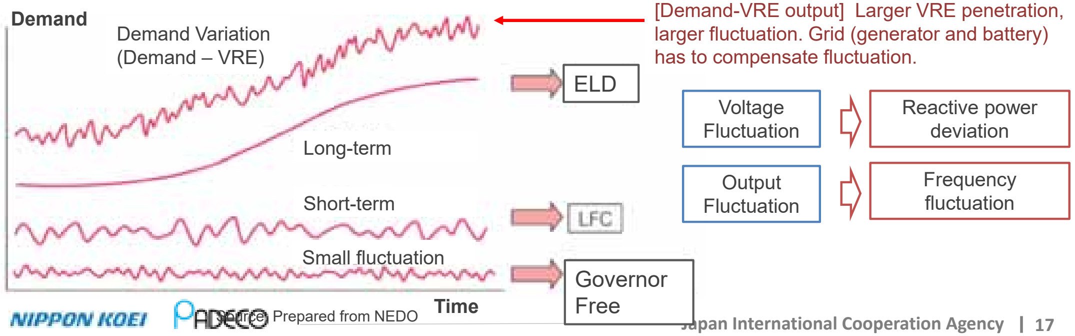




Source: NEDO Renewable Energy Technology White Paper Chapter 9

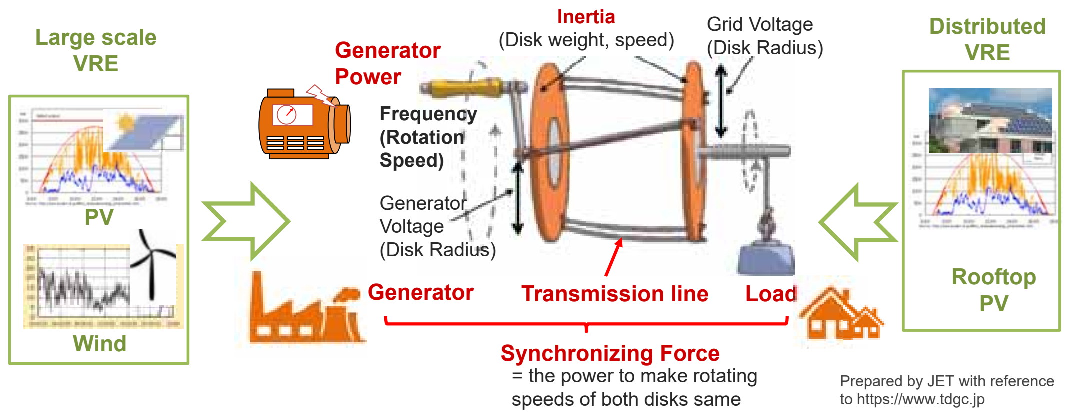
Grid Stabilization: GF, LFC, ELD

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



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 transmission line.

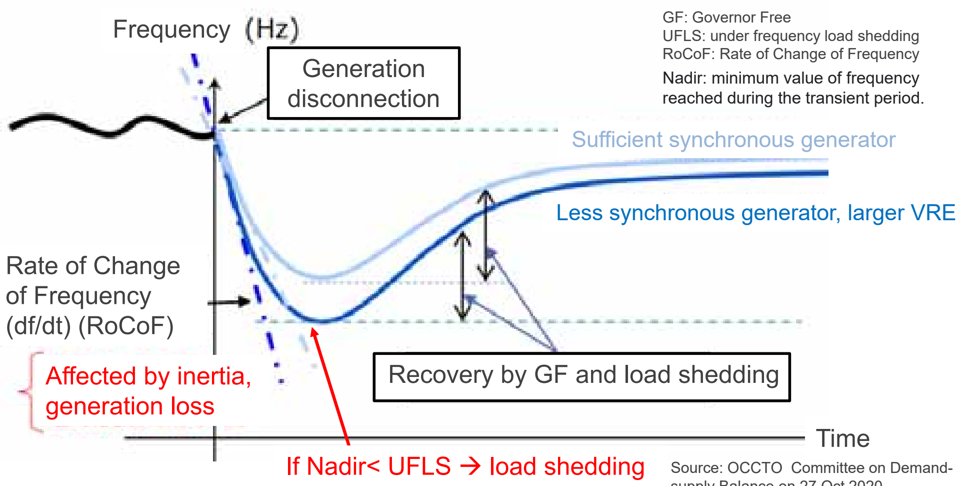
Fluctuation of large scale VRE affects to generator at generation side and load side

→ 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

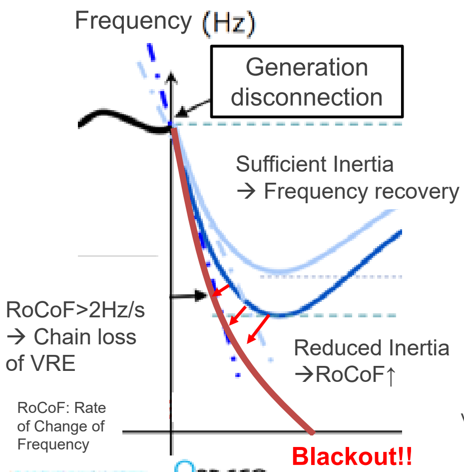
Black-out when insufficient Sync. Gen.

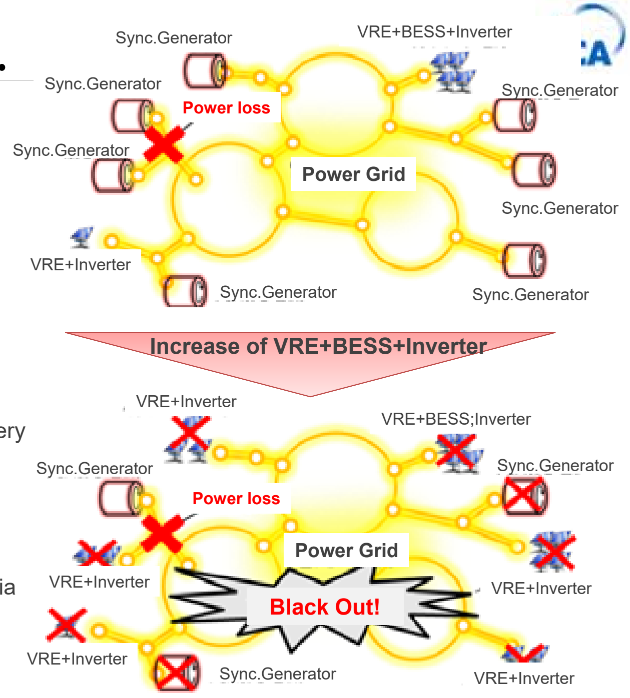
If synchronous generator is reduced and inertial is not sufficient, power loss

→ Frequency drop, with no recovery

→ Chain reaction of loss of VRE

→ **Black out**



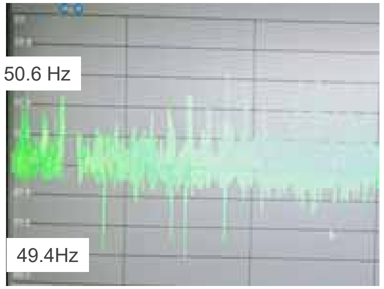


Source: Transmission and Grid Council, Japan

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?

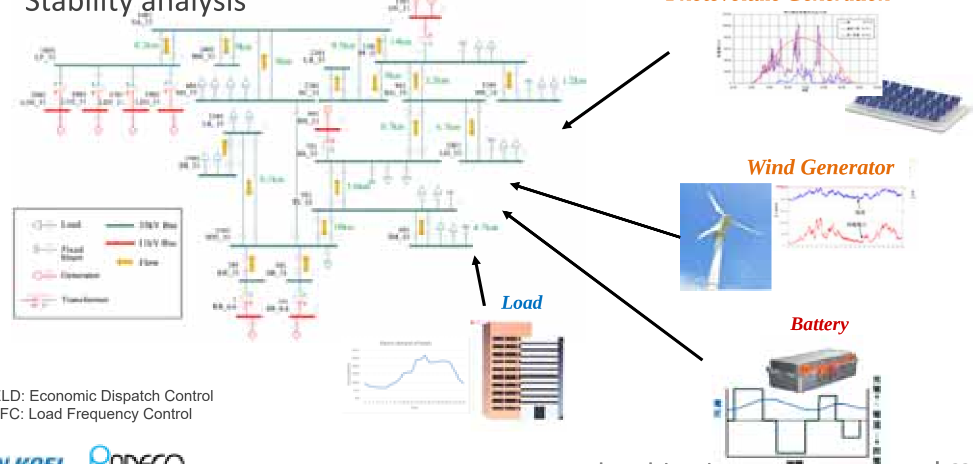
- Planning with **grid simulation** is necessary.
  - Load flow analysis
  - Stability analysis
- Grid code needs to be checked for condition of grid connection of VRE and BESS



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

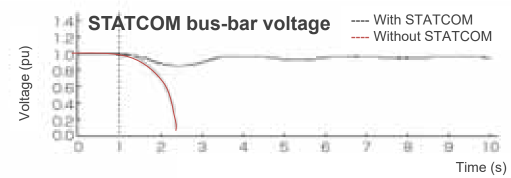
SCO (Synchronous Condenser) :

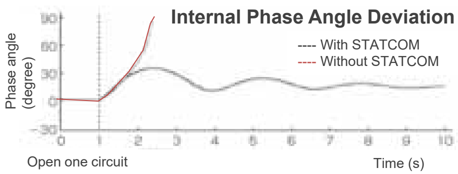
SCO is DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. Though changing field excitation, SCO adjusts reactive power and provides reactive power at the time of voltage drop.

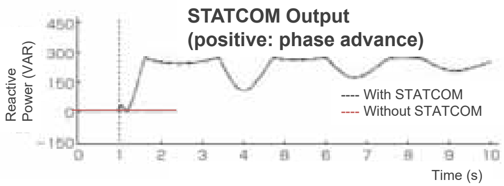

https://energy-shift.com/news/af737655-0462-4655-81ae-b17d86b5784d

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.



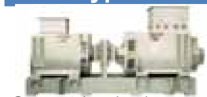
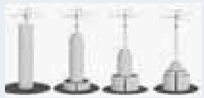
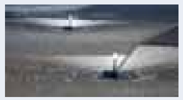




Source: Enhancement of Steady－State Stability and Suppression of Over－Voltage using 450MVA GCT－STATCOM, Mitsubishi Denki Giho, pp.52-55, Vol.87, No.11, 2013.

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

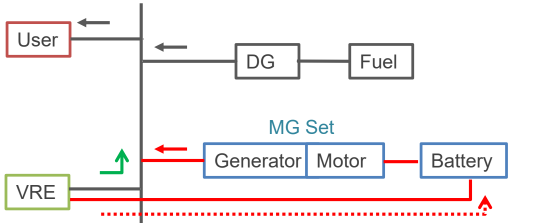
Type of Technology		Advantage	Develop stage
 Source: taiyo-electric	Motor generator (MG)	- Energy in battery provides synchronization and inertia - Small scale supply, for micro grid	- Used as frequency conversion - Commercial operation
 energyvault.com/gravity	Gravity Storage Battery	- Gravity of recycled 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)

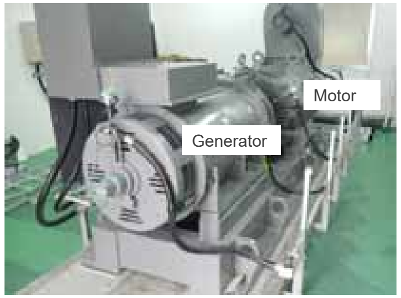
Hateruma Island: Southern most island in Japan
- Area：12.73 km2 , Population 527, hh 272 (2016)
- Peak power: 770 kW (2016)
- Generation: DG (Bunkar-A, total 1,250kW)
- Wind (245kW✕2, total 490kW)
- Lead-acid Batt (600kW/1,500kWh)
- **MG Set: Rated 300 kW**

Wind generator

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



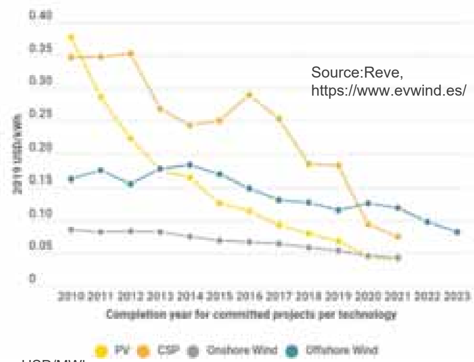
MG set is driven by battery charged from VRE and provides power with inertia → possible method to achieve 100% RE with inertia



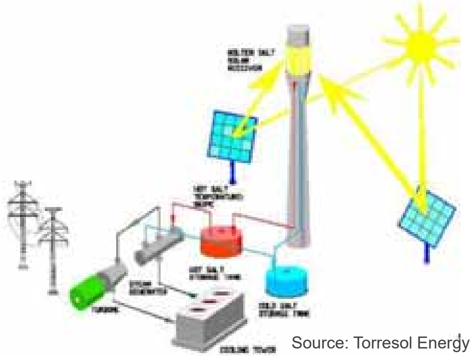
https://www.okiden.co.jp/shared/pdf/news_release/2017/180328.pdf

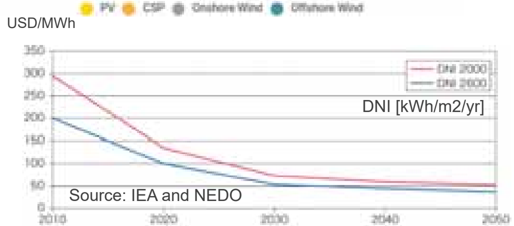
Option for 100% RE: CSP

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/m^2/yr
  - St Kitts&Nevis:1600-2300 kWh/m^2/yr
  - Jamaica: 1300-2200 kWh/m^2/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

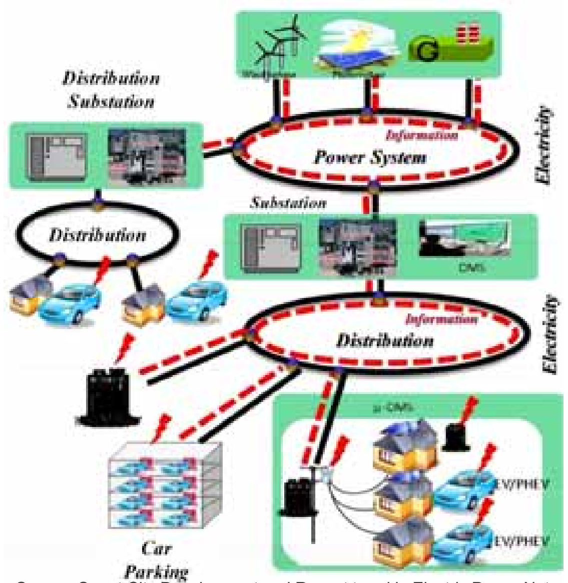
23 Aug 2018 Awaji, Japan
https://www.sankei.com/west/news/180828/wst1808280043-n1.html
600 kW, Fallen at 25.6m/s wind while 60m/s design
- Additional moment due to Excess of high speed
- Missing control power supply

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

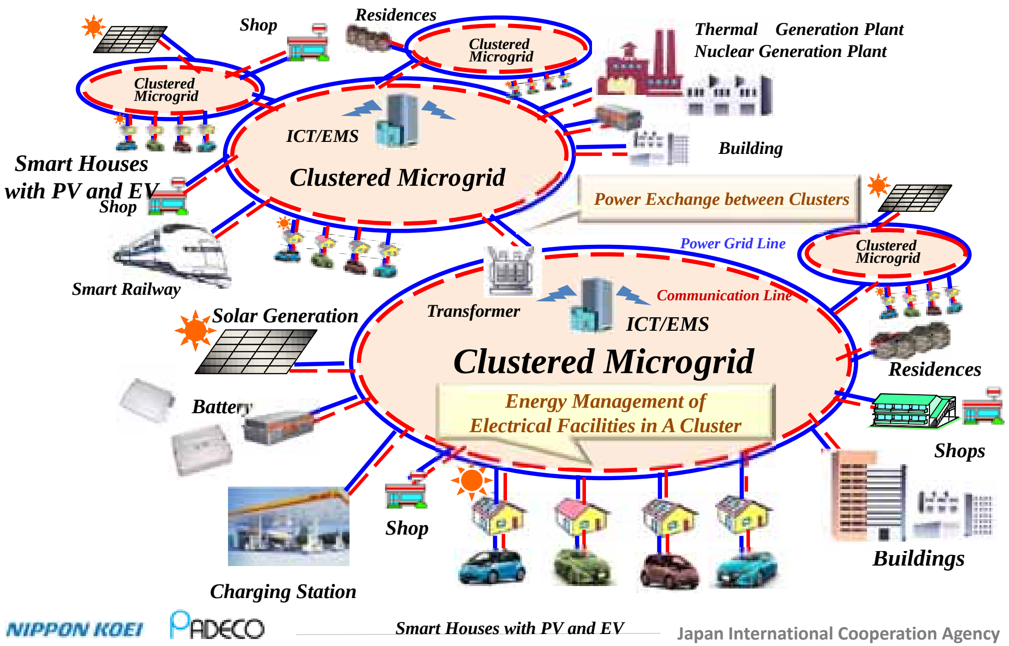


Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

Concept of Micro-grid

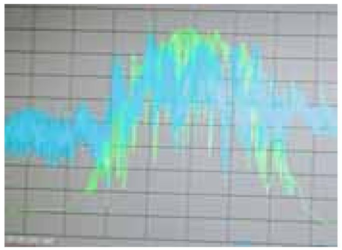
- ✓ Respective Micro-grid is connected each other, and each Micro-grid can work independently
- ✓ Local energy production for local consumption
  - ✓ Generation: PV, wind, biomass, DG, GT, battery, etc.
  - ✓ Demand: industry, commercial, home, EV, etc.
- ✓ No transmission → loss saving
- ✓ With IoT,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

Microgrid for Resilient System
-- Autonomous Micro Grid

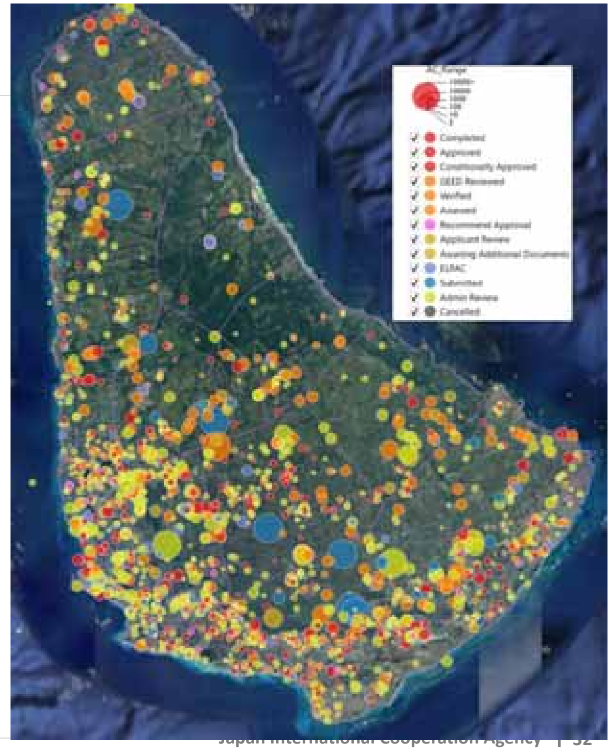


PV Installation and Plans in Barbados

- 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



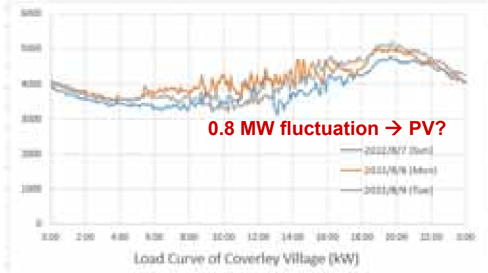
Planning of Microgrid of Coverley Village

- 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



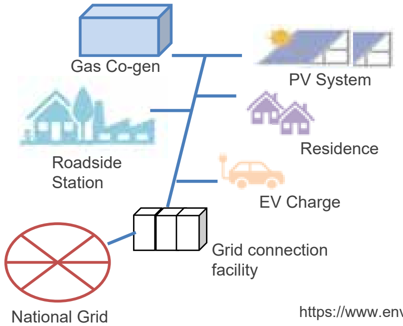
Example of system, to be reviewed

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



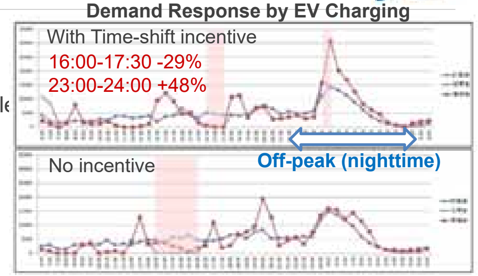
https://www.env.go.jp/press/files/jp/113284.pdf

Recommendation of DR and EV

(1) TOU or Unit charge rate according to load curve and weather and PV output with EMS

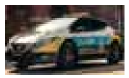
(Ex.) Range-1 : Daytime, sunny , lowest
Range-2 : Daytime, sunny/cloudy / off-peak, middle
Range-4: Rain and evening, peak-time highest

Demand Response by EV Charging

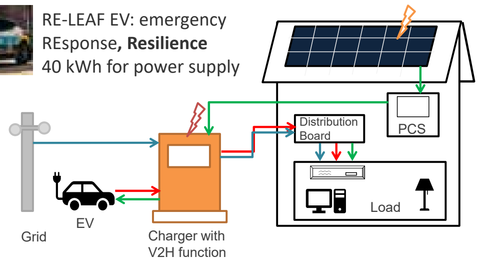


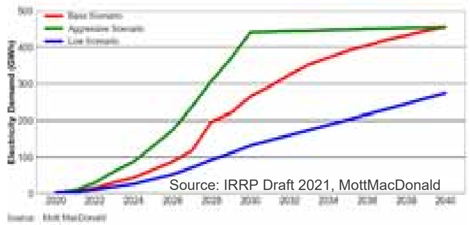
https://xtech.nikkei.com/dm/article/FEATURE/20150120/399714/?P=5

(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



RE-LEAF EV: emergency REsponse, **Resilience**
40 kWh for power supply





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

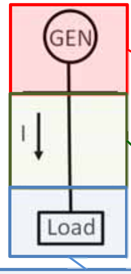
https://www.drive.com.au/

Grid Simulation: for Optimization of Load Flow Analysis

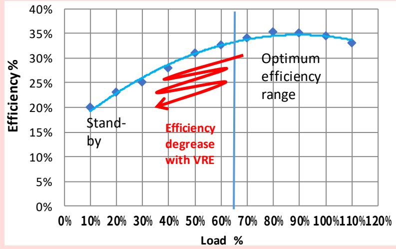
Microgrid Designer consists of tools of Economic Load Dispatch (ELD) and load flow analysis modules, developed by Energy & Environment Technology Research Institute, Japan (Venture company of Waseda Univ).

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.

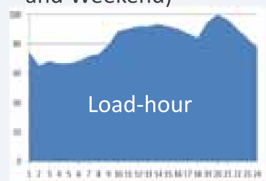
Input Data



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)

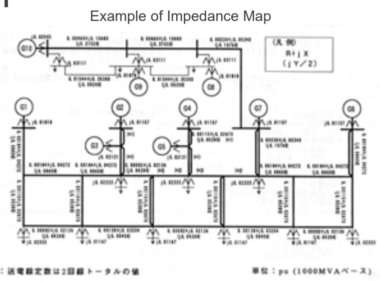


Transmission Line, Substation

[Common]
- Power flow limitation
- Voltage Magnitude

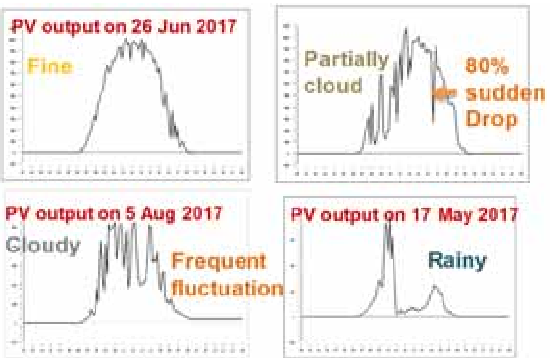
[Option 1]
- Impedance Map

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



Input Data

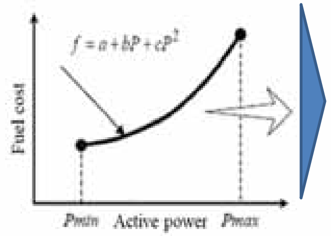
Necessary Data
- Fuel efficiency (heat rate) of each DG generator units at each load range
- PV generation 24 hr curve



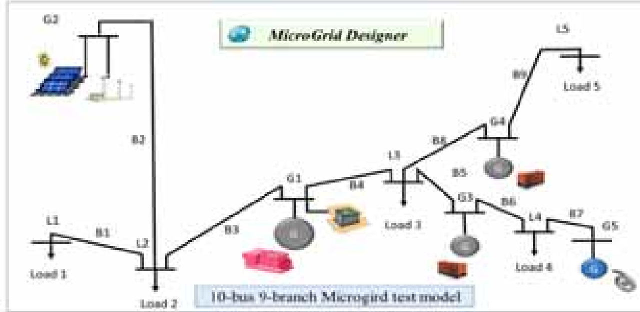
Battery
- Sum of MWh

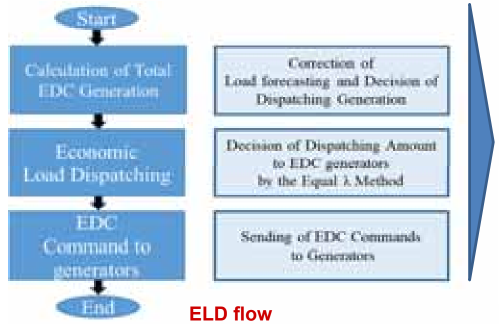
Battery A	5MWh
Battery B	3MWh
Battery C	1MWh
Sum of Battery Capacity	**9MWh**

ELD example with IEEE Microgrid Model

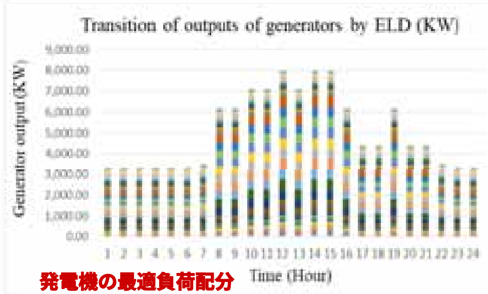


Load-fuel efficiency curve



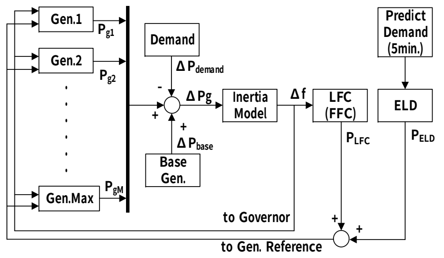


ELD flow

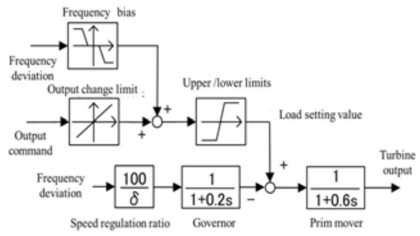


発電機の最適負荷配分

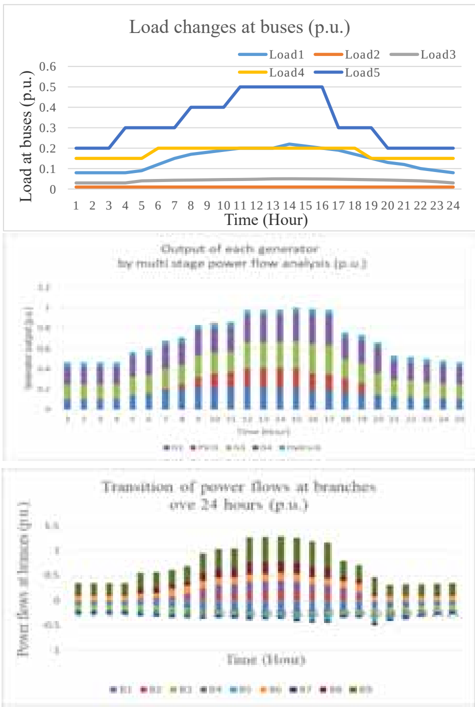
Load-flow Analysis



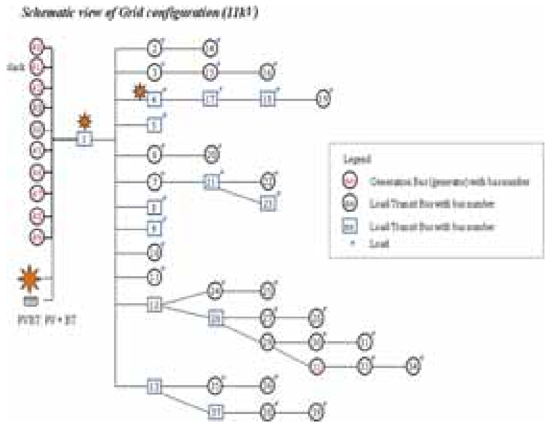
LFC model using ELD result



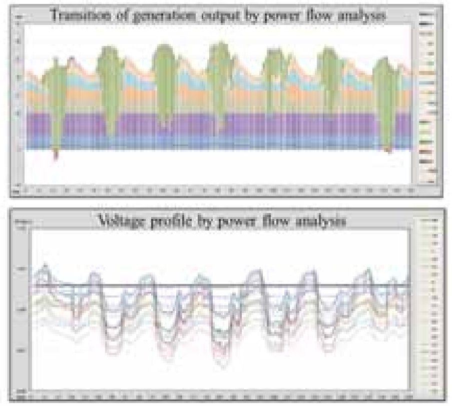
Output model of DG



Grid Analysis Model of Microgrid in St. Kitts



Example of micro-grid model (St. Kitts)

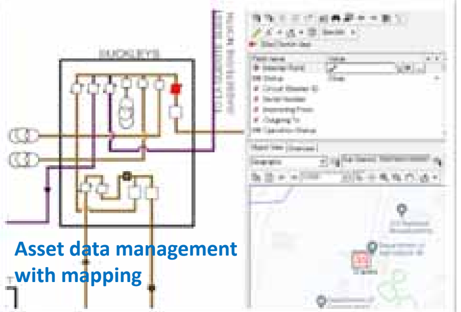


Grid analysis result (generator output, voltage, frequency)

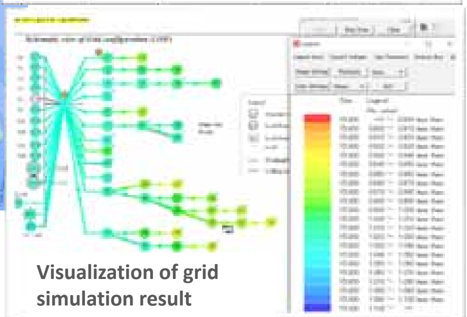
Analysis result is viewed in geographical information system
Smallworld is applied to visualization for investment plan and design

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

GIS mapping



Asset data management with mapping



Visualization of grid simulation result

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

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

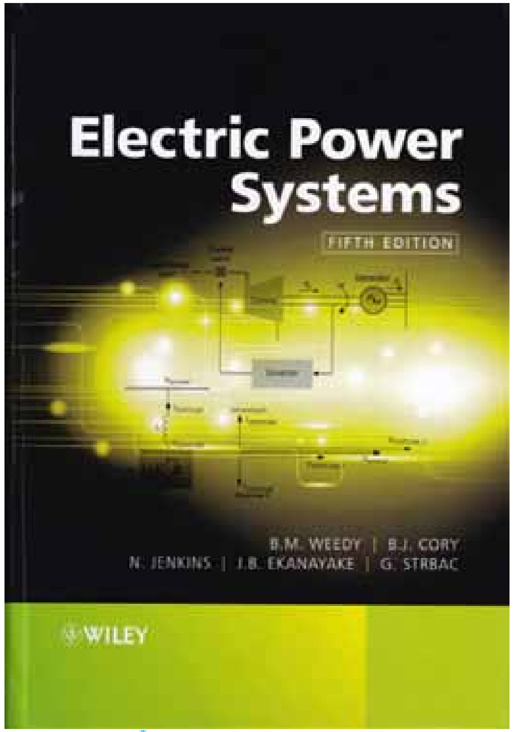
Essence of Power System Analysis and Control

M. Kato & H. Taoka

Suurikougaku-sha,

Tokyo, Japan

2011



Electric Power Systems

Fifth Edition

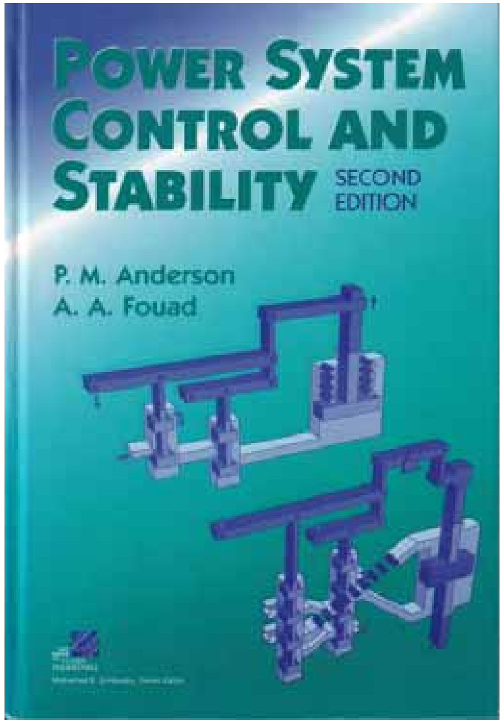
All-inclusive

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

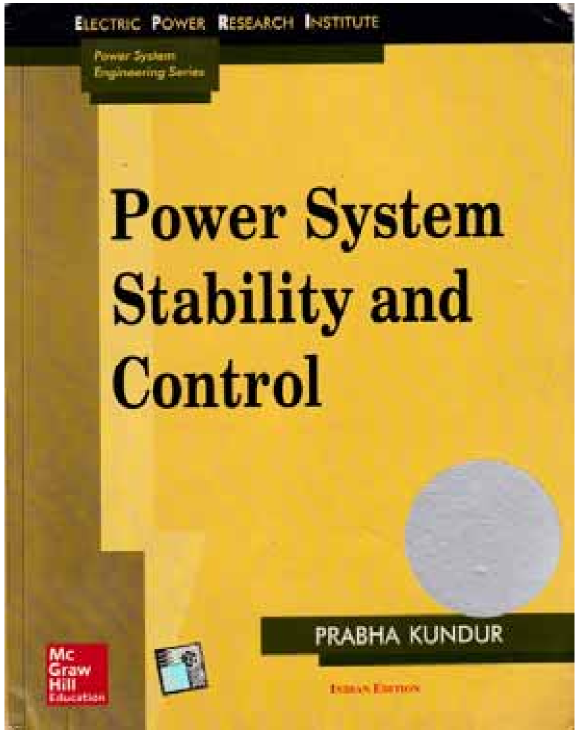
Second Edition

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

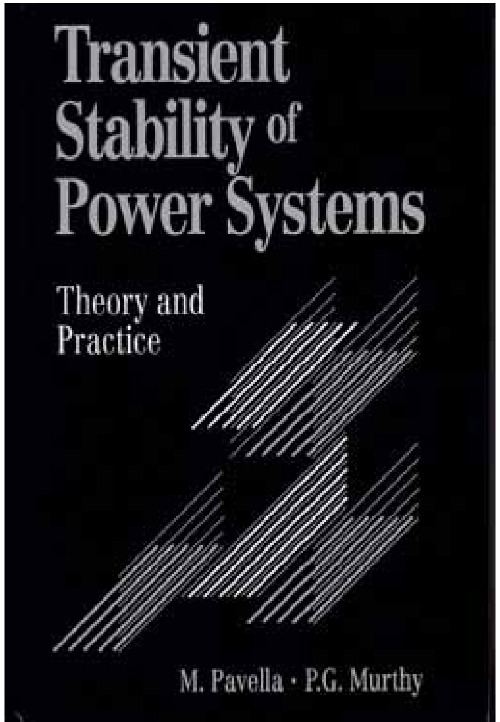


Power System Stability and Control

Widely Read Textbook

P. Kundur

McGraw-Hill,
New York, USA
1994



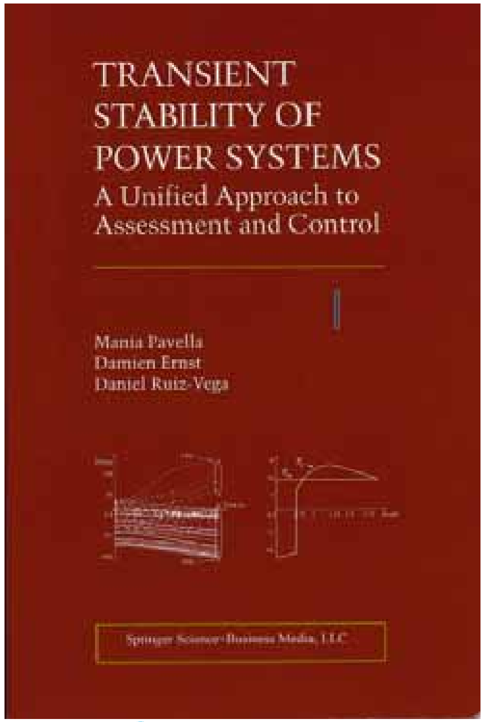
Transient Stability of Power Systems

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

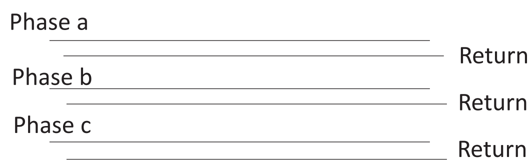
- Flow of Electricity
  - DC (Direct Current): Difficult to change voltage and switch off circuit
  - AC (Alternative Current): Stability problem
- AC
  - Single Phase & Three Phase
- Components of Power System
  - Transmission Line
  - Transformer & Switchgear (Substation)
  - Generator (Synchronous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

Methods of Power System Analysis

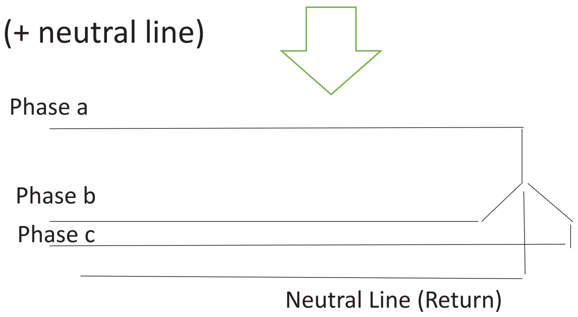
- Steady State: under Small Disturbance
  - Voltage, Power, Angle are constant at a certain time
  - It keeps the same state under small disturbance
  - ->Load Flow Analysis, Eigenvalue Analysis
- Transient State: under Large Disturbance
  - Voltage, Power, Angle are changing
  - ->Equal Area Criterion,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

Single-Phase to Three-Phase

- Single transmission line
  - Require 2 lines

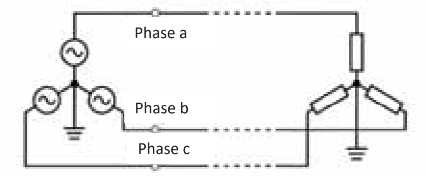


- Three-Phase transmission line
  - Require 3 or 4 lines (+ neutral line)
  - 3 times capacity

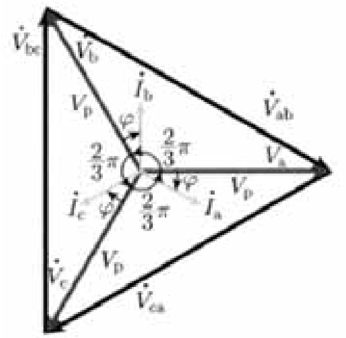


Three-Phase AC Circuit

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



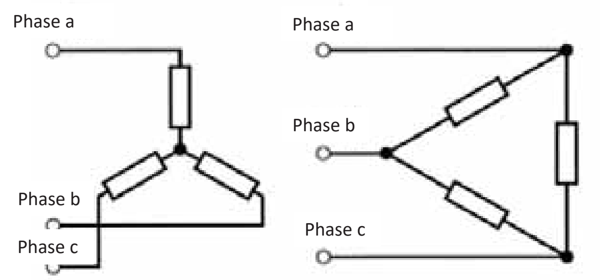
Va, Vb, Vc: Phase Voltage
Vac, Vbc, Vca: Line-to-Line Voltage
Ia, Ib, Ic: Phase Current
Iab, Ibc, Ica: Line Current



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

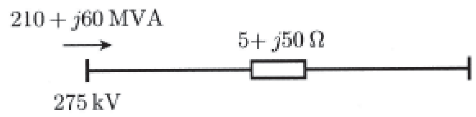
Example of Conversion to Per Unit

(1) Calculate Base Value

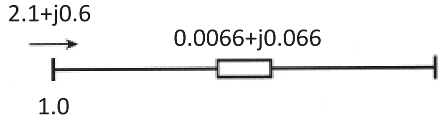
Vbase=275kV

(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:

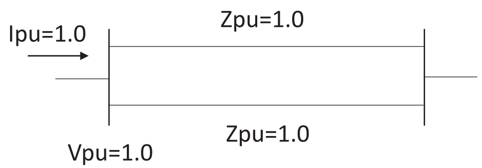
1pu(|Z|=1.32Ω) impedance transmission line can send 1pu(100MVA) power by 1pu(11.5kV) voltage. Its current is 1pu(8.7kA).

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

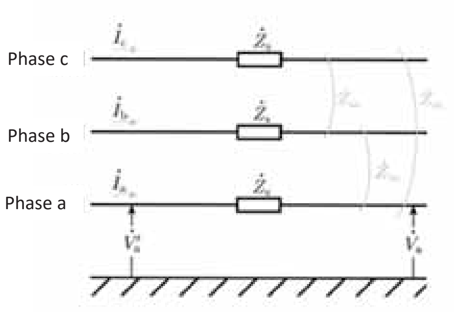


3. Modeling of Power System Equipment

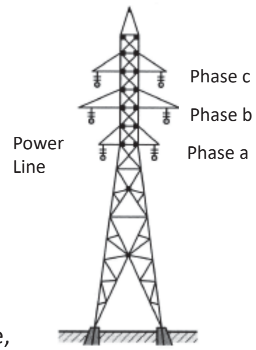
- Make it easy to analyze feature of power system equipment
- Modeling of Components of Power System
  - Transmission Line
  - Transformer & Switchgear (Substation)
  - Generator (Synchronous Generator, Photovoltaic, Wind Power)
  - Load

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.

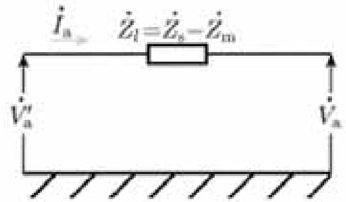
Impedance of Transmission Line

- Impedance of Transmission Line

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

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

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



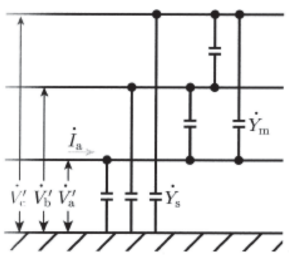
Zs: Self Impedance, Zm: Mutual Impedance
Z_l=Zs-Zm : Line Impedance, Sum of self and mutual impedance
R: Line Resistance
Ls: Self Inductance, Lm: Mutual Inductance
Ia, Ib, Ic: Phase Current
Va’, Va: Phase Voltage
(Sending Terminal Voltage, Receiving Terminal Voltage)

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

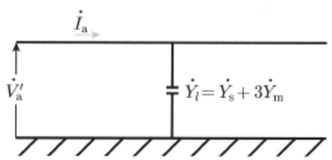
Admittance of Transmission Line

- 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

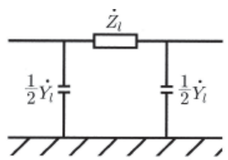


Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

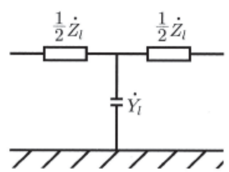
Equivalent Circuit of Transmission Line

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.

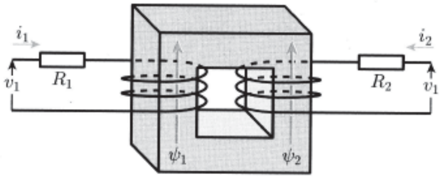
Transformer

- 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

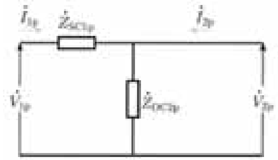
- Relationship of per unit base values

$$\frac{r\dot{I}_1}{I_{2\mathrm{base}}} = \frac{r\dot{I}_1}{rI_{1\mathrm{base}}} = \dot{I}_{1\mathrm{p}} \qquad rI_{1\mathrm{base}} = I_{2\mathrm{base}}, \quad Z_{1\mathrm{base}} = r^2 Z_{2\mathrm{base}}$$

$$\frac{\dot{I}_2}{rI_{1\mathrm{base}}} = \frac{\dot{I}_2}{I_{2\mathrm{base}}} = \dot{I}_{2\mathrm{p}}, \quad \frac{r^2\dot{Z}_{\mathrm{OC2}}}{Z_{1\mathrm{base}}} = \frac{\dot{Z}_{\mathrm{OC2}}}{Z_{2\mathrm{base}}} = \dot{Z}_{\mathrm{OC2p}}$$

- 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

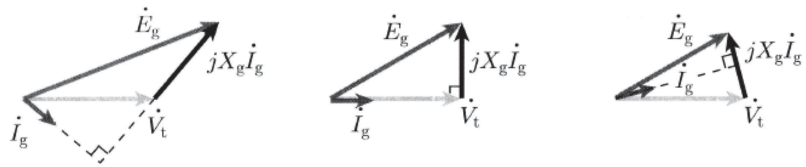
$$\frac{V_{1\mathrm{base}}}{V_{2\mathrm{base}}} = \frac{\dfrac{(VA)_{1\mathrm{base}}}{I_{1\mathrm{base}}}}{\dfrac{(VA)_{2\mathrm{base}}}{I_{2\mathrm{base}}}} = \frac{I_{2\mathrm{base}}}{I_{1\mathrm{base}}} = \frac{rI_{1\mathrm{base}}}{I_{1\mathrm{base}}} = r$$

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.

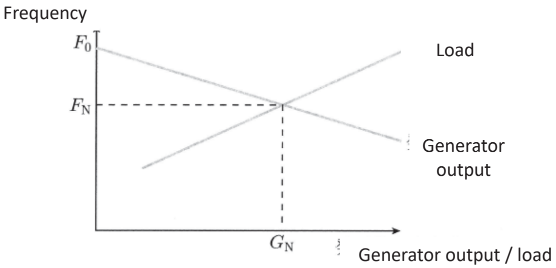
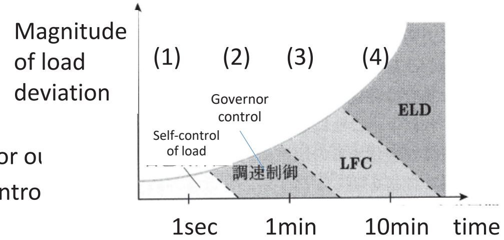


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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:
  ΔPG = (K1+K2/s)Δf
(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.

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

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

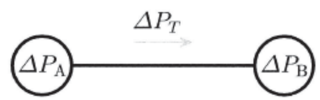
$$\Delta P + (\Delta G - \Delta L) = 0$$
$$\Delta P = (K_G + K_L)\Delta F$$

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

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.

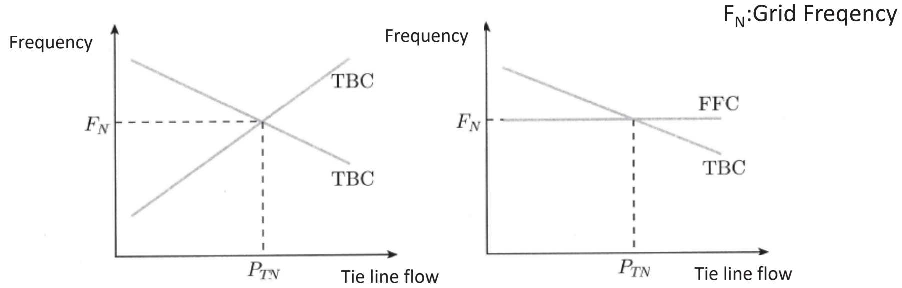
$$\begin{cases} \Delta F = \dfrac{\Delta P_A + \Delta P_B}{K_A + K_B} \\ \Delta P_T = \dfrac{K_B \Delta P_A - K_A \Delta P_B}{K_A + K_B} \end{cases}$$

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



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

5. Reactive Power & Voltage

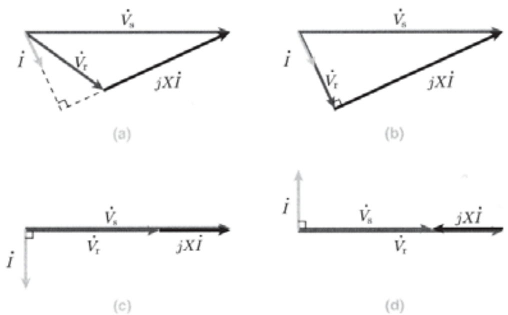
- Most of load consumes reactive power and its voltage will decrease.
- In order to keep voltage to a certain value, reactive power should be provided.
- Provider of reactive power
  - Synchronous generator
  - Synchronous Condenser/Capacitor (SC, SCO)
  - Static Var Compensator (SVC)
  - Static Synchronous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



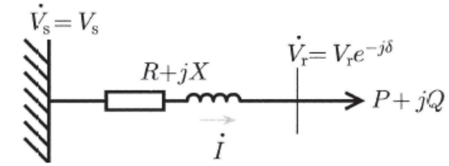
Vs: Sending Terminal Voltage, Vr: Receiving Terminal Voltage
I: Tiransmission Line Curent
X: Transmission Line Impedance

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.

$$\begin{cases} \Delta V_{r,P} = \left(\dfrac{\partial V_r}{\partial P}\right)\Delta P \\ \Delta V_{r,Q} = \left(\dfrac{\partial V_r}{\partial Q}\right)\Delta Q \end{cases}$$

$$\frac{\partial V_r}{\partial P} = -\frac{(R^2+X^2)P+RV_r^2}{V_r(2XQ+2RP+2V_r^2-V_s^2)}$$

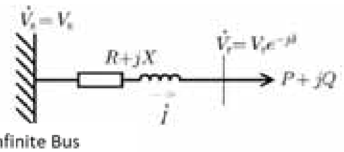
$$\frac{\partial V_r}{\partial Q} = -\frac{(R^2+X^2)Q+XV_r^2}{V_r(2XQ+2RP+2V_r^2-V_s^2)}$$

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

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

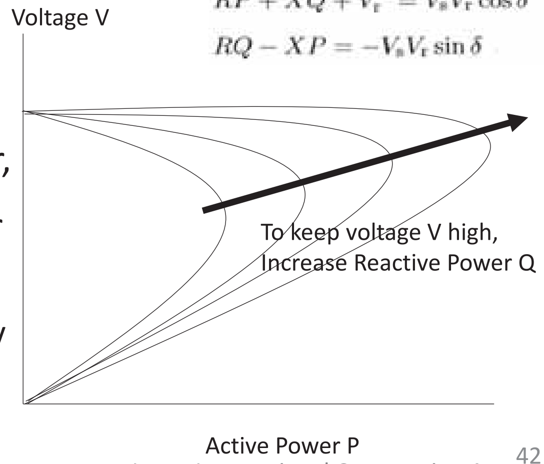
P-V Curve & Q(Reactive Power)

- 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.



$$RP + XQ + V_r^2 = V_s V_r \cos\delta$$

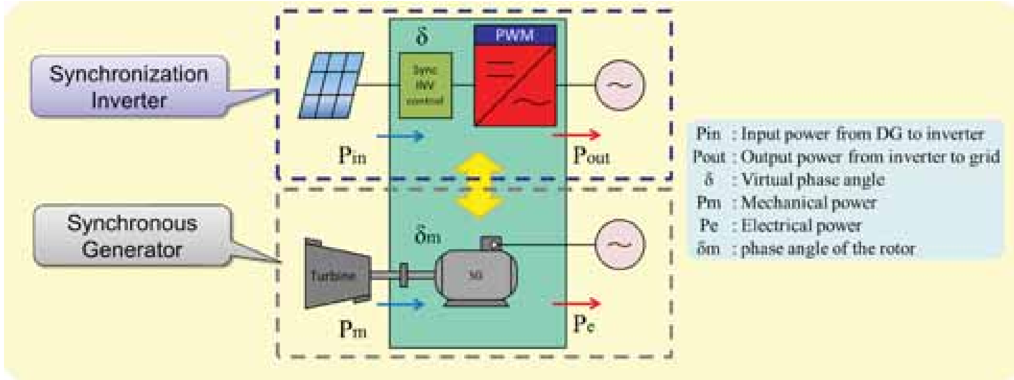
$$RQ - XP = -V_s V_r \sin\delta$$



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

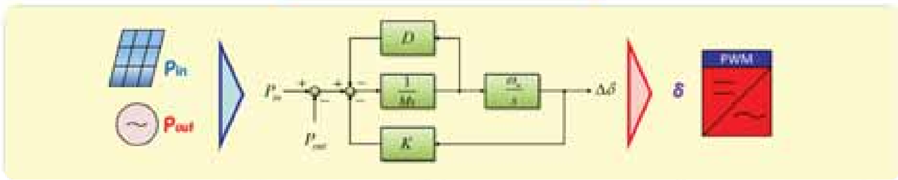
The control method of Synchronization Inverter is expressed by the swing equation. This equation is added damping term and synchronizing power term.

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

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
  - $P = \frac{V_i V_j}{X} sin\delta$
- Synchronizing Force
  - $\frac{dP}{d\delta} = \frac{V_i V_j}{X} cos\delta$
- Available Transmission Capacity from Heat Capacity Limit

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

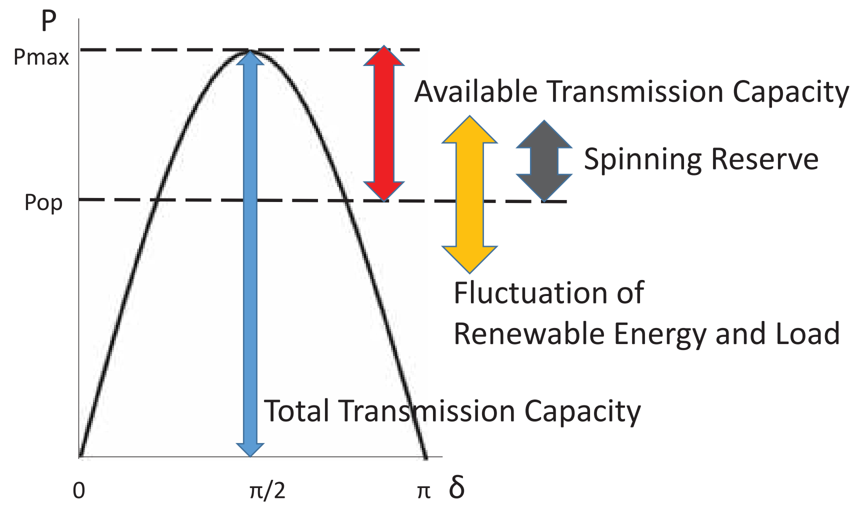
- Available Transmission Capacity from Transient Stability

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

Spinning Reserve

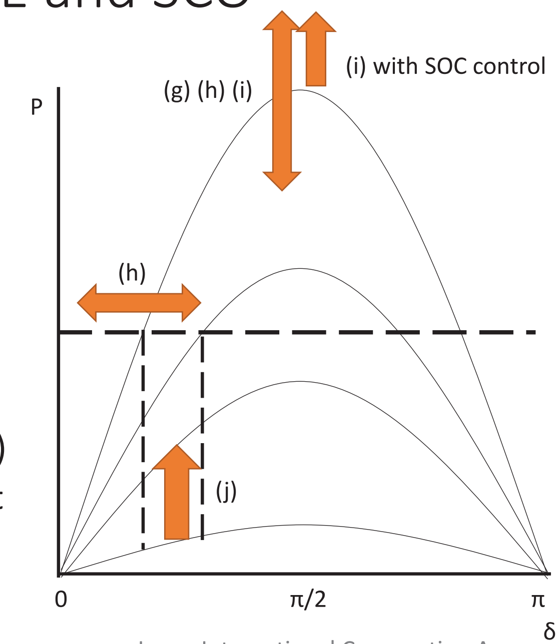
- In order to get electrical power under abnormal condition of grid, spinning reserve should be kept even if RE is installed. (under development)
- Spinning reserve should be more than mixed fluctuation of load and renewable energy.
  -> RE, EV and Battery with inertia is required for large RE penetration.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

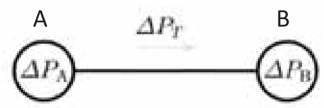
- Per Unit Calculation
  - Calculation of base current and impedance for several base voltage and base capacity
- Active Power - Frequency Relationship
  - Calculation of Area Requirement
  - The way to calculate Microgrid Interconnection
- Reactive Power - Voltage Relationship
  - Calculation of voltage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

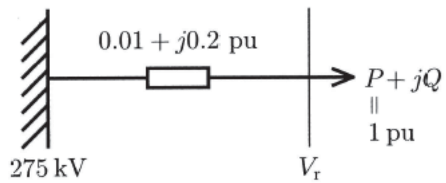


Exercise 3

- 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

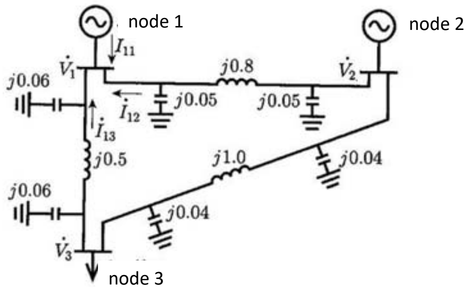
- Node Admittance Matrix
  - Relationship between voltage and current for multiple nodes in a power system
- Power Equation
  - Relationship between power and voltage
- DC Flow Method (manual calculation)
  - Simplified Load Flow Calculation of Three-phase AC Transmission Line
  - Solve relationship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

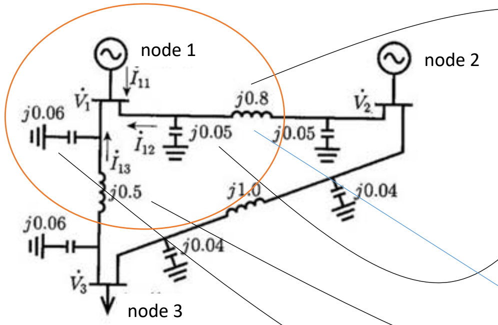


- Calculation example of power flow in 3 nodes network

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

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

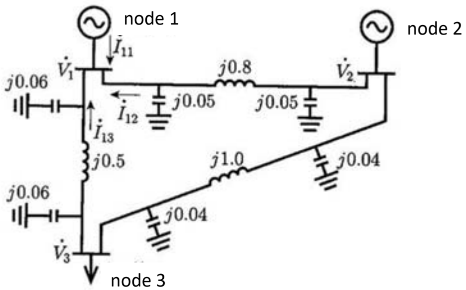
- Y11,Y22,Y33:
  - Driving Point Admittance
- Y12,Y21,Y13,Y31,Y23,Y32:
  - Transfer Admittance

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.

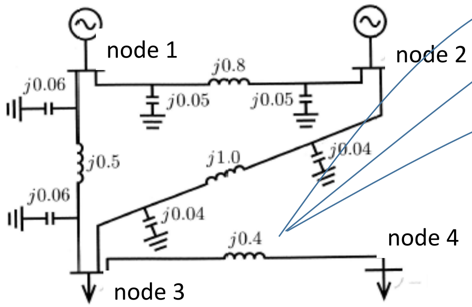
Node Admittance Matrix - Adding new node

- 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

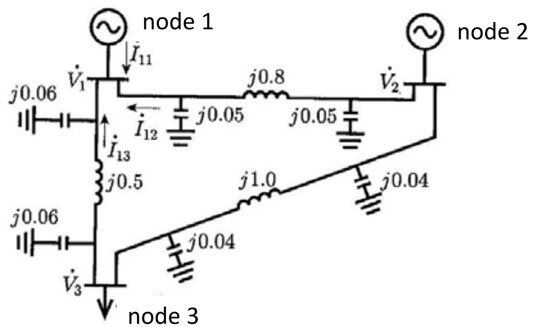
Load Flow Analysis

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

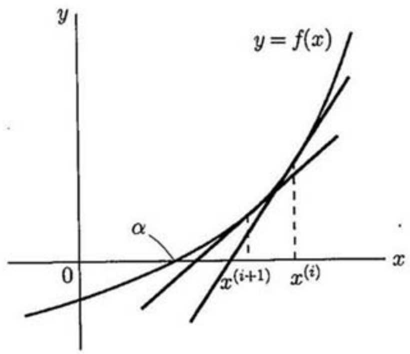


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

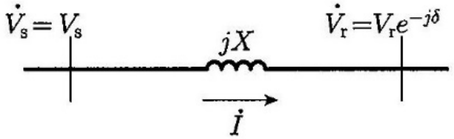
Manual method to calculate power flow.
Easy to calculate in manual.

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

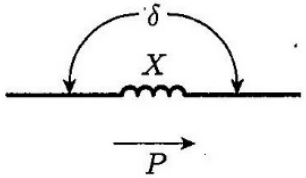
$$P_r + jQ_r = V_r e^{-j\delta}\dot{I}^* = V_r e^{-j\delta}\left(\frac{V_s - V_r e^{-j\delta}}{jX}\right)^* = \frac{V_s V_r e^{-j\delta} - V_r^2}{-jX} = \frac{V_s V_r}{X}\sin\delta + j\frac{V_s V_r \cos\delta - V_r^2}{X}$$

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

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

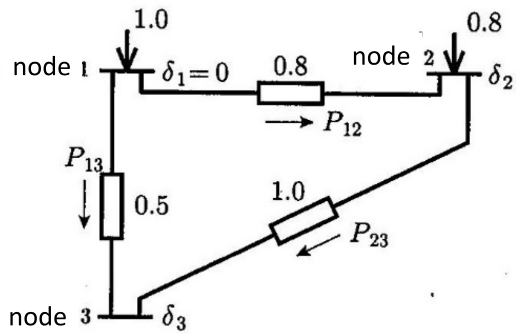


Simplified and Similar to DC circuit solution



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:

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

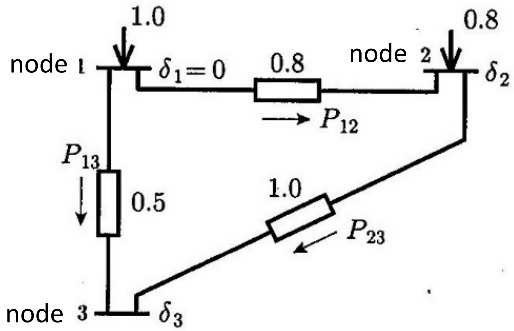
$$0.8 = \frac{\delta_2 - 0}{0.8} + \frac{\delta_2 - \delta_3}{1.0}$$

$$\delta_2 = 0.104$$

$$\delta_3 = -0.565$$

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.

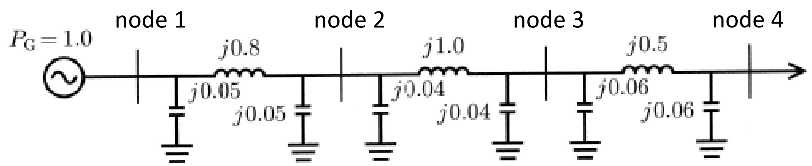
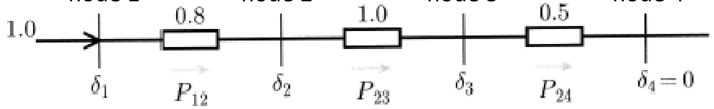


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

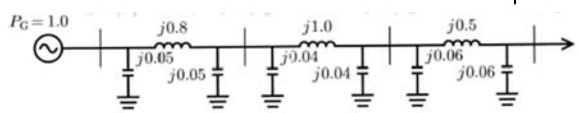
Exercise of DC Flow method

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

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

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

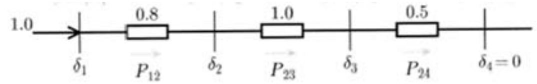
$$\dot{Y}_{34} = \dot{Y}_{43} = -\frac{1}{j0.5} = j2.0$$

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

Exercise 2 Answer

$$P_{1s} = \mathrm{Re}\{(-j1.20)^*(e_1 + jf_1)^*(e_1 + jf_1) + (j1.25)^*(e_2 + jf_2)^*(e_1 + jf_1)\}$$
$$= -1.25e_1 f_2 + 1.25 e_2 f_1$$
$$V_{1s}^2 = e_1^2 + f_1^2$$
$$P_{2s} = \mathrm{Re}\{(j1.25)^*(e_1 + jf_1)^*(e_2 + jf_2) + (-j2.16)^*(e_2 + jf_2)^*(e_2 + jf_2) + (j1.0)^*(e_3 + jf_3)^*(e_2 + jf_2)\}$$
$$= -1.25 e_2 f_1 + 1.25 e_1 f_2 - e_2 f_3 + e_3 f_2$$
$$Q_{2s} = \mathrm{Im}\{(j1.25)^*(e_1 + jf_1)^*(e_2 + jf_2) + (-j2.16)^*(e_2 + jf_2)^*(e_2 + jf_2) + (j1.0)^*(e_3 + jf_3)^*(e_2 + jf_2)\}$$
$$= -1.25 e_1 e_2 - 1.25 f_1 f_2 + 2.16 e_2^2 + 2.16 f_2^2 - e_2 e_3 - f_2 f_3$$
$$P_{3s} = \mathrm{Re}\{(j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) + (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3) + (j2.0)^*(e_4 + jf_4)^*(e_3 + jf_3)\}$$
$$= -e_3 f_2 + e_2 f_3 - 2.0 e_3 f_4 + 2.0 e_4 f_3$$
$$Q_{3s} = \mathrm{Im}\{(j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) + (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3) + (j2.0)^*(e_4 + jf_4)^*(e_3 + jf_3)\}$$
$$= -e_2 e_3 - f_2 f_3 + 2.9 e_3^2 + 2.9 f_3^2 - 2.0 e_3 e_4 - 2.0 f_3 f_4$$
$$e_4 = V_{4s}, \quad f_4 = 0$$

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

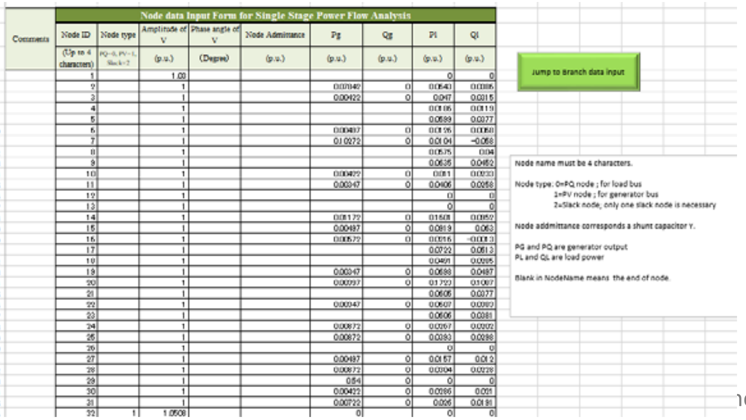
1) Capacity base is not shown here, it is assumed by user.
2) Newton-Raphson method is applied as the solver.
3) Convergence criterion is applied to the amplitude of node voltage.
4) Line addmittance is Y/2 in branch data, not Y.
5) Maximum branch number connected a node must be less than 39.

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.)

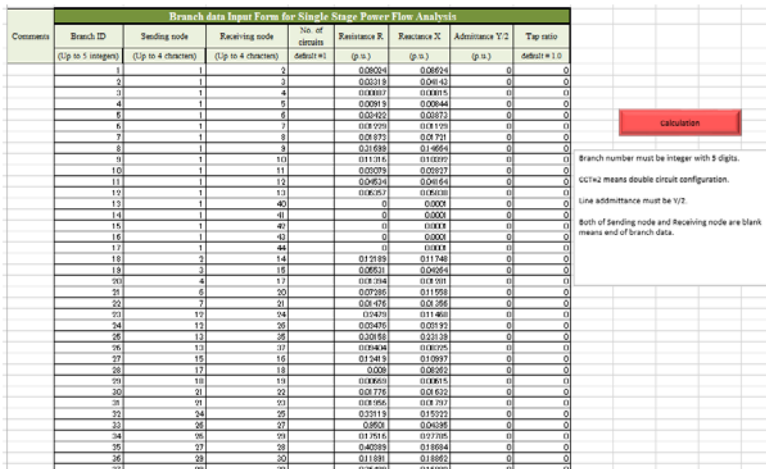


Branch Data

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

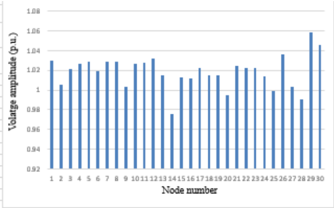


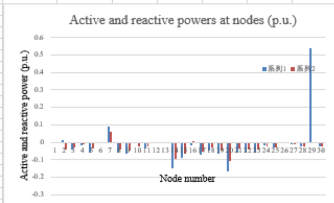
Calculation Results of Node

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	0.99694	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	0.03076	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

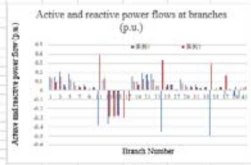


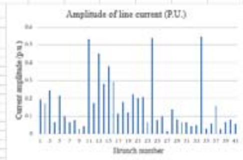


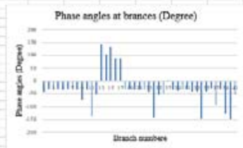
Calculation Results of Branch

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 agngel (Degree)	
1	1	2	0.14166	0.14056	−0.13826	−0.15764	0.19396	−44.84	
2	1	3	0.14737	0.09302	−0.14641	−0.09352	0.17025	−32.61	
3	1	4	0.20769	0.14413	−0.20712	−0.14356	0.24941	−34.78	
4	1	5	0.05994	0.03774	−0.0599	−0.0377	0.05877	−32.2	
5	1	6	0.18036	0.12192	−0.17868	−0.12019	0.21139	−34.08	
6	1	7	0.06893	0.05998	−0.06861	−0.05954	0.10091	−33.23	
7	1	8	0.03799	0.04006	−0.0575	−0.04	0.06812	−34.84	
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	0.03716	0.02585	−0.0371	−0.0258	0.04395	−34.83	
11	1	12	−0.28382	0.30495	0.28858	−0.28335	0.32457	−134.17	
12	1	13	0.11343	0.12969	−0.11348	−0.13006	0.17809	−30.47	
13	1	40	−0.3678	−0.26117	0.3678	0.26119	0.44949	142.8	
14	1	41	−0.0823	−0.26117	0.0823	0.26118	0.26444	106.32	
15	1	42	−0.2727	−0.26117	0.2727	0.26118	0.36029	134.12	
16	1	43	0	−0.29938	0	0.2996	0.29057	90	
17	1	44	0	−0.12033	0	0.12033	0.11683	90	
18	2	14	0.15298	0.09904	−0.1484	−0.0952	0.18069	−32.99	
19	3	15	0.10381	0.06232	−0.10263	−0.06173	0.11837	−31.19	
20	4	17	0.16892	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	0.11465	−0.17640	−0.11427	0.20891	−32.68	
23	12	24	0.0904	0.09083	−0.04921	−0.05028	0.0804	−43.42	
24	12	28	−0.44808	0.33222	0.45711	−0.32291	0.53995	−141.55	
25	13	35	0.04555	0.06087	−0.04365	−0.06057	0.07401	−53.06	
26	13	37	0.06792	0.07721	−0.06693	−0.07633	0.10132	−48.34	
27	13	16	0.01393	−0.00127	−0.0139	0.0013	0.01377	4.39	
28	17	18	0.11562	0.07979	−0.11545	−0.07623	0.13736	−34.66	
29	18	19	0.06656	0.04974	−0.0663	−0.04959	0.08166	−37.4	
30	21	22	0.05726	0.03836	−0.0572	−0.0383	0.06732	−33.87	
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	−41.75	
33	26	27	0.03496	0.03909	−0.03261	−0.03499	0.0476	−41.66	
34	26	29	−0.49209	0.26762	0.54507	−0.20377	0.55	−148.47	
35	27	28	0.02211	0.02296	−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	0.01897	0.01918	−0.0188	−0.0191	0.02579	−32.48	
39	32	33	−0.03624	0.04484	0.0392	−0.0442	0.05963	−129	
40	33	34	−0.06199	0.0227	0.0848	−0.0215	0.08042	−147.27	
41	35	36	0.03285	0.04137	−0.0314	−0.0407	0.0535	−50.96	
42	37	38	0.05695	0.07635	−0.05565	−0.07575	0.10132	−48.54	
43	38	39	0.04768	0.05495	−0.0458	−0.054	0.07365	−56.41	







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

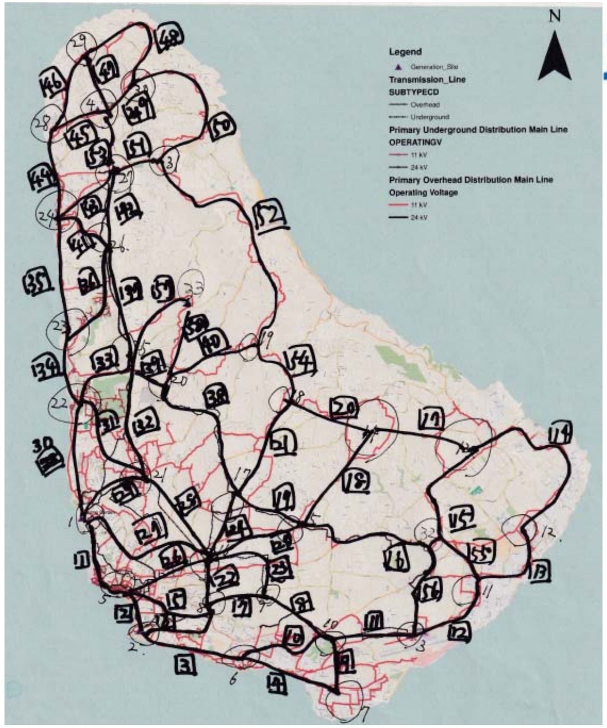
JICA Expert Team, Nippon Koei Co., Ltd.

Barbados Assumed Grid

Assumed values and network structure are used in this example.

33 nodes

No. 1~4 nodes have turbine generators.



Load Flow Data for Barbados

Node data Input Form for Single Stage Power Flow Analysis

Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)	(p.u.)
1	2	1.05			1.66	0	0	0
2	1	1.05			0.13	0	0	0
3	1	1.05			0.53	0	0	0
4	1	1.05			0.33	0	0	0
5	0	1			0	0	0.8	0
6	0	1			0	0	0.2	0
7	0	1			0	0	0.2	0
8	0	1			0	0	0.05	0
9	0	1			0	0	0	0
10	0	1			0	0	0.2	0
11	0	1			0	0	0.15	0
12	0	1			0	0	0.05	0
13	0	1			0	0	0	0
14	0	1			0	0	0.05	0
15	0	1			0	0	0	0
16	0	1			0	0	0.05	0
17	0	1			0	0	0.05	0
18	0	1			0	0	0	0
19	0	1			0	0	0.05	0
20	0	1			0	0	0	0
21	0	1			0	0	0.2	0
22	0	1			0	0	0.2	0
23	0	1			0	0	0.1	0
24	0	1			0	0	0.1	0
25	0	1			0	0	0	0
26	0	1			0	0	0	0
27	0	1			0	0	0.05	0
28	0	1			0	0	0.1	0
29	0	1			0	0	0.05	0
30	0	1			0	0	0	0
31	0	1			0	0	0	0
32	0	1			0	0	0	0
33	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	1	5	1	0.06	0.12	0.01	0
2	5	2	1	0.03	0.06	0.01	0
3	2	6	1	0.5	0.5	0.01	0
4	6	7	1	0.4	0.4	0.01	0
5	5	8	1	0.4	0.4	0.01	0
6	8	2	1	0.045	0.09	0.01	0
7	8	9	1	0.03	0.06	0.01	0
8	9	10	1	0.06	0.12	0.01	0
9	7	10	1	0.3	0.3	0.01	0
10	6	10	1	0.4	0.4	0.01	0
11	10	3	1	0.06	0.12	0.01	0
12	3	11	1	0.5	0.5	0.01	0
13	11	12	1	0.4	0.4	0.01	0
14	12	13	1	0.8	0.8	0.01	0
15	32	13	1	0.5	0.5	0.01	0
16	32	15	1	0.075	0.15	0.01	0
17	13	14	1	0.5	0.5	0.01	0
18	14	15	1	0.5	0.5	0.01	0
19	15	17	1	0.045	0.09	0.01	0
20	14	18	1	0.4	0.4	0.01	0
21	17	18	1	0.5	0.5	0.01	0
22	8	16	1	0.03	0.06	0.01	0
23	9	16	1	0.06	0.12	0.01	0
24	16	17	1	0.045	0.09	0.01	0
25	15	16	1	0.4	0.4	0.01	0
26	16	5	1	0.4	0.4	0.01	0
27	16	1	1	0.5	0.5	0.01	0
28	16	21	1	0.075	0.15	0.01	0
29	1	21	1	0.045	0.09	0.01	0
30	1	22	1	0.6	0.6	0.01	0
31	21	22	1	0.4	0.4	0.01	0
32	21	25	1	0.5	0.5	0.01	0
33	22	25	1	0.3	0.3	0.01	0
34	22	23	1	0.4	0.4	0.01	0
35	23	24	1	0.5	0.5	0.01	0
36	23	26	1	0.4	0.4	0.01	0
37	25	26	1	0.09	0.18	0.01	0
38	17	20	1	0.09	0.18	0.01	0
39	20	25	1	0.03	0.06	0.01	0
40	19	20	1	0.5	0.5	0.01	0
41	24	26	1	0.3	0.3	0.01	0
42	26	27	1	0.045	0.09	0.01	0
43	24	27	1	0.3	0.3	0.01	0
44	24	28	1	0.4	0.4	0.01	0
45	28	4	1	0.3	0.3	0.01	0
46	28	29	1	0.4	0.4	0.01	0
47	29	4	1	0.3	0.3	0.01	0
48	29	30	1	0.5	0.5	0.01	0
49	4	30	1	0.2	0.2	0.01	0
50	30	31	1	0.7	0.7	0.01	0
51	31	27	1	0.3	0.3	0.01	0
52	31	19	1	1.2	1.2	0.01	0
53	4	27	1	0.045	0.09	0.01	0
54	18	19	1	0.3	0.3	0.01	0
55	11	32	1	0.3	0.3	0.01	0
56	3	32	1	0.4	0.4	0.01	0
57	33	25	1	0.4	0.4	0.01	0
58	33	20	1	0.4	0.4	0.01	0

Load Flow Analysis Result in Barbados

R in distribution line is large and close to X value.
If you use R, Y should be considered.
If you use X without R, you need not consider Y.

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)
1	2	1.05	1.05	0
2	1	1.05	1.26549	−55.24
3	1	1.05	1.19482	−35.93
4	1	1.05	1.10686	−29.54
5	0	1	0.92199	−52.71
6	0	1	1.03808	−62.14
7	0	1	0.98019	−64.05
8	0	1	0.99889	−50.41
9	0	1	0.98303	−50.35
10	0	1	1.01163	−60.09
11	0	1	1.11709	−40.27
12	0	1	1.09856	−41.46
13	0	1	1.08755	−40.51
14	0	1	1.02667	−40.58
15	0	1	0.99768	−39.94
16	0	1	0.92187	−38.4
17	0	1	0.98322	−39.3
18	0	1	1.00925	−39.11
19	0	1	1.00345	−37.34
20	0	1	0.98384	−33.48
21	0	1	0.93375	−24.89
22	0	1	0.93417	−25.19
23	0	1	0.97502	−31.53
24	0	1	1.0238	−33.28
25	0	1	0.95417	−29.27
26	0	1	1.01269	−32.74
27	0	1	1.0499	−33.34
28	0	1	1.06794	−31.98
29	0	1	1.08979	−31.18
30	0	1	1.09848	−30.79
31	0	1	1.06041	−33.54
32	0	1	1.12571	−39.02
33	0	1	0.97223	−31.64

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)
1	2	1.05	1.05	0
2	1	1.05	1.05	−6.84
3	1	1.05	1.05	−5.66
4	1	1.05	1.05	−6.97
5	0	1	1.03218	−6.26
6	0	1	0.98264	−10.15
7	0	1	0.9705	−10.75
8	0	1	1.03368	−6.51
9	0	1	1.03002	−6.68
10	0	1	1.02468	−7.73
11	0	1	0.99645	−8.34
12	0	1	0.98567	−8.92
13	0	1	1.00499	−7.75
14	0	1	1.0037	−7.74
15	0	1	1.0199	−6.76
16	0	1	1.02831	−5.97
17	0	1	1.02155	−6.58
18	0	1	1.00977	−7.39
19	0	1	1.00734	−7.62
20	0	1	1.01779	−6.69
21	0	1	1.03307	−3.44
22	0	1	1.00044	−6.15
23	0	1	0.99832	−8.02
24	0	1	1.01337	−8.22
25	0	1	1.01706	−6.63
26	0	1	1.02481	−7.44
27	0	1	1.03423	−7.45
28	0	1	1.02208	−8.23
29	0	1	1.03305	−7.77
30	0	1	1.04299	−7.23
31	0	1	1.03246	−7.42
32	0	1	1.01856	−7.04
33	0	1	1.01742	−6.66

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)
1	2	1.05	1.05	0
2	1	1.05	1.05	−4.72
3	1	1.05	1.05	−3.49
4	1	1.05	1.05	−3.96
5	0	1	1.04877	−4.77
6	0	1	1.04765	−7.86
7	0	1	1.04728	−8.4
8	0	1	1.04887	−4.7
9	0	1	1.04857	−4.86
10	0	1	1.04822	−5.67
11	0	1	1.04848	−6.2
12	0	1	1.04837	−6.74
13	0	1	1.04839	−5.73
14	0	1	1.04838	−5.76
15	0	1	1.04846	−4.92
16	0	1	1.04847	−4.36
17	0	1	1.04843	−4.8
18	0	1	1.04842	−5.41
19	0	1	1.04849	−5.52
20	0	1	1.0484	−4.74
21	0	1	1.04832	−2.71
22	0	1	1.04787	−4.71
23	0	1	1.04848	−5.78
24	0	1	1.04905	−5.56
25	0	1	1.04839	−4.63
26	0	1	1.04894	−4.93
27	0	1	1.04935	−4.69
28	0	1	1.04949	−5.32
29	0	1	1.04971	−4.81
30	0	1	1.04979	−4.29
31	0	1	1.04931	−4.71
32	0	1	1.0486	−5.08
33	0	1	1.0484	−4.68

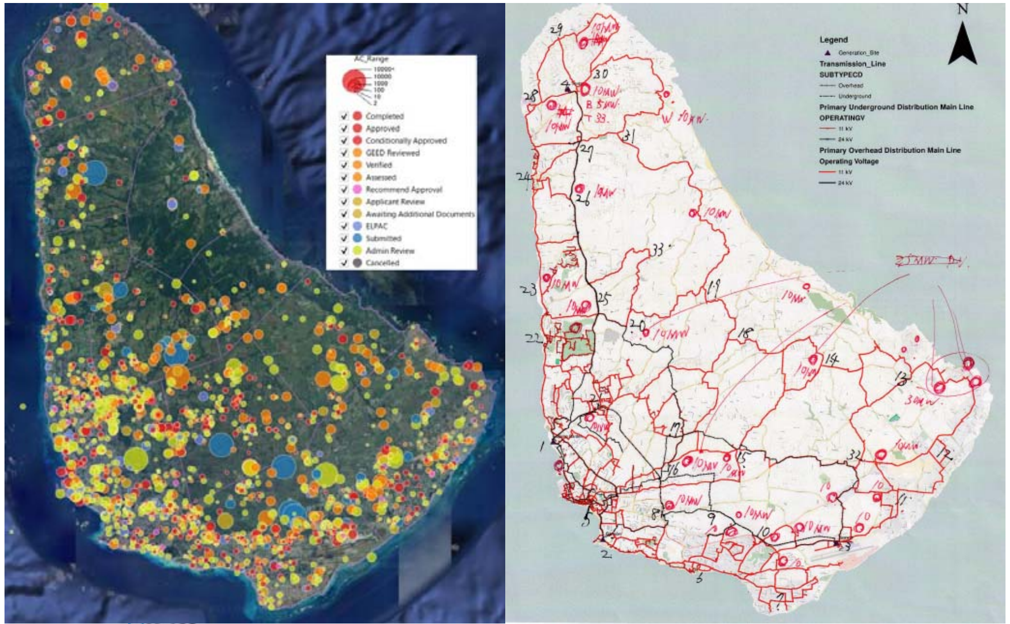
Transmission Line in Barbados

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.

Barbados PV Location

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



Load Flow Analysis Data 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		

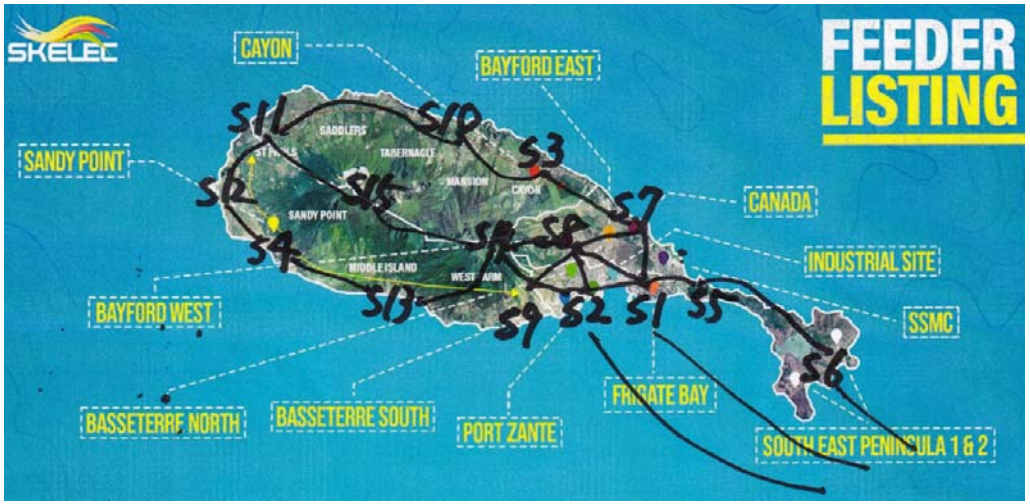
Seminar on Grid Stability with Large RE Day 2 (Exercise)

for Saint Kitts and Nevis

JICA Expert Team, Nippon Koei Co., Ltd.

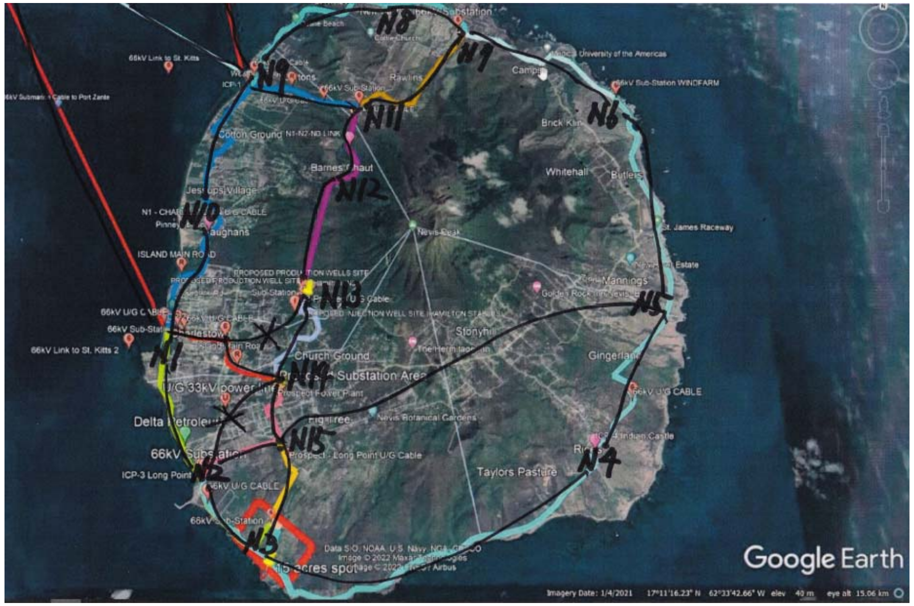
Saint Kitts Assumed Grid

15 nodes



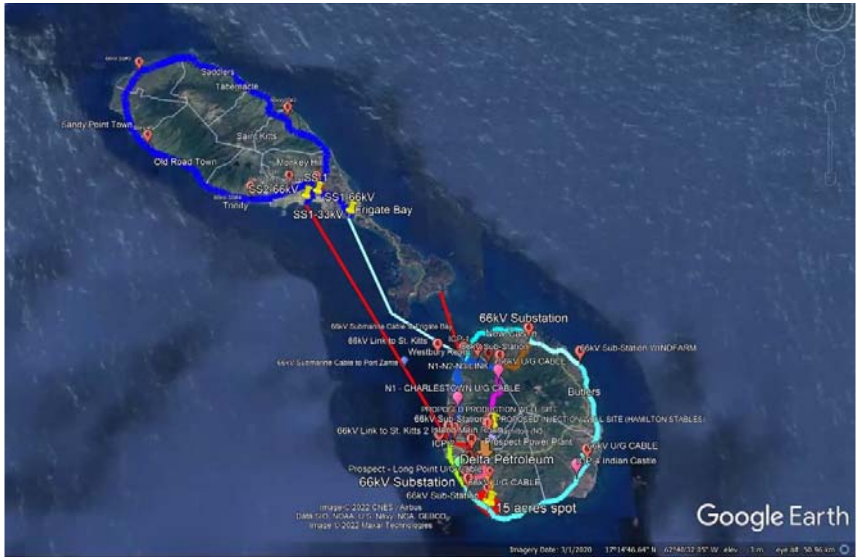
Nevis Assumed Grid

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.

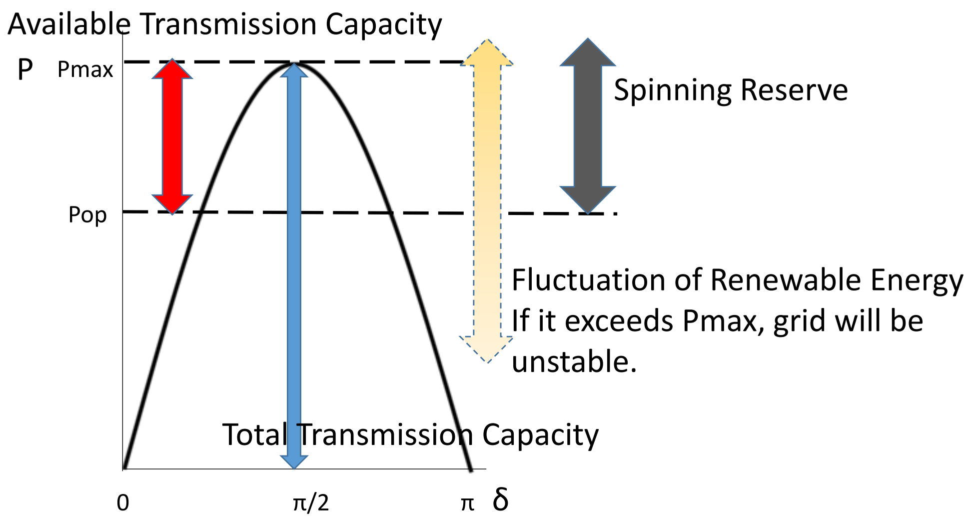
Role of Us: Power System Engineer

- 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

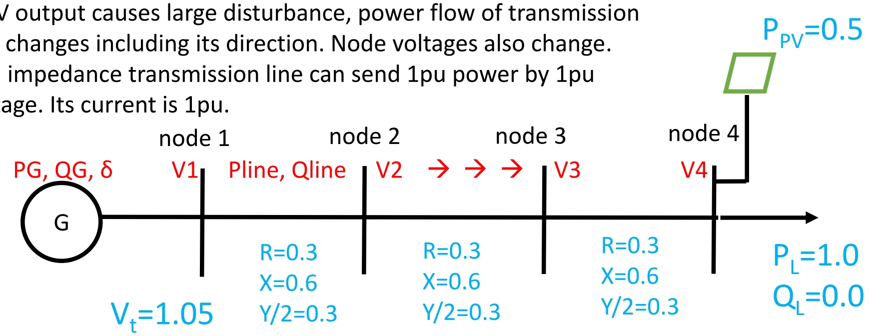
  -> Energy mix of several resources will be helpful for improving grid stability.
- RE Sources for Spinning Reserve: EV, Battery, Biofuel or Diesel Generator, etc.

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)

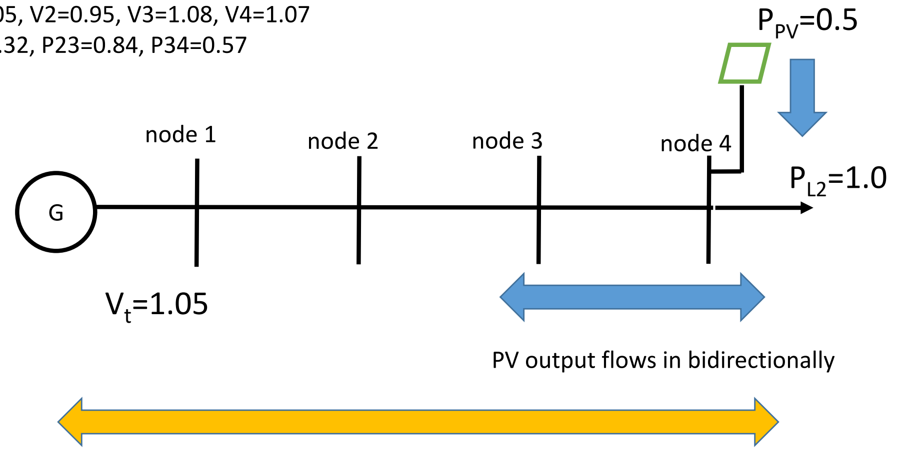
Load Flow Analysis

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



Power flow from generator has to be changed following the change of PV output.

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

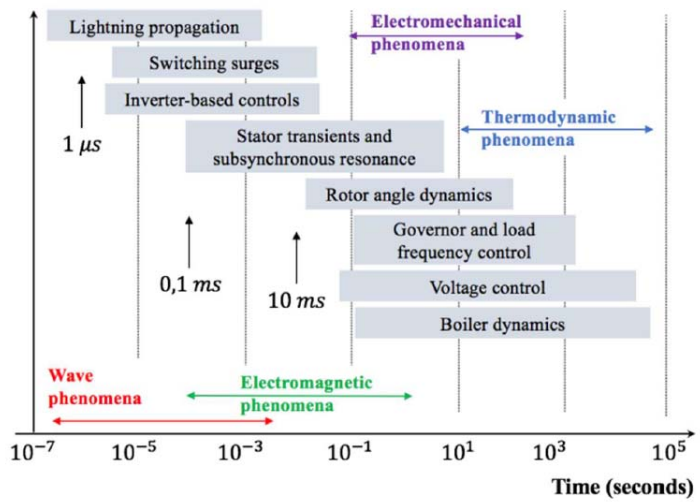
JICA Expert Team, Nippon Koei Co., Ltd.

Contents

1. Overview of Stability

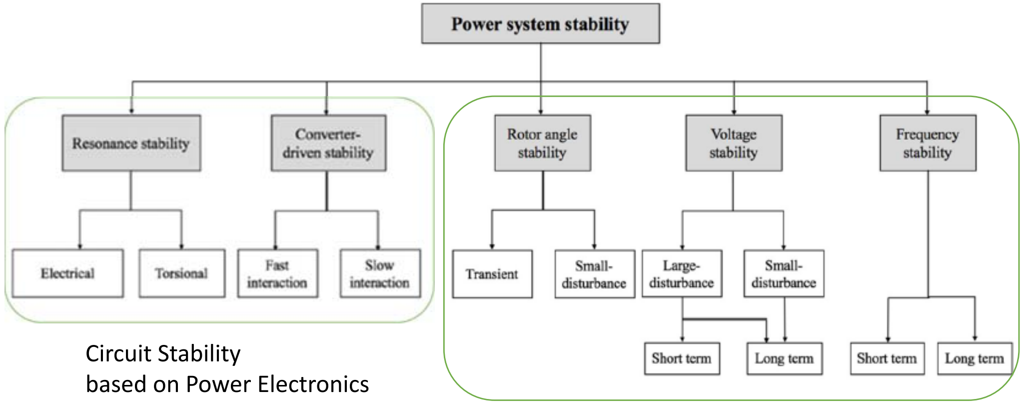
- STABILITY
  - If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.

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



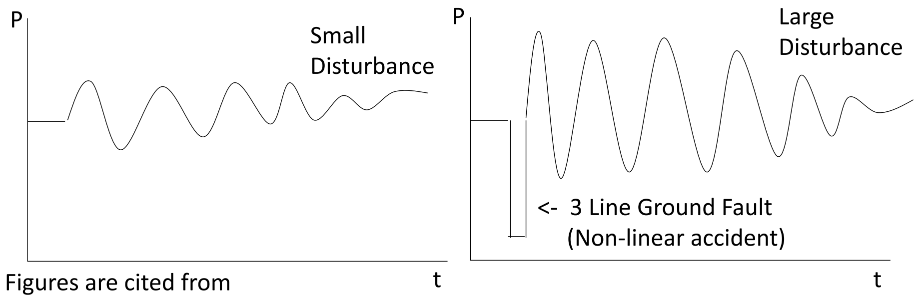
Circuit Stability based on Power Electronics Technology

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 Stability

- 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.

    $f = 2\pi\omega \qquad \omega = d\delta/dt$
  - 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.

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

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

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

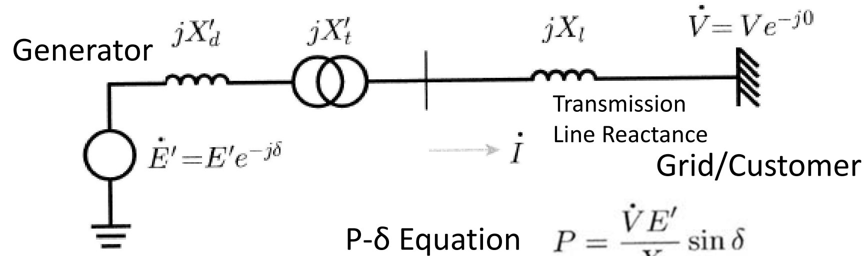
$$M = \omega J$$

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

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

$$P + jQ = \dot{V}\dot{I}^*$$

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

$$= \frac{\dot{V}E'}{X'_d + X_t + X_l}\sin\delta + j\frac{\dot{V}E'\cos\delta - \dot{V}^2}{X'_d + X_t + X_l}$$

$$X = X'_d + X_t + X_l$$

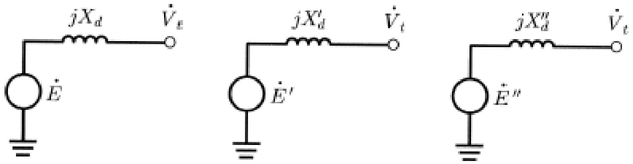
E': Transient Induced Electromotive Force
V: Grid Voltage
Xd': Transient Reactance
Xt': Transformer Reactance
Xl: Transmission Line Reactance
P: Active Power Output
Q: Reactive Power Output

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

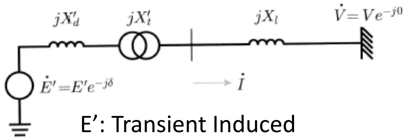
Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

Power equation



E': Transient Induced Electromotive Force

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

Active Power which flows from a generator to grid

$$P = \frac{\dot{V}E'}{X}\sin\delta \quad (\text{where } X = X'_d + X_t + X_l)$$

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

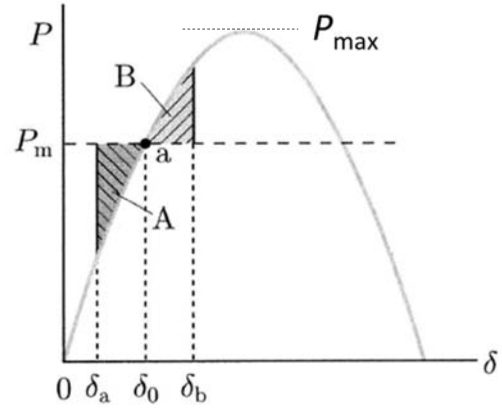


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

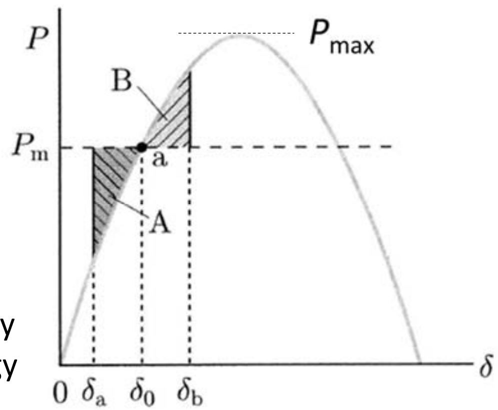
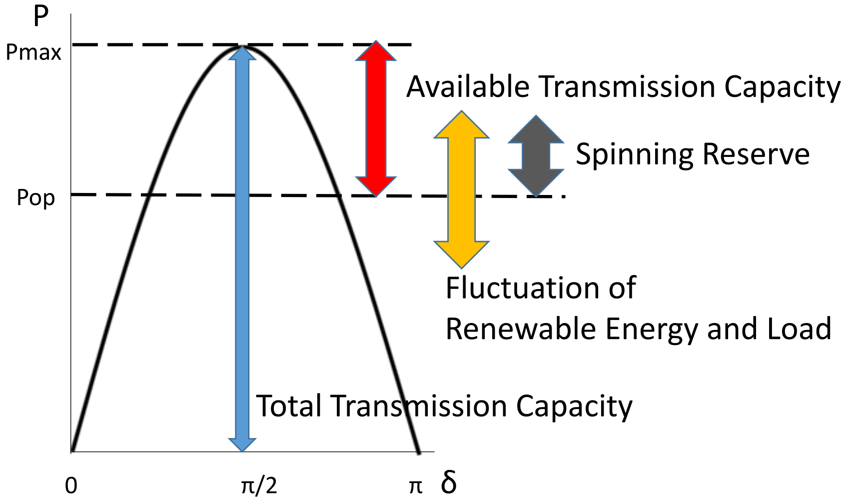


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

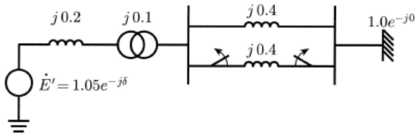
→Energy mix of several resources will be helpful for improving grid stability.

5. Exercise of Equal Area Criterion

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

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

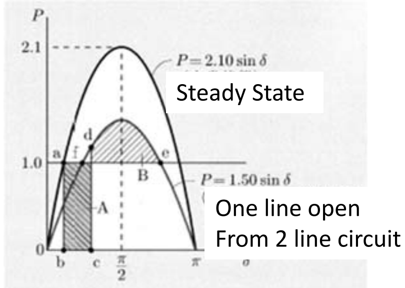
$$X = 0.2 + 0.1 + \frac{0.4}{2} = 0.5$$



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

$$X = 0.2 + 0.1 + 0.4 = 0.7$$

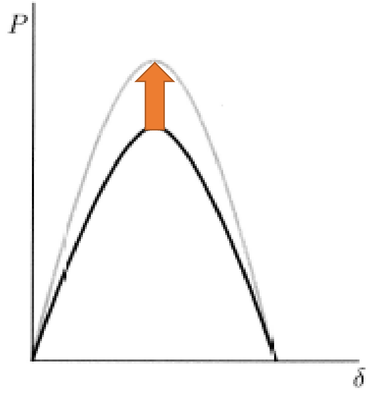
$$P = \frac{1.05}{0.7}\sin\delta = 1.50\sin\delta$$



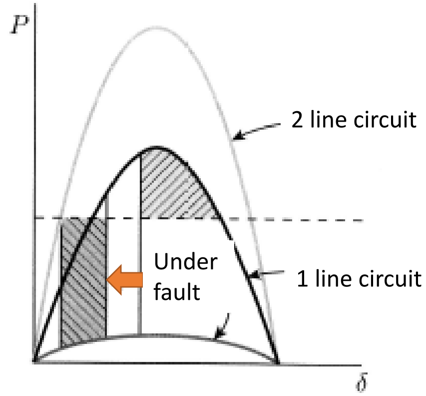
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

(a) Voltage to be High



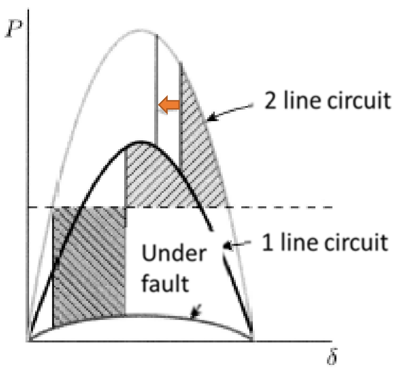
(b) High Speed Circuit Breaker



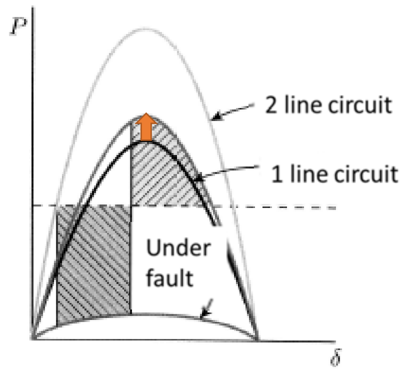
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

(c) High Speed Recloser



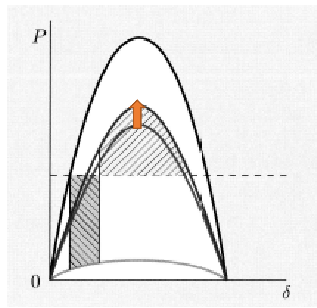
(d) High Speed AVR



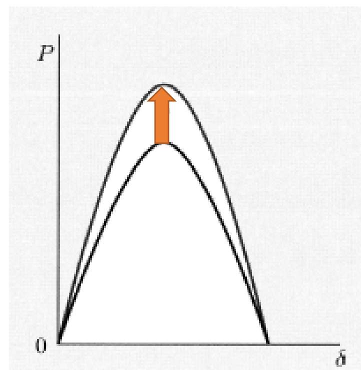
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

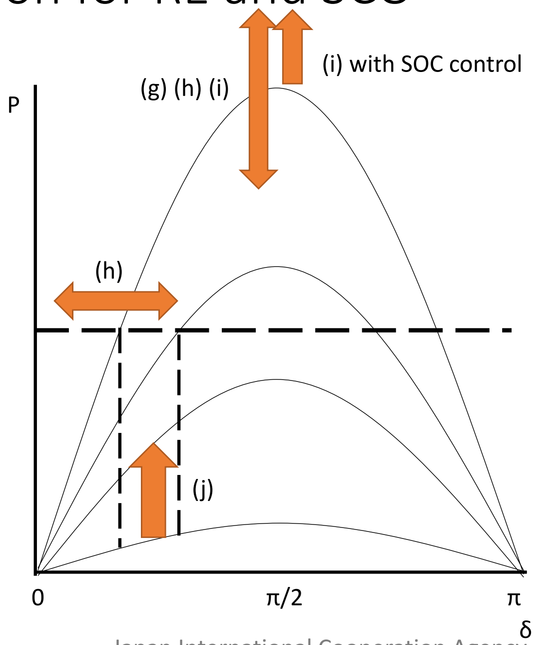
(i) Battery

Change Pmax

(j) SCO

(Synchronous Condenser)

Change P during fault



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

- Load Frequency Control (LFC)

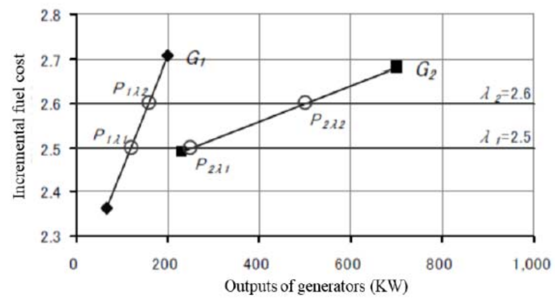
$$\Delta P = (-1/R) \times \Delta f$$

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

- Economic Load Dispatching (ELD)
  - Equal λ method

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

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



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

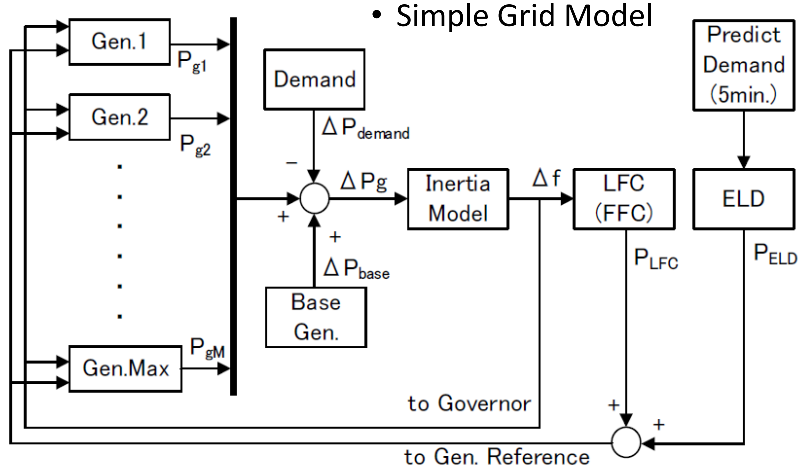


Figure is cited from MicroGrid Designer User and Technical Reference Manual

Inertia Model in Microgrid/VPP Designer

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

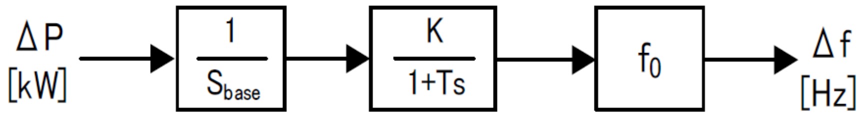
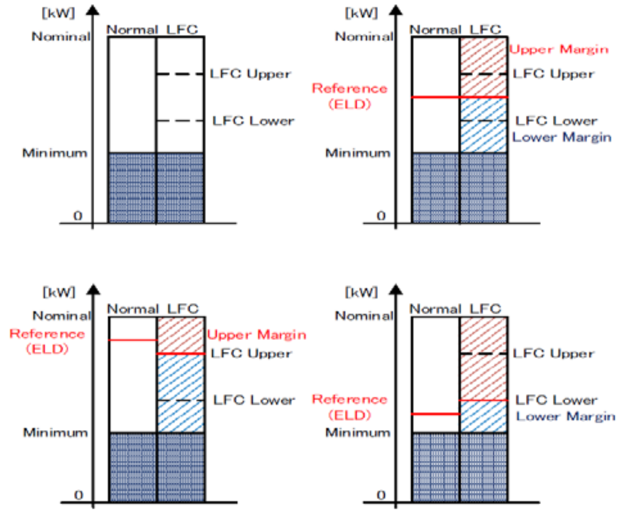


Figure is cited from MicroGrid Designer User and Technical Reference Manual

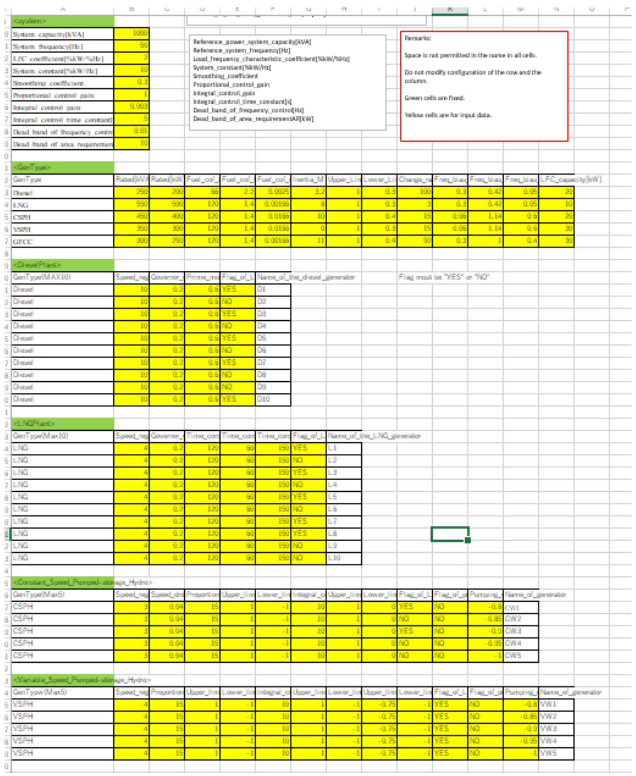
Reference of LFC & ELD

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

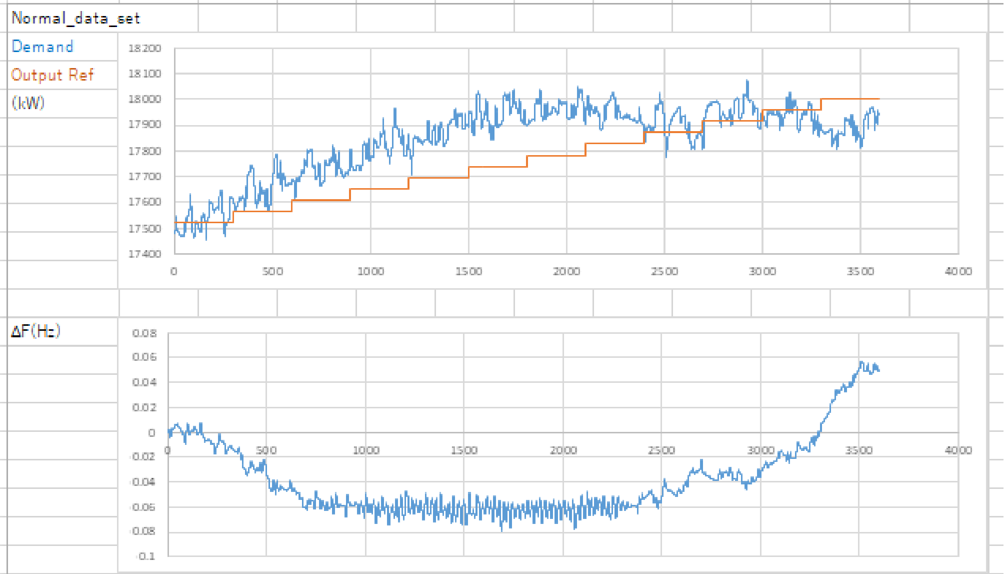


Figures are cited from MicroGrid Designer User and Technical Reference Manual

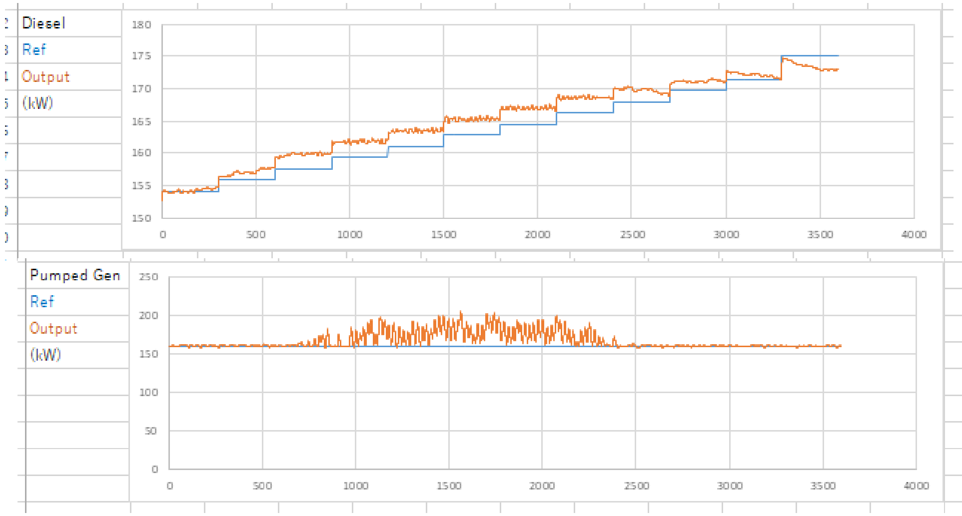
LFC Input Data



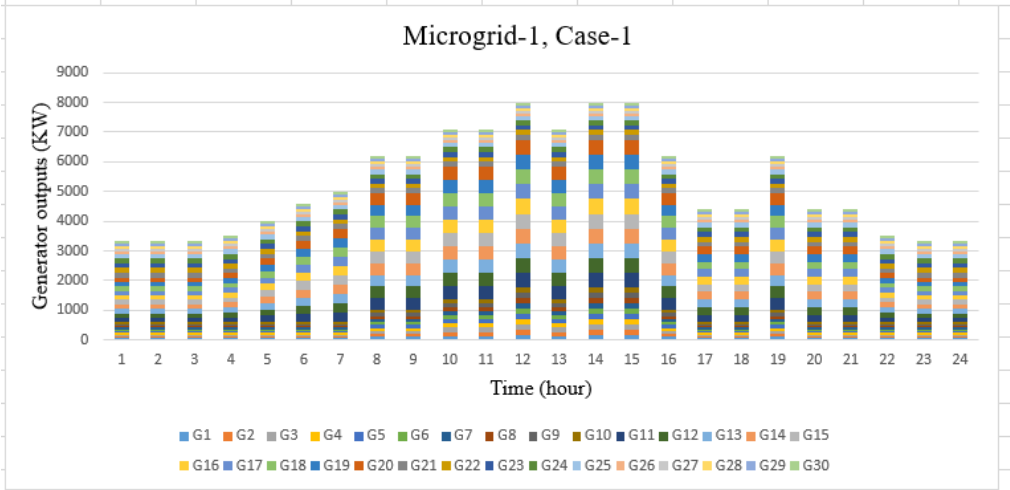
Demand and Frequency -Result of LFC-



Generator Output -Result of LFC-



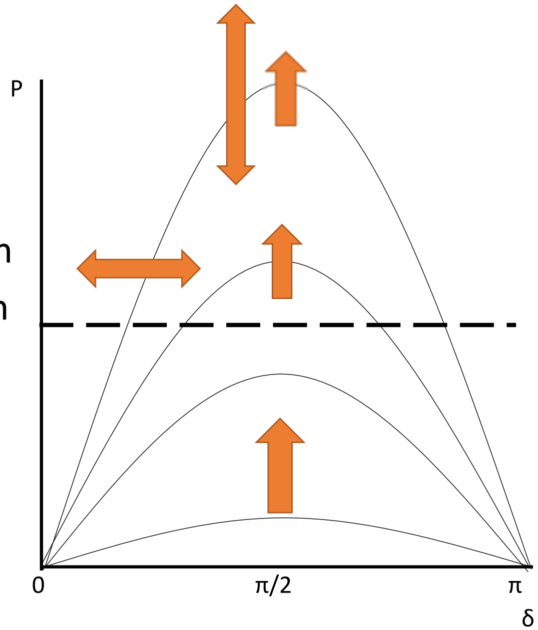
Result of ELD



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

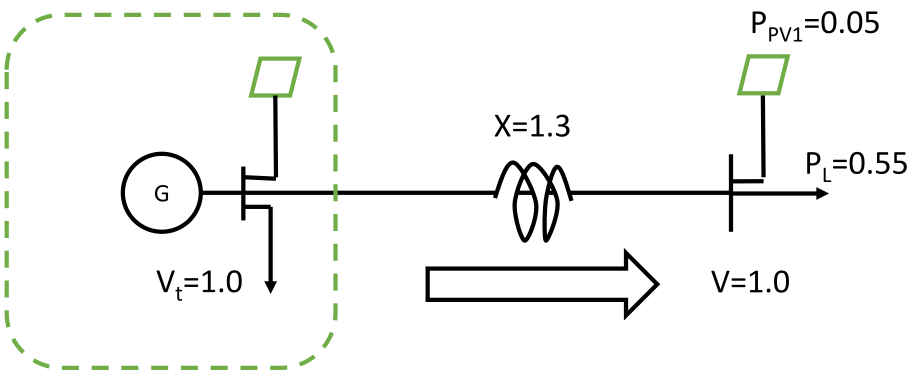


Case Study

- 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

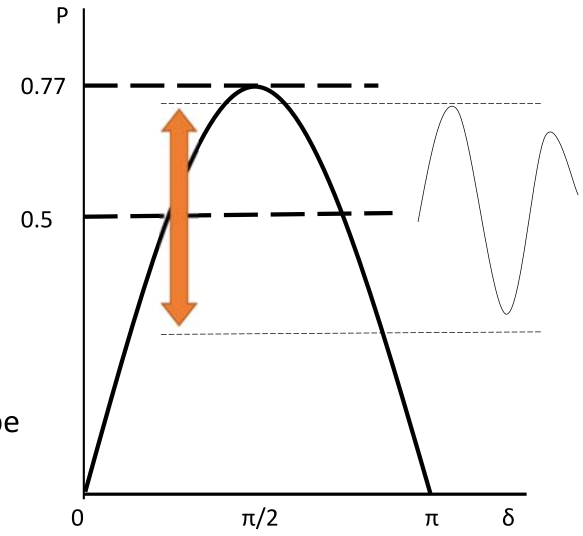
DC Flow Method: $P=\delta/X$

$0.55-0.55=\delta/1.3$

$\delta=0.65rad=37deg$

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



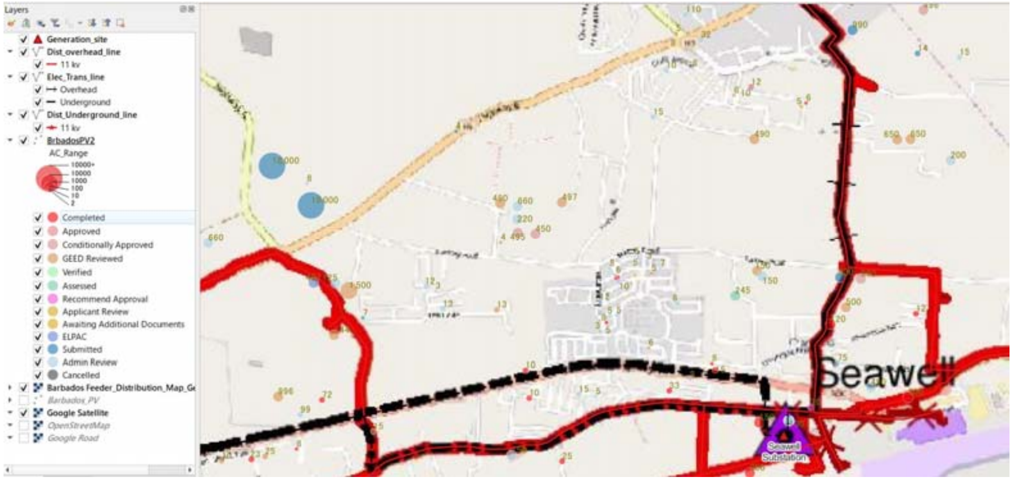
Seminar on Grid Stability with Large RE Day 3 (Exercise)

for Barbados

JICA Expert Team, Nippon Koei Co., Ltd.

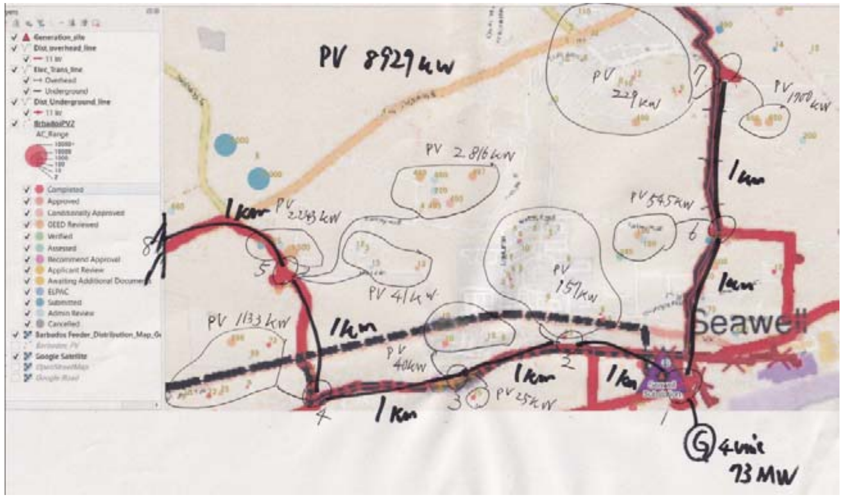
Microgrid (Coverley Villages)

Distribution Line around Coverley Villages

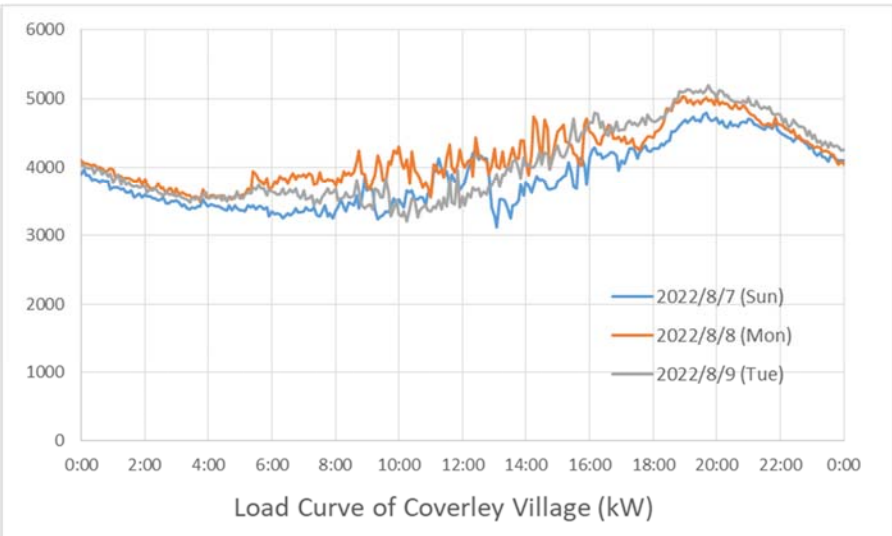


PV allocation and capacity around Coverley Villages

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.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

2nd Seminar on Grid Stability and Large RE: Q&A

Question from	Question	Answer
Day-1		
William Hinds, MEB	The installe PV is 65 MW distributed plus 10 MW by the utility	Thank you for pointing out.
Robert Goodridge, BREA	I believe BL&P utility appear to be including cost of Battery system in the rate base of the current rate hearing.	Thank you for the insites. BL&P would be discussing with regulator. The cost of battery will need to be covered by tariff.
ROBERT HAREWOOD, BLPC	I think that should be confirmed as the current battery has its own recovery mechanism which was applied for at implementation for that battery alone.	Control of battery is also important. Inverter/PCS and control requirement for battery need to be considered.
Horace Archer, MEB	I think there is a minor typo. It should be heat rate not heat late.	Thank you for pointing this out. We will make the modifications to the document
William Hinds, MEB	What is the benefit of grid forming inverters ?	This will be explained in the later session. ->Grid forming inverter is a voltage source inverter. It is also nemed by virtual synchronous generator It controls output voltage and its frequency as adjusting power to grid's, and supply virtual inertia to grid. PV, WT(Wind Turbine), EV(Electric Vehicle) and battery can be the source of grid forming inverter..
Robert Goodridge, BREA	from the first presentation, it was stated the VRE and Batteries are not sufficient for Grid Stability. Please explain this further and provide some examples of the additional devices needed for grid stability. Please also provide information on where these additional devices or technologies are currently being used. In you opinion, is the energy mix in Barbados's IRRP, realistic and effective in towards achieving Grid Stability?	IRRP includes consideration for grid stabiltiy with large RE, and proposed SCO (Synchronous Condenser) for grid for reactive power compensation.. Frequency control function is necessary to consider in the penetration of RE. For that synchronous generator is required.. PV, wind, BESS can not cope with frequency control. For IRRP, CSP (Concentrated Solar Power) which is synchronous generator is proposed for this issue. Meanwhile, grid forming inverter has that function and can provide synchronizing force together with PV and wind.
Robert Goodridge, BREA	Where has CSP been used successfully? Where has it been used on a Small Island Developing State?	CSP had a global total installed capacity of 6,800 MW in 2021, up from 354 MW in 2005 Spain accounted for almost one third of the world's capacity, at 2,300 MW, despite no new capacity entering commercial operation in the country since 2013 The United States follows with 1,740 MW. Interest is also notable in North Africa and the Middle East, as well as China and India. You can find these information from https://en.wikipedia.org/wiki/Concentrated_solar_power
Robert Goodridge, BREA	Please provide more information of grid forming inverters? what size and quantity are recommended? Where are they being used?	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 developped, according to the research institute who is
Day-2		
Pedthro Thompson	Can we use Microgrid Designer in Macbook?	We are sorry. The software is Windows only since it applies .dll file particular to Windows system.
Robert Harewood, BL&P	How is the PV output data included in power flow analysis?	In steady state analysis, PV output is just deducted from load. For multi-stage analysis, PV output variation data need to be incorporated. These various profiles are generated using a 30-min interval, as the standard in Japan.
Robert Harewood, BL&P	Can we place the battery in as a generator?	We will place in the battery in as the same as PV. It s decducted from the load, as -q.
Felcia Cox, Adaptive Intelligent Systems	We know P2=0.8 because it is a PV bus and power has been defined as 0.8? We didn't have to calculate P2, correct? Also, we're treating power like current and effectively using Kirchoff's current law? Also, Pr=d/X is used because d is assumed to be small? so sin d = d?	P2 is the set value as used in the second equation. You don't calculate P2 as variable. DC flow method is just Kirchhoff's current law by regarding AC circuit as DC circuit.
Felcia Cox, Adaptive Intelligent Systems	It was unclear about the derivation of the Power Equation for the exercise.	Prof. Taoka explained the method to create the power equation for transmission lines. The answer is to be distributed.
Day-3		
Pedthro Thompson	The total PV output according to the IRRP is over 300MW. Are you saying we should have this much conventional generation to back this up?	Thermal power or biodiesel (or biojetfuel) 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 disturbanve, battey can not support. How much thermal spinning reserve is necessary is depending on the requirement how much grid wants to avoid power cut and blackout.

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2nd Seminar on Grid Stability and Large RE: Q&A

Question from	Question	Answer
Robert Harewood, BL&P	Do we need to provide spining reserve for all RE?	It is depending on how much are you need to keep stability. If it is for small area, spining reserve coverage will be OK to be small. Another way is the combination with special protection system that includes load shedding andgenerator tripping.
Horace Archer, MEB	Can independent generator of large facility like hospital contribute stability?	It is depending on rule. If reverse flow is allowed, it can contribute for stability if it is normal operation. If the rule stipulates distributed resource must stop after accident, it can not supply to grid.
Felcia Cox, Adaptive Intelligent Systems	How can the value of c be determined? So c=b+wt where t is the time from the fault to the opening of the breaker?	C is moving point from B. It is right, but it depends on speed of relay. But relay operates with some deleay.
Felcia Cox, Adaptive Intelligent Systems	SO the area A would typically be a rectangular area but B would be the area under the sine curve?	Yes, it is Sin curve minus load.
Felcia Cox, Adaptive Intelligent Systems	Ideally wouldn't we want to limit the position of e have a phase angle of no more than pi/2? or is e simply another theoretical operating point?	Yes, voltage angle should be less than pi/2=90degree in steady state. But if phase angle δ is less than point e, it can come back to steady state due to delerelation energy.
Felcia Cox, Adaptive Intelligent Systems	The deceleration energy is the sum of the energies available from different interventions? Is AVR automatic voltage regulator?	It is mathmatical concept. It is only calculated by diference between P different condition and time. It is sumation of dP. It is force to return to stable point. Yes. AVR is automatic voltage regulator.

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Seminar on Grid Stability and Large RE: Attendant Day-1 (3 Oct 2022)

No.	Name	Position	Org.	Note
1	Adeko Collymore		Allahar Associated Ltd.	
2	Alex Harewood		JET	
3	Allison Davis		MEB	
4	Andrew Gittens	PS	MEB	
5	Angie Dorie			
6	Antiono Elcock	ELPAC Committee		
7	Bertil Browne			
8	Chandrabhan Sharma			
11	Charmaine Gill-Evans			
9	Curleane Liburd		NEVLEC	SKN
10	Curtis Morton		Physical Planning, Electrical Inspector	
12	Cyprian Moore			
13	Damian Harewood			
14	Dara Haynes Fergusson		MEB	
15	David Green			
16	Debra Dowridge	DPS	MEB	
17	Denasio Frank		Energy Unit	SKN
18	Dorian Browne			
19	Frances Scantlebury		MEB	
20	Felicia Cox			
21	Frank Branch	Technical Officer	MEB	
22	George Collin Brown			
23	Geran Liburd			SKN
24	Giovanni Buckle			SKN
25	Gleeson Roach		Willams Solar	
26	Glenn Amory		Ministry of Pulic Infrastructure	SKN
27	Haniff Woods	Operations Engineer	SKLEC	SKN
28	Heather Sealy		GEED	
29	Horace Archer		MEB	
30	Jason Andalcio			
31	Jason Clarke	Project Officer	NPC	
32	Jesse Hunkins		Planning Dept., Nevis	SKN
33	Jon Kelly		SKLEC	SKN
34	Juila Gittens			
35	Justin Taylor			
36	Kenrod			
37	Kirk King	Operations Engineer		
38	Morland Williams			
39	Natasha		UWI?	
40	Nelson Stapleton	Transmission and Dist	NEVLEC	SKN
41	Omar Allhar			
42	Paula Agbowu	DES	QEH	
43	Pedthro Thompson			
44	Prof. Hisao Taoka		JET	
45	Raoul Pemberton			

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE: Attendant Day-1 (3 Oct 2022)

No.	Name	Position	Org.	Note
46	Rhondel Phillip		SKLEC	SKN
47	Richard Goddard			
48	Robert Goodridge			
49	Robert Harewood		BLPC	
50	Ron T. Farley		Next Generation Electrical Inc.	
51	Sanjay Bahadoorsingh			MEB Consultant
52	Stuart Bannister		BNOCL	
53	Terry Neblett			
54	William Hinds			
55	Yuka Nakagawa		JET	
56	I-Ronn Audain		JET	
57	Jonathan			
58	Terrance Straughn			
59	Tyrone White		GEED?	
60	Joy Cox			
61	M. Mayers			
62	Victor			

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Seminar on Grid Stability and Large RE: Attendant Day-2 (4 Oct 2022)

No.	Name	Present	Position	Org.	Comments
1	Alex Harewood	y		JET	
2	Allison Davis	y		MEB	
3	Andrew Gittens	y	PS	MEB	
4	Angie Dorie	y			
5	Antiono Elcock	y	ELPAC Committee	MEB	
6	Bertil Browne	y	Director	Energy Unit	SKN
7	Charmaine Gill-Evans	y	System Engineer	BLPC	
8	Curleane Liburd	y	HR Manager	NEVLEC	SKN
9	Curtis Morton	y	Electrical Inspector	Physical Planning, NIA	SKN
10	Cyprian Moore	y			
11	Damian Harewood	y	Technical Officer	MEB	
12	Dara Haynes Fergusson	y		MEB	
13	Debra Dowridge	y	DPS	MEB	
14	Denasio Frank	y		Energy Unit	SKN
15	Frances Scantlebury	y	Admin	MEB	
16	Felicia Cox	y	CEO	Adaptive Intelligence Energy	
17	Frank Branch	y	Technical Officer	MEB	
18	George Collin Brown	y			
19	Geran Liburd	y	Lines Manager	NEVLEC	SKN
20	Giovanni Buckle	y	Junior Engineer	CCREEE	SKN
21	Gleeson Roach	y	General Manager	Willams Solar	
22	Glenn Amory	y	Senior Assistant Secretary	Ministry of Pulic Infrastructure	SKN
23	Haniff Woods	y	Operations Engineer	SKLEC	SKN
24	Heather Sealy	y	Deputy Chief Electrical Officer	GEED	
25	Horace Archer	y	Senior Technical Officer	MEB	
26	Jason Andalcio	y	Junior Engineer	CCREEE	
27	Jason Clarke	y	Project Officer	NPC	
28	Jesse Hunkins	y		Planning Dept., Nevis	SKN
29	Jon Kelly	y		SKLEC	SKN
30	Juila Gittens	y	Admin	MEB	
31	Justin Taylor	y	Junior Engineer	CCREEE	
32	Kenrod	y			
33	Kirk King	y	Operations Engineer		
34	Morland Williams	y	Mechanical Engineer	GAIA	
35	Nelson Stapleton	y	Transmission and Distribution Manager	NEVLEC	SKN
36	Paula Agbowu	y	Director of Engineering Services	QEH	
37	Pedthro Thompson	y	RE Lead	Emera Caribbean	
38	Prof. Hisao Taoka	y		JET	
39	Rhondel Phillip	y		SKLEC	SKN
40	Robert Goodridge	y	President	BREA	
41	Robert Harewood	y	System Engineer	BLPC	
42	Ron T. Farley	y	Managing Director	Next Generation Electrical Inc.	
43	Stuart Bannister	y	Renewable Energy Coordinator	BNOC	

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE: Attendant Day-2 (4 Oct 2022)

No.	Name	Present	Position	Org.	Comments
44	Terry Neblett	y	Licensing Officer	MEB	
45	Yuka Nakagawa	y		JET	
46	I-Ronn Audain	y		JET	
47	Joy Cox	y	CFO	Adaptive Intelligence Energy	
48	Natasha Corbin	y	Project Officer	UWI	

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Seminar on Grid Stability and Large RE: Attendant Day-3 (5 Oct 2022)

No.	Name	Present	Position	Org.	Comments
1	Alex Harewood	y		JET	
2	Allison Davis	y		MEB	
3	Andrew Gittens	y	PS	MEB	
4	Angie Dorie	y			
5	Antiono Elcock	y	ELPAC Committee	MEB	
6	Bertil Browne	y	Director	Energy Unit	SKN
7	Charmaine Gill-Evans	y	System Engineer	BLPC	
8	Curleane Liburd	y	HR Manager	NEVLEC	SKN
9	Curtis Morton	y	Electrical Inspector	Physical Planning, NIA	SKN
10	Cyprian Moore	y			
11	Damian Harewood	y	Technical Officer	MEB	
12	Dara Haynes Fergusson	y		MEB	
13	Debra Dowridge	y	DPS	MEB	
14	Denasio Frank	y		Energy Unit	SKN
15	Frances Scantlebury	y	Admin	MEB	
16	Felicia Cox	y	CEO	Adaptive Intelligence Energy	
17	Frank Branch	y	Technical Officer	MEB	
18	George Collin Brown	y			
19	Geran Liburd	y	Lines Manager	NEVLEC	SKN
20	Giovanni Buckle	y	Junior Engineer	CCREEE	SKN
21	Gleeson Roach	y	General Manager	Willams Solar	
22	Glenn Amory	y	Senior Assistant Secretary	Ministry of Pulic Infrastructure	SKN
23	Haniff Woods	y	Operations Engineer	SKLEC	SKN
24	Heather Sealy	y	Deputy Chief Electrical Officer	GEED	
25	Horace Archer	y	Senior Technical Officer	MEB	
26	Jason Andalcio	y	Junior Engineer	CCREEE	
27	Jason Clarke	y	Project Officer	NPC	
28	Jesse Hunkins	y		Planning Dept., Nevis	SKN
29	Jon Kelly	y		SKLEC	SKN
30	Juila Gittens	y	Admin	MEB	
31	Justin Taylor	y	Junior Engineer	CCREEE	
32	Kenrod	y			
33	Kirk King	y	Operations Engineer		
34	Morland Williams	y	Mechanical Engineer	GAIA	
35	Nelson Stapleton	y	Transmission and Distribution Manager	NEVLEC	SKN
36	Paula Agbowu	y	Director of Engineering Services	QEH	
37	Pedthro Thompson	y	RE Lead	Emera Caribbean	
38	Prof. Hisao Taoka	y		JET	
39	Rhondel Phillip	y		SKLEC	SKN
40	Robert Goodridge	y	President	BREA	
41	Robert Harewood	y	System Engineer	BLPC	
42	Ron T. Farley	y	Managing Director	Next Generation Electrical Inc.	
43	Stuart Bannister	y	Renewable Energy Coordinator	BNOC	
44	Terry Neblett	y	Licensing Officer	MEB	

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Seminar on Grid Stability and Large RE: Attendant Day-3 (5 Oct 2022)

No.	Name	Present	Position	Org.	Comments
45	Yuka Nakagawa	y		JET	
46	I-Ronn Audain	y		JET	
47	Joy Cox	y	CFO	Adaptive Intelligence Energy	
48	Natasha Corbin	y	Project Officer	UWI	

Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

3rd Seminar on Grid Stability and Large RE
Barbados / St. Kitts and Nevis

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

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

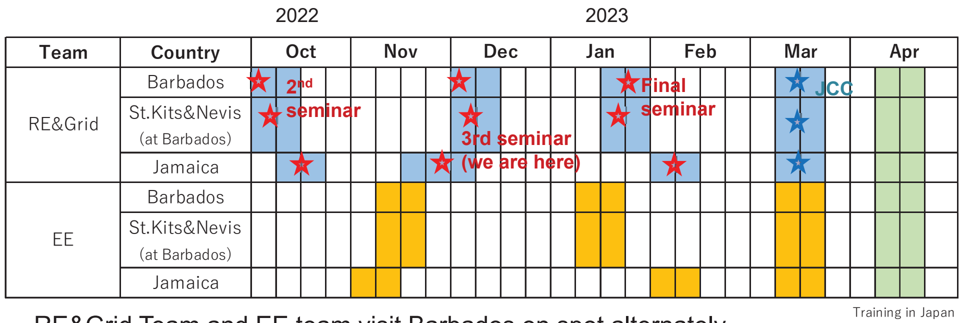
Output 3
The human and institution capacity are enhanced for the mass introduction of RE

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



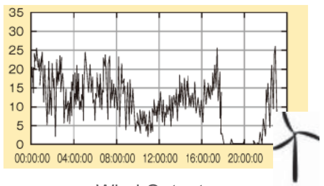
- RE&Grid Team and EE team visit Barbados on spot alternately.
- 1st Seminar on Grid Stability and RE (Introduction, Barbados only) on 27 Jul 2022
- 2nd Seminar on Grid Stability and RE on 3-5 Oct 2022
- **3rd Seminar on Grid Stability and RE on 6-7 Dec 2022**

  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

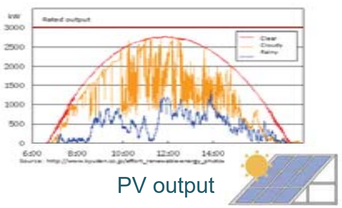
Outline and Agenda for 3rd Seminar on 6 - 7 Dec 2022

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)

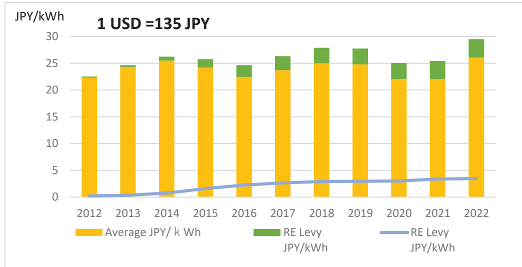
Both (VRE):
- It does not always generate when needed. **Load-supply matching** is an issue
- Time coincidence of VRE, there can be times when there is too much supply. Curtailment of VRE is necessary →**energy storage/control cost need to be considered.**

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

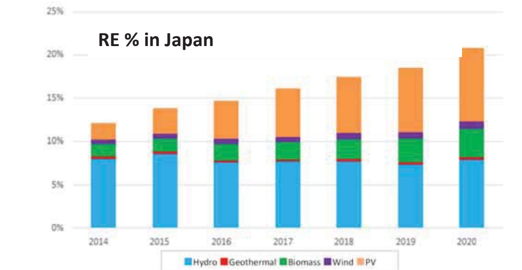
Is the increase in RE penetration so far helping or hurting electricity price?



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 ??



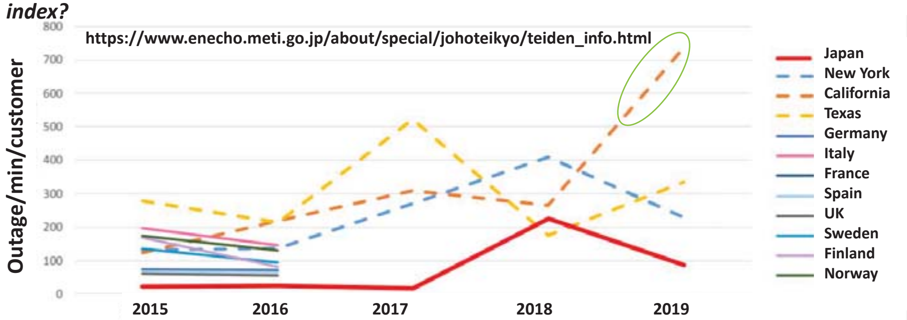
Prepared by JET from METI and Enetech data

Power Tariff in Germany (Usc/kWh)

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

Outage trend and VRE affect on Outage

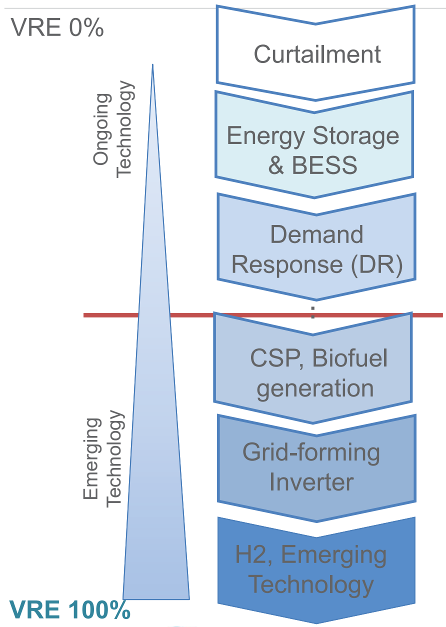
Has the increase in RE penetration begun to affect the momentary interruption(MAIFI) index?



- 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

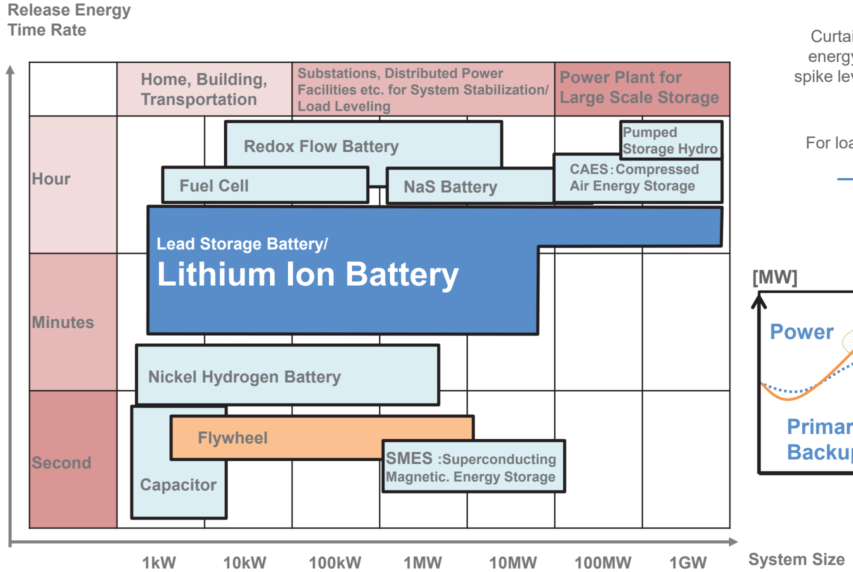
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- **Synchronous condenser, Statcom**
- EV charging time shift
- Demand side management
- Regulatory framework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

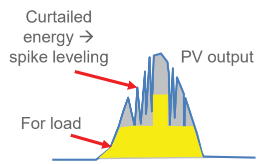
Insufficient Inertia, Synchronizing Force

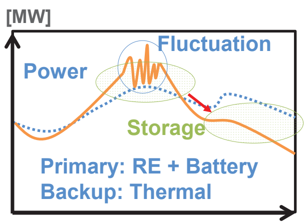
- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale storage

Battery and Energy Storage

Positioning for Energy Storage Technology



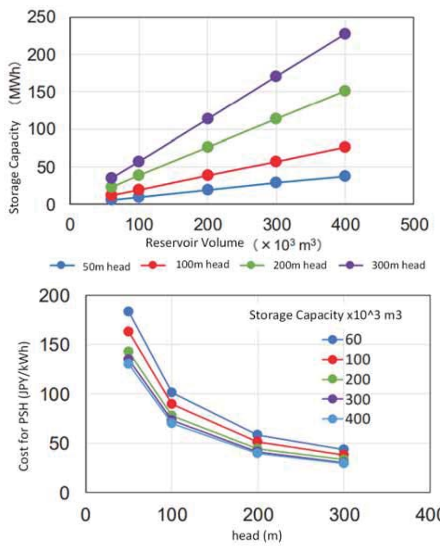




Source: NEDO Renewable Energy Technology White Paper Chapter 9

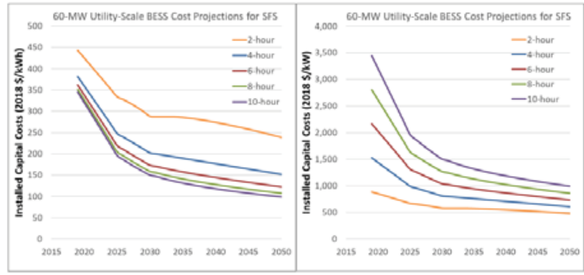
Pumped Storage vs Li-Battery

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%

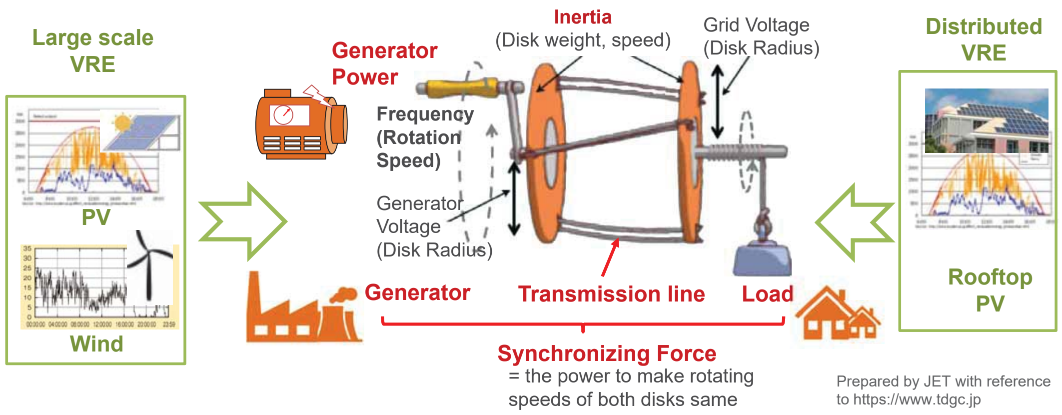
DoD: Depth of Discharge



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

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

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.

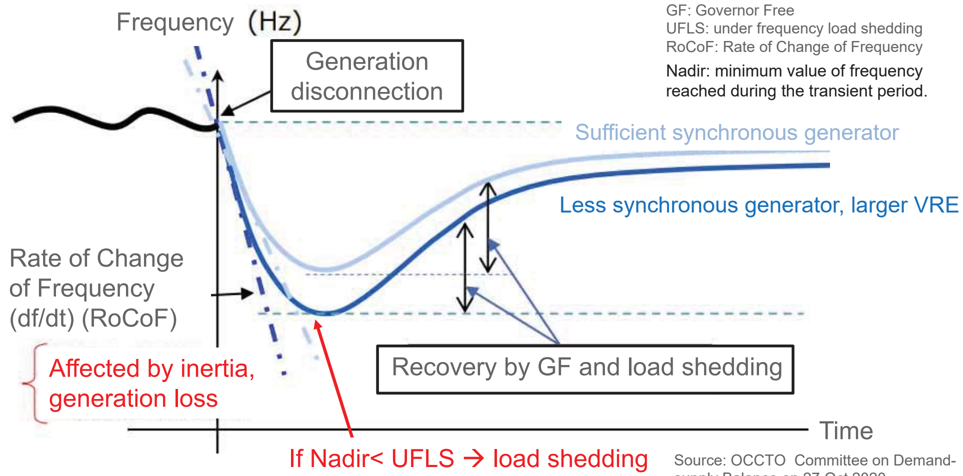
Fluctuation of large scale VRE affects to generator at generation side and load side

→ 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

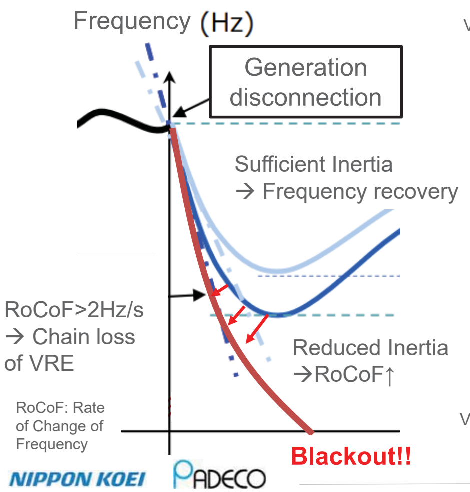
Black-out when insufficient Sync. Gen.

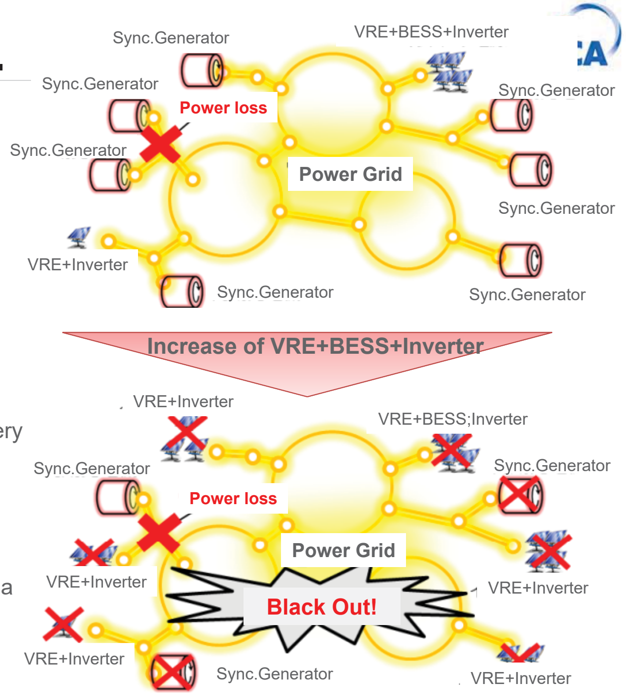
If synchronous generator is reduced and inertial is not sufficient, power loss

→ Frequency drop, with no recovery

→ Chain reaction of loss of VRE

→ **Black out**





Source: Transmission and Grid Council, Japan

SCO and STATCOM for Reactive Power

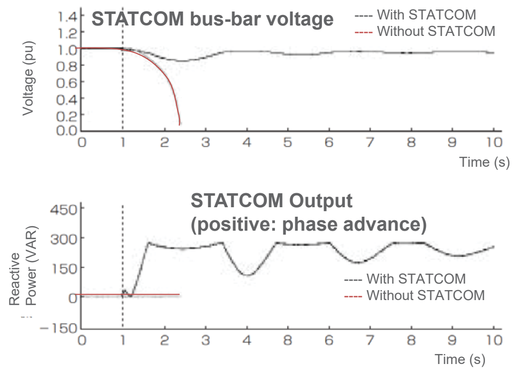
SCO (Synchronous Condenser) :

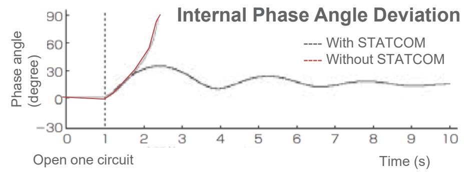
SCO is DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. Though changing field excitation, SCO adjusts reactive power and provides reactive power at the time of voltage drop.

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.

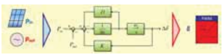




Source: Enhancement of Steady−State Stability and Suppression of Over−Voltage using 450MVA GCT−STATCOM, Mitsubishi Denki Giho, pp.52-55, Vol.87, No.11, 2013.

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

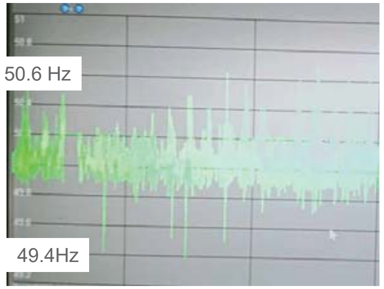
Emerging technology for large RE with Grid stabilization : Generation with Inertia and Synchronous Power

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.

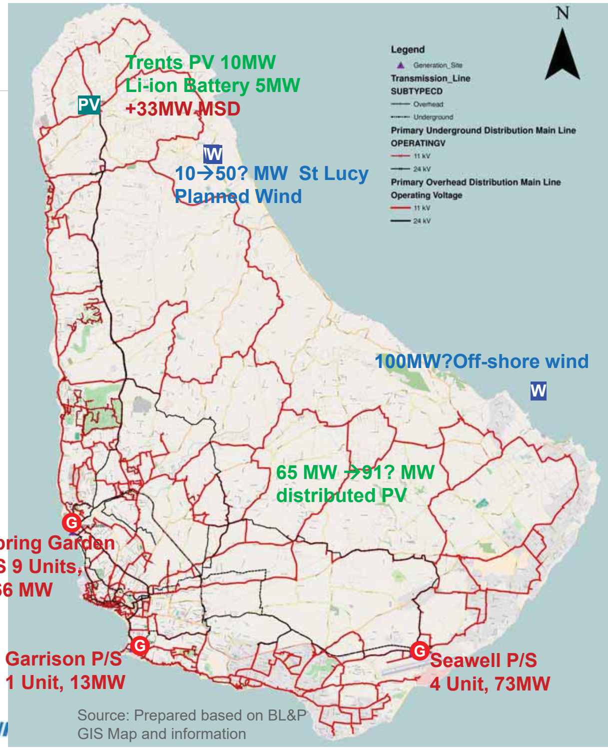
	Question	Feedback
A1	Place, capacity and function of Battery	• For large PV station, battery is effective to decrease the fluctuation caused by uncertain change of sunshine. • For small PV such as roof top home PV, battery had better to be located to neighboring substation with another roof top PV. • 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



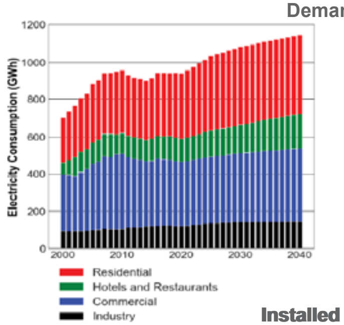
Location	MW/u	Qy	MW	Remark
Existing				
Total thermal power			265	
Spring Field Total		9	166	LDS, ST, GT
Garrison	13	1	13	Gas Tubine
Seawell	13	1	13	Gas Tubine
Seawell	20	2	40	Gas Tubine
Trents	8.3	4	33	MSD Engine
Total PV			75.6	
Trents	10	1	10	PV
Distributed PV	LS		65.6	PV
Total Battery			5	
Trents	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

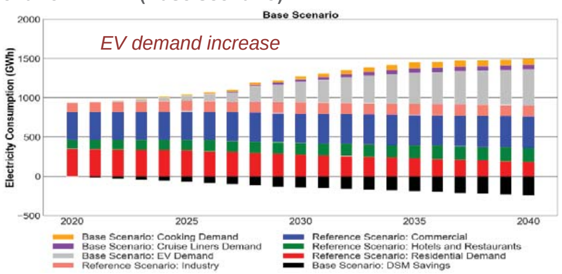
Tentative. Please let us confirm the status and update if any.

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

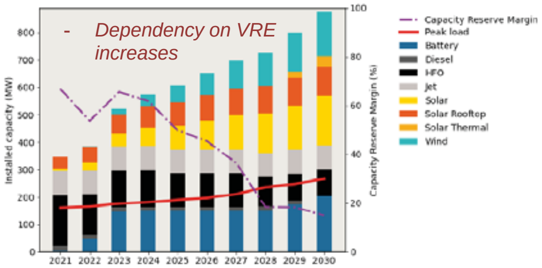
Source: IRRP Draft 2021, MottMacDonald

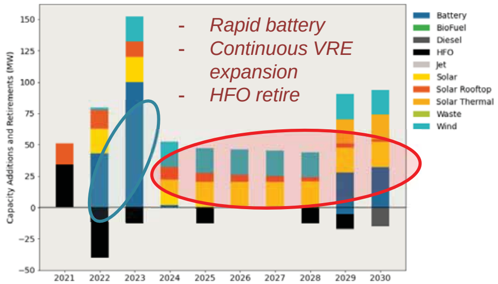
Demand Scenario in IRRP (Base scenario)





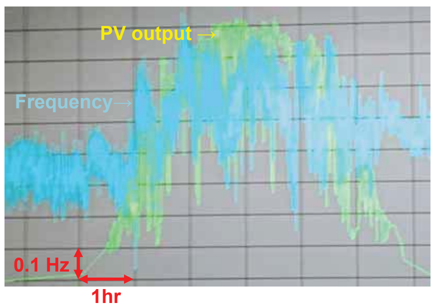
Installed capacity and capacity addition in IRRP (Base Case)

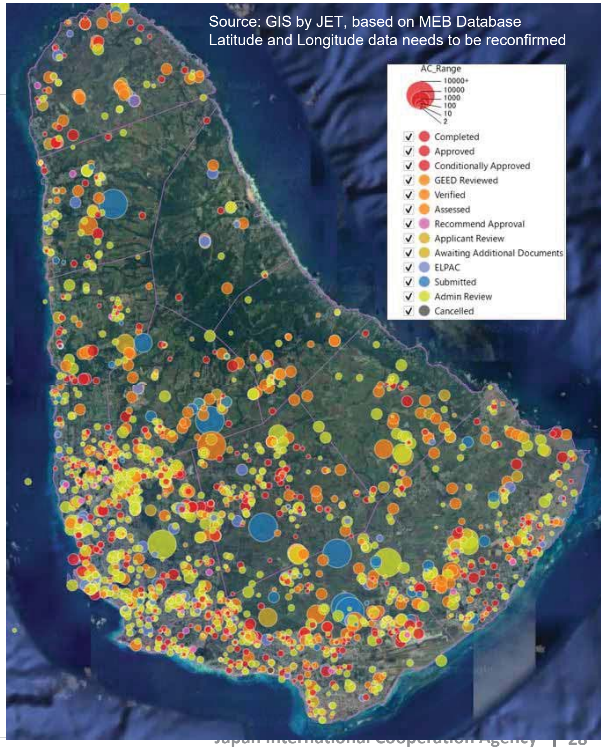




PV and Fluctuation of Frequency in Barbados

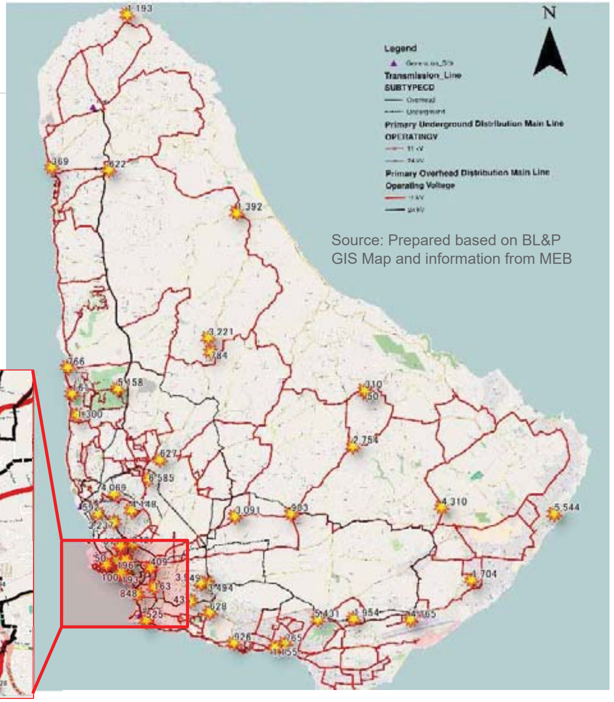
- Currently 65MW distributed PV, to be increased to 91MW.
- Frequency fluctuation
- It needs for confirmation of feeder holding capacity considering fluctuation
- Utility Scale PV is planned for future





PV and Feeder capacity

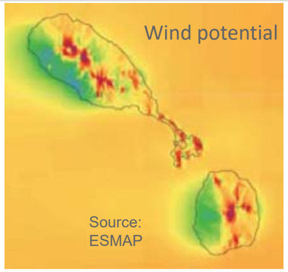
- Can the feeder accommodate distributed PV
- Distributed PV 65 MW at present , increased to be 91 MW near future
- Feeder-wise capacity assessment is necessary in grid simulation

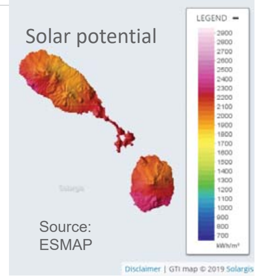


Present Situation and Future Planing of St. Kitts and Nevis

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





Necessary consideration for future RE

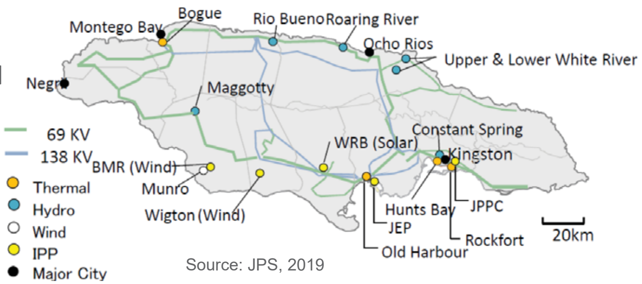
1) Grid stability analysis for new 35MW PV system
2) Update of geothermal development
3) Interconnection (11kV, 66 kV)?

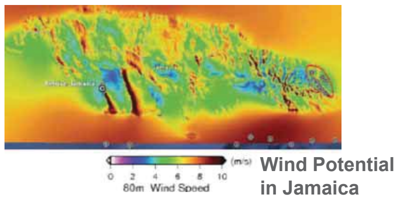
Phase	Nevis Geothermal and Grid Interconnection Plan (provisional)
Phase-1	Power Grid Reinforcement from 11kV to 66kV
Phase-2	Expand 66kV, 30 MW Geothermal at N3, Connect into St. Kitts Power System
Phase-3	Hydrogen Based Project at Long Point, Install 15 MW Geothermal at N3
Phase-4	66KV from Long Point 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: Sustainable Energy Roadmap 2013

VRE Projects in Jamica

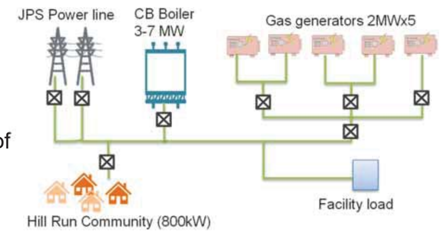
Location/Project		Capacity MW	Generation GWh estimated	Year	Tariff USc/kWh	Investment mil USD
Wigton Ⅰ	Wind	20.7	52	2004	10.21	26
Wigton II	Wind	18	47	2010	10.723	45
Wigton III	Wind	24	63	2016	13.4	46.5
Munro	Wind	3	10.5	2010	(JPS)	
BMR Wind	Wind	36.3	120	2016	12.9	90
Content Solar (WRB)	PV	20	34	2016	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: Prepared by JET with several data sources

Difficulty due to VRE and Good Practice of Jamaica

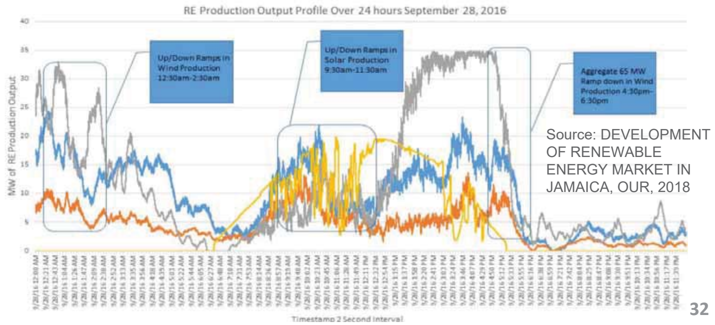
To cope with ＞140MW VRE for 650 MW peak grid in 2016, JPS took following measurement:

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

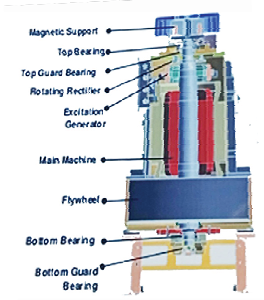
JPS System Control Center

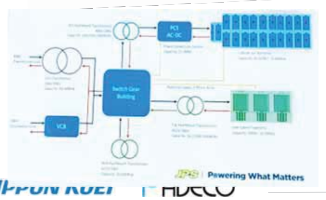


Source: DEVELOPMENT OF RENEWABLE ENERGY MARKET IN JAMAICA, OUR, 2018

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

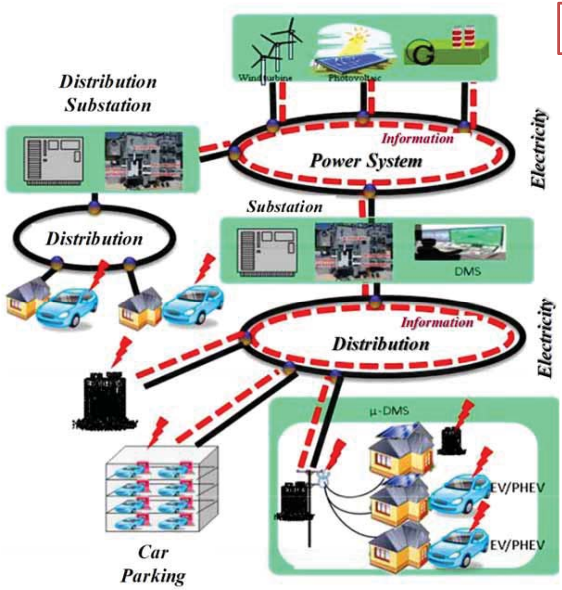
23 Aug 2018 Awaji, Japan
https://www.sankei.com/west/news/180828/wst1808280043-n1.html
600 kW, Fallen at 25.6m/s wind while 60m/s design
- Additional moment due to Excess of high speed
- Missing control power supply

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

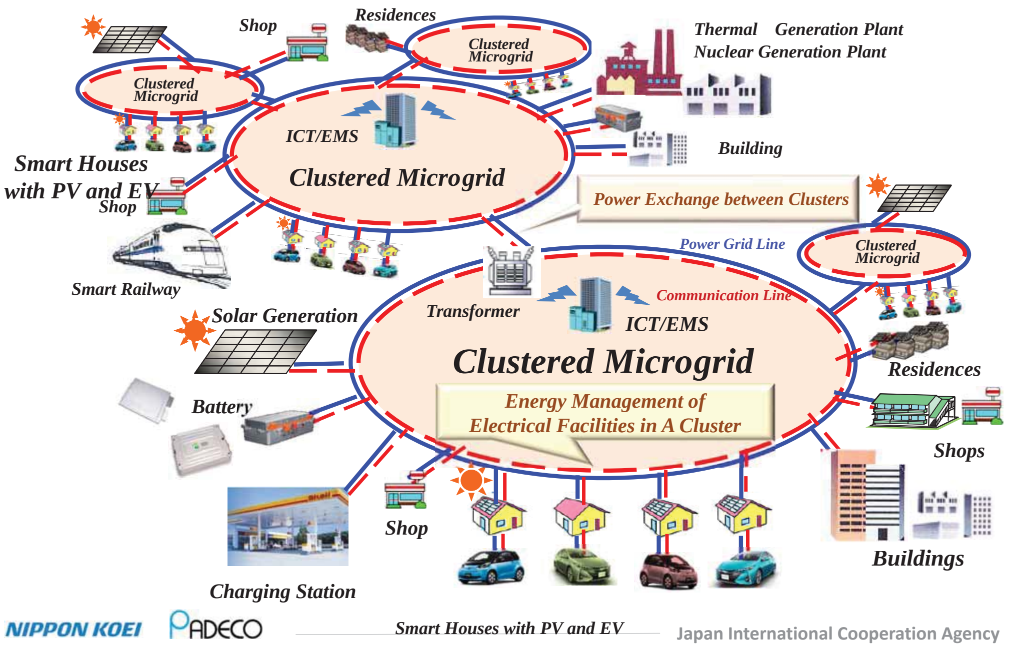


Concept of Micro-grid

- ✓ 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.

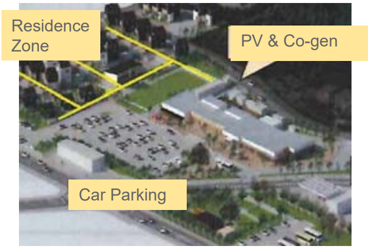
Microgrid for Resilient System
-- Autonomous Micro Grid



Microgrid Planning

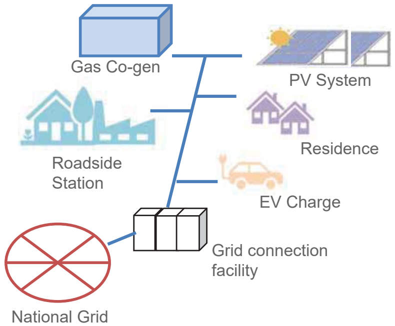
1	**Study for legal requirement of regulators considering affect on transmission line outside of Microgrid**	- Legal requirement for microgrid by the regulatory authority - Method for emergency recovery, switching from microgrid to master grid, Affect on adjacent areas.
2	**Estimation of load and demand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

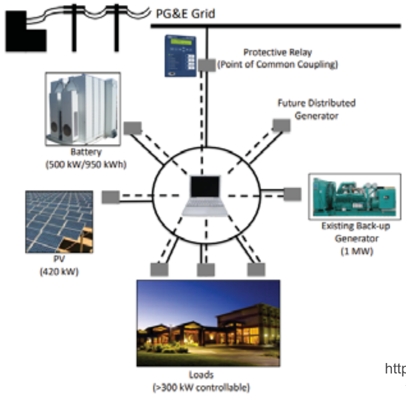
- Gas co-generation (80kWx2), PV system (20kW), Solar heating (37 kW) EV charger,
- Independent power supply for residence zone
- Thermal supply for hot spring by co-gen
- Microgrid area connected with grid
- Continuous supply during Typhoon (large scale regional power cut approx. 1 week) in Sep 2019
  - 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%, $170,000 of electricity saving in 2018



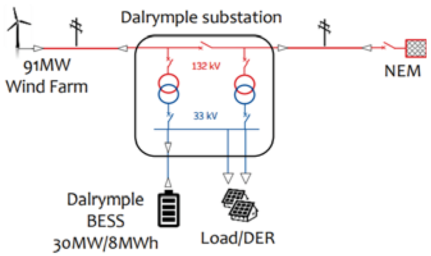
Component	Spec/details
Schedule	July 2015 – March 2018
Utility	PG&E
Generation	PV 420 kW and back up DG 1MW
Inverter	SMA TP30-TL-US10
BESS	500kW/950 kWh Tesla Powerpack
Control (EMS)	Siemens Spectrum Power TM MGMS
Project cost	USD6.32 million

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
- 91 MW Windfarm provides power
- BESS provides virtual inertia, reactive power compensation, and black start function
- System provides ancillary service with frequency adjustment



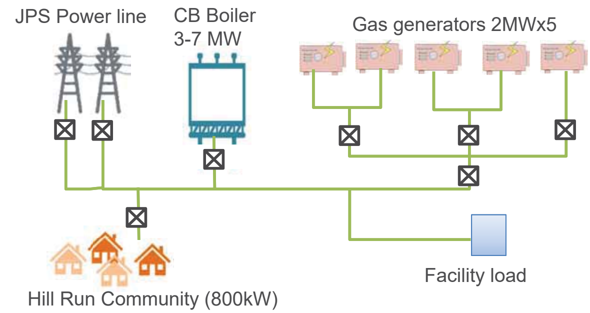
Grid Forming Energy Storage System addresses challenges of grids with high penetration of renewables (A case study), CIGRE, 2020

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)

Microgrid Ex.-4: Jamaica Caribbean Boiler-JPS

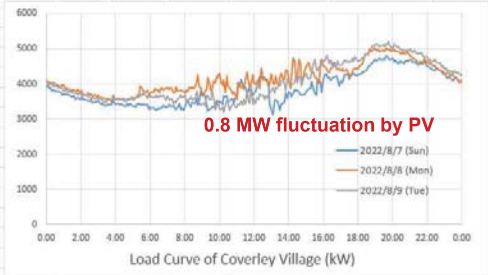
- Microgrid with Combined heat and power (CHP) generation plant and supply to community
- The exhaust heat converted into energy and improve efficiency
- improve its operational efficiency and reliability.
- 5 generators + CB boilers
- Provides power to Hill Run community
- 30% CO2 reduction by fuel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



Load Curve of Coverley Village (kW)

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

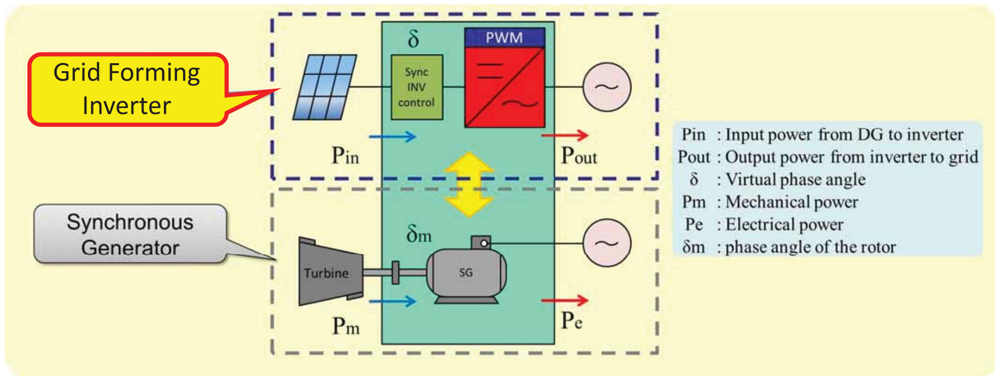
Simple Method of Grid Stability Evaluation

- 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.

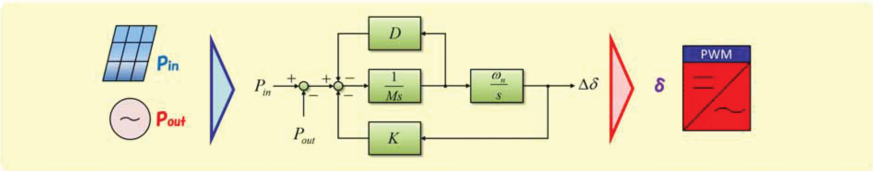
$$\frac{M}{\omega_n}\frac{d^2\delta_m}{dt^2}+\frac{D}{\omega_n}\frac{d\delta_m}{dt}+K\delta_m=P_m-P_e$$

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)

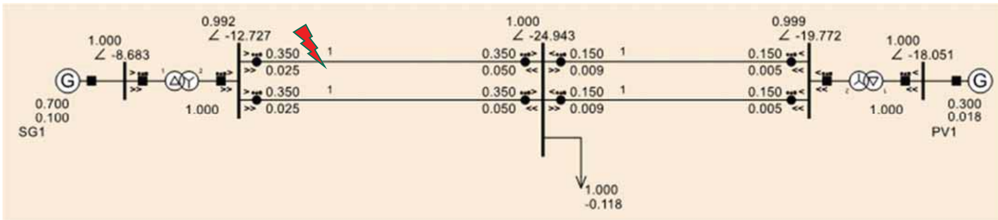
- SCR is the factor to be considered in large RE penetration for grid stability.
- SCR=AC System Capacity/Rated IBR Capacity
  - SCR>3 -------- High SCR, Stable
  - 3>SCR>2 ----- Low SCR
    Small fluctuation continues.
  - 2>SCR -------- Very Low SCR
    Sensitivity of IBR to Grid goes high.
    Grid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

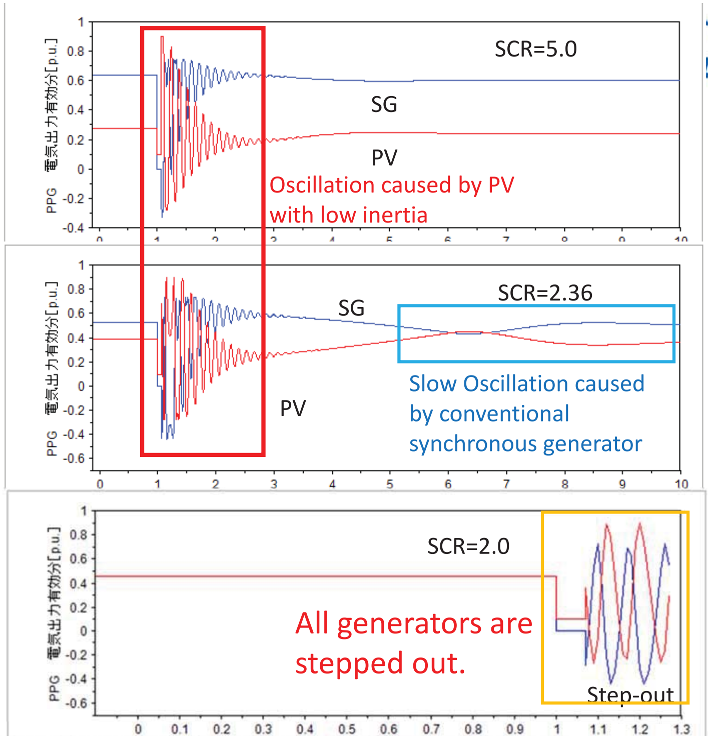


Calculated by CPATFree(CRIEP's Power System Analysis Tools

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

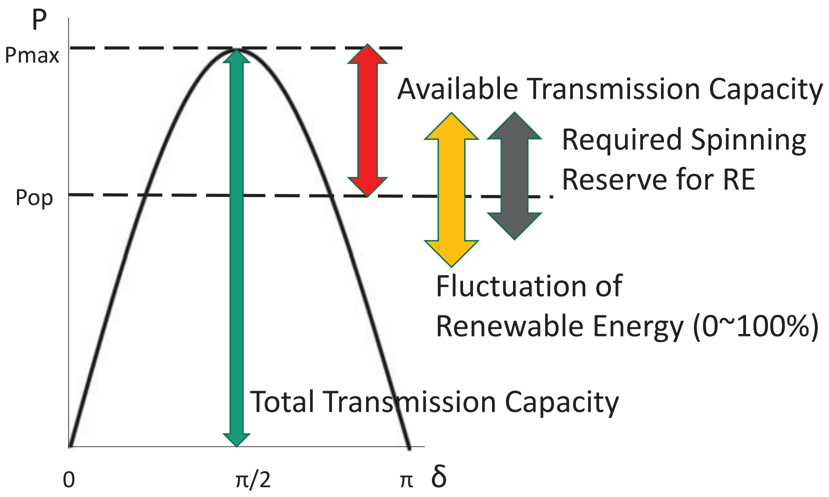
(4) Spinning Reserve

- 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

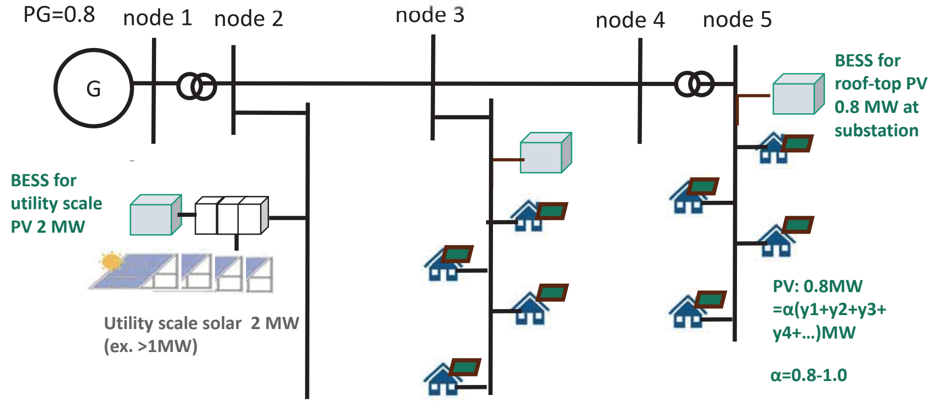
  -> Energy mix of several resources is highly recommended for improving grid stability.
- **RE Sources for Spinning Reserve**
  - **EV, Battery, Fly Wheel -> Short period, Quick response**
  - **Biofuel or Diesel Generator -> Long period, Slow response**

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

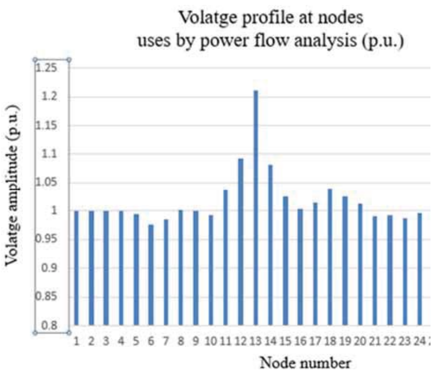
Costs and Benefits ($/year)	Capacitor Banks (5.0 MVAR)	Small Generator Retrofitted to Synchronous Condenser (5.0 MVAR)
Capital Cost	$22,000	$50,000
Technology Life Time	10 years	20 years
Preventive Maintenance Cost	$6,000	$3,500
Cost of Voltage Regulator Maintenance	$6,600	$3,300
Annual Cost in Present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

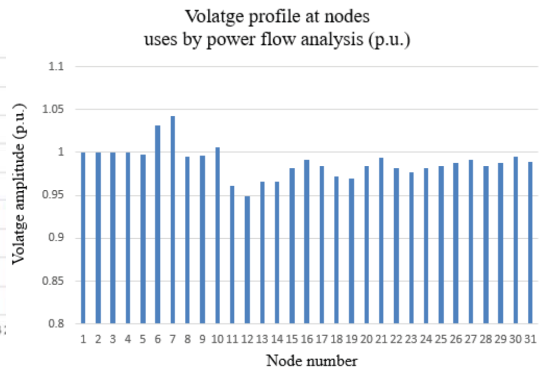
Famous O. Igbinovia, Ghaeth Fandi, Zdenek Müller, Jan Švec, Josef Tlusty,
“Cost implication and reactive power generating potential of the synchronous condenser”
2016 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG)

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

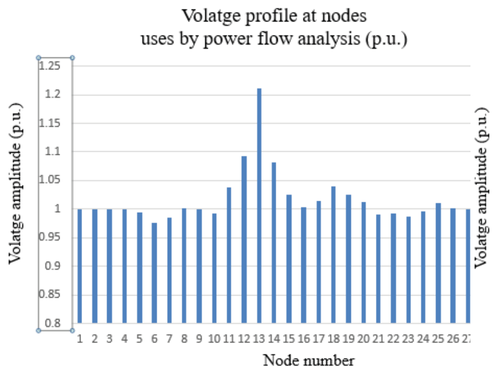
without Battery in end nodes　　　　with Battery in end nodes

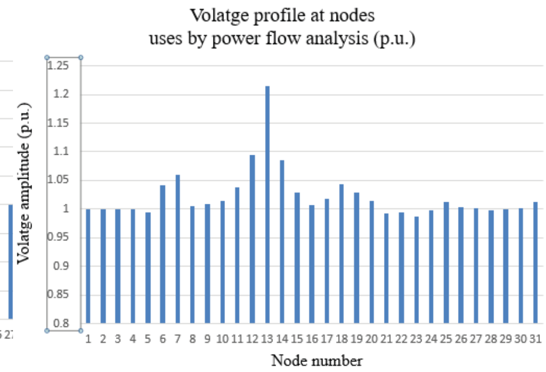
Wind turbine is located at node 13, which is north east area.
Because of no measures in an estimated grid, the voltage is high.
Battery is a good solution to keep grid voltages as appropriate values.

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

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

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

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

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

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

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

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

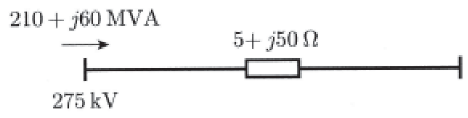
V: Voltage, I: Current, Z: Impedance
Vbase: Base Voltage, Ibase: Base Current
Zbase: Base Impedance, Ybase: Base Admittance
(VA)base: Base Apparent Power
Vp: Per Unit Voltage, Ip: Per Unit Current
Zp: Per Unit Impedance

Example of Conversion to Per Unit

(1) Calculate Base Value

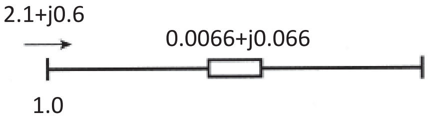
Vbase=275kV

(VA)base=100MVA



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

(2) Change Actual Value to Per Unit Value



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

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

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

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

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

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

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

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

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

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=$\sqrt{0.42*0.42+0.83*0.83}$=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

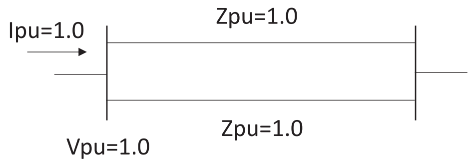
Ipu: Current in Per Unit

Zpu: Impedance in Per Unit

Rpu: Resistance in Per Unit

Xpu: Reactance in Per Unit

2 Circuit Transmission Line

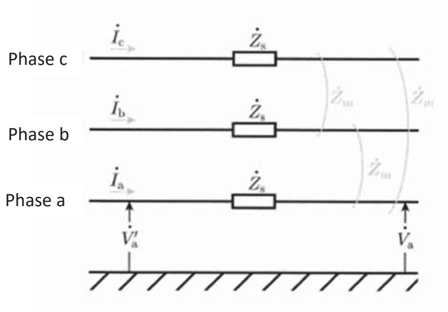


2. Modeling of Power System Equipment

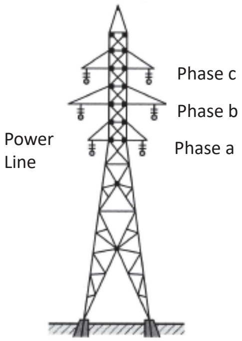
- Make it easy to analyze feature of power system equipment
- Modeling of Components of Power System
  - Transmission Line
  - Synchronous Generator
  - PV(Photovoltaic Generator)
  - WT(Wind Turbine Generator)
  - Load

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)

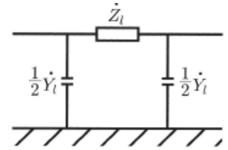


Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

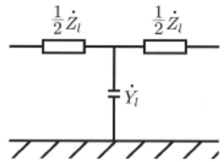
Equivalent Circuit of Transmission Line

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.

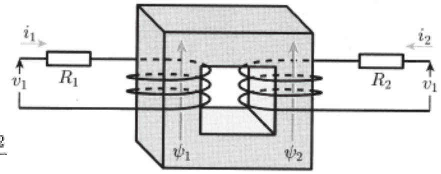
Transformer

- 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

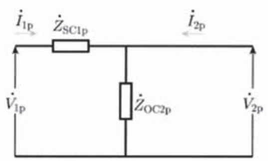
- Relationship of per unit base values

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

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

- 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 $\dot{E}_g = E_g e^{j\delta}$

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

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

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 (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

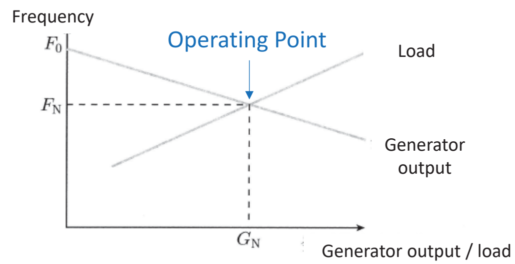


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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.

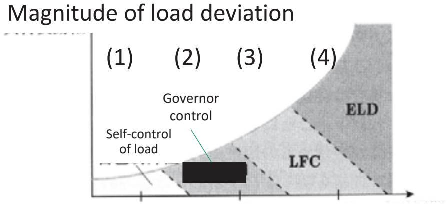
(3) Load Frequency Control

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

ΔPG = (K1+K2/s)Δf

(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.

$$\%K_G = \frac{100}{F_0 - F_N} \; \%\mathrm{MW/Hz} \qquad \varepsilon = \frac{F_0 - F_N}{F_N} \times 100\,\%$$

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

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

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

F0: Rated Frequency

FN: Current Frequency

ΔG: Generator Output Change

ΔL: Load Change

ΔP: Chang of Power

ΔF: Change of Frequency

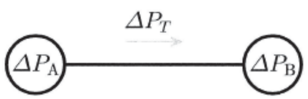
KG: Gain for Generator Output Change

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 Change

KL: Gain for Load Change

K: Power-Frequency Coefficient

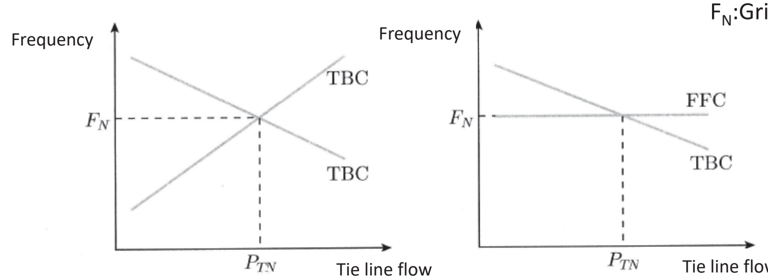
Figure is cited from

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

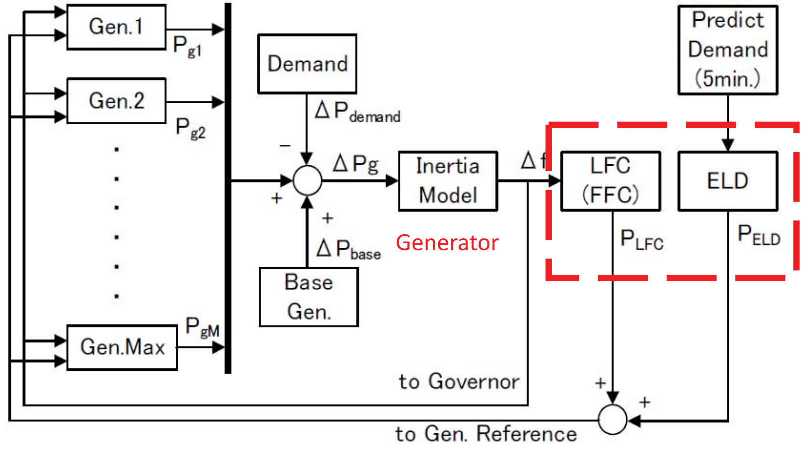
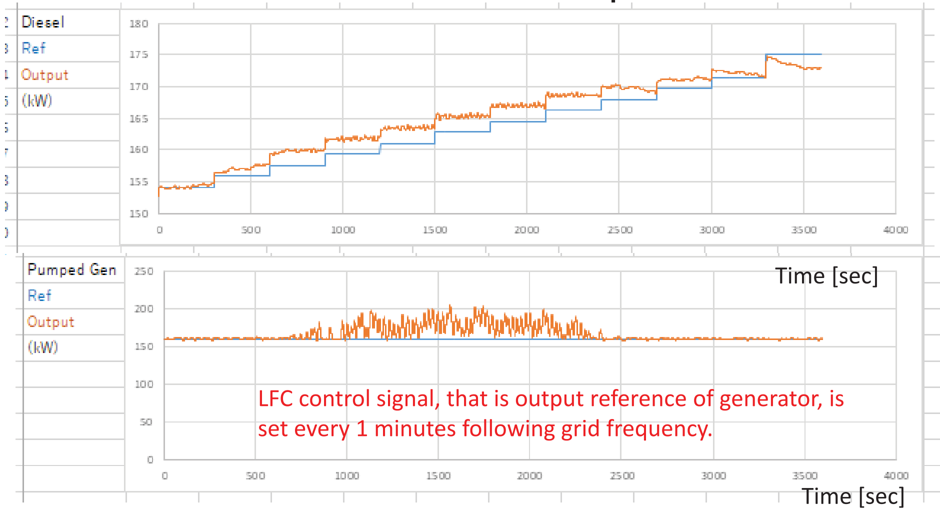


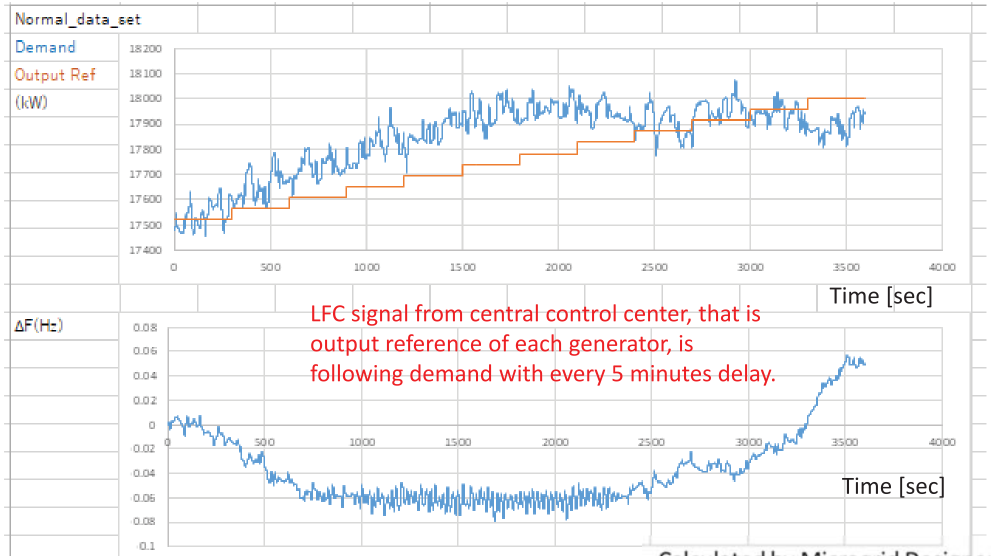
Figure is cited from MicroGrid Designer User and Technical Reference Manual

Example of LFC - Generator Output -



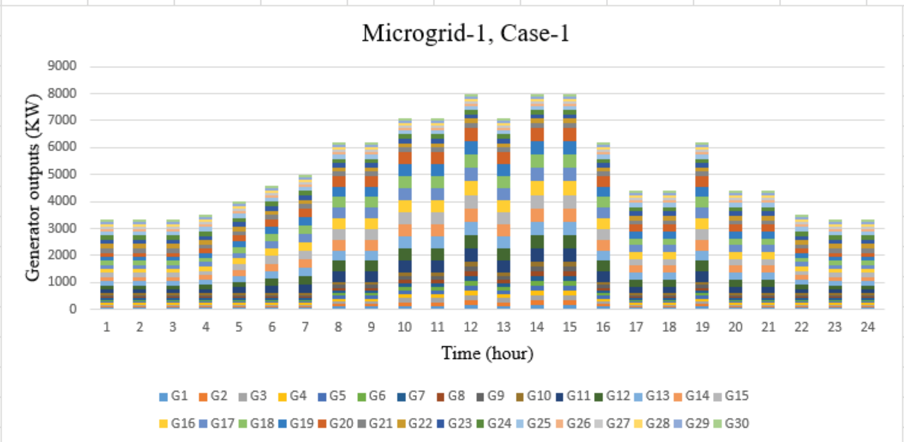
Calculated by Microgrid Designer

Example of LFC - Demand and Frequency -



Calculated by Microgrid Designer

Example of ELD



Calculated by Microgrid Designer

4. Reactive Power & Voltage

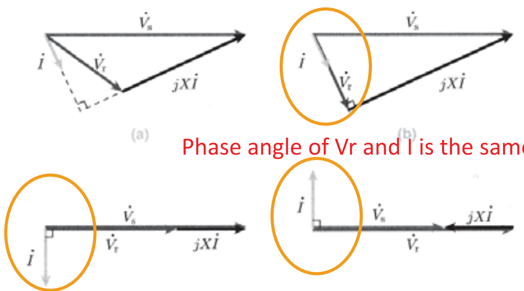
- Most of load consumes reactive power and the voltage of load node will be low.
- Reactive power should be provided or controlled to keep voltage as a set value.
- Providers of reactive power
  - Synchronous generator (SG)
  - Shunt Capacitor (SC)
  - Synchronous Condenser/Capacitor (SCO, RC: Rotary 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)

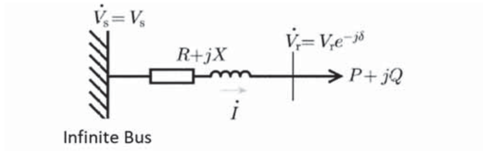


Vs: Sending Terminal Voltage, Vr: Receiving Terminal Voltage
I: Transmission Line Current
X: Transmission Line Impedance

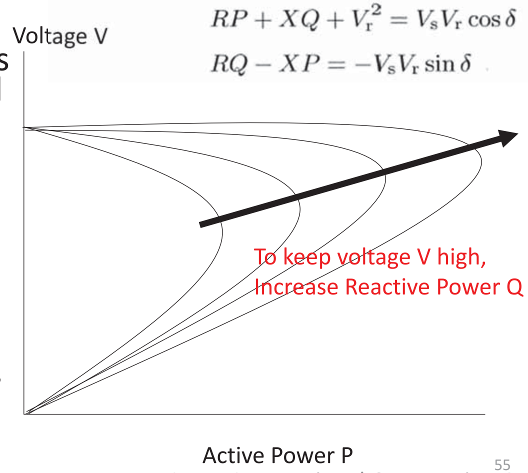
Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

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.

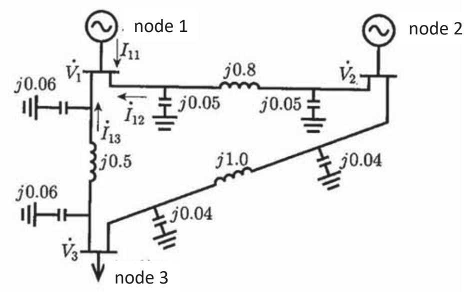
- Slack (Swing) Node
  - Node with largest capacity generator with constant voltage is generally selected.
  - Only the magnitude and phase angle of the voltage are specified.
  - This node supplements the difference between the scheduled loads and generated power that are caused by the losses in the 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

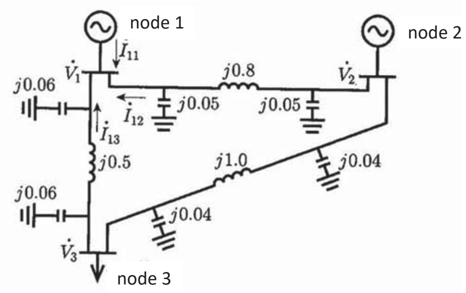


- Calculation example of power flow in 3 nodes network

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.

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

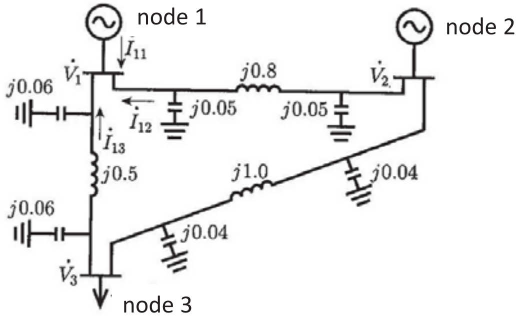
$$P_{ks} = \mathrm{Re}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$
$$Q_{ks} = \mathrm{Im}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$
$$V_{ks}^2 = e_k^2 + f_k^2$$

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.



$$P_{2s} = \mathrm{Re}\{(j1.25)^*(e_1 + jf_1)^*(e_2 + jf_2) + (-j2.16)^*(e_2 + jf_2)^*(e_2 + jf_2) + (j1.0)^*(e_3 + jf_3)^*(e_2 + jf_2)\}$$
$$= 1.25e_1f_2 - 1.25e_2f_1 + e_3f_2 - e_2f_3$$
$$V_{2s}^2 = e_2^2 + f_2^2$$
$$P_{3s} = \mathrm{Re}\{(j2.0)^*(e_1 + jf_1)^*(e_3 + jf_3) + (j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) + (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3)\}$$
$$= 2.0e_1f_3 - 2.0e_3f_1 + e_2f_3 - e_3f_2$$
$$Q_{3s} = \mathrm{Im}\{(j2.0)^*(e_1 + jf_1)^*(e_3 + jf_3) + (j1.0)^*(e_2 + jf_2)^*(e_3 + jf_3) + (-j2.9)^*(e_3 + jf_3)^*(e_3 + jf_3)\}$$
$$= 2.9e_3^2 + 2.9f_3^2 - 2.0e_1e_3 - 2.0f_1f_3 - e_2e_3 - f_2f_3$$
$$e_1 = V_{1s}, \quad f_1 = 0$$

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

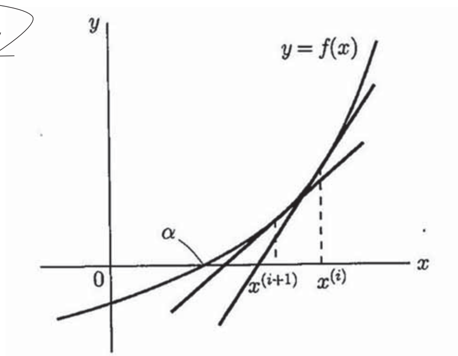


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

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

eq.(1)

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

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

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

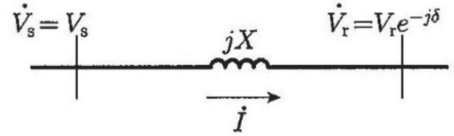
δ : Phase Difference of voltages between both side of a transmission line
X : Transmission line inductance
Pr : Active power that flows in a transmission line

DC Flow Method

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

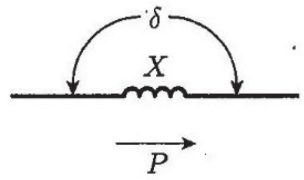
δ : Phase Difference of voltages Vs, Vr between both side of a transmission line
X : Transmission line inductance
Pr, Qr : Active power that flows through a transmission line

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



Simplified and Similar to DC circuit solution

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



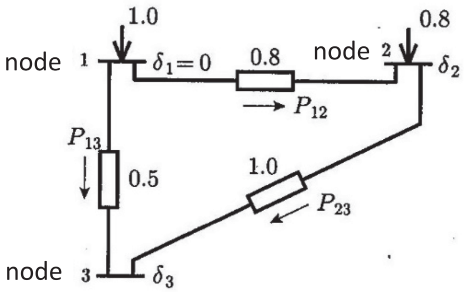
$$P_r = \frac{\delta}{X}$$

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

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

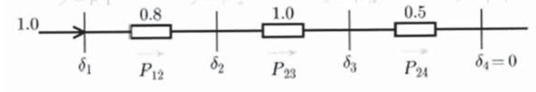
Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Example of DC Flow method

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

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

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



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

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

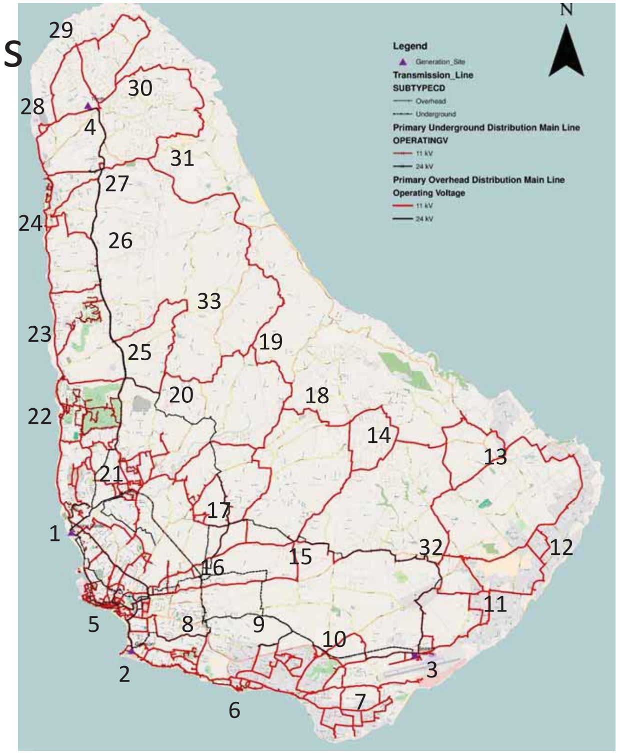
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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.

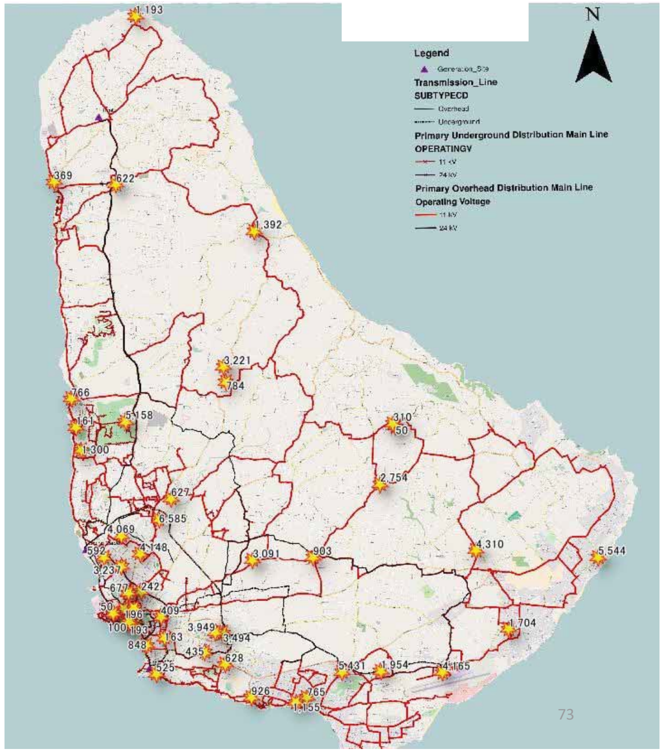


NIPPON KOEI PADECO

PV location to feeder

Total Capacity of PV in our estimated grid is:

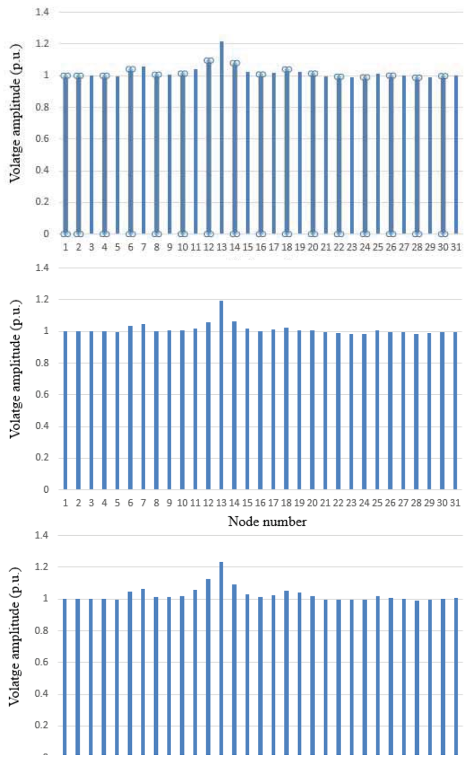
Installed PV + Licensed and to be installed PV = 91MW



NIPPON KOEI PADECO

Influence of Total Installed Capacity of PV -Bus Voltages-

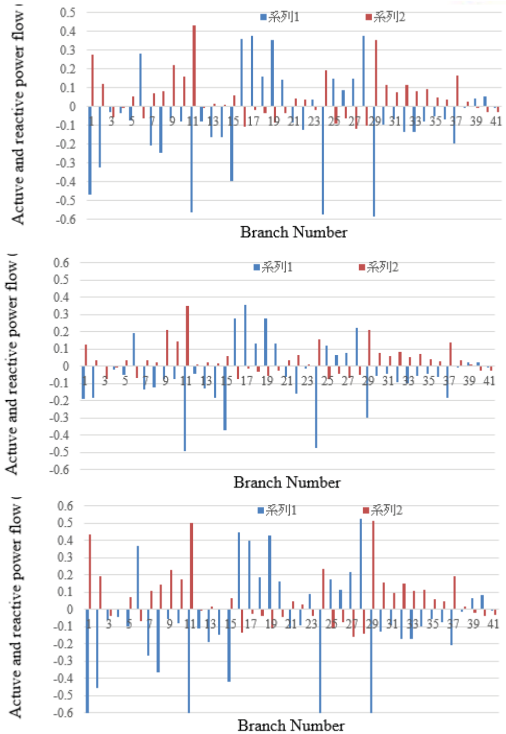
The total installed capacity of all PV's connected to feeders is 91MW.
(1) Planned PV(91MW)
(2) No PV(0MW)
(3) Twice capacity of PV(182MW)
Each PV 's output is twice of rated value.
->
Distributed PV can keep voltage equally in every nodes.
I doesn't give some instability to grid.



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:

[redacted]

Session No. 5
Transient Stability Analysis and Evaluation of Stability

1. Overview of Stability

2. Equal Area Criterion
   Simple method to solve stability manually

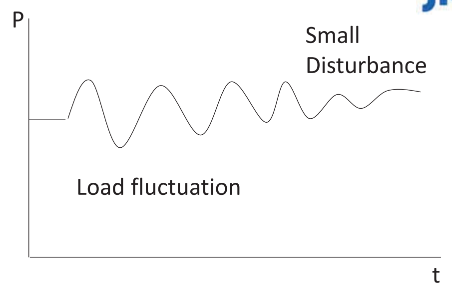
3. Exercise of Equal Area Criterion

1. Overview of Stability

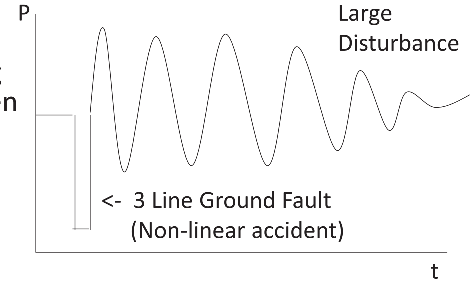
- **STABILITY (Definition)**
  - If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable.
  - If the system is not stable, it is considered unstable.

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.

    $f=2\pi\omega \qquad \omega= d\delta/dt$
  - 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

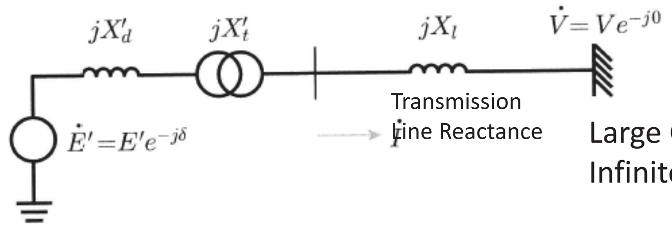
2. Equal Area Criterion

- 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

Generator



Large Grid
Infinite Bus

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

$$X = X'_d + X_t + X_l$$

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

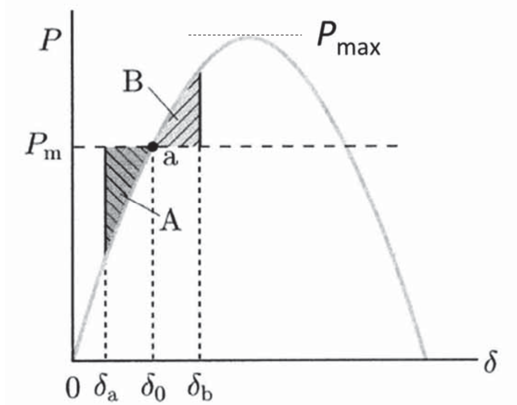


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

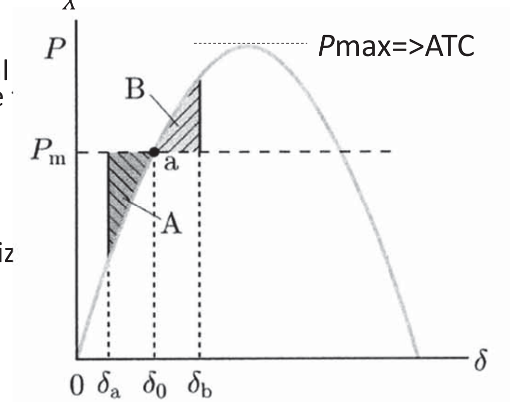


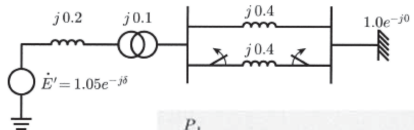
Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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.

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

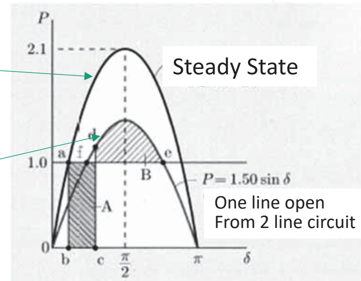
$X = 0.2 + 0.1 + \frac{0.4}{2} = 0.5$



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

$X = 0.2 + 0.1 + 0.4 = 0.7$

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

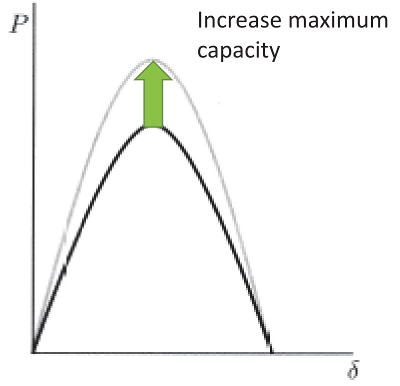


Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

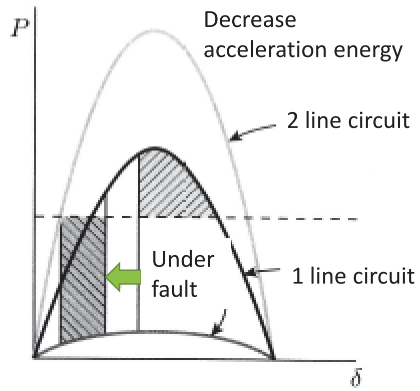
Solution for stability(1) through Equal Area Criterion

$$P = \frac{V_i V_j}{X} \sin\delta$$

(a) To increase Voltage



(b) High Speed Circuit Breaker

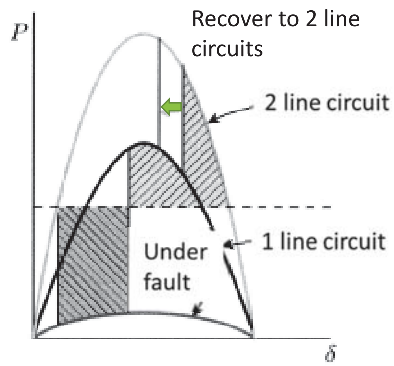


Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

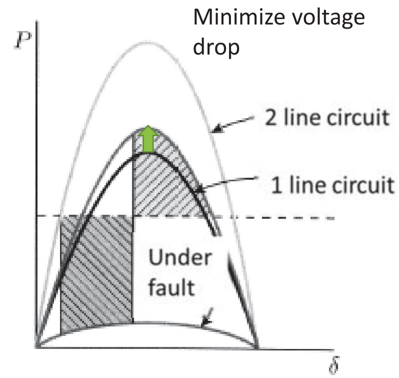
Solution for stability(2) through Equal Area Criterion

$$P = \frac{V_i V_j}{X} \sin\delta$$

(c) High Speed Recloser



(d) High Speed AVR



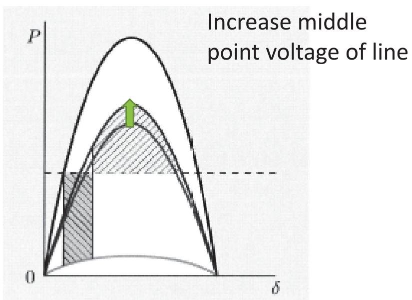
Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Solution for stability(3) through Equal Area Criterion

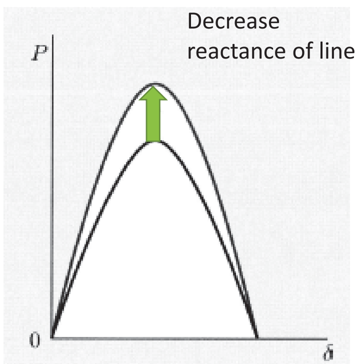
$$P = \frac{V_i V_j}{X} \sin\delta$$

(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

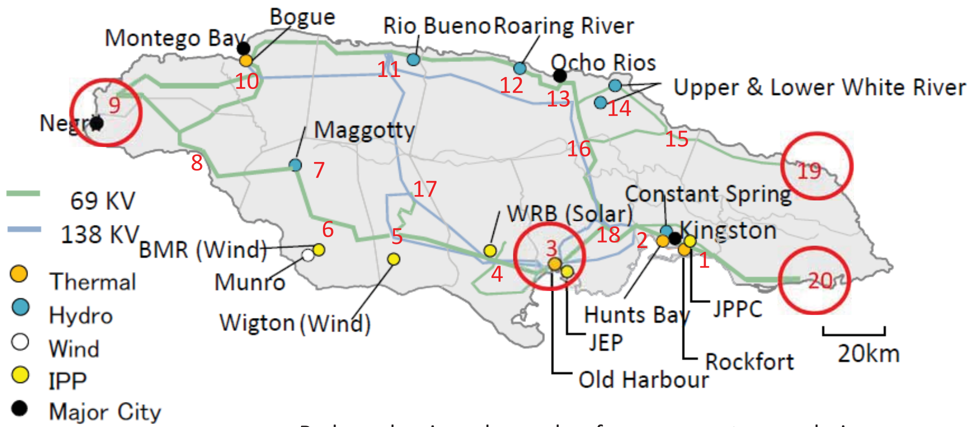
<Definition>

-> 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

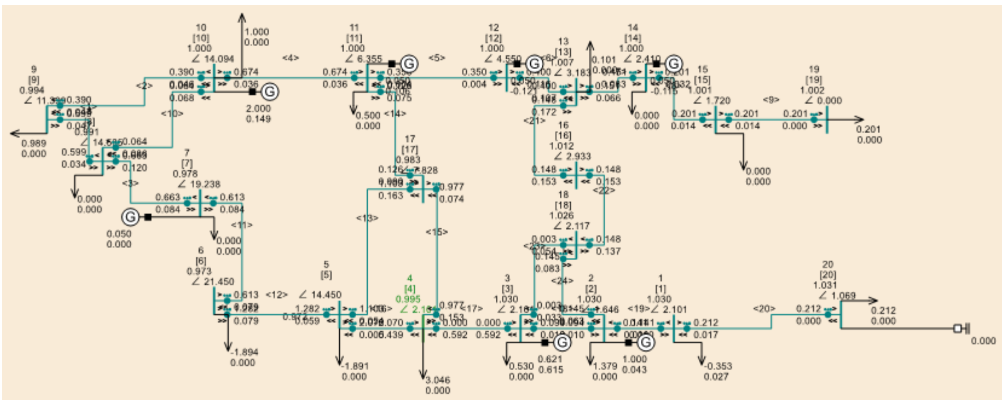
- To Solve Short Term Spinning Reserve Problem -



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.

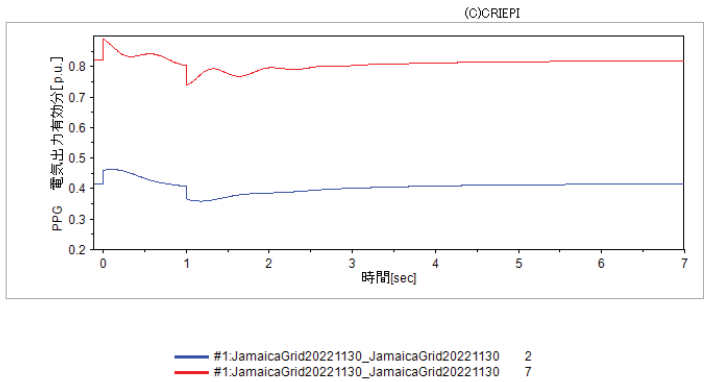
Load Flow Analysis of Jamaica Grid



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Transient Stability Analysis (Case Study)

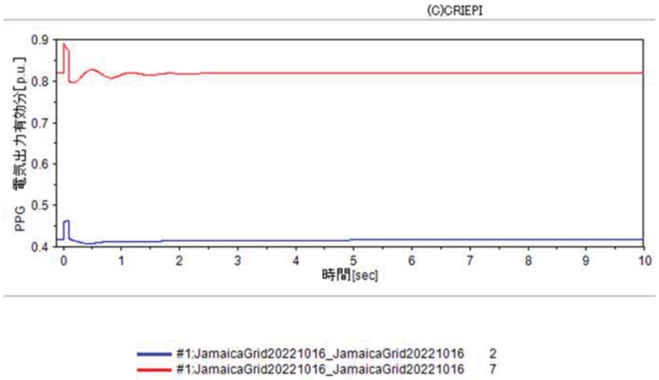
- In case output of PV drops from Max to Zero for 1 second -> Stable



Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Transient Stability Analysis (Case Study)

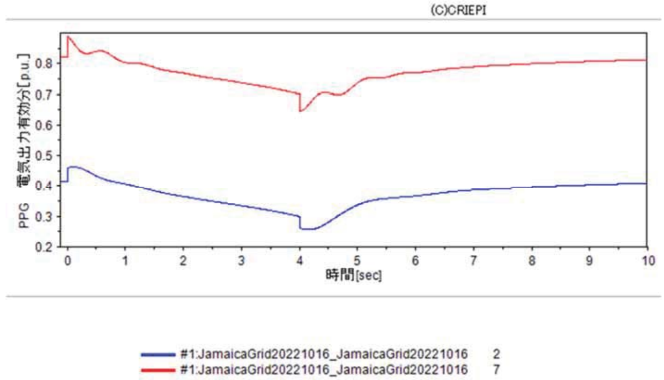
- In case output of PV at node 4 drops from Max to Zero for 1 second -> Stable



Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Transient Stability Analysis (Case Study)

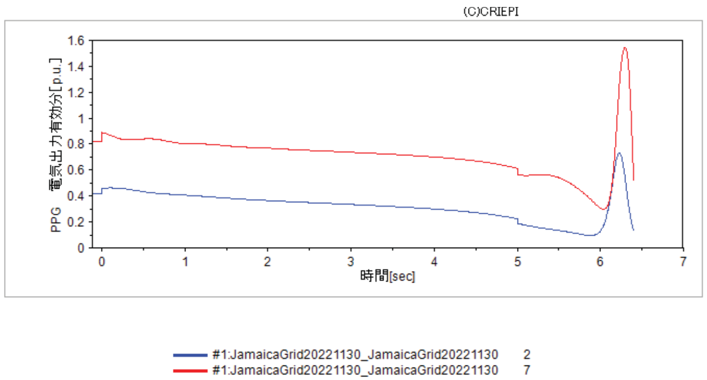
- In case output of PV at node 4 drops from Max to Zero for 4 second -> Stable



Calculated by CPATFree(CRIEP's Power System Analysis Tools)

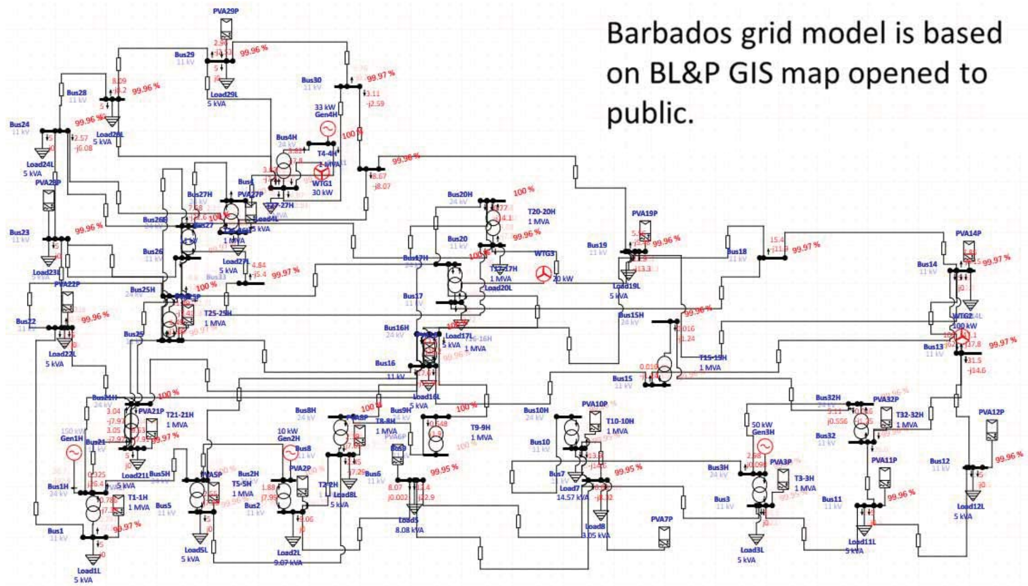
Transient Stability Analysis (Case Study)

- In case output of PV at node 4 drops from Max to Zero for 5 second -> Unstable



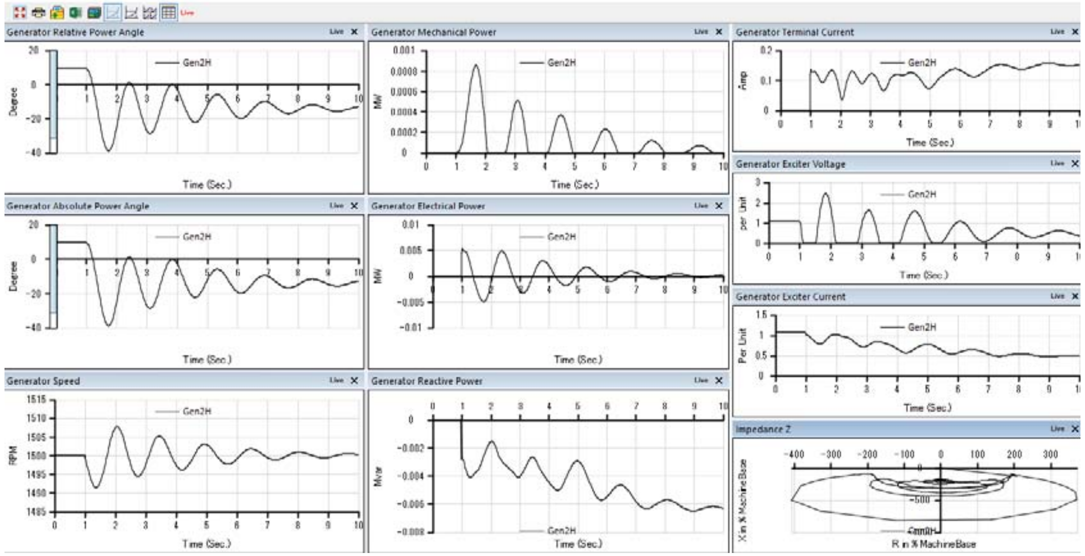
Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Barbados 50 nodes grid map in ETAP

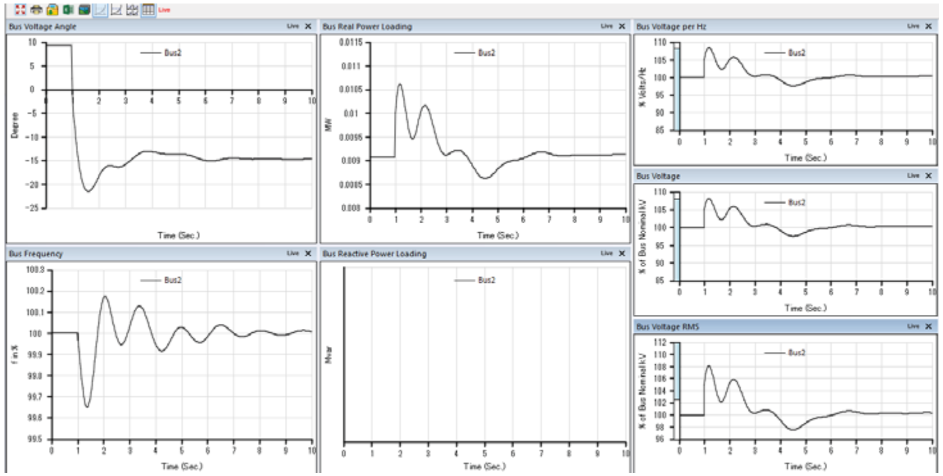


Barbados grid model is based on BL&P GIS map opened to public.

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

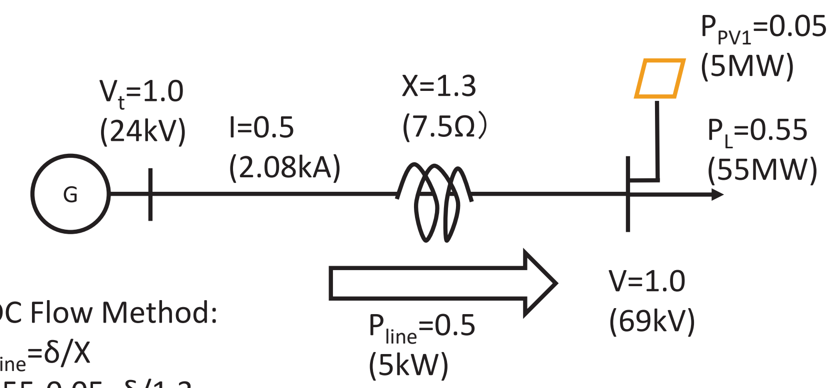
Steps to evaluate stability will be as follows:

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 $0.174\Omega^{-1}$ (=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 $0.625\Omega^{-1}$ (=1/1.6)

Transmission Network Model



(1) DC Flow Method:

$P_{line}=\delta/X$

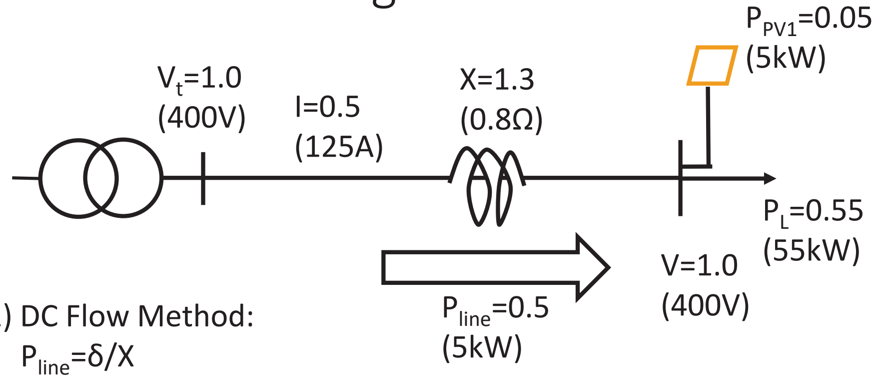
$0.55-0.05=\delta/1.3$

$\delta=0.65rad=37deg$

If $\delta<90deg$, 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:

$P_{line}=\delta/X$

$0.55-0.05=\delta/1.3$

$\delta=0.65rad=37deg$

If $\delta<90deg$, 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

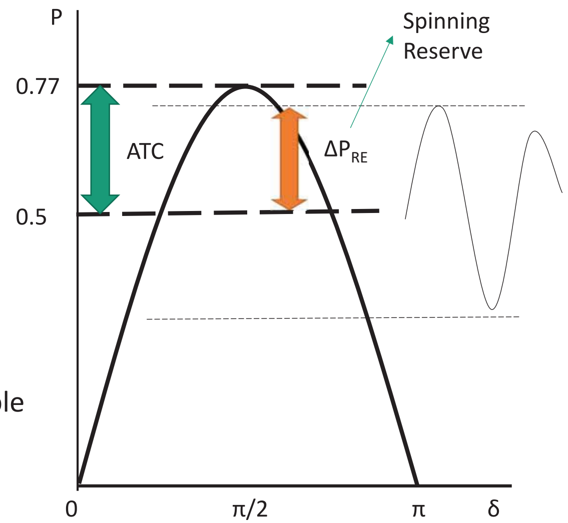
(a) Currently ΔP_{RE}= 0.15
-> Stable

(b) If ΔP_{RE}> 0.27
-> Unstable

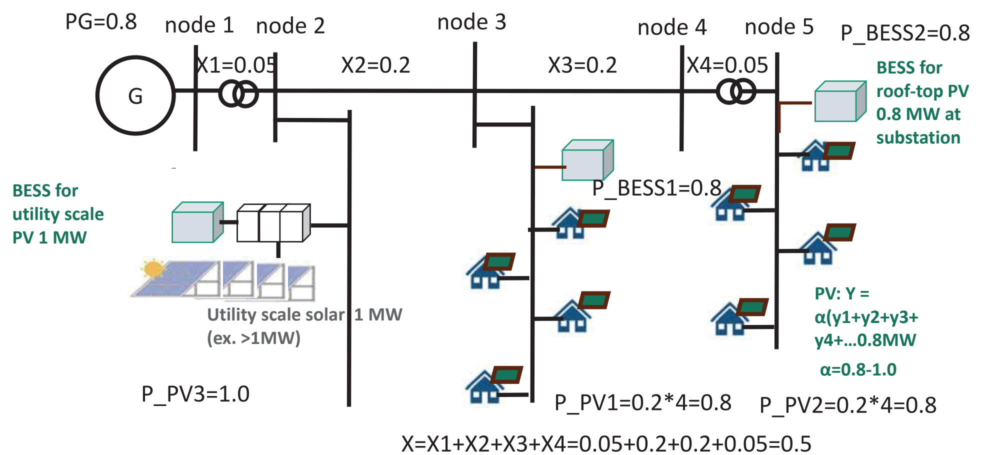
$SCR=Pop/\Delta P_{RE}$
should be over 3
=(a) 3.33 -> Stable
=(b) 1.85 -> Unstable

(4) ATC=0.27 -> If ΔP_{RE}> 0.27
-> Unstable

(5) Spinning Reserve should be more than ΔP_{RE}
=0.15

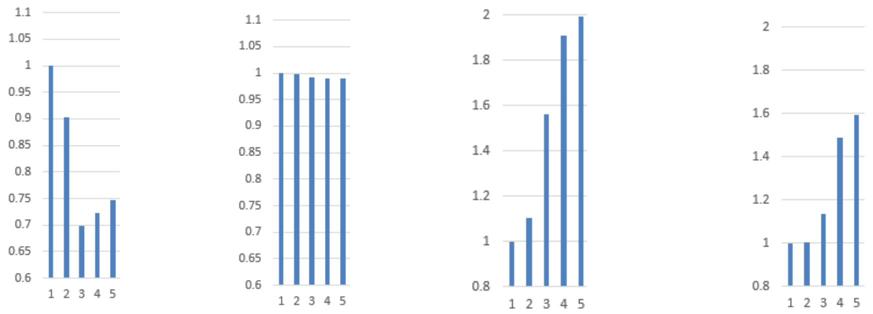


Simple Grid Model for RE



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!!

3rd Seminar on Grid Stability and Large RE Day 2

JICA Expert Team, Nippon Koei Co., Ltd.

Agenda

- 9:30-10:30 Evaluation of Load Flow Analysis by Microgrid Designer
- 10:30-11:30 Evaluation of Load Flow Analysis & Transient Stability by ETAP
- 11:30-11:55 Discussion for 100% RE achievement
- 11:55-12:00 Closing Remarks

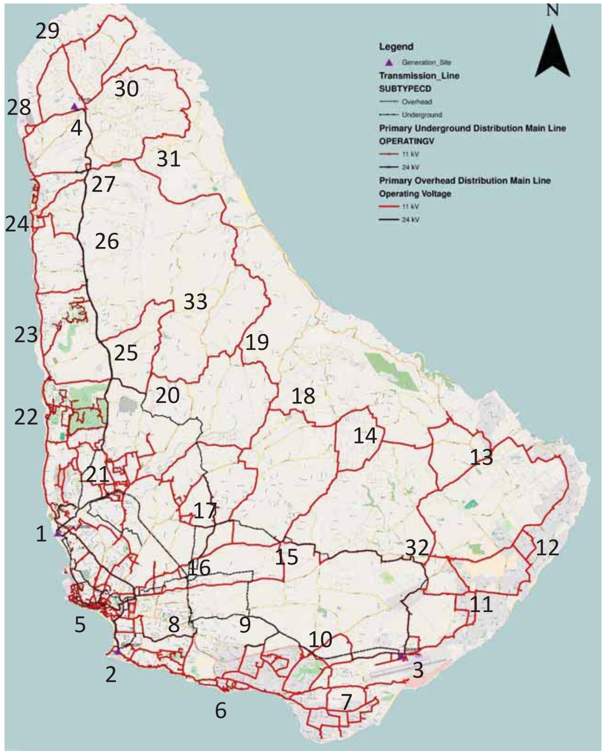
Evaluation of Load Flow Analysis by Microgrid Designer: Example of Input model

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			0.07	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
4	1	1			0.33	0	−0.5	0			0	0.3	0.2
5	0	1			0	0	−0.2189	0	0.1	0.1	0.109902		0.109
6	0	1		0.2	0	0	0.058985	0	0.1		0.021015		0.02
7	0	1		0.2	0	0	−0.54599	0	0.1	0.6046	0.021387		0.02
8	0	1			0	0	−0.07833	0	0.1		0.088329		0.09
9	0	1			0	0	0	0	0		0		
10	0	1			0	0	−0.01944	0	0.1		0.059444		0.06
11	0	1			0.6	0	−0.38283	0	0.1	0.357	0.065825		0.06
12	0	1			0	0	−0.02068	0	0.1		0.060681		0.06
13	0	1			0	0	−1.02447	0	0.1		0.030067	1	0.0944
14	0	1			0	0	−0.10014	0	0.05	0.09	0.030143		0.03
15	0	1			0	0	0	0	0		0		
16	0	1			0	0	−0.03672	0	0.05		0.043716		0.043
17	0	1			0	0	−0.2	0	0		0	0.2	
18	0	1			0	0	0	0	0		0		
19	0	1			0	0	−0.05496	0	0.05		0.054957		0.05
20	0	1			0	0	0	0	0		0		
21	0	1			0	0	−0.14894	0	0.05		0.098935		0.1
22	0	1			0	0	0.019009	0	0.05		0.015991		0.015
23	0	1			0	0	0.016035	0	0.05		0.016965		0.017
24	0	1			0	0	0.05	0	0.05		0		
25	0	1			0.5704	0	−0.11247	0	0		0.056467		0.056
26	0	1			0	0	0	0	0		0		
27	0	1			0	0	0.036203	0	0.05		0.006797		0.007
28	0	1			0	0	0.05	0	0.05		0		
29	0	1			0	0	−0.23386	0	0.05		0.013058	0.1635	0.1073
30	0	1			0	0	0	0	0		0		
31	0	1			0	0	0	0	0		0		
32	0	1			0	0	−0.02035	0	0	0.01	0.00535		0.005
33	0	1			0	0	0	0	0		0		
				Sum	2.2974		−5.0601		1.5	1.8616	1.0013	1.6635	2.0337

Calculated by Microgrid Designer

Barbados Grid

modeled with 33 nodes



Barbados grid model is based on BL&P GIS map opened to public.

Barbados Generation Capacity with Existing &Current Planned RE Projects

Nodes with marked resources are set to P-V node.
Others are set to P-Q node.
Value of P and Q should be under the following value.

- Capacity of near future

Power Resources	Capacity[MW]	Node
• Thermal Generator	150*	1,2,3,4
• Utility PV	52+7	13
• Distributed PV	65	1~33
• West to Energy	30*	25
• WT	100+50	13, 19
• BESS	200	1~33
• Hydrogen Storage	20	25

- Total 654.05

Barbados Future Grid Model for 100% RE for the Case of IRRP Scenario-1

Nodes with marked resources are set to P-V node.
Others are set to P-Q node.
Value of P and Q should be under the following value.

- Generation Capacity in 2030 from IRRP Report (Scenario-1)

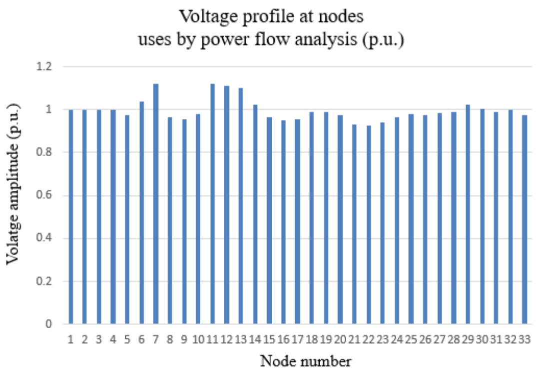
→ Let's input in Microgrid Designer to obtain load flow result

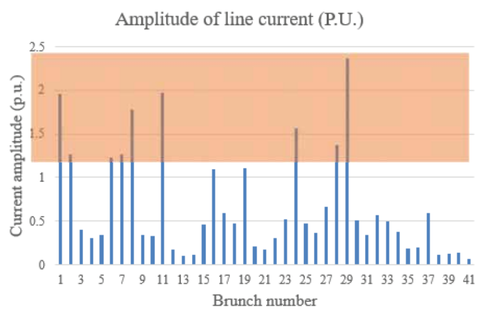
Power Resources	Capacity [MW]	Node
• Thermal Generator	145.4*	1,2,3,4
• WH	3.7*	2
• Distributed Solar	100.13	1~33
• Utility Scale Solar	185.70	3,7,11
• Biofuel	34.04*	25
• Onshore Wind	161.77	29
• Solar CSP	40.00*	11
• Battery	204.64	1~33
• Total	875.38	

Input model in Microgrid Designer: Case-1 IRRP Scenario 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	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
4	1	1			0.33	0	−0.6	0		0.1	0	0.3	0.2
5	0	1			0	0	−0.1189	0	0.1		0.109902		0.109
6	0	1		0.2	0	0	0.058985	0	0.1		0.021015		0.02
7	0	1		0.2	0	0	−0.54139	0	0.1	0.6	0.021387		0.02
8	0	1			0	0	−0.07833	0	0.1		0.088329		0.09
9	0	1			0	0	0	0	0		0		
10	0	1			0	0	−0.01944	0	0.1		0.059444		0.06
11	0	1			0.4	0	−0.38283	0	0.1	0.357	0.065825		0.06
12	0	1			0	0	−0.02068	0	0.1		0.060681		0.06
13	0	1			0	0	−1.02447	0	0.1		0.030067	1	0.0944
14	0	1			0	0	−0.10014	0	0.05	0.09	0.030143		0.03
15	0	1			0	0	0	0	0		0		
16	0	1			0	0	−0.03672	0	0.05		0.043716		0.043
17	0	1			0	0	−0.2	0	0		0	0.2	
18	0	1			0	0	0	0	0		0		
19	0	1			0	0	−0.05496	0	0.05		0.054957		0.05
20	0	1			0	0	0	0	0		0		
21	0	1			0	0	−0.14894	0	0.05		0.098935		0.1
22	0	1			0	0	0.019009	0	0.05		0.015991		0.015
23	0	1			0	0	0.016035	0	0.05		0.016965		0.017
24	0	1			0	0	0.05	0	0.05		0		
25	0	1			0.3404	0	−0.11247	0	0		0.056467		0.056
26	0	1			0	0	0	0	0		0		
27	0	1			0	0	0.036203	0	0.05		0.006797		0.007
28	0	1			0	0	0.05	0	0.05		0		
29	0	1			0	0	−0.20076	0	0.05		0.013058	0.1177	0.12
30	0	1			0	0	0	0	0		0		
31	0	1			0	0	0	0	0		0		
32	0	1			0	0	−0.02035	0	0	0.01	0.00535		0.005
33	0	1			0	0	0	0	0		0		

Load Flow Analysis Result by Microgrid Designer: Node Voltage & Line Current (Case: IRRP Scenario-1)





Voltages of south area is high. BLPC did some measurements Additional measurement will be Required. (Node 6, 7, 11, 12 and 13 are south coast area.
Current of transmission lines are over their rated values. The upgrade of line voltage will be required (for example, 24.9 kV → 69 kV) to decrease the impedance and obtain required transmission capacity, especially for transmission lines and distribution lines of south area.

Barbados Future Grid Model for 100% RE for the Case of IRRP Scenario-3

Nodes with marked resources are set to P-V node.
Others are set to P-Q node.
Value of P and Q should be under the following value.

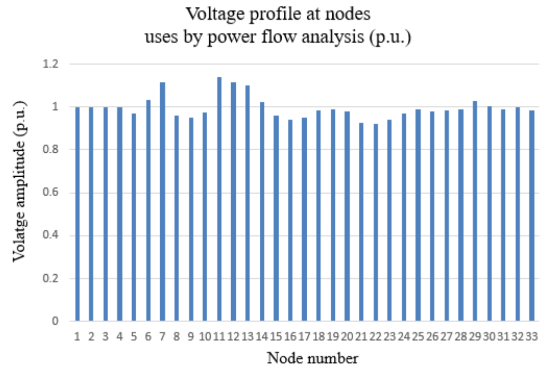
- Generation Capacity planned in 2030 : IRRP Scenario-3

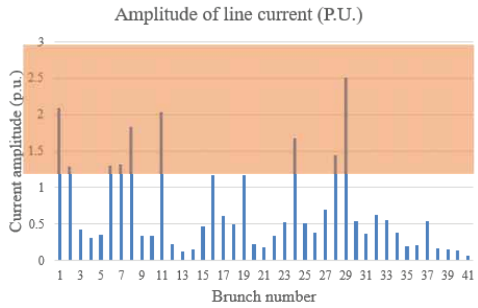
Power Resources	Capacity [MW]	Node
• Thermal Generator	102.7*	1,2,3,4
• WH	3.7*	2
• Distributed Solar	100.13	1~33
• Utility Scale Solar	186.16	3,7,11
• Biomass and WtE	57.04*	25
• Onshore Wind	166.35	29
• Solar CSP	60.00*	11
• Battery	203.37	1~33
• Total	879.45	

Input model on Microgrid Designer : For IRRP Scenario-3 case

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
4	1	1			0.33	0	−0.6	0		0.1	0	0.3	0.2
5	0	1			0	0	−0.1189	0	0.1		0.109902		0.109
6	0	1		0.2	0	0	0.058985	0	0.1		0.021015		0.02
7	0	1		0.2	0	0	−0.54139	0	0.1	0.6	0.021387		0.02
8	0	1			0	0	−0.07833	0	0.1		0.088329		0.09
9	0	1			0	0	0	0	0		0		
10	0	1			0	0	−0.01944	0	0.1		0.059444		0.06
11	0	1			0.4	0	−0.38283	0	0.1	0.357	0.065825		0.06
12	0	1			0	0	−0.02068	0	0.1		0.060681		0.06
13	0	1			0	0	−1.02447	0	0.1		0.030067	1	0.0944
14	0	1			0	0	−0.10014	0	0.05	0.09	0.030143		0.03
15	0	1			0	0	0	0	0		0		
16	0	1			0	0	−0.03672	0	0.05		0.043716		0.043
17	0	1			0	0	−0.2	0	0		0	0.2	
18	0	1			0	0	0	0	0		0		
19	0	1			0	0	−0.05496	0	0.05		0.054957		0.05
20	0	1			0	0	0	0	0		0		
21	0	1			0	0	−0.14894	0	0.05		0.098935		0.1
22	0	1			0	0	0.019009	0	0.05		0.015991		0.015
23	0	1			0	0	0.016035	0	0.05		0.016965		0.017
24	0	1			0	0	0.05	0	0.05		0		
25	0	1			0.3404	0	−0.11247	0	0		0.056467		0.056
26	0	1			0	0	0	0	0		0		
27	0	1			0	0	0.036203	0	0.05		0.006797		0.007
28	0	1			0	0	0.05	0	0.05		0		
29	0	1			0	0	−0.20076	0	0.05		0.013058	0.1177	0.12
30	0	1			0	0	0	0	0		0		
31	0	1			0	0	0	0	0		0		
32	0	1			0	0	−0.02035	0	0	0.01	0.00535		0.005
33	0	1			0	0	0	0	0		0		

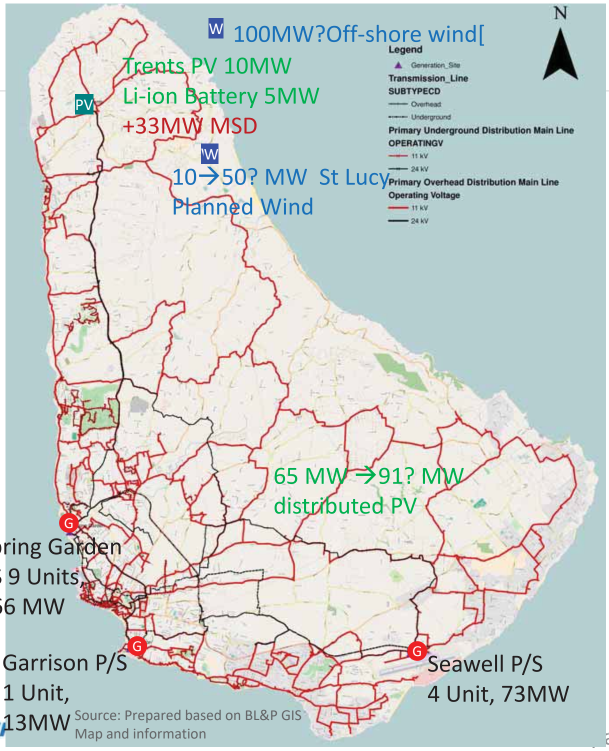
Load Flow Analysis Result by Microgrid Designer : Node Voltage & Line Current (Case: IRRP Scenario-3)





Voltages of south area is high. BLPC did some measurements but additional measurement will be Required. (Node 6, 7, 11, 12 and 13 are south coast area from the result.

Current of transmission lines are over their rated values. The upgrade of transmission line voltage will be required to decrease the impedance and obtain required the transmission capacity, especially for transmission lines and distribution lines of south area.



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

Grid and Generation of Barbados

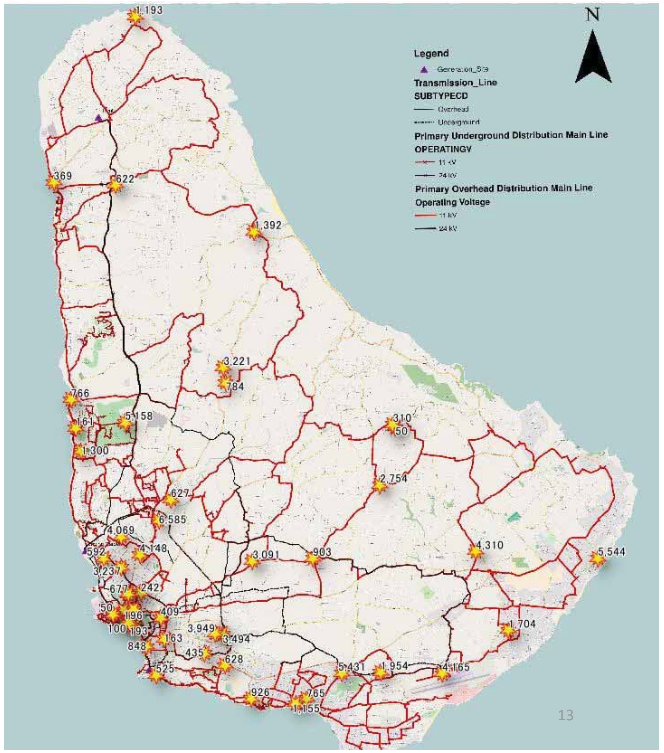
Location	MW/u	Qy	MW	Remark
Existing				
Total thermal power			265	
Spring Field Total		9	166	LDS, ST, GT
Garrison	13	1	13	Gas Tubine
Seawell	13	1	13	Gas Tubine
Seawell	20	2	40	Gas Tubine
Trents	8.3	4	33	MSD Engine
Total PV			75.6	
Trents	10	1	10	PV
Distributed PV		LS	65.6	PV
Total Battery			5	
Trents	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.

PV location to feeder

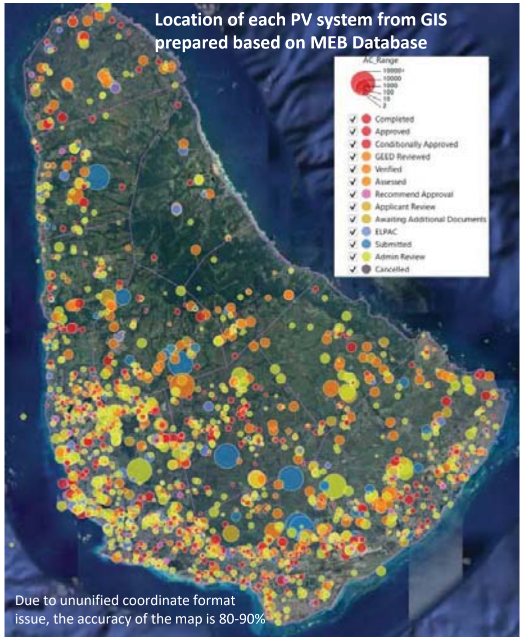
Total Capacity of PV of each feeder :

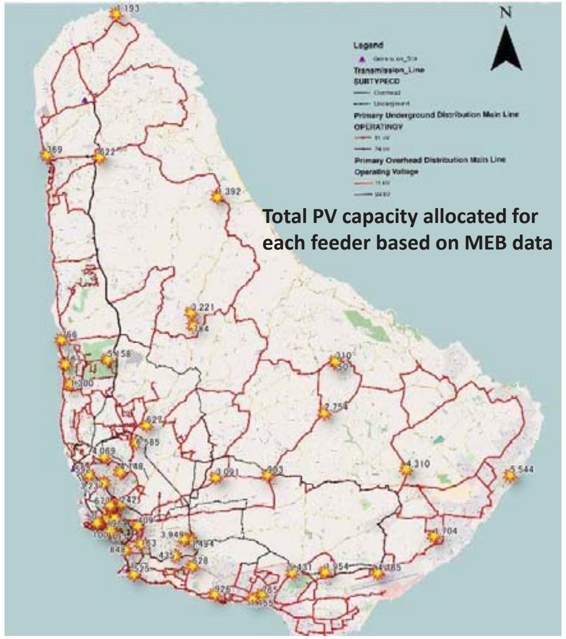
Installed PV + Licensed to be installed PV = 91MW



Barbados PV Location

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

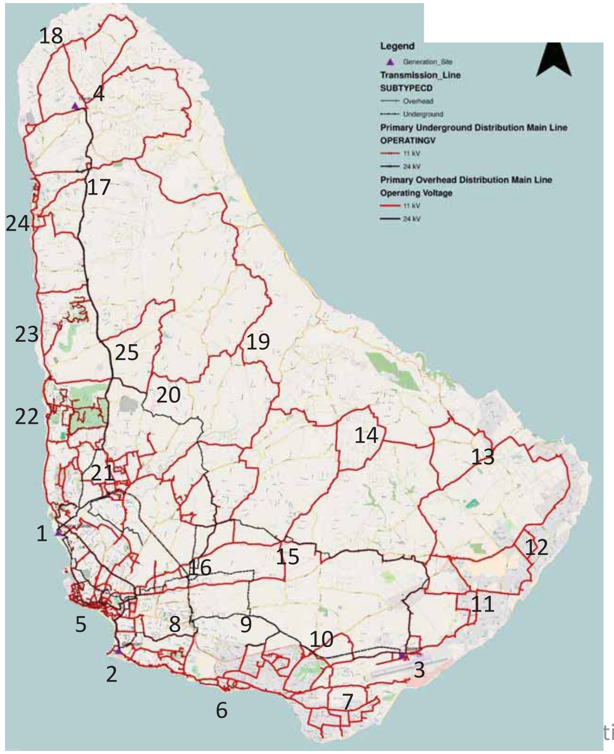




Barbados Grid

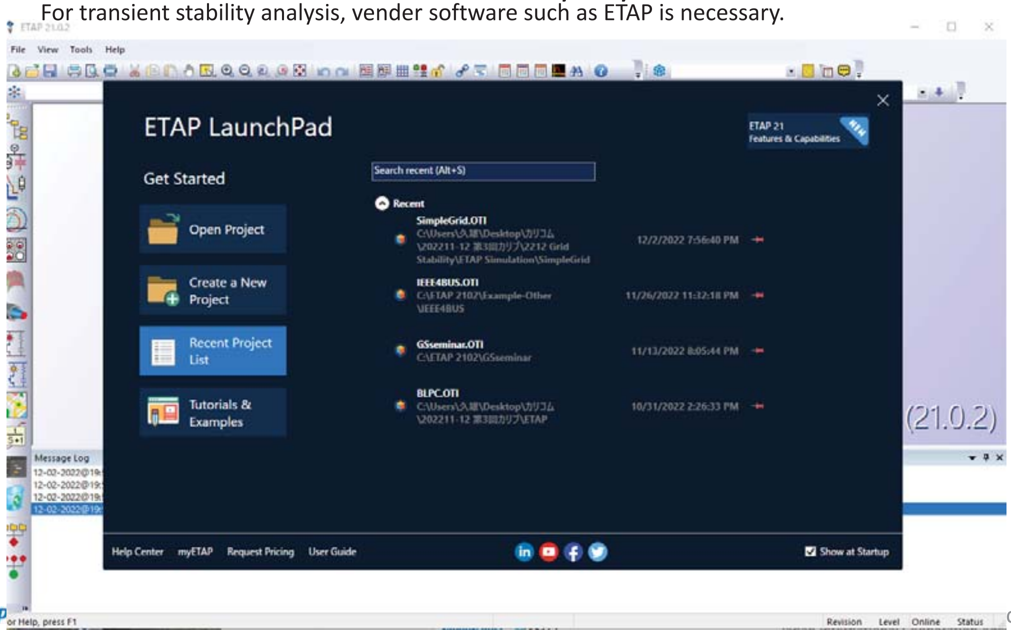
25 nodes

Barbados grid model is based on BL&P GIS map opened to public.

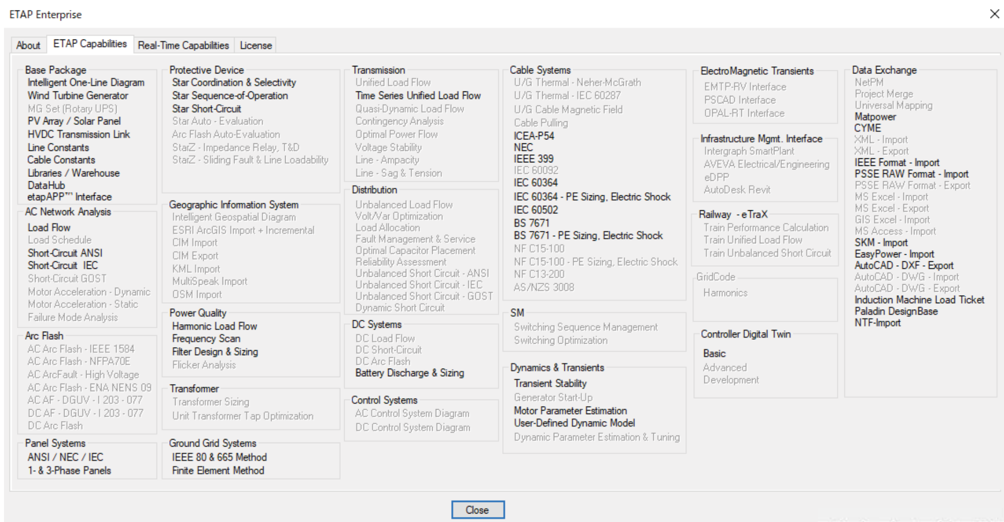


Evaluation of Load Flow Analysis & Transient Stability by ETAP

For transient stability analysis, vender software such as ETAP is necessary.

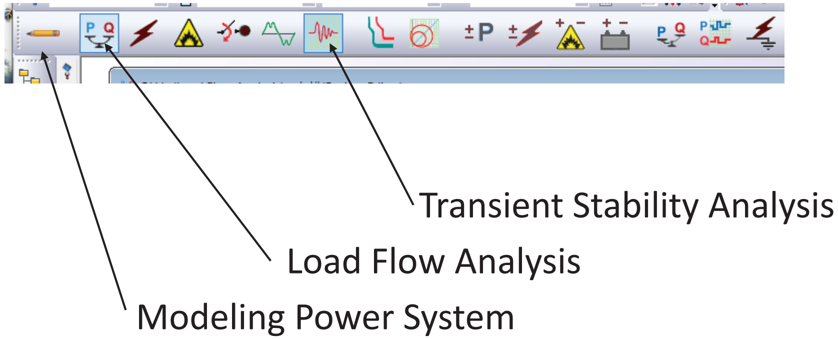


Functions of ETAP



Calculated by ETAP

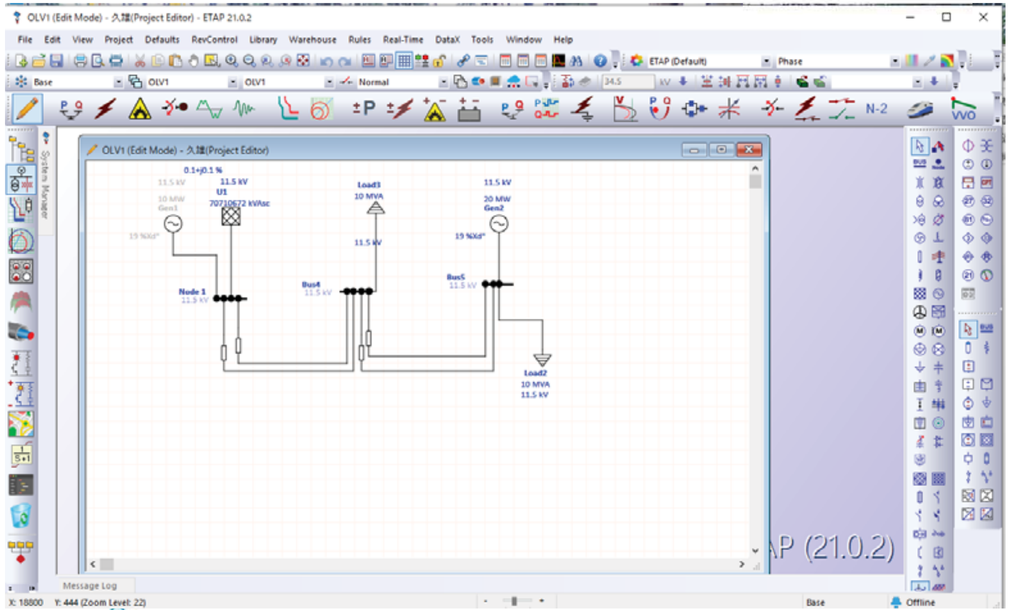
Menu of ETAP



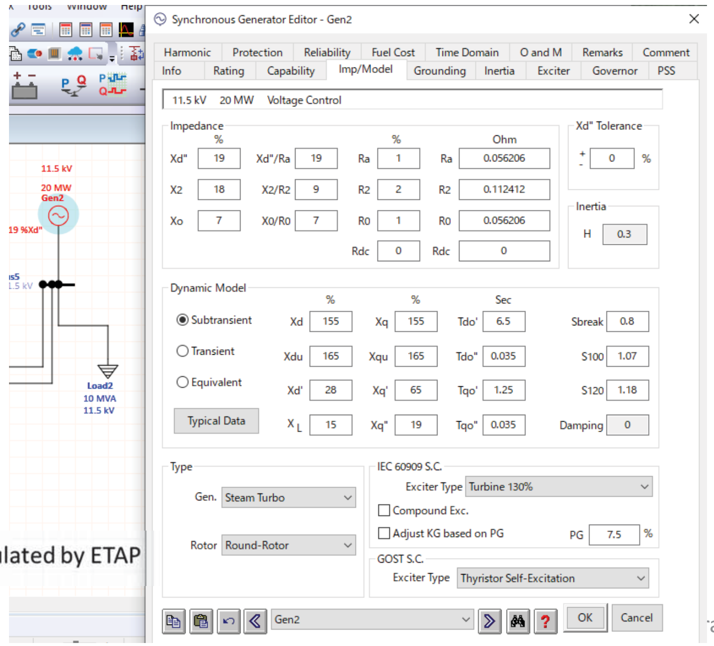
Calculated by ETAP

Example of model input in ETAP
Load Flow Analysis with 3-Bus Power System

Calculated by ETAP



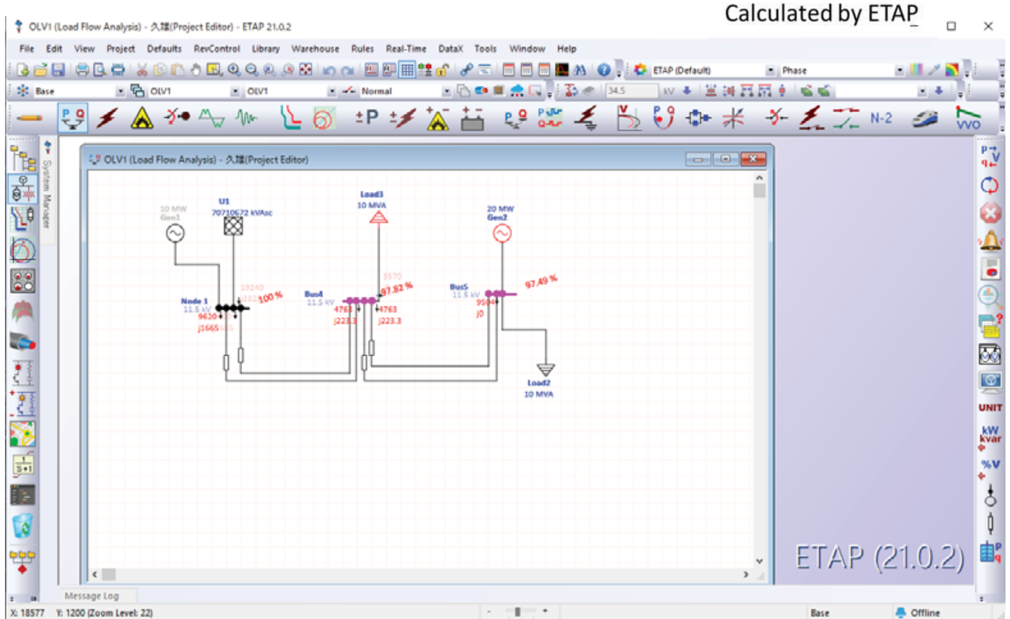
Example of model input in ETAP:
Input for Generator Parameters



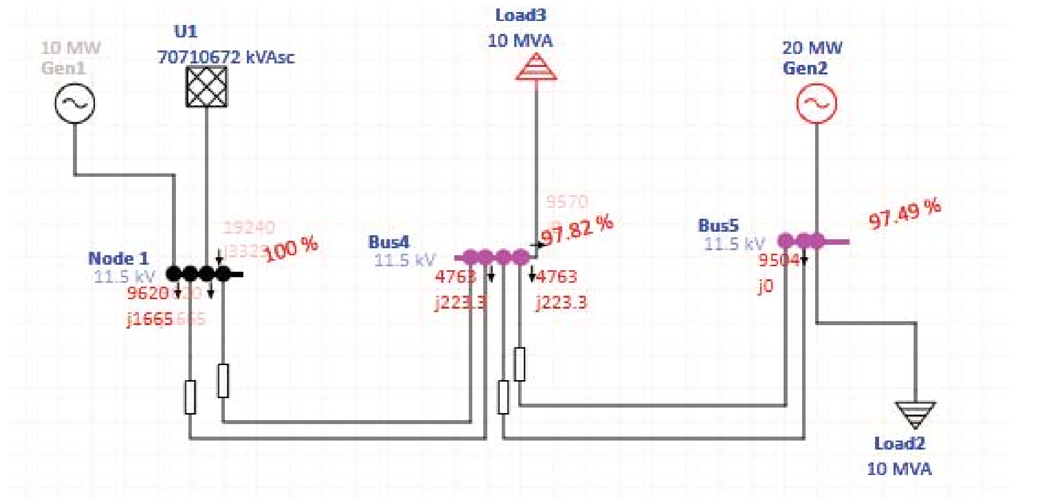
Calculated by ETAP

Example of Load Flow Analysis: Result in ETAP

Calculated by ETAP



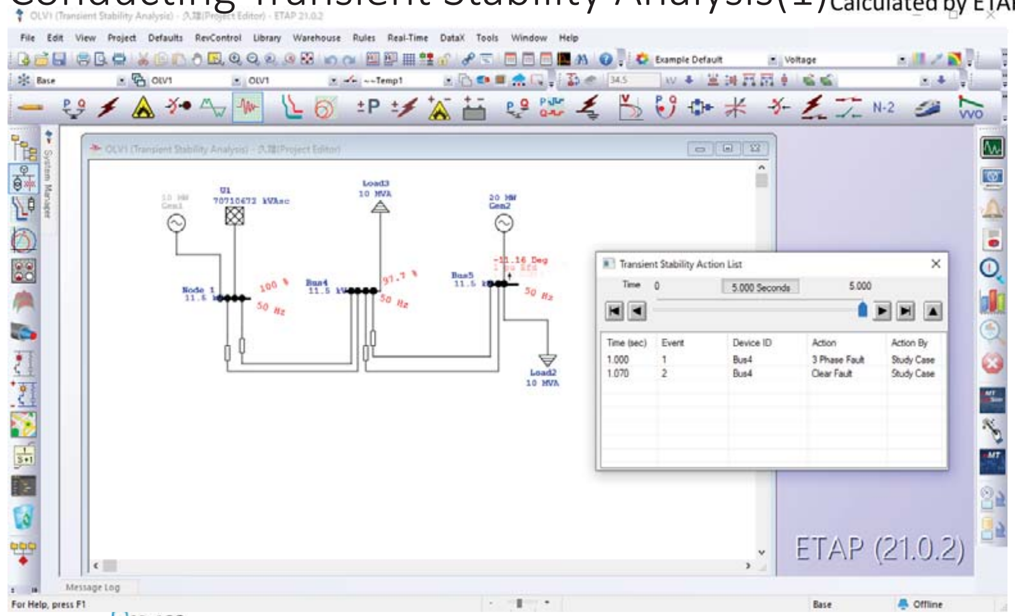
Example of Load Flow Analysis: Result in ETAP



Calculated by ETAP

Example of ETAP with the Simple Model Conducting Transient Stability Analysis(1)

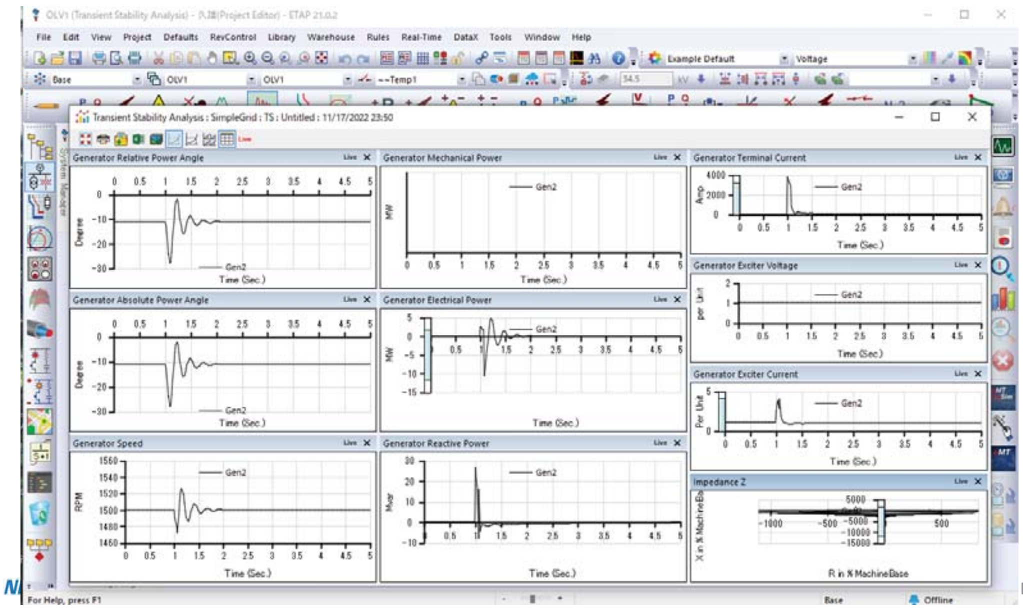
Calculated by ETAP



Example of ETAP with the Simple Model Result of Transient Stability Analysis(1)

Calculated by ETAP

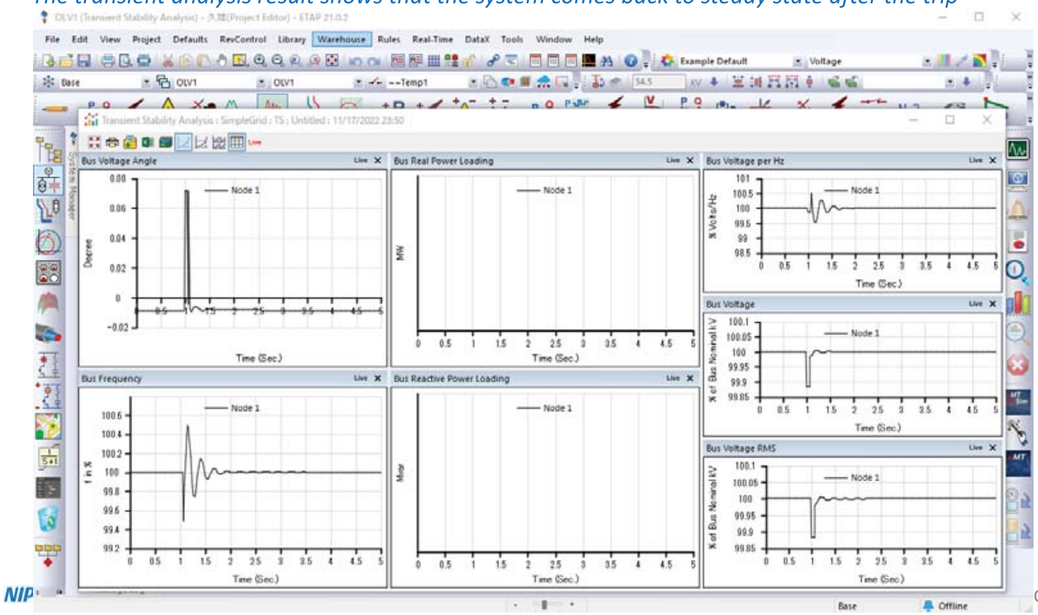
The transient analysis result shows that the system comes back to steady state after the trip



Example of ETAP with the Simple Model Result of Transient Stability Analysis(2)

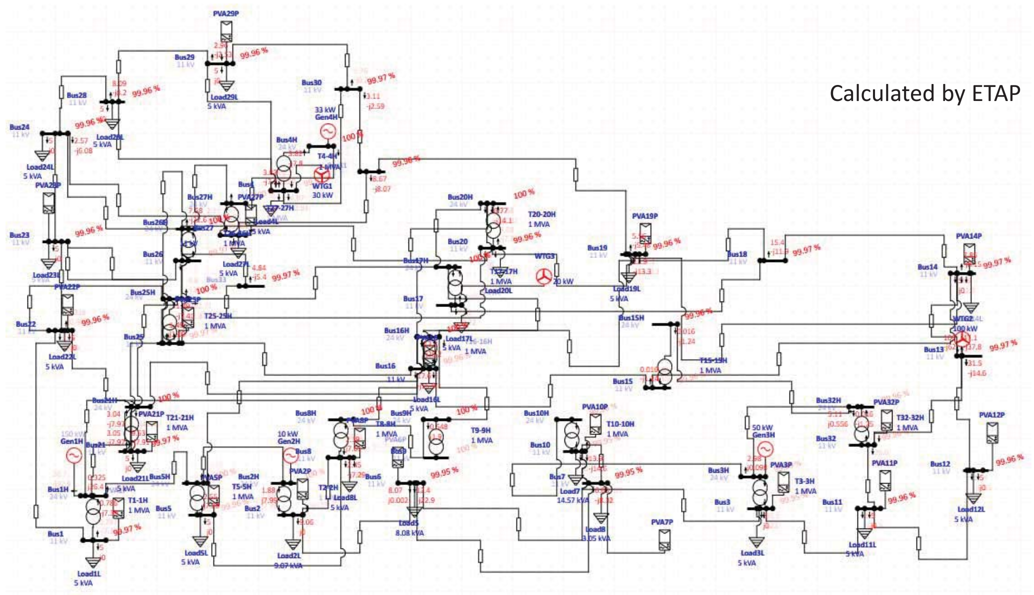
Calculated by ETAP

The transient analysis result shows that the system comes back to steady state after the trip



Barbados 50 nodes grid map in ETAP

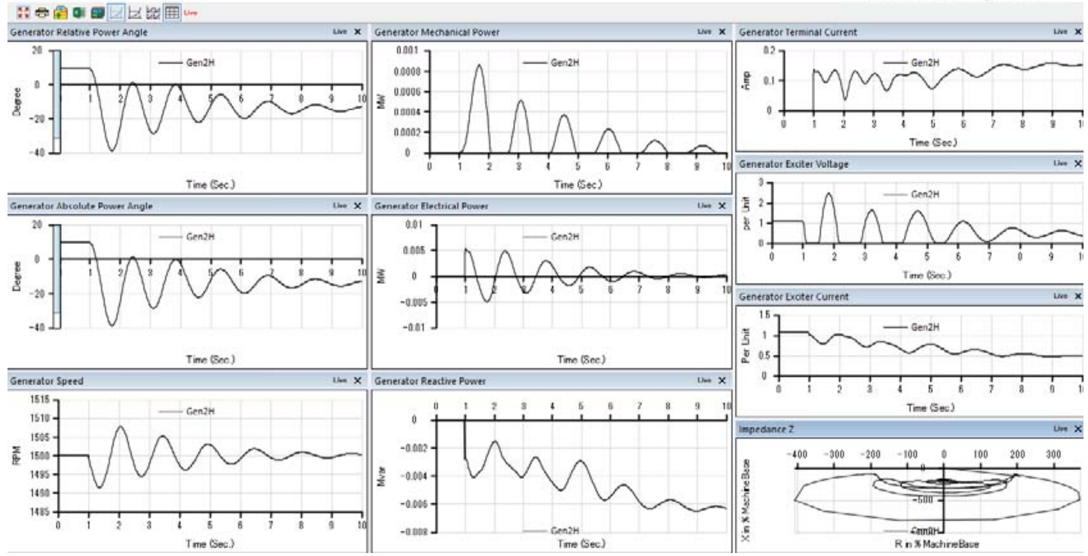
Calculated by ETAP



Example of Transient Analysis Result with 50 node model Generator No.1 Transient Status after 100MW Wind Turbine Trip

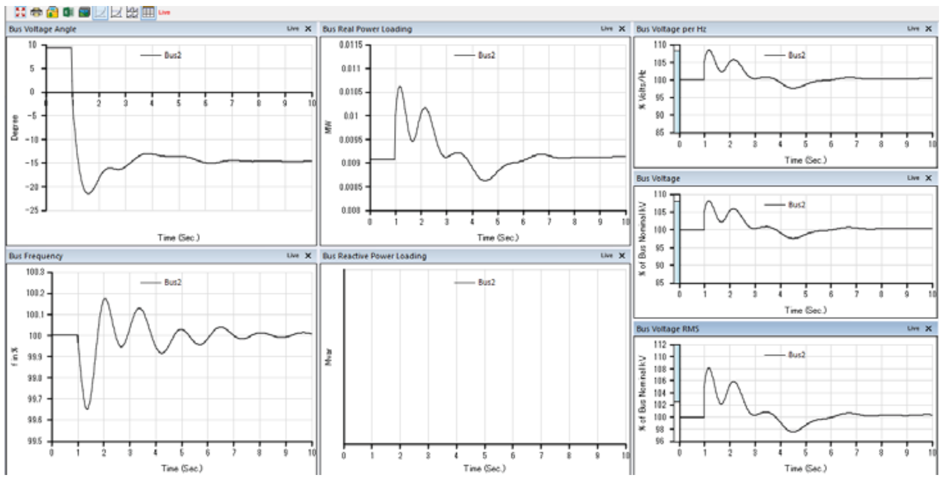
The transient analysis result shows that the system comes back to steady state after the trip

Calculated by ETAP



Example of Transient Analysis Result with Barbados 50 node model: Bus Voltage and Powers connected to Generator 1 after 100 MW Wind Turbine Trip

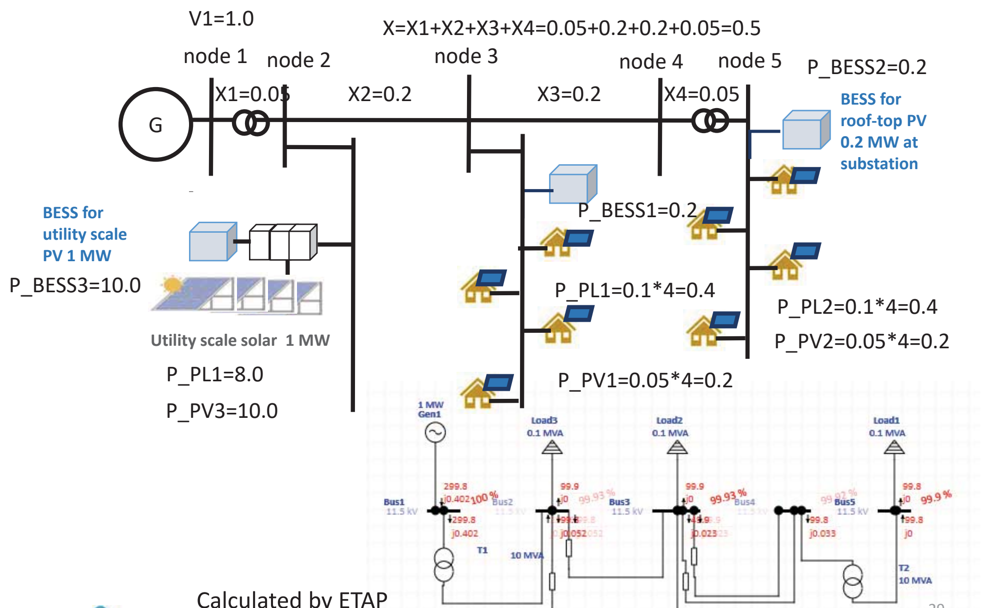
The transient analysis result shows that the system comes back to steady state after the trip



Calculated by ETAP

Simple Grid Model for RE and Battery

Lets prepare a simple model with ETAP and practice!



Calculated by ETAP

Appendix 4-5-2 Attendant list, and Q&A, of the 3rd RE & Grid Stability Seminar (Barbados)

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 Barbados (Day-1)

25-26 Jan 2023

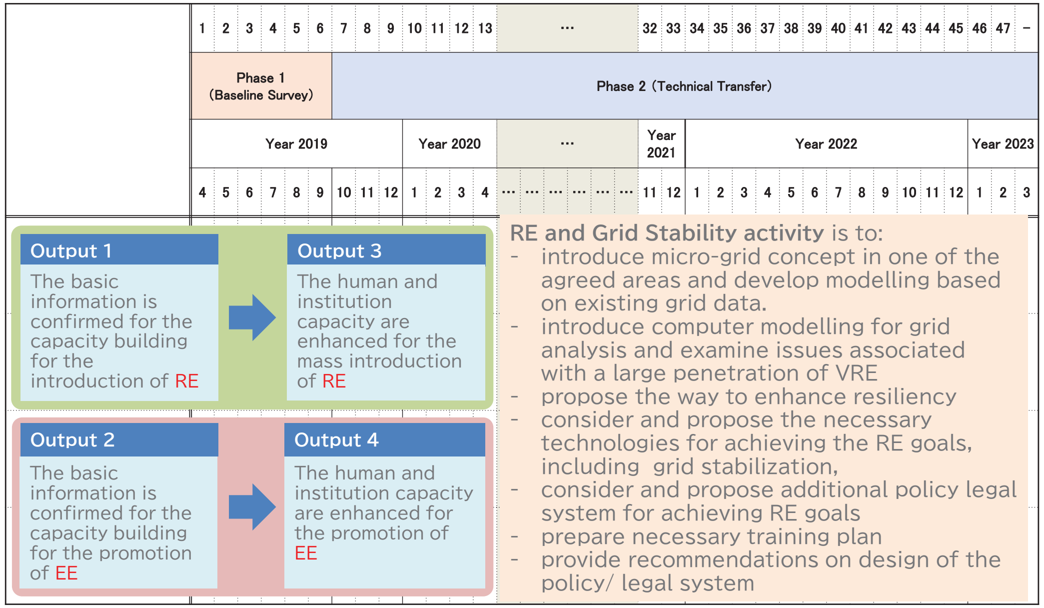
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Agenda (Day-1)

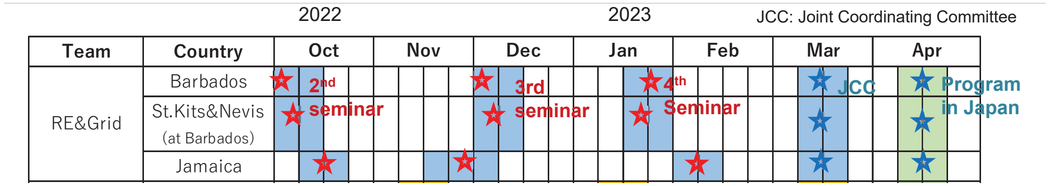
4th Seminar on Grid Stability and Large RE For Barbados (Day-1)

Introduction

Project Outline and Schedule



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	6-7 Dec 2022	To conduct and exercise grid modeling and analysis	Grid modeling, Microgrid, example, Load flow analysis and stability analysis, evaluation
4th Seminar	25-26 Jan 2023	Review and exercise of grid analysis with scenario cases	Detailed system and countermeasures, protection, Exercise of tools for grid analysis with various RE scenarios
Final JCC	Mar 2023	To confirm outcome of project and way forward	Review of TC activity output, policy recommendation, Program in Japan

Feedback at the 3rd Seminar

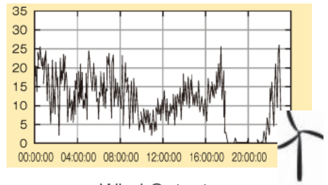
SCO: Synchronous Condenser
BESS: Battery Energy Storage System
GFM: Grid Forming Inverter
T&D: Transmission and Distribution

Items	Feedback	4th Seminars
To achieve 100% RE, what generation source do you want to try simuattion	Solar 70% Wind 10% biofuel 20% 70% PV (including CSP), 12% Wind, 18% WTE/Biomass 60% PV, 30% Wind, 10% other RE baseload 65% PV 25%Biomass, 10%wind, etc…	In Day-2, 60% PV、20% Wind,20%Biomass(BDF +WtE) will be assessed in the grid model.
What is necessary for grid stability in Barbados?	- Battery, SCO, bi-directional relays &controls - Weather forecasting based on locating 100 solar& 20 wind measuring systems - Batteries, GFM, demand response, microgrid integration - Include pumped storage, Hydrogen and Inverters providing Q - SCO. GFM if commercially available - Create multiple interconnected micro grids	-GFM updated situation is provided in Day1 - Weather forecasting system is presented in Day1
Other requests to consider in grid model and simulation.	1) Flywheels for larger battery installations 2) Short circuit analysis. 3) RE over 150% of the maximum demand and how to efficiently storage or curtail the excess energy	1) Design matter 2) Day-1, no,6 3) Day-2 case analysis
Please provide Additional suggestion for seminar	- incentive/tariffs for other types of grid improvement beyond storage - Weather prediction (15 min. ahead) required with microgrids - Addition of BESS and flywheel will aid the conversion to 100%RE.	-Demand side management -Weather prediction system Day-1 no.2 -FW is for short/large Fluctuation

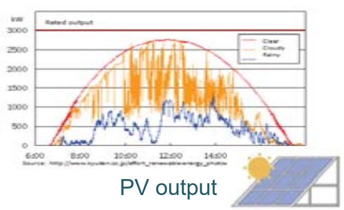
Feedback at the 3rd Seminar (2)

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 & Day-2 2) Let's try in Day-2 (most severe case) 3) Included in Day-1, no.7 4) Included in Day-2 5) Included in Day-1 no.5 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 6) biofuel	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 6) Good for spinning reserve but costlys

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)

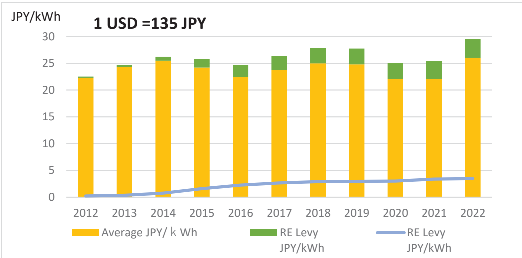
Both (VRE):
- It does not always generate when needed. **Load-supply matching** is an issue
- Time coincidence of VRE, there can be times when there is too much supply. Curtailment of VRE is necessary **→energy storage/control cost need to be considered.**

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

Power Tariff and RE Levy

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

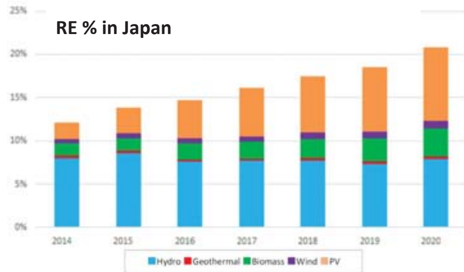


Power Tariff in Japan (JPY/kWh)

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 ??

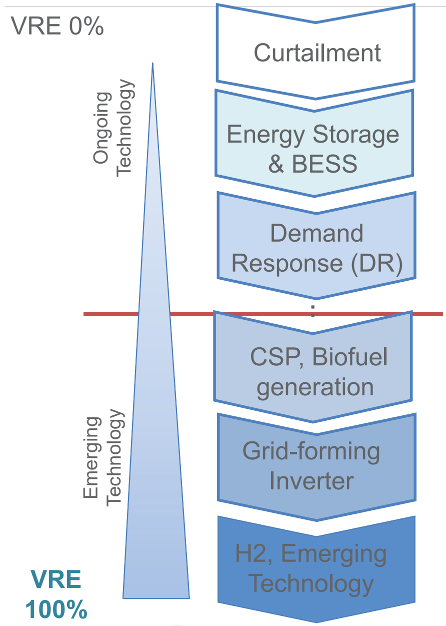


Power Tariff in Germany (Usc/kWh)

Prepared by JET from METI and Enetech data

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

Arrangement toward 100% RE



Voltage and frequency Stabilization

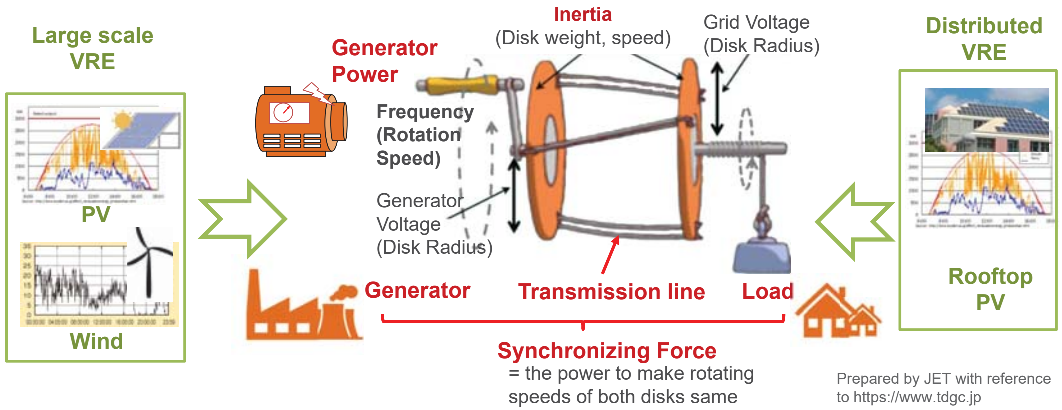
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- **Reactive power supply: SCO, Statcom**
- EV charging time shift
- Demand side management
- Regulatory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

Inertia and Synchronizing Force with RE



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

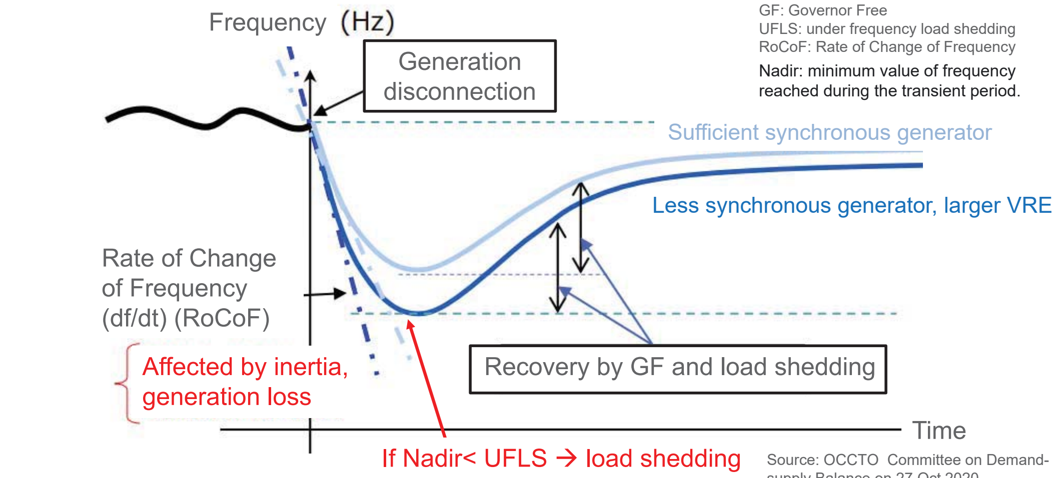
Inertia: The force to keep the rotation of disk when load is changed
Synchronizing Force: The force to keep rotation speed of disks. It keeps back to the same rotation when generation power and load is varied, without entangling.

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

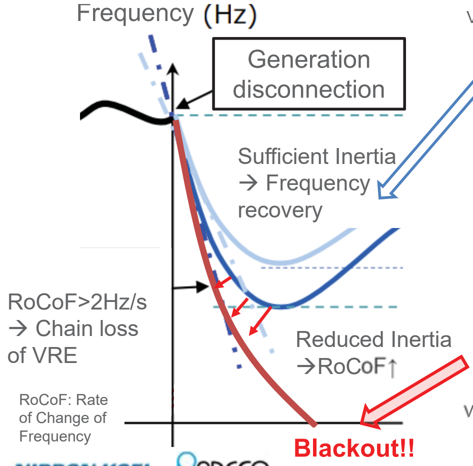


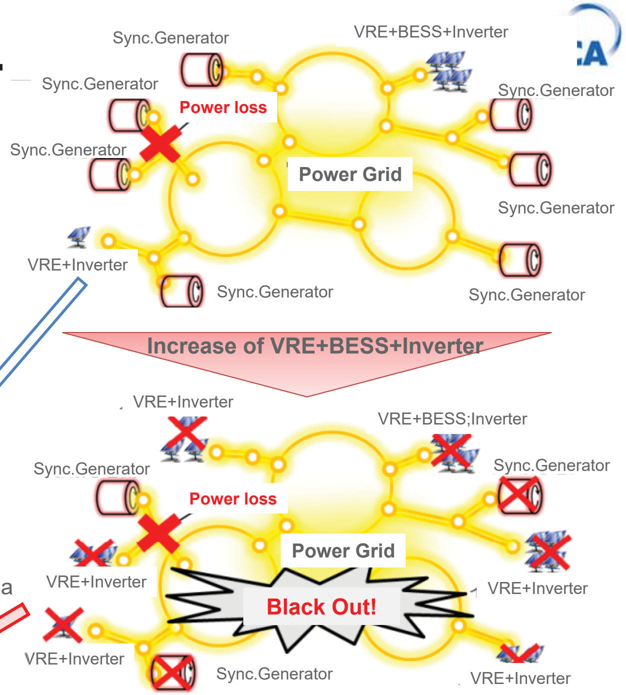
GF: Governor Free
UFLS: under frequency load shedding
RoCoF: Rate of Change of Frequency
Nadir: minimum value of frequency reached during the transient period.

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

Black-out when insufficient Sync. Gen.

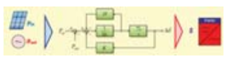
If synchronous generator is reduced and inertia is not sufficient:
→ Frequency sudden drop
→ Chain reaction of loss of VRE and further frequency drop
→ **Black out**





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 - >9000USD/kW, 11 USc/kWh
 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)

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%

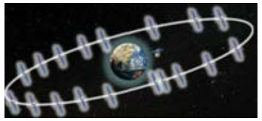
Source: RENEWABLE POWER GENERATION COSTS IN 2021 (IRENA)

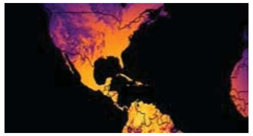
Cost of comparison of Grid Stability for various RE

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

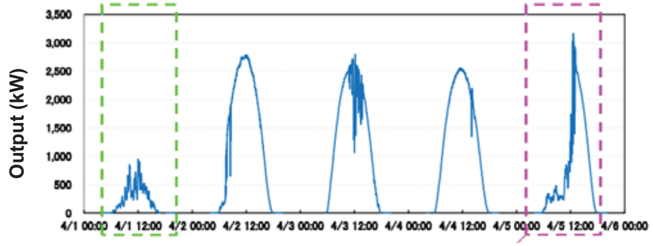
Type	Data source	+1 hours ahead error(%)	+3 hours ahead error(%)	+24 hours ahead error(%)
Tropical/Subtropical, Humid (7 sites)	Solcast	(2.4% to 3.8%)	(3.2% to 5.6%)	(4.5% to 7.0%)
	Smart Persistence	(3.0% to 5.3%)	(3.7% to 6.9%)	(3.8% to 8.6%)
	GFS	(4.6% to 8.5%)		

https://solcast.com/forecast-accuracy

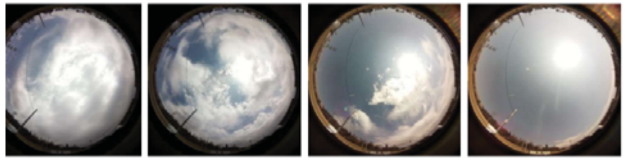
Feedback: Weather prediction (LIDAR/satellite/etc; 15 min. ahead)

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)



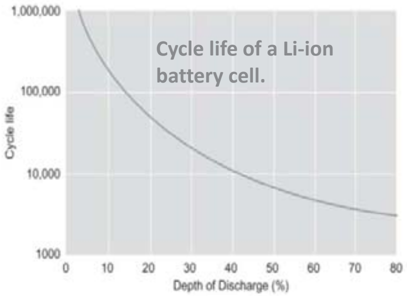
PV output time series variation (1 Apr to 4 Apr9)



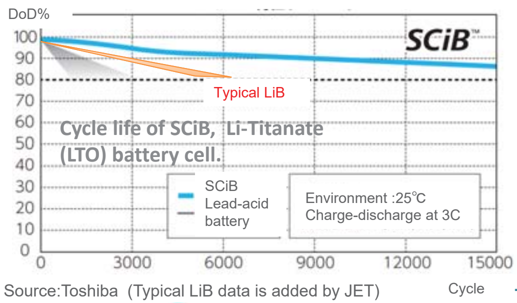
https://www.data.jma.go.jp/sat_info/himawari/kondan/kai3/shiryou3_2-2.pdf

Feedback: Using a BESS for frequent discharge, affect in battery degradation and the life of the battery.

Affect of Cycle time on Battery Life



Source:www.sciencedirect.com/topics/engineering/cycle-life



Source:Toshiba (Typical LiB data is added by JET)

Battery life cost depends much on cycle.

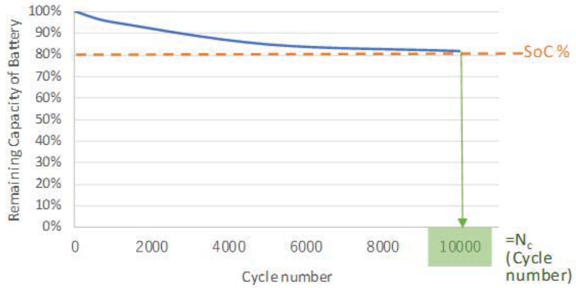
- DoD (Percentage of chargeable and dischargeable against rated capacity) is deteriorated according to increase of cycle. (1 cycle: 1 charge and 1 discharge at full capacity)
- Cycle life is defined as the number of cycles (with a 100% DOD: depth of discharge) a cell can perform before its capacity drops to 80% of its initial specified capacity and then starts to reduce its performance. (Cubesat Handbook, 2021)
- How much DoD is affected by cycle life is depending on environment (especially temperature) and manufacture's specification, which is usually not opened to public
- Generally, 5000-6000 cycle life with DoD 80%. Cheaper battery has shorter life.
- Long-life battery has 20,000 cycle with >80% DoD
- Accumulation of small fluctuation may be referred to asses affect on battery
  (Affect on cycle n = (ΣP_out + ΣP_in)/ 2 / Capacity)
- Flywheel may mitigate deterioration of battery

Example of Lifecycle Unit Cost Evaluation in Procurement

Financial evaluation to consider lifecycle unit cost of battery in competitive bidding is recommended.

Example for 20years project:

$$LUC = \frac{P_{bid} + N_{br} \times P_{BESS}}{C_{BESS} \times N_c \times \frac{SoC}{100}}$$



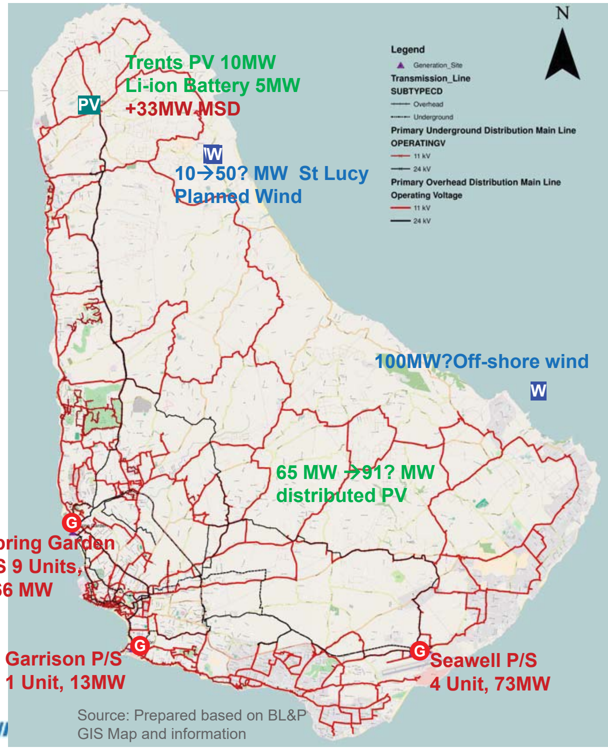
Source: Procurement of Design, Supply, and Installation of EMS and BESS of PV Diesel Hybrid System in Addu City of Maldives

LUC	Lifecycle unit cost in USD/kWh
C_{BESS}	Overall capacity of BESS specified in specification submitted by the bidder
N_c	Number of battery cycle tested and guaranteed from the test report with capacity above SoC%
SoC	State of Charge, corresponding to remaining usable capacity of battery in % in kWh against initial capacity of battery in kWh, guaranteed after battery is charged and discharged Nc number of times
N_{br}	Number of times of required battery replacement in 20 years, assuming battery is fully charged and discharged once in a day. When N_c > 7.300 times (=20 year x 365 days), N_{br}=0. When N_c ≦7,300, N_{br} shall be the rounded up to the integer value of 7,300/N_c
P_{BESS}	Total price of "BESS and related equipment" in USD, put by the bidder in Schedule No.1 and Schedule No.4 in Section 4. $P_{BESS} = P_{BESS1} + P_{BESS2}$, Where P_{BESS1} is the cost of BESS and related equipment in Schedule No.1 of Section 4 and P_{BESS2} is the cost of Installation of BESS and related equipment, including container in Schedule No.4 of Section 4
P_{bid}	Bid Price in USD

4th Seminar on Grid Stability and Large RE For Barbados (Day-1)

1 Introduction for the Seminar, Power system, 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. Scenario cases of modified IRRP, Simulation Cases for Exercise
7. Cost of stability and Sharing Responsibility for stability
8. Harmonics and filtering
9. Measurement Function of Inverter, Grid Code
10. A Sample of Other Countries Situations of Grid and RE
11. Investment of MW and MWh of Energy Storage for VRE

Grid and Generation of Barbados



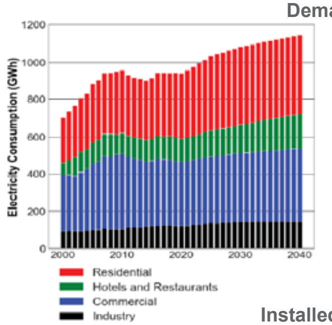
	Location	MW/u	Qy	MW	Remark
Existing					
Total thermal power				265	
	Spring Field Total		9	166	LDS, ST, GT
	Garrison	13	1	13	Gas Tubine
	Seawell	13	1	13	Gas Tubine
	Seawell	20	2	40	Gas Tubine
	Trents	8.3	4	33	MSD Engine
Total PV				75.6	
	Trents	10	1	10	PV
	Distributed PV		LS	65.6	PV
Total Battery				5	
	Trents	1	LS	5	BESS
Planned					
Total Planned RE & BESS				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
	BESS	10	6	60	by BL&P, 2023

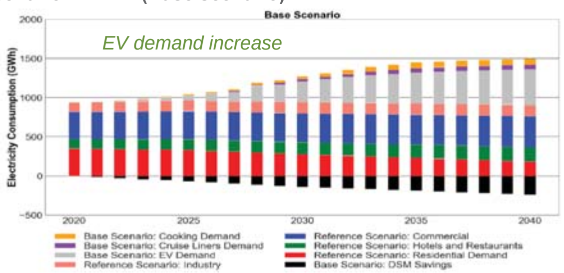
Tentative. Please let us confirm the status and update if any.

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

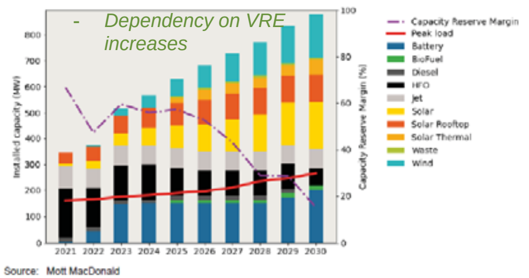
Source: IRRP Draft 2021, MottMacDonald

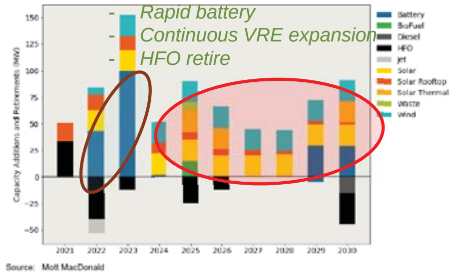
Demand Scenario in IRRP (Base scenario)





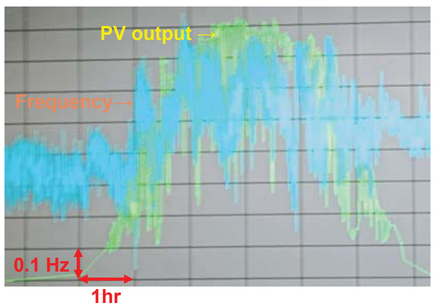
Installed capacity and capacity addition in IRRP (Base Case)

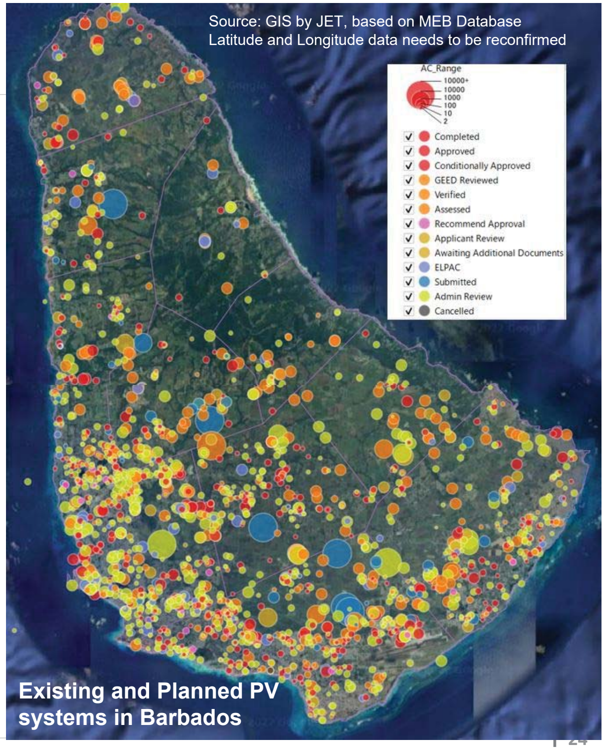




PV and Fluctuation of Frequency in Barbados

- 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

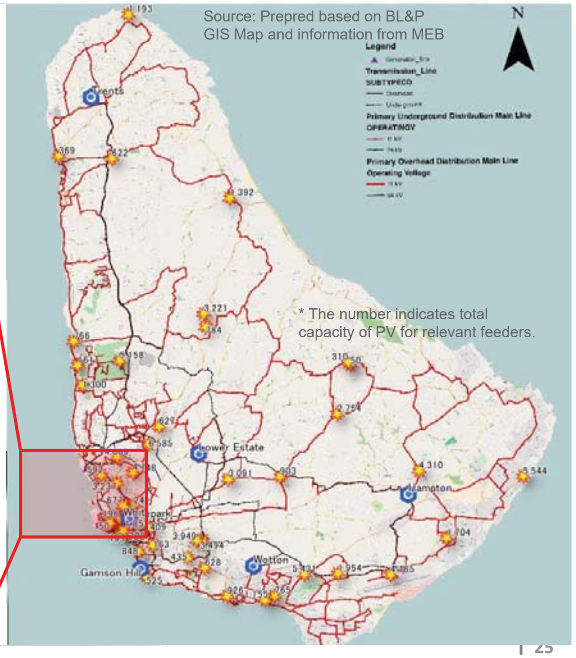




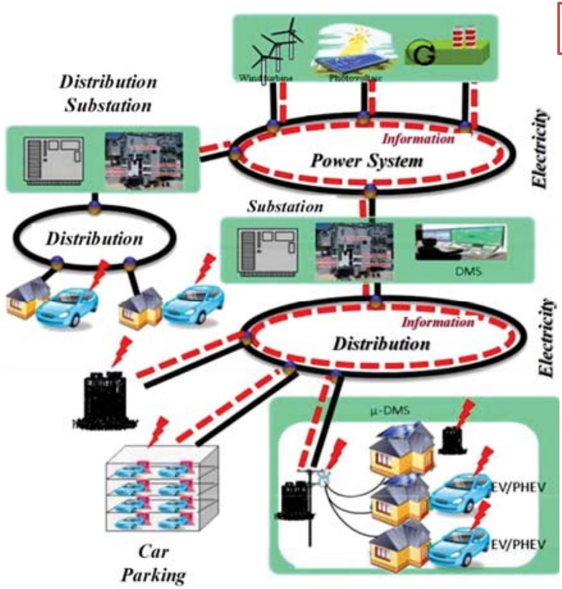
PV and Feeder capacity

- Can the feeders accommodate all existing and planned distributed PV ?

- Distributed PV 65 MW at present, increased to be 91 MW near future
- Feeder-wise capacity assessment is necessary in grid simulation
- 10 MW x 6nos BESS is planned at Trents, Lower Estate, Hampton, Wotton, Garrison Hill, and White Park



Microgrid Concept

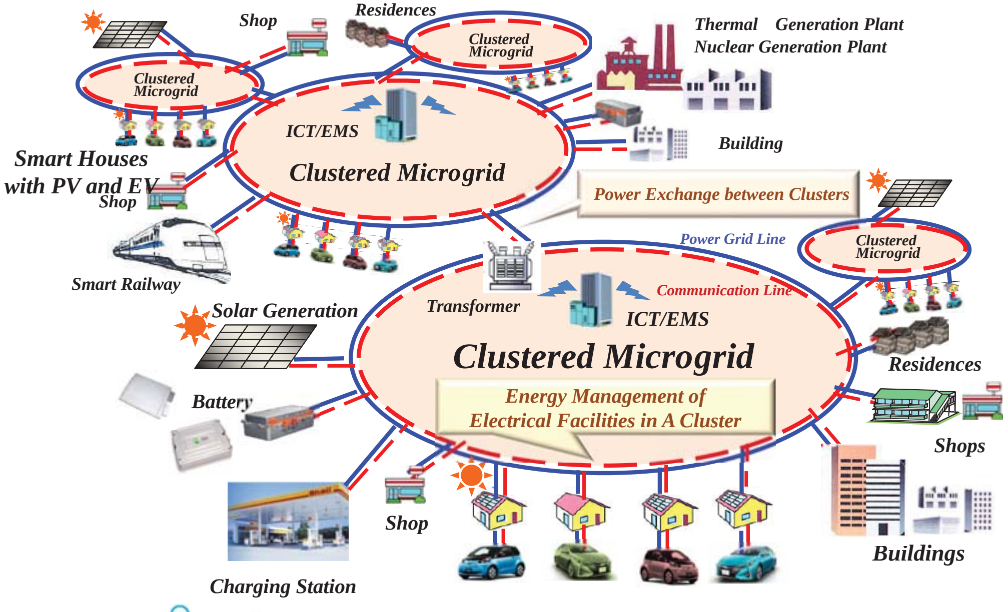


Concept of Micro-grid

- ✓ 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 : 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

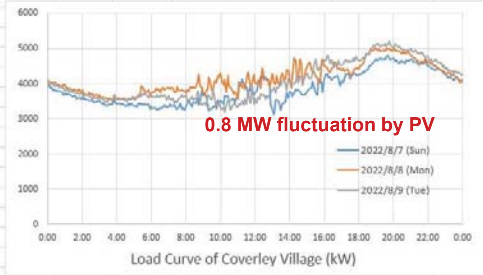
Voltage and frequency will fluctuate according to VRE
→ **Transient Analysis** is necessary :
- Power system stability with VRE fluctuation need to be calculated by using acceleration and deceleration of energy
- Necessity of Available Transmission Capacity and Spinning Reserve can be analyzed
- Requirement 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

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

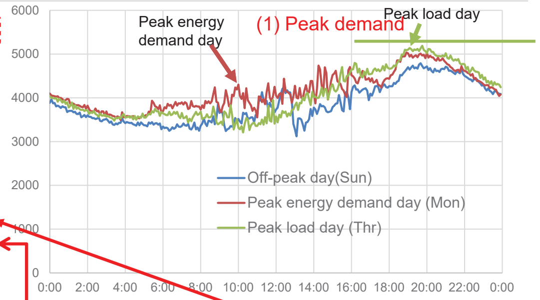


Example of system, to be reviewed

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

Microgrid Planning
Determination of generation output (in case of PV)

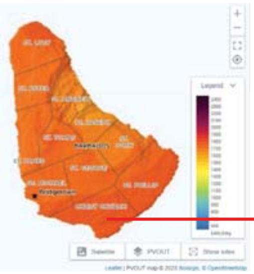
(1)	Max kW of peak day	5,191
(2)	Demand consideration yr (2021-2030)	10
(3)	Demand increase incl. EV %/yr	2.6%
(4)	Peak demand kW in 2030	6,710
(5)	PV Capacity to cover Peak demand	6,710
(6)	Present energy demand kWh/d	99,973
(7)	Design energy demadn kWh/d	129,228
(8)	Specific PV generation kWh/kW/day	4.901
(9)	Tentative PV Output kW	26,368
(10)	BESS PCS output kW	6,710

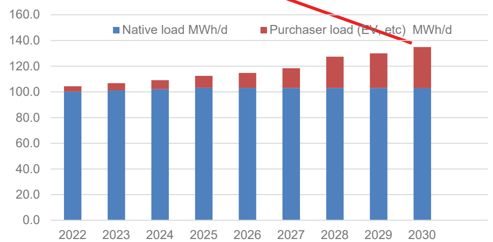


Load Curve of Coverley Village (kW)

(9) Calculated from
- Irradiation: I kWh/m2
- PV output: P kW/m2
- Design coefficient K

E =I･P･K
Solar Atlas provides typical kWh/kW/day @Coverley





Demand Increase of Coverley Village

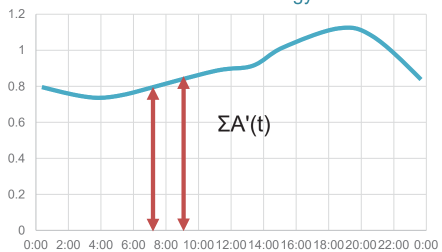
Microgrid Planning: Determination of Battery Capacity

(7)	Design energy demadn kWh/d	129,228
(11)	Efficiency of PCS	97%
(12)	Battery Capacity kW	6,918
(13)	Capacity rate after cycle life K	0.9
(14)	Depth of Discharge D	0.9
(15)	Charge-discharge efficiency η	0.9
(16)	Nos of days to store energy n	1
(17)	Design Battery Energy MWh	182
(18)	Required PV Output for batetery MW	37.2

$$S = n\frac{\sum_{t=0}^{24} A'(t)}{L \cdot \eta}$$

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

Quite large to store all 24h energy!



Example of Load Curve for Microgrid (MW)

Requirement of Battery becomes too much and cost will be too high.
→ Need to consider other measurement.

Prepared by JET

4th Seminar on Grid Stability and Large RE

Day-1 Session

3. Development Status of Grid Forming Inverter(GFM) and its Safety (Feedback from 3rd Seminar)
    - 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 (Feedback from 3rd Seminar)
6. Scenario cases of modified IRRP, Simulation Cases for updating Exercise
9. Measurement Function of Inverter, Grid Code
11. Investment of MW and MWh of Energy Storage for Variable Renewable Energy(VRE)

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
      Grid Code: National Grid GC0137, VDE2020
    - USA: Department of Energy(DOE) SuNLaMP, SETO,
      Grid Code: IEEE2800-2022, NERC IRPS, UNIFI

OSMOSE : https://www.osmose-h2020.eu/
MIGRATE : https://www.h2020-migrate.eu/
SmartNet : https://smartnet-project.eu/

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.

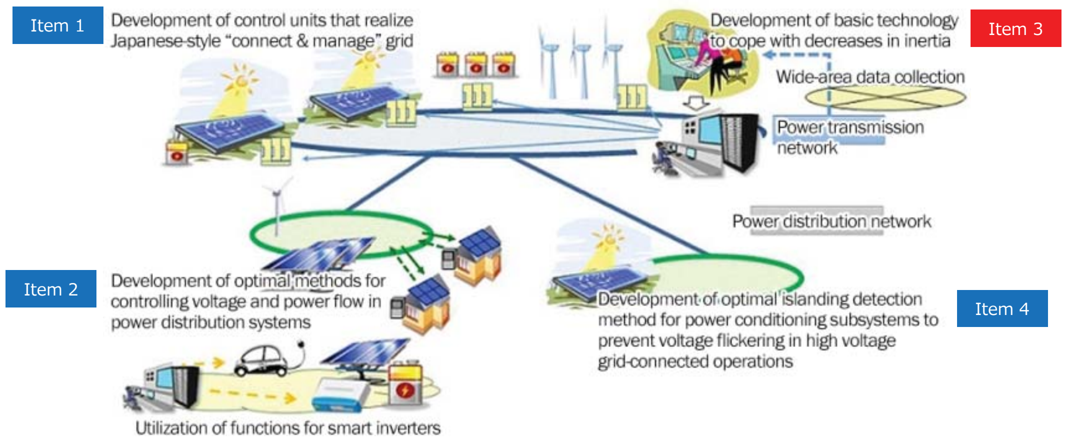
Item1: Development of control units for Japanese connect and manage grid (last to 2023)
Item2: Development of control method to cope with decrease in inertia using phasor measurement unit
Item3: Development of optimal method to control voltage and power flow in distribution system with IBR
Item4: Development 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.

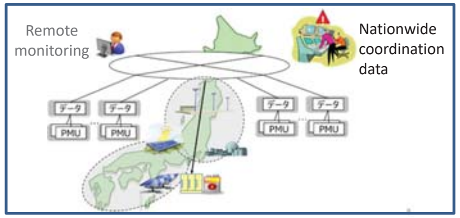


https://www.nedo.go.jp/english/activities/activities_ZZJP_100150.html

National R&D project in 2019-2021 in Japan

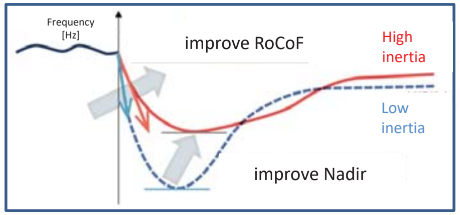
Item 3: Development of basic technology to cope with decreases in inertia (Scope)

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

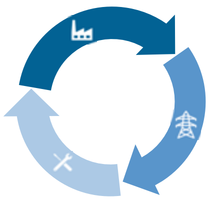
STREAM Project overview of Group1 and Group2

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

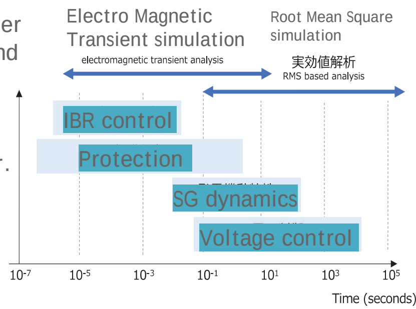
STREAM Project overview of Group3

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 IEEJ-EAST10 model.

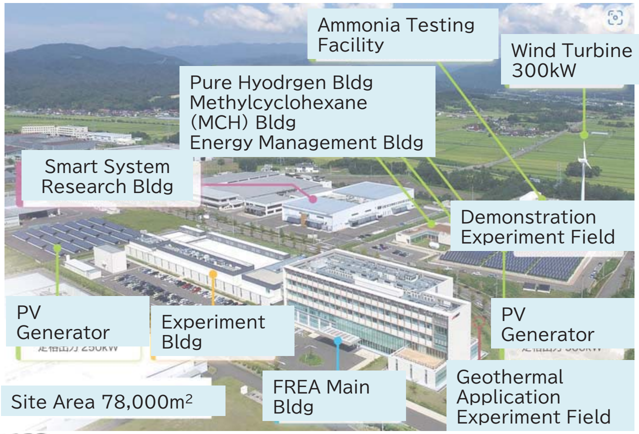
The Fukushima Renewable Energy Institute, AIST (FREA)

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 for Grid

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 for large grid, Grid Forming Inverter(GFM) can be a kick starter, when black start will be applied after blackout, if energy resources, such as charged battery, battery with PV are available with GFM.

If not, hydro turbine generators or gas turbine generators excited by permanent magnet is alternative way.

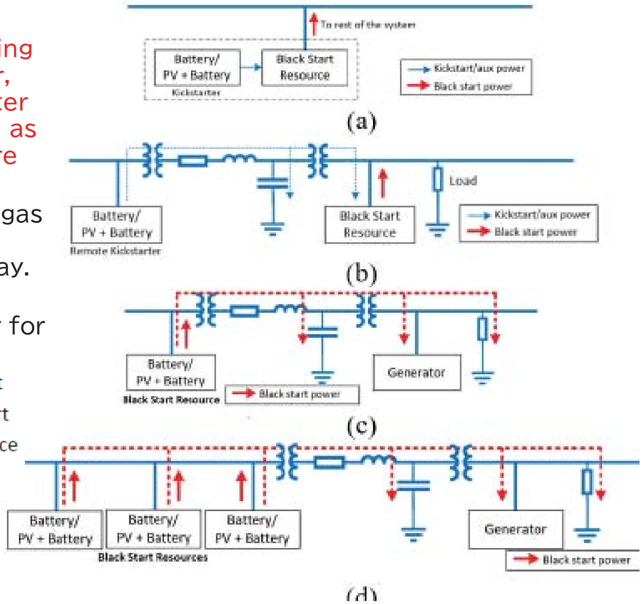
NREL(National Renewable Energy Laboratory), USA proposes the way for black start using GFM in 4 ways.

(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

Feedback from 3rd Seminar on Grid Stability and Large RE

Black Start using BESS for Microgrid

This is a feedback about question of the way to supply power to the grid when the grid power goes off.

Grid Forming Inverter(GFM) can be a main electricity resource for black start.

Prime generators are:

GFM + battery (if it is enough to be charged)

GFM + battery + PV

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

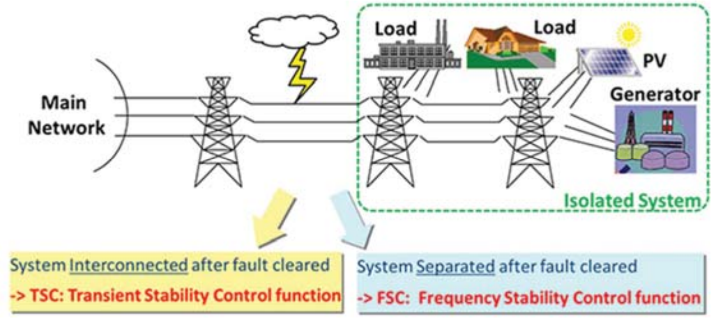
5. Special Protection System(SPS) including Load Shedding, PV/WT Trip

- 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 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.



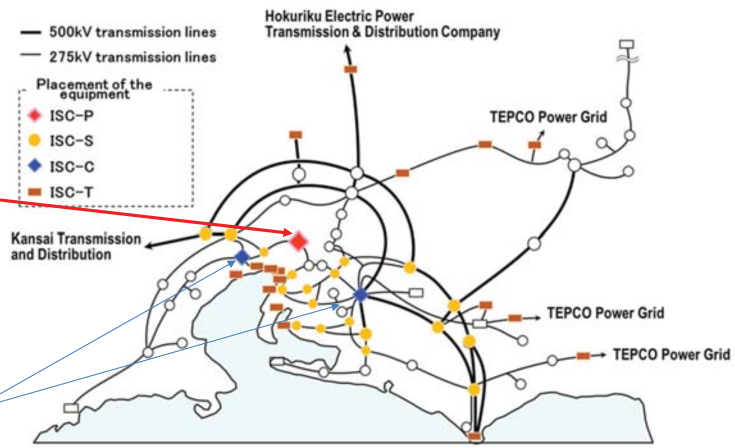
https://powergrid.chuden.co.jp/english/technical/operation/isc/

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

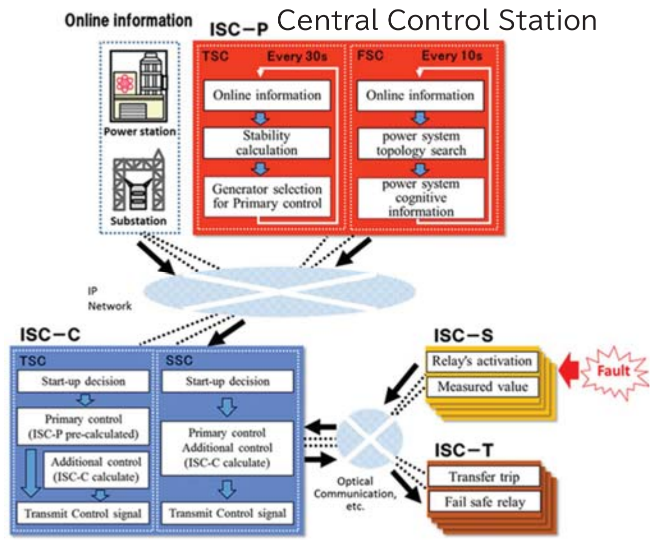
ISC-C



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.

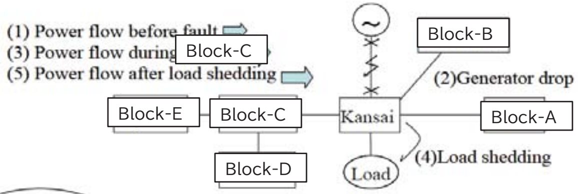


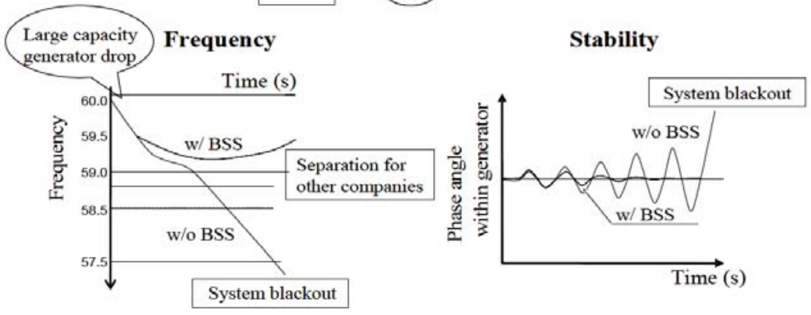
https://powergrid.chuden.co.jp/english/technical/operation/isc/

Block System Stabilizer(BSS) : 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 shed
(5) After load shedding, grid will be stable.

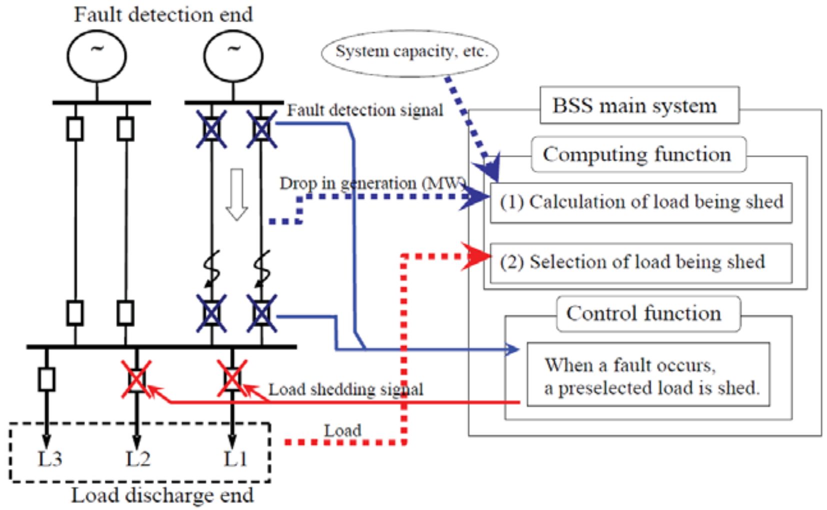




A. Nakajima, m. Morita, T. Hayashi, T. takeyasu, K. Kurose, T. Aramaki & A. kadokami., "Development of an Advanced Wide-area Special Protection System," Journal of International Council on Electrical Engineering, Vol.3, No.4, pp.334-339, 2013.

Block System Stabilizer : Advanced Wide-area Special Protection System - Control Scheme -

Control Scheme of Block system Stabilizer

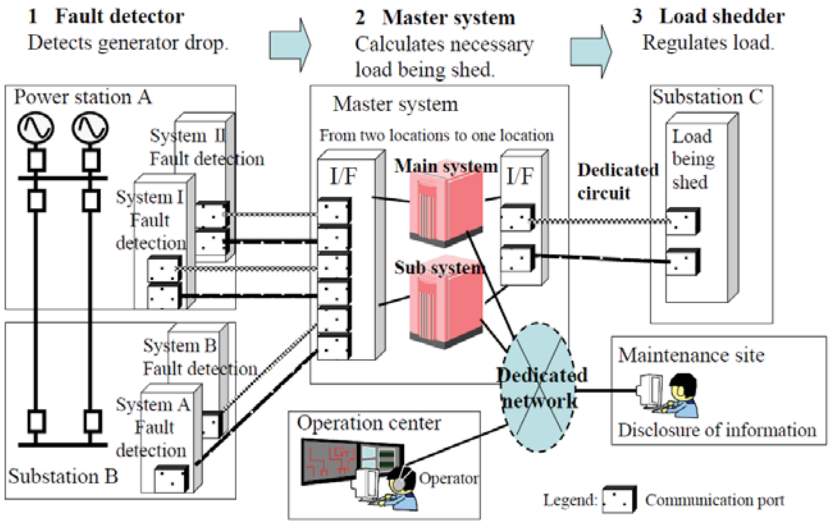


A. Nakajima, m. Morita, T. Hayashi, T. takeyasu, K. Kurose, T. Aramaki & A. kadokami., "Development of an Advanced Wide-area Special Protection System," Journal of International Council on Electrical Engineering, Vol.3, No.4, pp.334-339, 2013.

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.

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. Scenario cases of modified IRRP, Simulation Cases for updating Exercise

- 1 MW wind power has been commissioned at Cliffs, St. Johns.
- PV IPP which includes 10 MW PV at Kendal Sporting, north beach, 5MW PV at Sipaple Golf Club at St. George, 4 MW Pan-African Solar at Cliff Plantation, St. George, 8 MW PV by Spanish company, standard utility type, without battery.
- 52 MW PV with 3 MW BESS and Hydrogen storage.
- 13 MW is the maximum output to the grid, and remaining will be stored in hydrogen storage.
- 13 MW will be used as base load. 30 MW WtE at Vancluse,St. Thomas.
- 100 MW off-shore wind at northeast by IFC finance.
- 50 MW Wind at Lambert by BL&P (which was once 10MW plan)
- 10MW BESS has been installed at Lower Estate, garrison Hill, Whitepark, Hampton, Trents and Wotton.

These value should be set as PU.
In the simulation (VA)base is set as 100MVA.

Plan of Exercise in Day-2

- Exercise 1: Simple Grid
- Exercise 2: Case A and B Grid
- Exercise 3: Simple Grid with RE
- Exercise 4: Coverley Villages Microgrid (53nodes)
- Exercise 5: Coverley Villages Microgrid(100nodes)
- Exercise 6: Current Barbados Grid
- Exercise 7: Future grid of IRRP Scenario 3

  – Grid structure is drawn based on Google map.
  – Generation capacity, load capacity, line impedance, battery, capacity of renewable energy are assumed.

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) {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

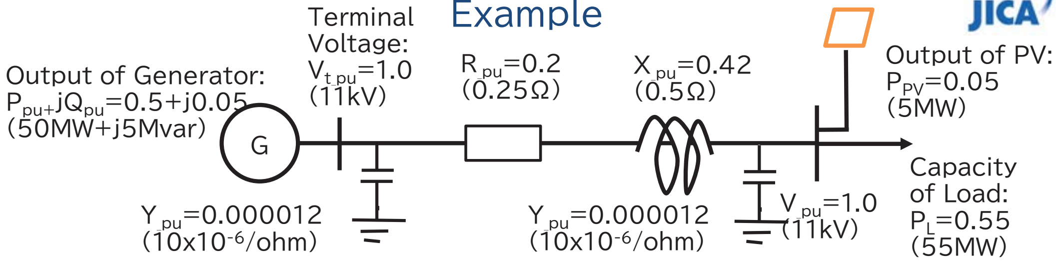
(5) Set P_pu to 0 for substation.

(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

Calculation Per Unit Value Example



(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]ˉ0+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}+Q_{pu}=(50[MW]+j5[Mvar])/100 [MVA]=0.5+j0.05

Please prepare to change your data to PU value.

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

Rule of Setting Value

- Capacity of RE is set as negative load P
- Capacity of Battery is set as negative load P
- Var Compensator
  - Set the value of Var Compensator at 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

4th Seminar on Grid Stability and Large RE For Barbados (Day-1)

1 Introduction for the Seminar, Power system, 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. Scenario cases of modified IRRP, Simulation Cases for Exercise
7. Cost of stability and Sharing Responsibility for stability
8. Harmonics and filtering
9. Measurement Function of Inverter, Grid Code
10. A Sample of Other Countries Situations of Grid and RE
11. Investment of MW and MWh of Energy Storage for VRE

Discussion for Responsibility of Grid Stability

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 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 Responsibility of Grid Stability

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 policy	- 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

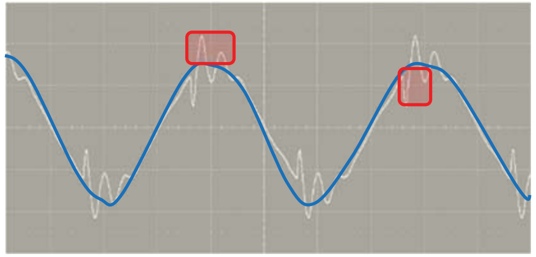
Item	Description
Storage for smoothing output and peak shift	- Mandatory installation of BESS, for example, more than 80% (or 100%) of Peak MW and 4hrs storage for utility scale VRE
Investment to secure inertia and spinning reserve for grid	- Maintaining sufficient synchronous generator for spinning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

4th Seminar on Grid Stability and Large RE For Barbados (Day-1)

1 Introduction for the Seminar, Power system, 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. Scenario cases of modified IRRP, Simulation Cases for Exercise
7. Cost of stability and Sharing Responsibility for stability
8. Harmonics and filtering
9. Measurement Function of Inverter, Grid Code
10. A Sample of Other Countries Situations of Grid and RE
11. Investment of MW and MWh of Energy Storage for VRE

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

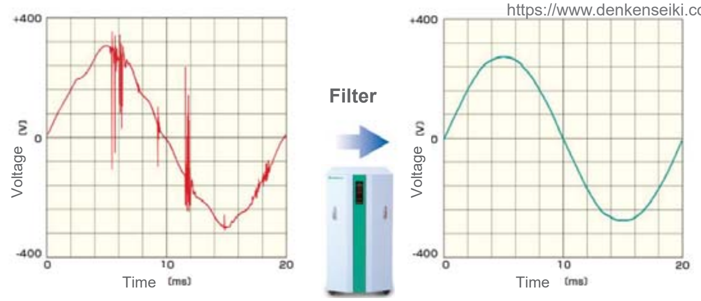
Harmonic :

- 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 Harmonics

- 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.)

9. Measurement Function of Inverter, Grid Code -Smart Inverter and 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

出典：Hawaiian Electric: 3 Utilities

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).

$$\%TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}} \times 100\%$$

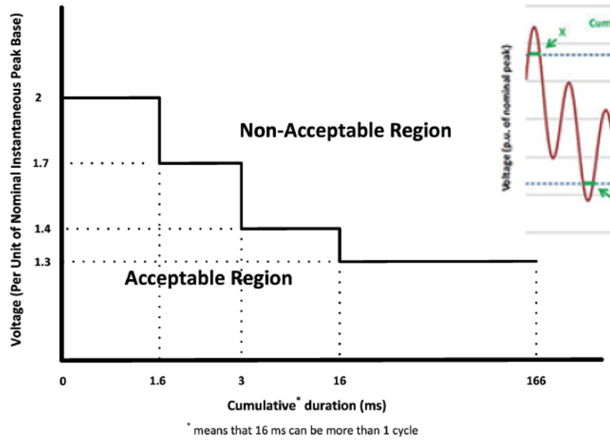
I_1 is the fundamental current as measured at the RPA

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.



[110] Cumulative duration is illustrated as follows:

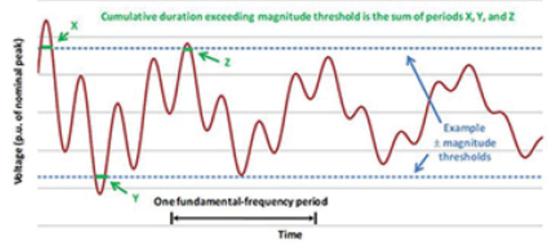


Figure 3 —Transient overvoltage limits

Grid Code of Barbados Light & Power Co.

1. System Frequency:
   During normal operation, the frequency deviate from 49.8Hz to 50.2Hz.

2. Voltage Limits and Voltage Regulation

Table 19: Voltage Limits 0 to 11,000V on Distribution System

Low Limit (% of nominal)	Nominal Voltage (%)	High Limit (% of nominal)
94	100	106

3. Voltage and Current Unbalance
   Voltage : under 2%
   Current : under 15%

4. Power Quality : based on IEEE Std. 519 "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems"
   Fundamental Frequency: 3%
   Total Voltage Harmonic Distortion(THD) : 5%

Overview of Advanced Smart Inverter Capabilities

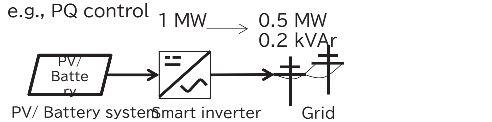
Smart Inverter includes several functions including grid forming control.

- 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 to increase penetration of variable renewable energy generation

Advanced function for Grid stability

① Active/ Reactive power control

e.g., PQ control

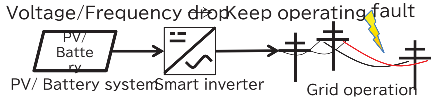


Voltage and Frequency support function

② Grid protection

e.g., Faut ride through

Voltage/Frequency drop Keep operating fault

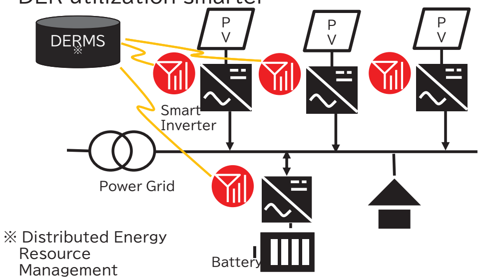


Restoration from fault

DER/smart inverter operation

③ Remote control and setting

Communication Capability to make DER utilization smarter



※ Distributed Energy Resource Management Systems

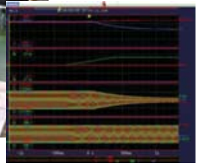
NEDO Project:FY2016–FY2018

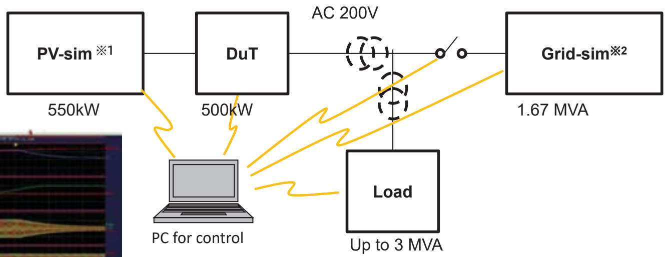
Smart inverter testing – NEDO project

※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

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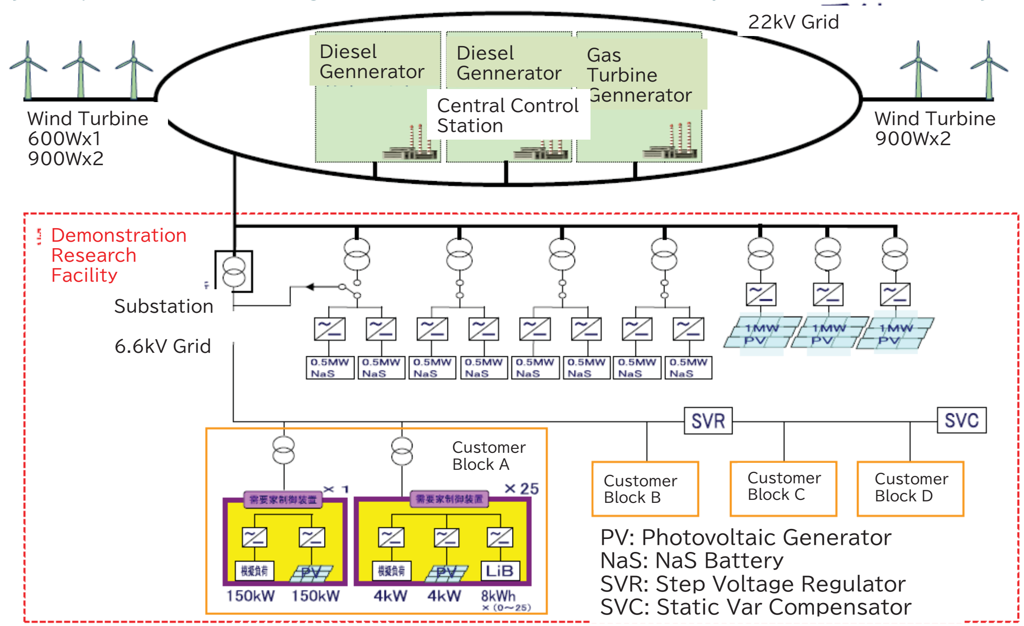
Feedback from 3rd Seminar on Grid Stability and Large RE

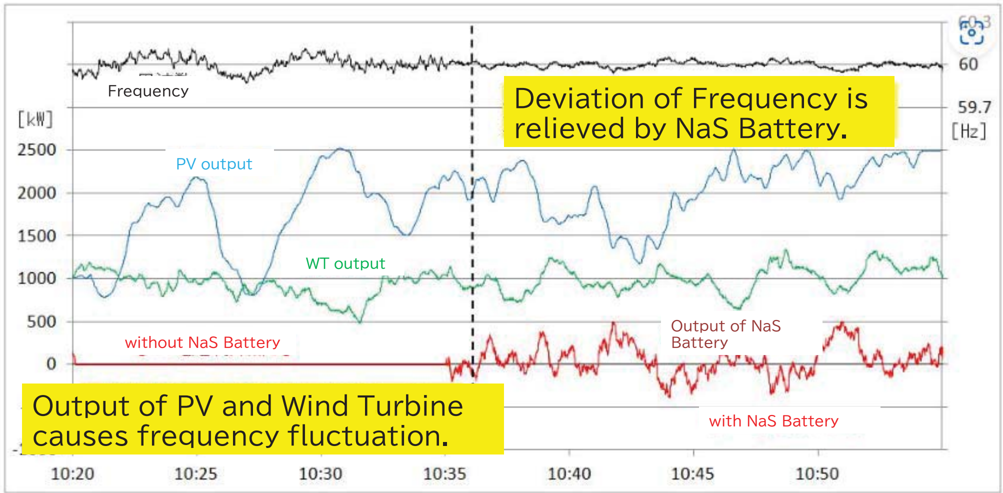
Miyakojima Island Mega Solar Demonstration Experimental Facility



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



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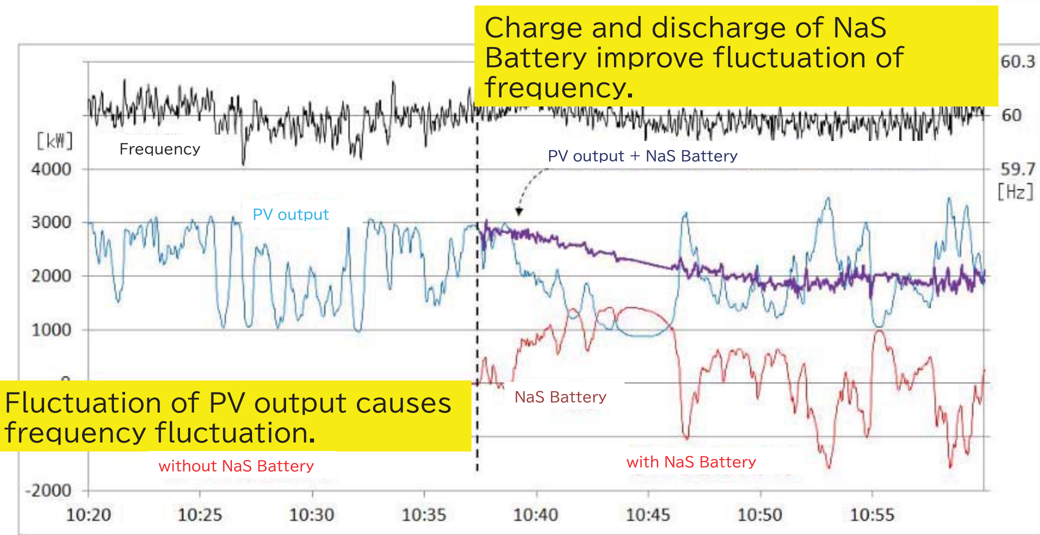
PV, NaS Battery and Frequency

in Miyakojima Island Mega Solar Demonstration Experimental Facility



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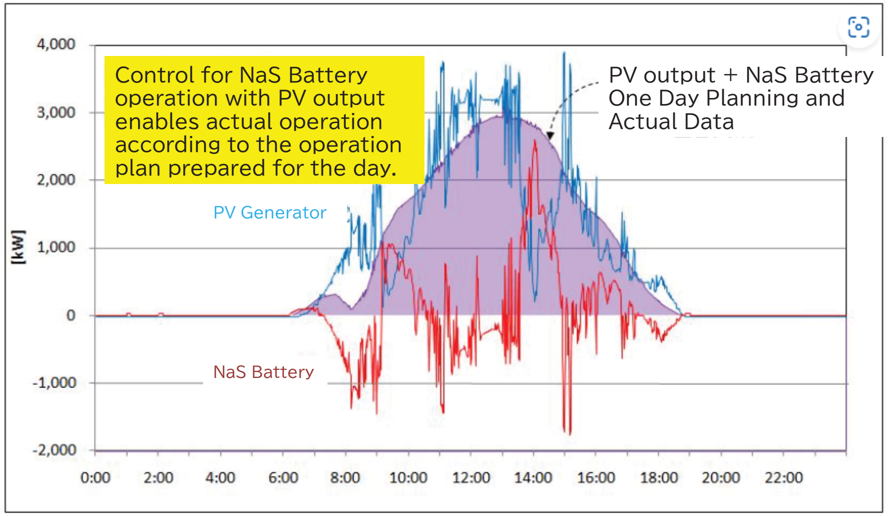
Demand and Supply of one day
in Miyakojima Mega Solar Demonstration Experimental Facility



https://www.okiden.co.jp/active/r and d/miyako/index.html

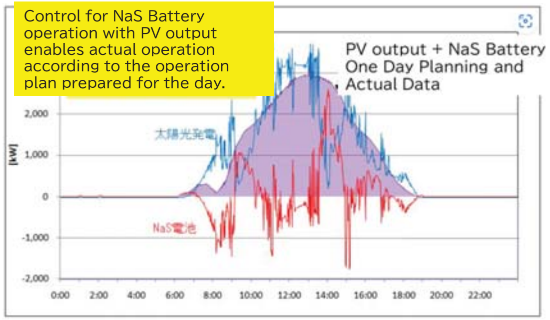
11. Investment of MW and MWh of Energy Storage for VRE

This section is a feedback and request of optimal capacity of battery.

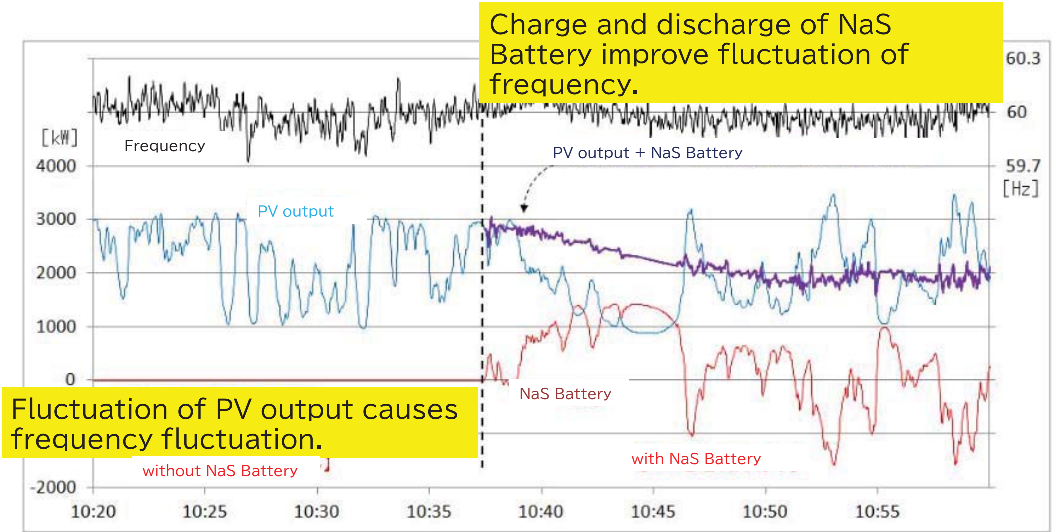
MWh of battery can be less than MWh of PV output.
The following equation can calculate only fluctuation capacity of PV.

(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

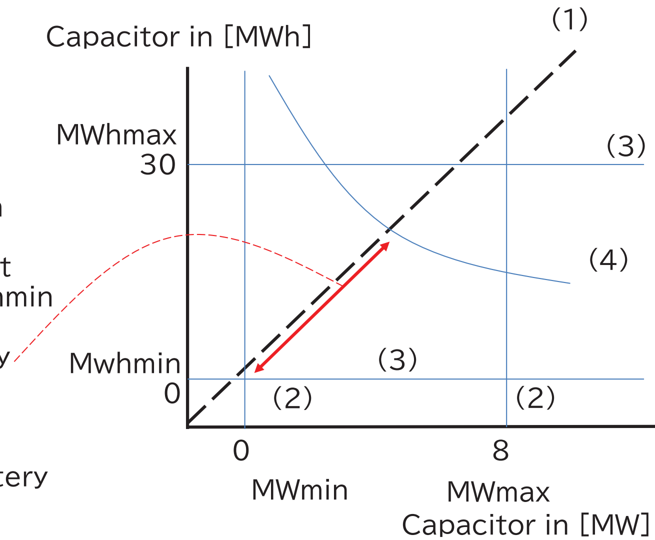


https://www.okiden.co.jp/active/r and d/miyako/index.html

Linear Programming Method to determine Battery Capacity

(1) Definition of Capacity
MWh=MW x hour
20MWh=5MW x 4
(2) Range of MW PV output
MWmax>MW>Mwmin
8>MW>0
(3) Range of MWh PV output
Mwhmax>MWh>Mwhmin
30>MWh>0
(4) Characteristic of Battery
MWh=k / MW
MWh=100 / MW

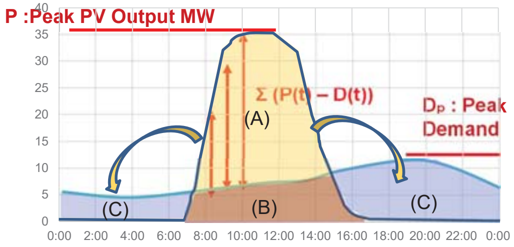
-> Red Line is available Battery Capacity Area



4th Seminar on Grid Stability and Large RE For Barbados (Day-1)

Microgrid Planning: Determination of Battery Capacity

In case of peak shift, it can reduce PV and BESS capacity, but…



Load Curve and PV Output (kW)

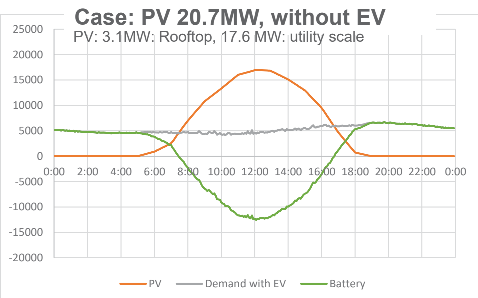
(A): Energy to be stored in Battery
(B): Day demand directly covered by PV
(C): Night demand need to be covered by battery
D_p = 6.7 MW
P = 37 MW (if 100% storage)
PV generated E kWh = (A) + (B)
Demand D kWh = (B) + (C)
(A) > (C) / L・η

L: Maintenance factor
η: Charge-discharge efficiency of battery

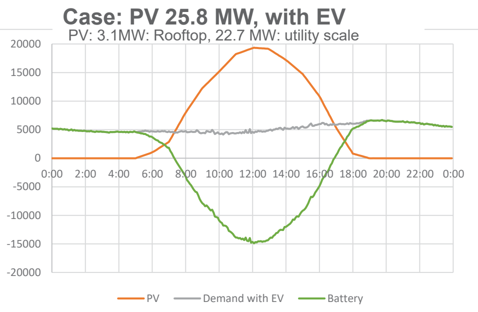
In case battery covers night load :
P_{PV} = 37 MW
PV generated E kWh = (A) + (B)
Demand D kWh = (B) + (C)
Σ (P(t) – D(t)) =(A) > (C) / L・η

Dp: Peak Demand
Ppv: PV Peak Output
P(t): PV output at the time (t)
D(t): Demand at the time (t) c

Cost Estimation for Microgrid in Coverley Village, 100% PV



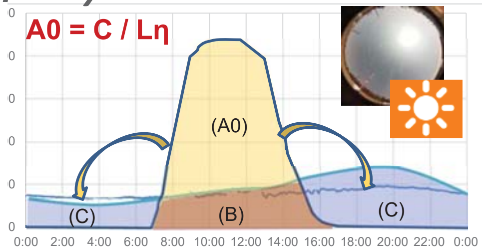
Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	20,700	kW	
Cost of PV installation	20,700,000	USD	
Requirement of SCO	5,175	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	1,035,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	63.0	MWh	11.4MW, 5.5 hr
Cost of Battery	25,206,678	USD	
Total Cost	**46,941,678**	**USD**	



Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	25,800	kW	
Cost of PV installation	25,800,000	USD	
Requirement of SCO	6,450	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	1,290,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	89.9	MWh	15.5 MW, 5.9 hrs
Cost of Battery	35,957,294	USD	
Total Cost	**63,047,294**	**USD**	

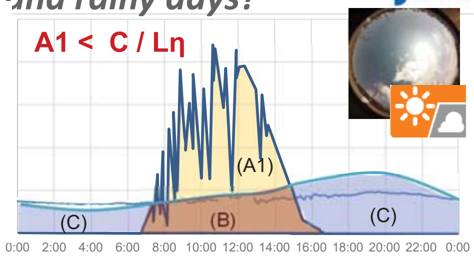
Pattern of Weather: If 100% PV, how much Battery capacity should be to cover cloudy and rainy days?

A0 = C / Lη



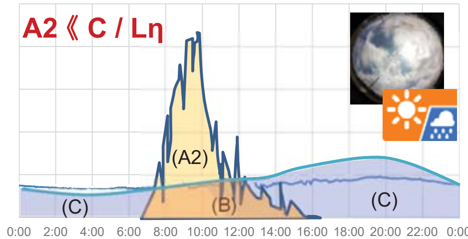
Load Curve and PV Output (kW)

A1 < C / Lη



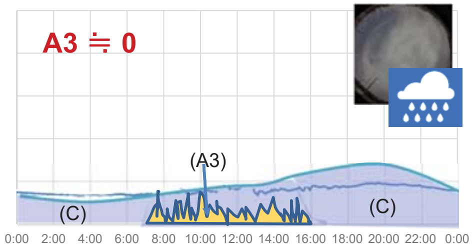
Load Curve and PV Output (kW)

A2 《 C / Lη



Load Curve and PV Output (kW)

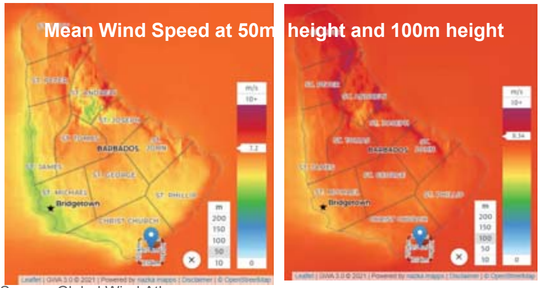
A3 ≒ 0



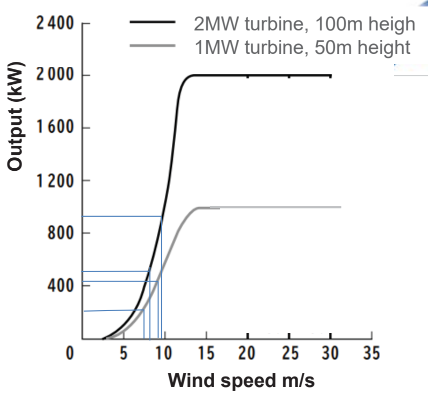
Load Curve and PV Output (kW)

→ **Much more BESS capacity is necessary to cover cloud/rainy weather**
→ **Support from grid is necessary for back-ups**

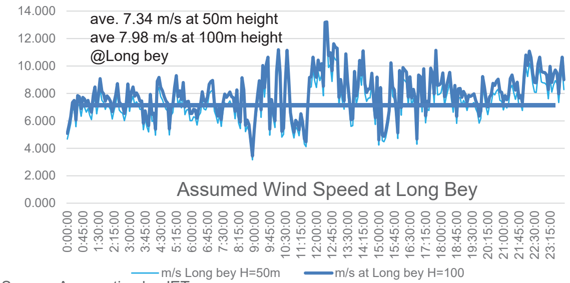
Microgrid with PV and Wind: Assessment of wind potential



Source: Global Wind Atlas



Power Curve of Wind Turbine Source: Mitsubishi

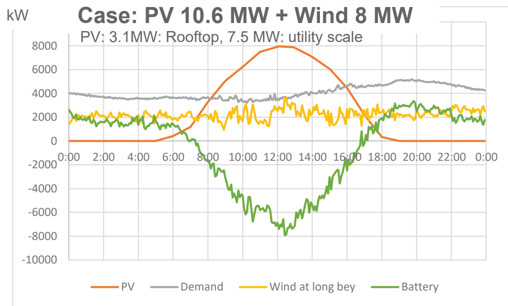


Source: Assumption by JET

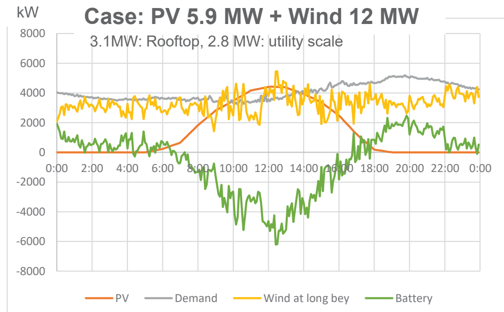
Location, Wind height, Speed, Output
Long Beach : 5km away from Coverley village

Location	Height	Wind speed m/s	Average kW by 1MW turbine	Average kW by 2MW turbine
Long Beach	50	7.34	210	
Long Beach	100	7.98		550
Windy Hill	50	9.26	420	
Windy Hill	100	9.62		880

Cost Estimation for Microgrid in Coverley Village without EV

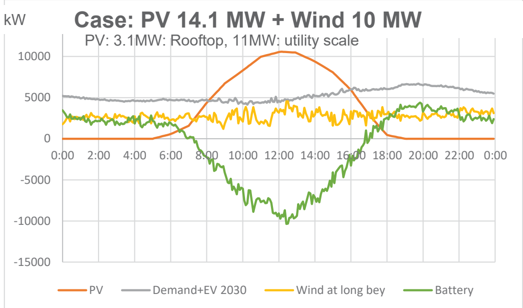


Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	10,600	kW	
Cost of PV installation	10,600,000	USD	
Unit cost of Wind	1,500	USD/kW	
Rated output of Wind	8,000	kW	
Cost of Wind	12,000,000	USD	
Unit cost of 22 kV system	400,000	USD/km	
Length of 22 kV	5	km	
Cost of 22 kV system	2,000,000	USD	
Requirement of SCO	4,650	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	930,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	40.9	MWh	8.1 MW, 5 hr
Cost of Battery	16,360,809	USD	
Total Cost	41,890,809	USD	

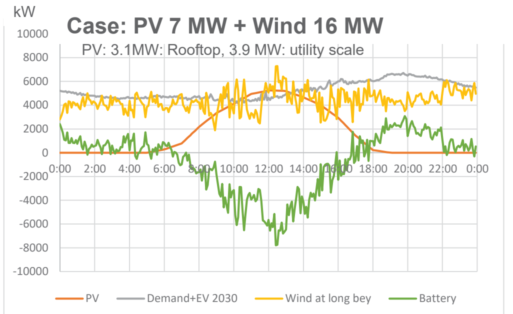


Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	5,900	kW	
Cost of PV installation	5,900,000	USD	
Unit cost of Wind	1,500	USD/kW	
Rated output of Wind	12,000	kW	
Cost of Wind	18,000,000	USD	
Unit cost of 22 kV system	400,000	USD/km	
Length of 22 kV	5	km	
Cost of 22 kV system	2,000,000	USD	
Requirement of SCO	4,475	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	895,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	26.9	MWh	6.4 MW, 4.2 hr
Cost of Battery	10,751,475	USD	
Total Cost	37,546,475	USD	

Cost Estimation for Microgrid in Coverley Village with EV



Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	14,100	kW	
Cost of PV installation	14,100,000	USD	
Unit cost of Wind	1,500	USD/kW	
Rated output of Wind	10,000	kW	
Cost of Wind	15,000,000	USD	
Unit cost of 22 kV system	400,000	USD/km	
Length of 22 kV	5	km	
Cost of 22 kV system	2,000,000	USD	
Requirement of SCO	6,025	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	1,205,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	54.1	MWh	10.7 MW, 5.1 hr
Cost of Battery	21,633,178	USD	
Total Cost	53,938,178	USD	



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

Finding about Microgrid in Coverley Village

- 100% RE supply by PV only will require tremendous investment for battery.
- About 22% larger investment cost (approx. additional 10 mil USD) is necessary to introduce EV demand in case no demand side management.
  - Incentive to charge EV in daytime may reduce battery requirement.
- Application of Wind reduces requirement of battery, depending on wind potential
- The wind potential much depends on wind velocity at site.
  - Wind output is proportional to the cube of wind speed : $P_{wind} \propto V^3$
  - Cost with installation of wind at high wind potential site with transmission line will be smaller.
- BESS cost/kWh much affect on total cost.
  - If BESS cost <140 USD/kWh, 100% PV cost may be smaller than PV +Wind.
- Frequent small charge-discharge by wind fluctuation may cause battery deterioration. The affect of frequent small charge-discharge need to be assessed by totaling fluctuation amount
  - Installation of wind at different place to achieve smoothing effect is recommended to mitigate small fluctuation
  - Hybrid energy storage system with Flywheel may be cost-effective to absorbed small frequent charge-discharge.

Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

4th Seminar on Grid Stability and Large RE for Barbados (Day-2)

25-26 Jan 2023

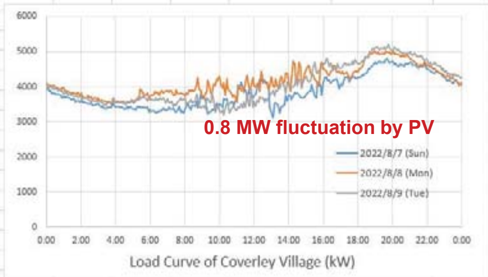
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

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. Microgrid model with Coverley Village example
3. Exercise on simple model and Microgrid
   - Design &Operation Planning, - Load Flow Analysis,
   - Transient Stability Analysis
4. Exercise on Future Grid and IRRP Scenario (by Taoka)
   - Design and Operation Planning, – Load Flow Analysis
   - Transient Stability Analysis
5. Analysis Result and Countermeasure of Grid Stability
6. Discussion and Way forward
7. Conclusion and Closing Remarks

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 rool area	31080	m2
Rooftop PV Capacity	3108	kWp
Specific PV Generation	4.917	kWh/kW/day
PV Generation by Rooftop	15,282	kWh/day
Current peak demand	5191	kW
Current energy demand	99,637	kWh/day

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 : Analysis for Stability

New system installation/enhancement for stabilization facility requirement for RE and supply-load balancing

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

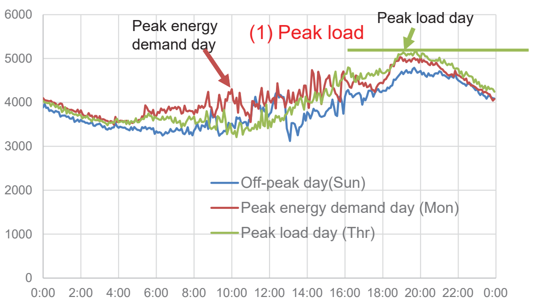
Voltage and frequency will fluctuate according to VRE
→ **Transient Analysis** is necessary :
- Power system stability with VRE fluctuation need to be calculated by using acceleration and deceleration of energy
- Necessity of Available Transmission Capacity and Spinning Reserve can be analyzed
- Requirement for Stabilizing equipment to be assessed

Optimum operation
→Economic Load Dispatch / LFC

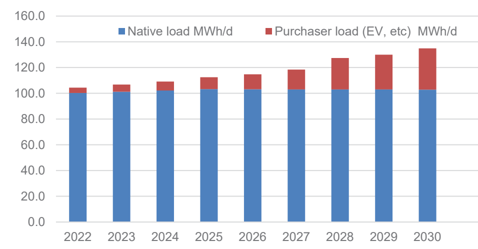
Operation of generators based on merit order to minimize fuel cost for generators (especially with thermal spinning reserve)
→ **Economic Load Dispatch** provides operation mode for optimized operation
- ex. Cost of Battery vs Cost of biodiesel

Determination of kW (power) and kWh (energy)

Estimation of load and demand at peak condition in Microgrid



Load Curve of Coverley Village (kW)



Demand Increase of Coverley Village

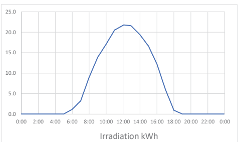
Output (kW) is determined from Peak Load. It is minimum output requirement.
- Peak load: Peak load data of highest peak load day among 3-10 years

Energy Demand (kWh) is determined from the day of largest energy demand (kWh)
- Largest energy demand of the year among 3-10 years(kWh)
- Output need to be adjusted so that it can produce necessary amount of energy demand considering reserve rate. It will be much larger than peak load.

Both need to consider future increase of peak and demand.

Microgrid Planning : Determination of kW and kWh

Plan for system structure of Microgrid in distribution lines based on demand


Irradiation kWh

PV	(7) 8,200	kW
Wind output	550	kW
Nos Wind units	(6) 5	units
Wind capacity	10	MW
Battery capacity	33.5	MWh
Battery output	7.2	MW
Battery hrs	4.6	hrs
Total PV + Wind output	18.2	MW

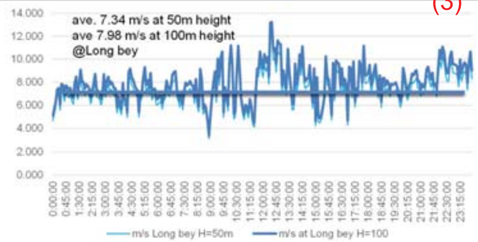
Time	Irradiation kWh/d	PV kW (1)	Wind kW (2)	PV+Wind kW	Demand kW	Battery charge-discharge	Battery charge kWh
0:00	0.0	0.0	1,752.5	1,752.5	4,036.0	2,283.5	
0:05	0.0	0.0	1,954.7	1,954.7	4,001.0	2,046.3	
0:10	0.0	0.0	2,171.9	2,171.9	3,994.0	1,822.1	
0:15	0.0	0.0	2,531.4	2,531.4	3,981.0	1,449.6	
0:20	0.0	0.0	2,583.8	2,583.8	3,995.0	1,411.2	
:							
11:50	21.5	6,068.2	3,669.8	9,738.0	3,952.0	-5,786.0	5,786.0
11:55	21.6	6,095.5	3,340.3	9,435.7	3,410.0	-6,025.7	6,025.7
12:00	21.7	6,122.7	3,160.5	9,283.2	3,575.0	-5,708.2	5,708.2
12:05	21.8	6,150.0	3,594.9	9,744.9	3,439.0	-6,305.9	6,305.9
12:10	21.8	6,144.6	3,347.7	9,492.3	3,614.0	-5,878.3	5,878.3
:							
23:35	0.0	0.0	3,272.9	3,272.9	4,358.0	1,085.1	
23:40	0.0	0.0	2,748.6	2,748.6	4,301.0	1,552.4	
23:45	0.0	0.0	3,332.8	3,332.8	4,318.0	985.2	
23:50	0.0	0.0	3,669.8	3,669.8	4,302.0	632.2	
23:55	0.0	0.0	3,100.6	3,100.6	4,243.0	1,142.4	
				(3)	(4)	(5)	
Total		46,073	66,000	112,073	97,390	-14,683	33,531.2
			Output-Demand	14,683			7,020.4
			Reserve	15.08% (5)			

$P_{PV,t}$: PV output at the time of t, P_{PVp} : Peak output of PV
η: total efficiency (design coefficient) of PV
Etotal: total energy of PV and Wind
P wind, t: output of Wind at the time of t
Btotal C,D: total of charged and discharged amount of Battery
Bloss: charge-discharge loss of Battery, Bcharge: Charge of Battery
Dt: Demand at the time of t

(1) PV kW at every 5 min: calculated from irradiation data and specific output/d
$P_{PV,t} = P_{PVp} \times \eta \quad \eta \fallingdotseq 0.75$
(2) Determine Wind kW (next slide)
$P_{wind} = P_{wind/unit} \times unit$
(3) PV and Wind total E_{total} (kWh)
$E_{total} = \Sigma \ (P_{PV,t} + P_{wind,t}) \times 5/60$
(in case of 5 min data)
(4) Demand kWh/d : $\Sigma D_t \times 5/60$
(5) Battery Charge-Discharge (kWh)
$\Sigma B_{totalC,D} < 0$,
Battery capacity $B_c > \Sigma B_{charge} + B_{loss}$
$B_{loss} > 15\% \times (-1) \times \Sigma B_{total\,c,d}$
(6) Set unit nos of turbine for wind
(7) Set P_{PVp} so that (5) is satisfied.

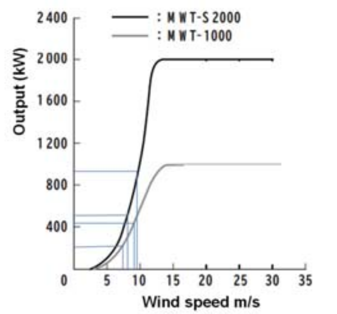
Microgrid Planning : Determination of Wind powers

# Record: 288					50m, 7.34m/s	100m, 7.98 m/s	
			Turbine output from Power Curve		210	550 (1)	
Timestamp	**Reference Wind Speed m/s**	Wind Speed m/s at Long bey H=50m	Wind Speed m/s at Long bey H=100	Difference from average speed m/s	Wind 50mH kW	Wind100mH kW	Batt charge-discharge
0:00:00	2.34	4.678	(2) 5.085	-2.66	133.83	(2) 350.50	2.66
0:05:00	2.61	5.217	5.672	-2.12	149.27	390.94	2.12
0:10:00	2.90	5.797	6.303	-1.54	165.86	434.38	1.54
0:15:00	3.38	6.757	7.346	-0.58	193.31	506.28	0.58
0:20:00	3.45	6.896	7.498	-0.44	197.31	516.77	0.44
:							
23:30:00	4.47	8.935	9.715	1.60	255.65	669.55	1.60
23:35:00	4.37	8.736	9.497	1.40	249.93	654.57	1.40
23:40:00	3.67	7.336	7.976	-0.00	209.89	549.72	0.00
23:45:00	4.45	8.895	9.671	1.56	254.50	666.55	1.56
23:50:00	4.90	9.795	10.649	2.45	280.24	733.96	2.45
23:55:00	4.14	8.276	8.997	0.94	236.77	620.12	0.94
	3.67	7.34	7.98		210.00	550.00	160.91
Total kWh					5,040.00 (3)	13,200.00	26.82



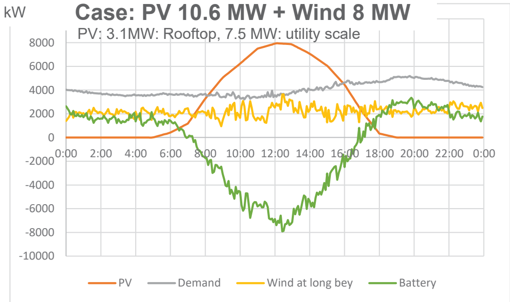
$P_{wind,t}$: Wind output at the time of t
E_{wind}: Total generated energy of the day by wind

(1) Determine average output from Power curve of turbine
(2) Calculate $P_{wind,t}$ from wind speed data and power curve with wind speed
(3) Total $E_{wind} = \Sigma P_{wind,t} \times 5/60$

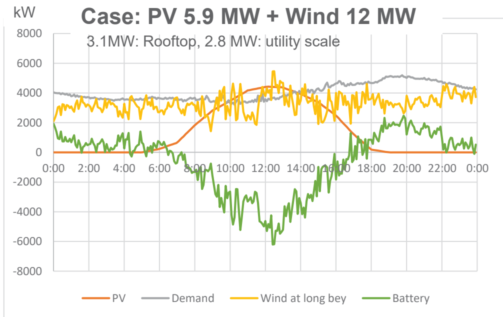


Power Curve of Wind Turbine Source: Mitsubishi

Cost Estimation for Microgrid in Coverley Village *without EV*



Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	10,600	kW	
Cost of PV installation	10,600,000	USD	
Unit cost of Wind	1,500	USD/kW	
Rated output of Wind	8,000	kW	
Cost of Wind	12,000,000	USD	
Unit cost of 22 kV system	400,000	USD/km	
Length of 22 kV	5	km	
Cost of 22 kV system	2,000,000	USD	
Requirement of SCO	4,650	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	930,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	40.9	MWh	8.1 MW, 5 hr
Cost of Battery	16,360,809	USD	
Total Cost	**41,890,809**	**USD**	



Item	Amount	unit	Remark
Unit cost of PV	1000	USD/kW	
Rated Output of PV	5,900	kW	
Cost of PV installation	5,900,000	USD	
Unit cost of Wind	1,500	USD/kW	
Rated output of Wind	12,000	kW	
Cost of Wind	18,000,000	USD	
Unit cost of 22 kV system	400,000	USD/km	
Length of 22 kV	5	km	
Cost of 22 kV system	2,000,000	USD	
Requirement of SCO	4,475	kVA	25% of PV+Wind output
Unit cost of SCO	200	USD/kVA	
Cost of SCO	895,000	USD	
Unit cost of Battery	400	USD/kWh	
Battery Strorage	26.9	MWh	6.4 MW, 4.2 hr
Cost of Battery	10,751,475	USD	
Total Cost	**37,546,475**	**USD**	

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
3. Exercise on simple grid example and Microgrid
   - Design and Operation Planning
   - Load Flow Analysis, Transient Stability Analysis
4. Exercise on Future Grid and IRRP Scenario
   - Design and Operation Planning
   - Load Flow Analysis
   - Transient Stability Analysis
5. Analysis Result and Countermeasure of Grid Stability

1. Introduction of Microgrid Designer and 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.

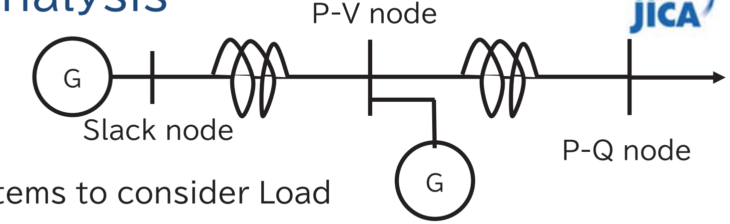
Application	Load Flow Analysis	Transient Stability Analysis	Electro Magnetic Transient Analysis
Design and Test of Equipment	O	O	O
Generation Planning for SG, RE, Battery and other resources	O		
Planning of Transmission Line, Distribution Line and Substation	O		
Operation and Control for Frequency Stability 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. Copy "Sample.xlsm" to your new file of ***.xlsm
5. Input prepared data to the new excel file
6. Start to calculate

Load Flow Analysis



These are 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 constant which need to be input
  - The phase angles of the voltages and the reactive power are unknown and to be calculated
- P-Q Nodes (Load Nodes or Substation Nodes)
  - The active and reactive power are unknown and to be calculated.
  - The magnitude and the phase angle of the bus voltages are unknown.

Load Flow Analysis

Set value P & Q -> Result V & θ of V
Set value P & V -> Result Q & θ of V
Set value V -> Result P, Q & θ of V for slack node

Parts of Grid	Input	Output /Result	Evaluation
Generator node	Generated P (Active Power) and V (voltage) are set.	Q (reactive Power) and phase angle of V are calculated.	Generated P should be < rated capacity
Slack node	The main power resource which will adjust demand and supply capacitor P, Q of grid (only V is given)	P, Q at slack	--
Load or Substation node	P and Q are set according to consuming power. **RE(Solar PV or WT) is deducted from Load. (i.e. negative load)**	V (Voltage) and phase angle θ of V against slack generator are calculated.	--
Line branch	Resistance R, Reactance X, Admittance Y/2 of transmission line and distribution line spec	Line current I and phase angle between nodes ae calculated.	Line flow should be <Total Transmission capacity
Transformer branch	Resistance R, Reactance X, Admittance Y/2 Tap	V (Voltage), phase angle of V at each node are	Phase Angle θ of V should be <90°

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 for RE and reactive power control equipment

- Capacity of RE(PV, WT) is set as negative load P
- Capacity of Rotating Type Generator(Biofuel Generator, WtE, Geothermal Generator) is set as synchronous generator model.
- Capacity of Battery is set as negative load P
- Reactive Power Supplier(Var Compensator)
  - Set the value of reactive power as admittance or negative reactive power of load at node
- Node which can keep voltage constant such as synchronous generator or STATCOM
  - Set voltage as constant value at node and set the node as P-V node

Evaluation Steps of 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

Calculation of Per Unit Base Value

<Distribution Grid>

This is an example.

- Vbase=11kV
- (VA)base=100MVA
- Ibase=100/11=9.1kA
- Zbase=Vbase²/(VA)base=11²/100=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

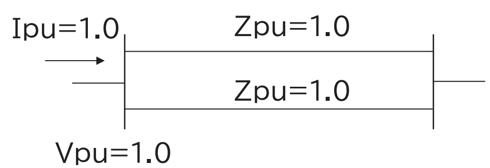
<Meaning of Per Unit>

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



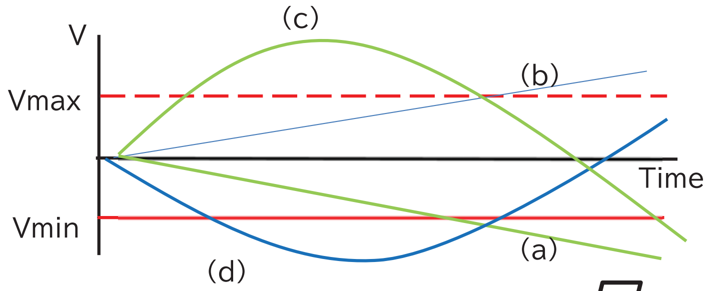
2 Circuit Transmission Line

3. Exercise on simple model and Microgrid

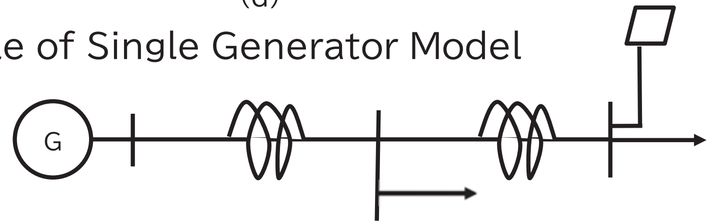
Single Generator with Infinite Bus Model is popular for research and development, and it is used for several application or evaluation.

(a) Fall evenly
(b) Rise evenly
(c) Rise and fall
(d) Fall and rise

Let's exercise !



This is an example of Single Generator Model



Notes for Load Flow Analysis in Microgrid Designer

Followings are the notes to use Microgrid Designer.

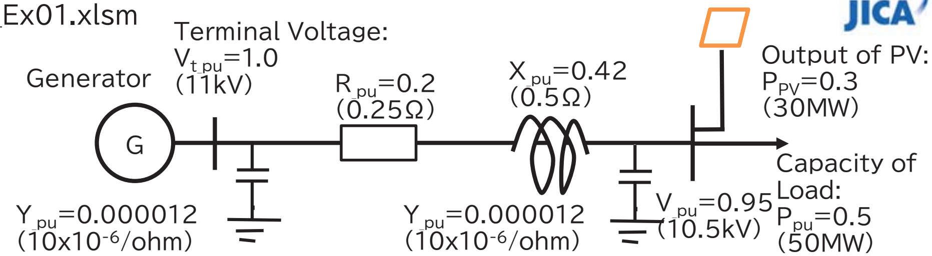
1. This program is composed of an excel file and execution file.
2. Your set of excel file and execution file should be in the same folder as a set.
3. Calculated data is overwritten. In order to save the results, you should move the excel file to another place.
4. Edge node should have some load or 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.

Plan of Exercises

- Exercise 1: Simple Grid
- Exercise 2: Case A and B Grid
- Exercise 3: Simple Grid with RE
- Exercise 4: Coverley Villages Microgrid (53nodes)
- Exercise 5: Coverley Villages Microgrid(100nodes)
- Exercise 6: Current Barbados Grid (2023)
- Exercise 7: Future grid of IRRP Scenario 3 (2030)
- Exercise 8: Proposed Energy Mix Scenario (2030)
-
  - Grid structure for Barbdos is drawn based on Google map.
  - Generation capacity, load capacity, line impedance, battery, capacity of renewable energy are assumed.

Exercise 1 Per Unit & Load Flow Analysis

4thREGS_Ex01.xlsm



(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

Load Flow Analysis of 4thREGS_Ex01 simple model

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	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 Node Data Sheet 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.)	(p.u.)
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 Branch Data Sheet for Load Flow Analysis in 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 in Microgrid Designer

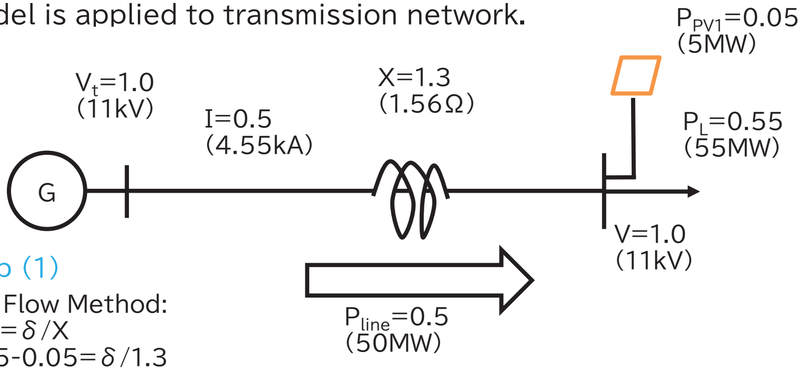
Load can be calculated by setting data in the yellow cell.
Please input capacity of
Load,
Utility PV, Distributed PV,
Wind Turbine and BESS,
Then the total capacity of each node is calculated and input Pl automatically.

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

Exercise 2 4thREGS_Ex02.xlsm

Case A Grid Model

PU based model is applied to transmission network.



Evaluation step (1)

(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.

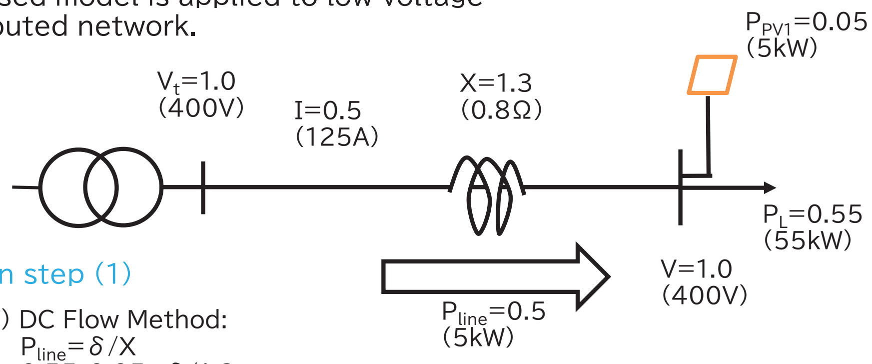
$I=(P_L-P_{PV1})/V=0.5/1.0=0.5=4.55A$

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.



Evaluation step (1)

(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

P-δ Curve and Stability Evaluation

Evaluation step (2)-(5)

(2) Pmax=1*1/1.3=0.77

(3) Pop=0.5

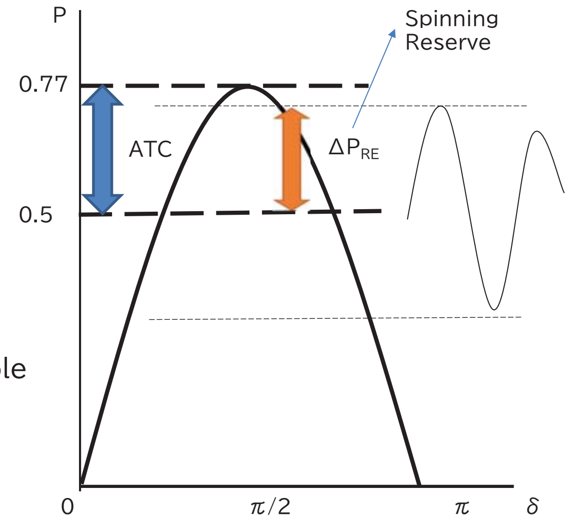
(a) Currently ΔP_{RE}= 0.15
-> Stable

(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 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

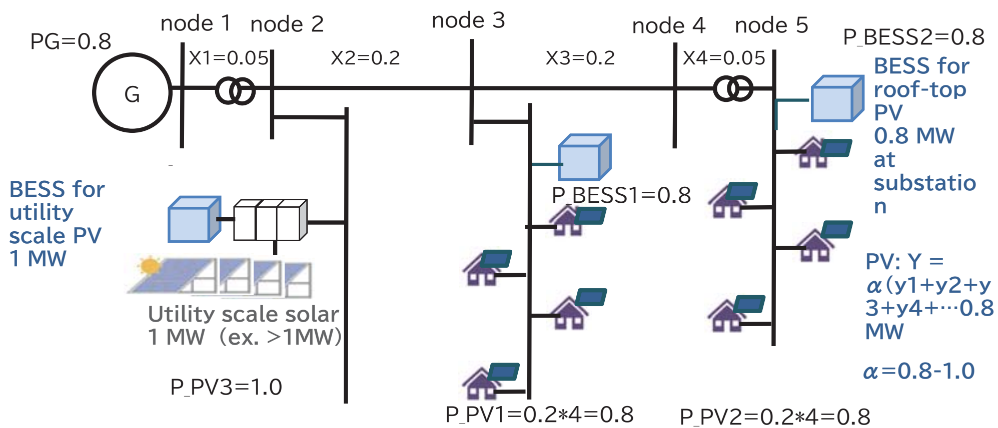
Results_Branch

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	

Exercise 3 4thREGS_Ex03-*.xlsm

Simple Grid Model with 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

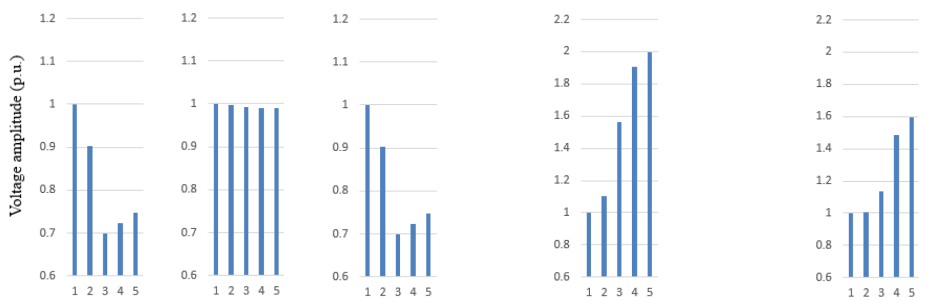
BranchData

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

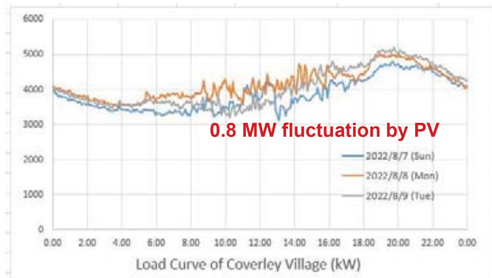


only Load 4thREGS_Ex03-1.xlsm | Load+PV 4thREGS_Ex03-2.xlsm | Load+PV+Battery 4thREGS_Ex03-3.xlsm | PV+Battery+largePV(node2) 4thREGS_Ex03-4.xlsm | PV+Battery+largePV(nod5) 4thREGS_Ex03-5.xlsm

- 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.

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 rool area	31080	m2
Rooftop PV Capacity	3108	kWp
Specific PV Generation	4.917	kWh/kW/day
PV Generation by Rooftop	15,282	kWh/day
Current peak demand	5191	kW
Current energy demand	99,637	kWh/day

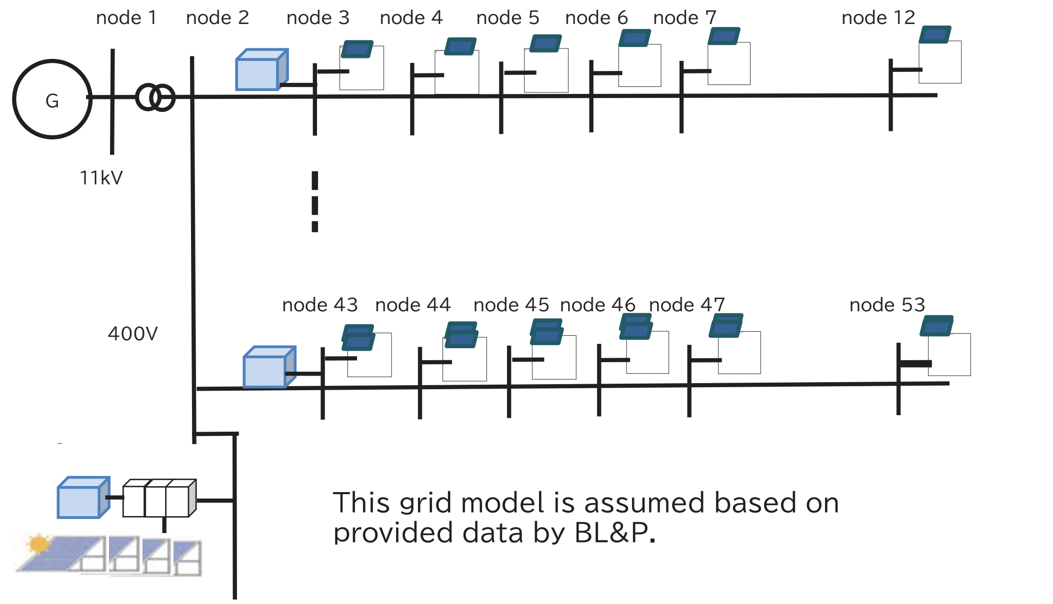
Exercise 4 4thREGS_Ex04-*_CoverleyVillage_53_2022.xlsm

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-*_CoverleyVillage_53_2022.xlsm

Coverley Village Microgrid Model for Load Flow Analysis



This grid model is assumed based on provided data by BL&P.

Exercise 4 4thREGS_Ex04-1_CoverleyVillage_53_2022.xlsm

Load Flow Analysis of 4thREGS_Ex04 Mocrogrid Model

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		

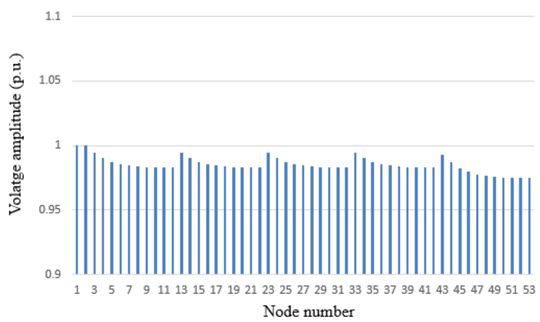
BranchData

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

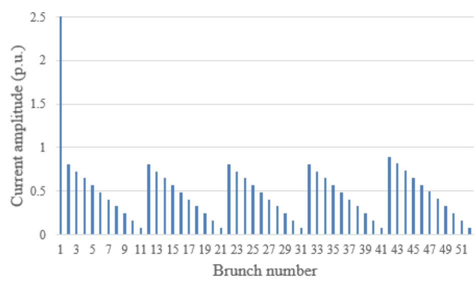
Exercise 4 4thREGS_Ex04-1_CoverleyVillage_53_2022.xlsm

Load Flow Analysis of Coverley Village Microgrid Model without PV and BESS

- Node voltage decrease a little gradually to the end of feeder.
- Line current of feeder is under the rated value except for the switch gear station.



Node Voltage

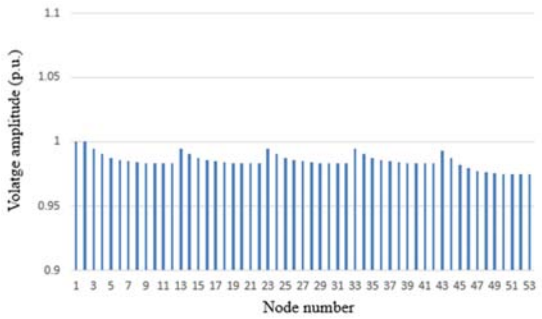


Line Current

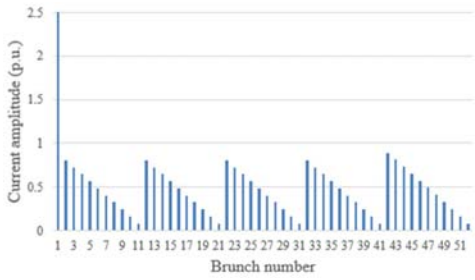
Exercise 4 4thREGS_Ex04-2_CoverleyVillage_53_2022.xlsm

Load Flow Analysis of Coverley Village Microgrid Model with PV and charging mode of BESS

- Node voltage decrease a little gradually to the end of feeder.
- Line current of feeder is within the rated value.
- Output of PV is used for charging BESS.



Node Voltage

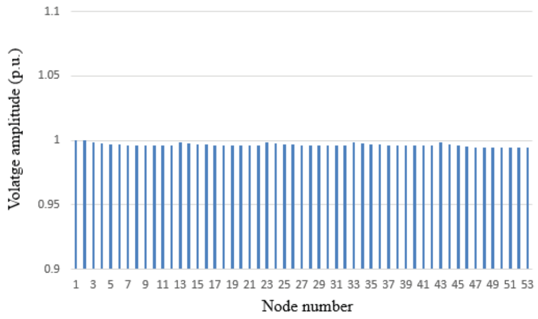


Line Current

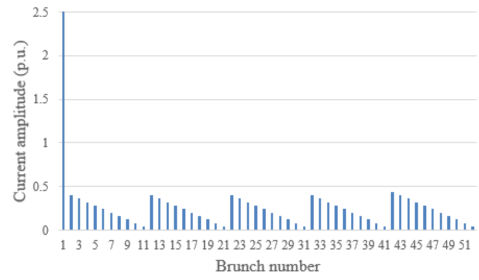
Exercise 4 4thREGS_Ex04-3_CoverleyVillage_53_2022.xlsm

Load Flow Analysis of Coverley Village Microgrid Model 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

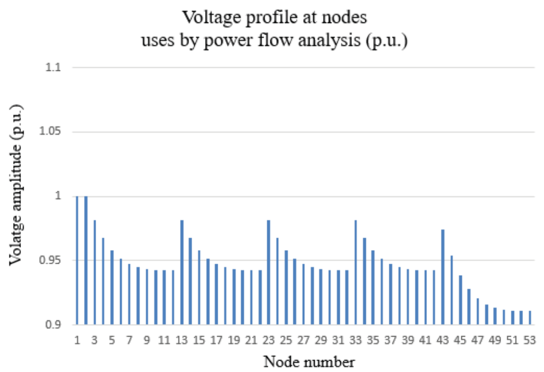


Line Current

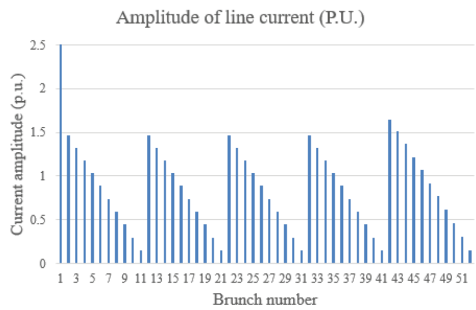
Exercise 4 4thREGS_Ex04-4_CoverleyVillage_53_2022.xlsm

Load Flow Analysis of Coverley Village Microgrid Model 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

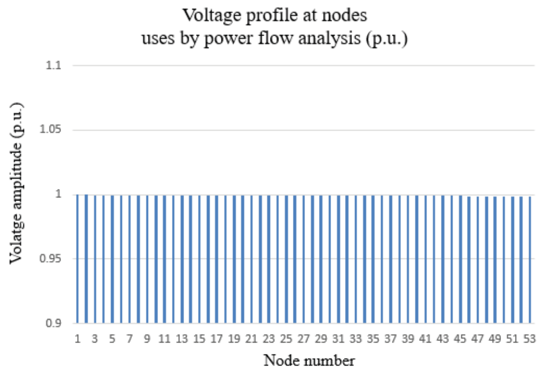


Line Current

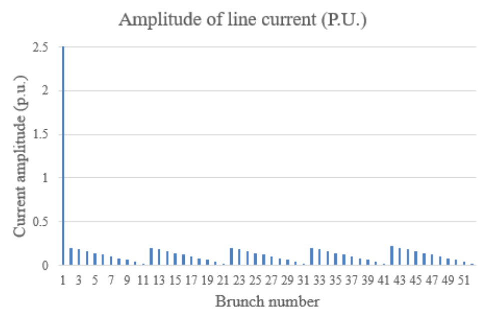
Exercise 4 4thREGS_Ex04-5_CoverleyVillage_53_2022.xlsm

Load Flow Analysis of Coverley Village Microgrid Model 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.



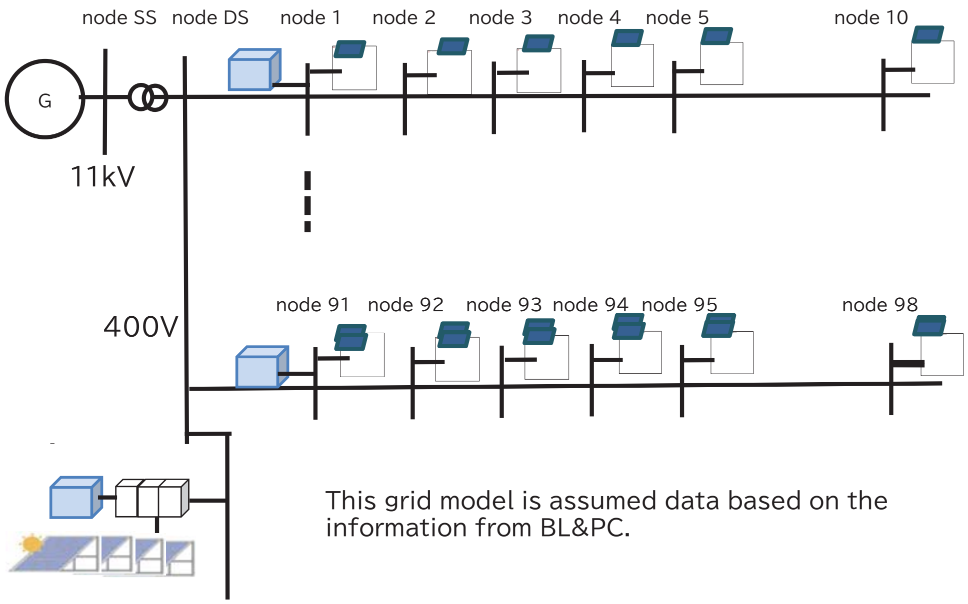
Node Voltage



Line Current

Exercise 5 4thREGS_Ex05_CoverleyVillage_100_2022.xlsm

Coverley Village Microgrid Model of 100 node



This grid model is assumed data based on the information from BL&PC.

Exercise 5 4thREGS_Ex05_CoverleyVillage_100_2022.xlsm

Load Flow Analysis of 4thREGS_Ex05

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		

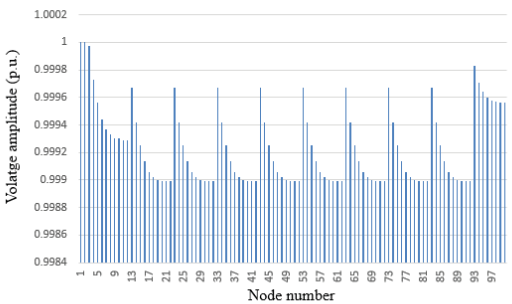
BranchData

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

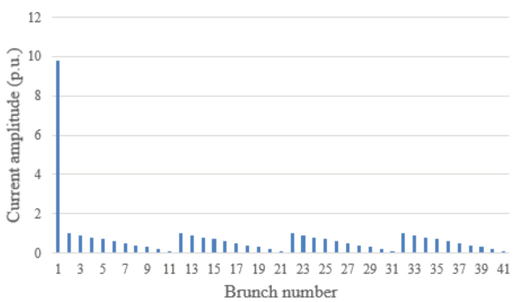
Exercise 5 4thREGS_Ex05_CoverleyVillage_100_2022.xlsm

Load Flow Analysis of Coverley Village 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

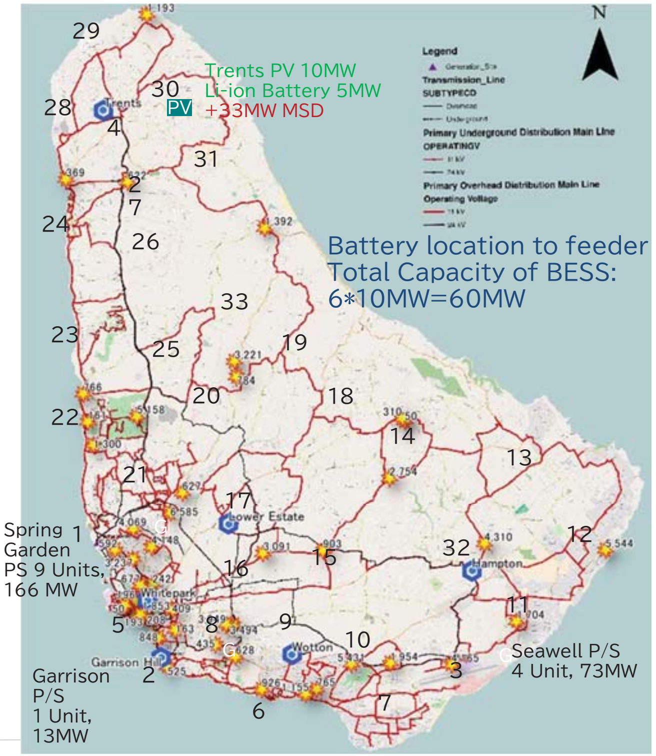
4. Exercise on Future Grid and IRRP Scenario

- In order to achieve sustainable future grid for Barbados, 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.

Barbados 33 nodes Grid

	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

Barbados grid model is based on BL&P GIS map opened to public and information.



Steps of Load Flow Analysis

"Node" is a terminal such as generation plant, substation, switch gear station and consumer.

1. Draw single phase network of grid.
2. Measure the length of transmission lines and distribution lines.
3. Get impedance:
   0.1[ohm/km]x10[km]=1[ohm]
4. Calculate per unit:
   1[ohm]/10[ohm]=0.1
5. Calculate pu voltage
   12.1[kV]/11[kV]=1.1
6. Calculate pu capacity of generator, Load, RE, Battery
   10[MW]/100[MW]=0.1

Exercise 6

Current Barbados Grid

Power resources of synchronous generator types are set to P-V node.
Others are load. Renewable energy is modelled as negative load. They are set to P-Q node.
Capacity of generators and RE are as follows. Total demand is 150MW.

*: modelled as synchronous generator

- Capacity of near future

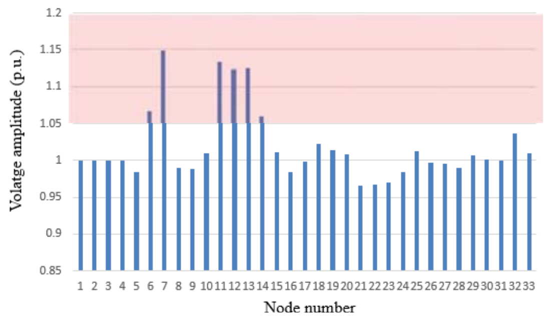
Power Resources	Capacity[MW]	Node
– Thermal Generator	150*	1,2,3,4
– Utility PV	52+7	13
– Distributed PV	(65->91->) 100	1-33
– West to Energy	30*	25
– WT	100+50	13, 19
– BESS	60 (->200)	2, 4, 5, 9, 17, 32
– Hydrogen Storage	20	25
• Total	514.05 (->654.05)	

Input data is per unit value.
(VA)base is defined as 100MW in the load flow analysis.

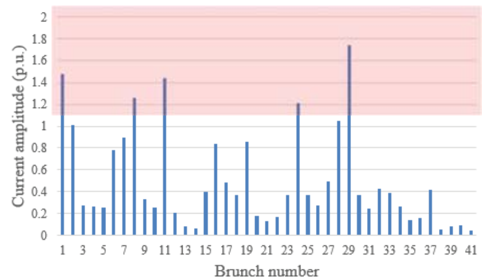
Exercise 6 4thREGS_Ex06-1_Barbados_33_VREscenario.xlsm

Current Barbados Grid No Battery

RE generation parameters are set.
There are no batteries.
Node 6,7,11,12,13,14 are over voltage, because capacity of generators are larger than capacity of loads at these nodes.



Node Voltages (pu)



Line Currents (pu)

Sending node and receiving node of branch

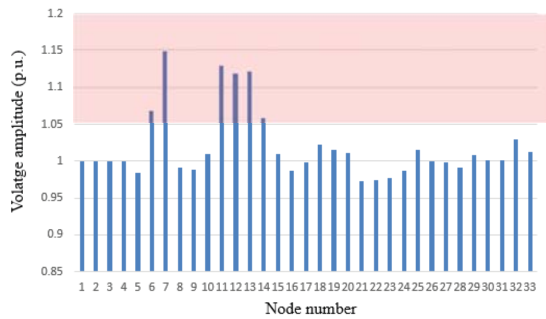
Branch ID	Sending node	Receiving node
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)
1	1	5
2	5	2
3	2	6
4	6	7
5	5	8
6	8	2
7	8	9
8	9	10
9	7	10
10	6	10
11	10	3
12	3	11
13	11	12
14	12	13
15	32	13
16	32	15
17	13	14
18	14	15
19	15	17
20	14	18
21	17	18
22	8	16
23	9	16
24	16	17
25	15	16
26	16	5
27	16	1
28	16	21
29	1	21
30	1	22

Branch ID	Sending node	Receiving node
(Up to 5 integers)	(Up to 4 chracters)	(Up to 4 chracters)
31	21	22
32	21	25
33	22	25
34	22	23
35	23	24
36	23	26
37	25	26
38	17	20
39	20	25
40	19	20
41	24	26
42	26	27
43	24	27
44	24	28
45	28	4
46	28	29
47	29	4
48	29	30
49	4	30
50	30	31
51	31	27
52	31	19
53	4	27
54	18	19
55	11	32
56	3	32
57	33	25
58	33	20

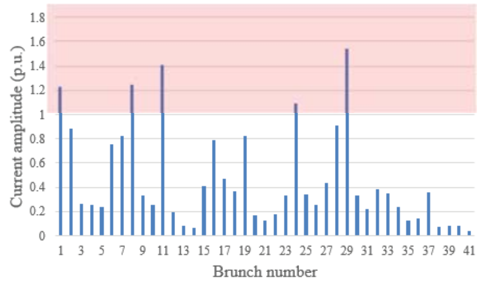
Exercise 6 4thREGS_Ex06-2_Barbados_33_VREscenario.xlsm

Current Barbados Grid Batteries at 6 nodes, charging mode

RE generation parameters are set.
There are no batteries.
Node 6,7,11,12,13,14 are still over voltage.



Node Voltages (pu)

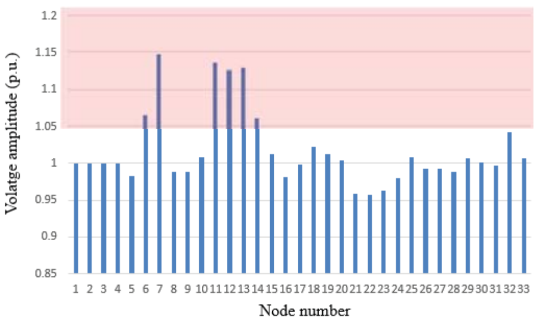


Line Currents (pu)

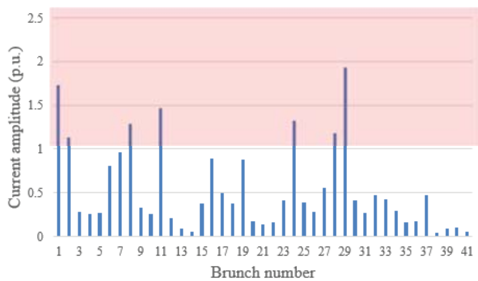
Exercise 6 4thREGS_Ex06-3_Barbados_33_VREscenario.xlsm

Current Barbados Grid Batteries at 6 nodes, discharging mode

RE generation parameters are set.
There are no batteries.
Node 6,7,11,12,13,14 are still over voltage.
Capacity of battery around node 11, 12 and 13 is small.



Node Voltages (pu)



Line Currents (pu)

Exercise 7

Load Flow Analysis of IRRP Scenario 3

Power resources of synchronous generator types are set to P-V node.
Others are load. Renewable energy is modelled as negative load. They are set to P-Q node.
Capacity of generators and RE are as follows. Total demand is set to 250MW.

＊: modelled as synchronous generator

- Capacity in 2030 from IRRP Report

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

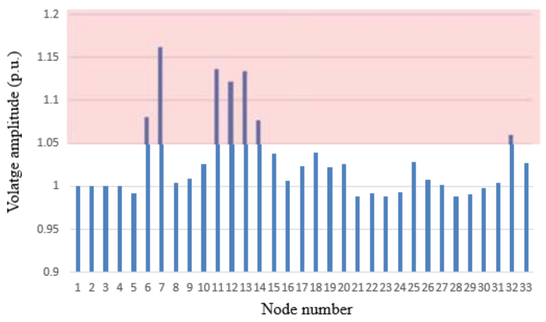
- Total 879.45

Input data is per unit value.
1.0PU is defined as 100MW in the load flow anslysis.

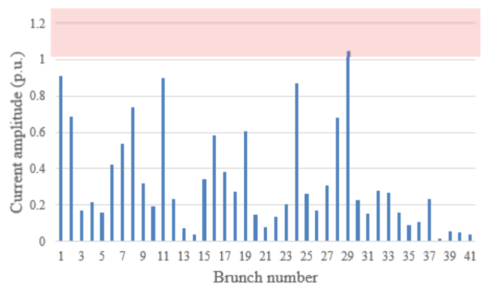
Exercise 7 4thREGS_Ex07-1_Barbados_33_IRRPScenario3 .xlsm

Load Flow Analysis of IRRP Scenario 3 Charging mode of Battery (at PV installed nodes)

Node 6,7,11,12,13,14,32 are over voltage.



Node Voltages (pu)

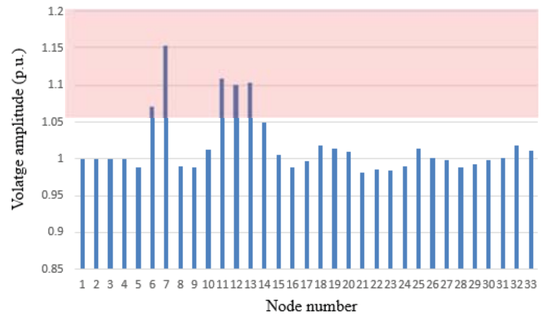


Line Currents (pu)

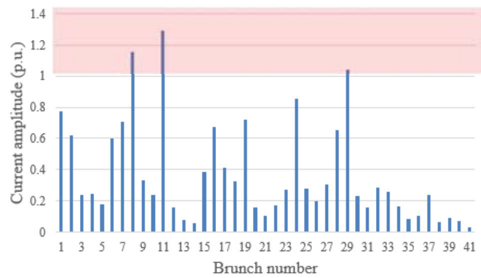
Exercise 7 4thREGS_Ex07-2_Barbados_33_IRRPScenar...

Load Flow Analysis of IRRP Scenario 3 Charging mode of Battery (at 6 nodes and others)

Voltage of south area nodes 6, 7, 11, 12, 13, 14 is over voltage.
Current of transmission lines in city area (node 1-5, 1-21, 9-10) is large.



Node Voltages (pu)

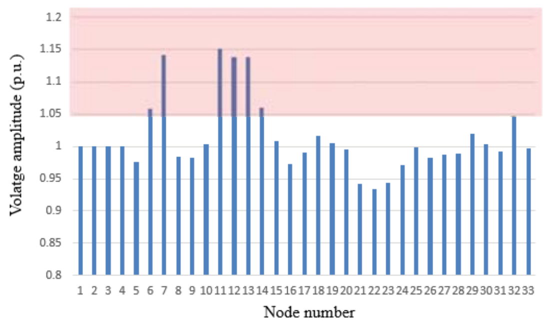


Line Currents (pu)

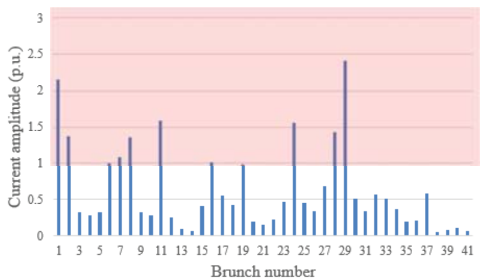
Exercise 7 4thREGS_Ex07-3_Barbados_33_IRRPScenario3 .xlsm

Load Flow Analysis of IRRP Scenario 3 Discharging mode of Battery (at 6noed and others)

Voltage of south area nodes is over voltage.
Current of transmission lines in city area is large.



Node Voltages (pu)



Line Currents (pu)

Exercise 8

Proposed Energy Mix Scenario

Power resources of synchronous generator types are set to P-V node.
Others are load. Renewable energy is modelled as negative load. They are set to P-Q node.
Capacity of generators and RE are as follows. Total demand is 250MW.

＊: modelled as synchronous generator

- Capacity in 2030 from proposed energy mix scenario
  - Capacity/hour = Total MWh in 2030 / 365/24=976.94/365/24=111MW
  - Re capacity = Capacity/hour x ratio x capacity factor

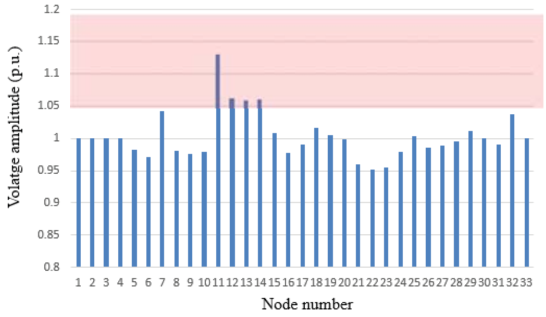
Power Resources	ratio	Capacity factor	Capacity [MW]
PV	60%	0.15	444.4
Wind	20%	0.4	55.5
Biofuel	20%	0,5*	44.4
(Battery			203.37)
Total			543.9

Input data is per unit value.
1.0PU is defined as 100MW in the load flow anslysis.

Exercise 8 4thREGS_Ex08-1_Barbados_33_IRRPScenario3_EnergyMix.xlsm

Proposed Energy Mix Scenario No Battery

Voltage of south area nodes is over voltage.
Current of transmission lines in city area is large.

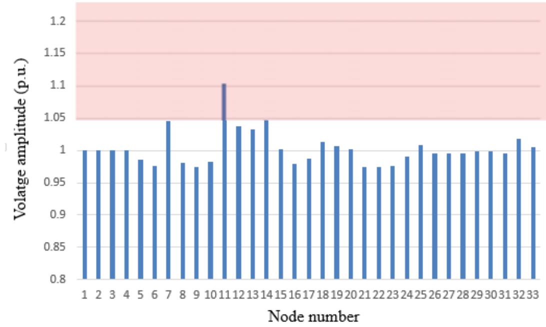


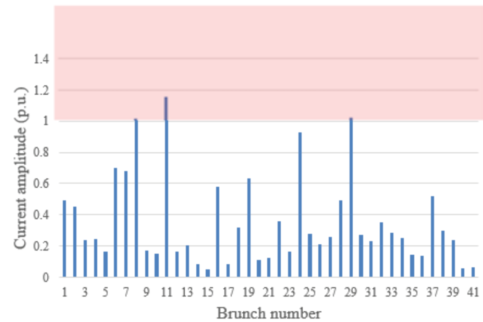
Node Voltages (pu) Line Currents (pu)

Exercise 8 4thREGS_Ex08-2_Barbados_33_IRRPScenario3_EnergyMix.xlsm

Proposed Energy Mix Scenario Battery is located to 6 nodes Charging mode

Voltage of south area nodes is over voltage.
Current of transmission lines in city area is large.



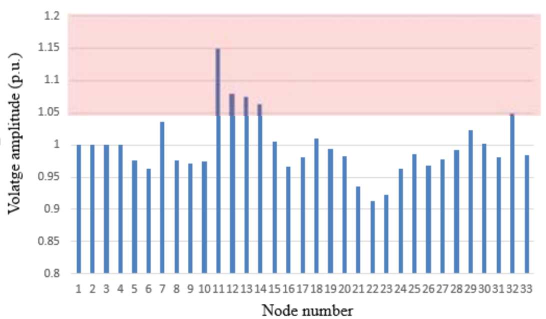


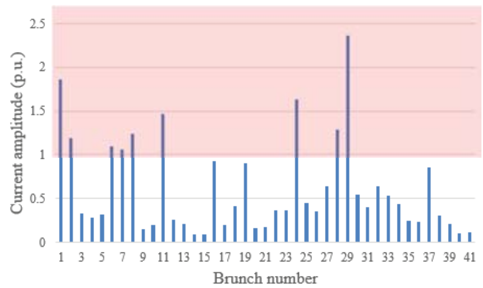
Node Voltages (pu) Line Currents (pu)

Exercise 8 4thREGS_Ex08-3_Barbados_33_IRRPScenario3_EnergyMix.xlsm

Proposed Energy Mix Scenario Battery is located to 6 nodes Discharging mode

Voltage of south area nodes is over voltage.
Current of transmission lines in city area is large.



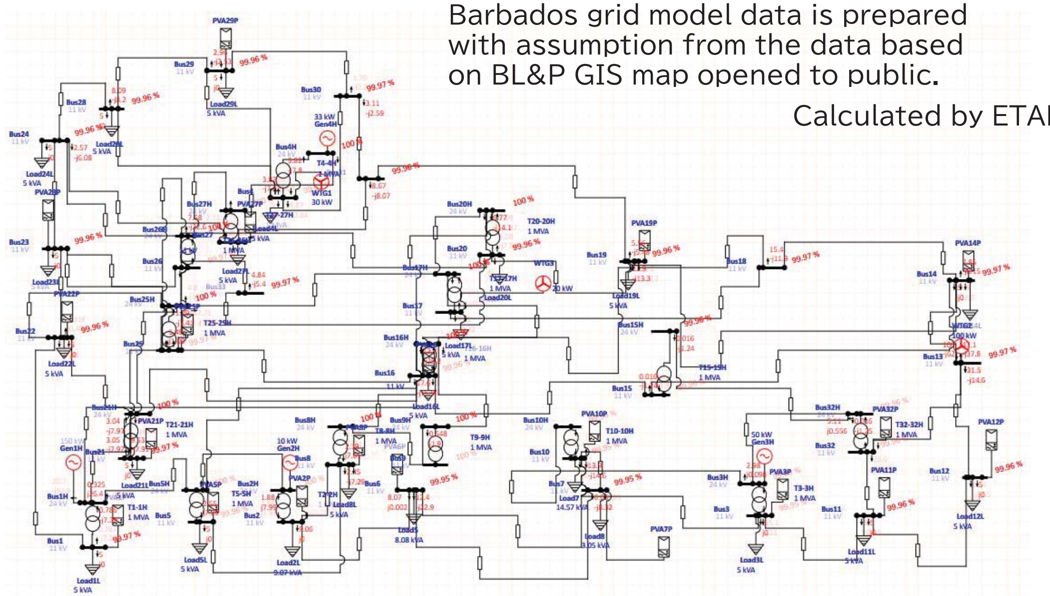


Node Voltages (pu) Line Currents (pu)

Barbados 50 nodes grid map in ETAP

Barbados grid model data is prepared with assumption from the data based on BL&P GIS map opened to public.

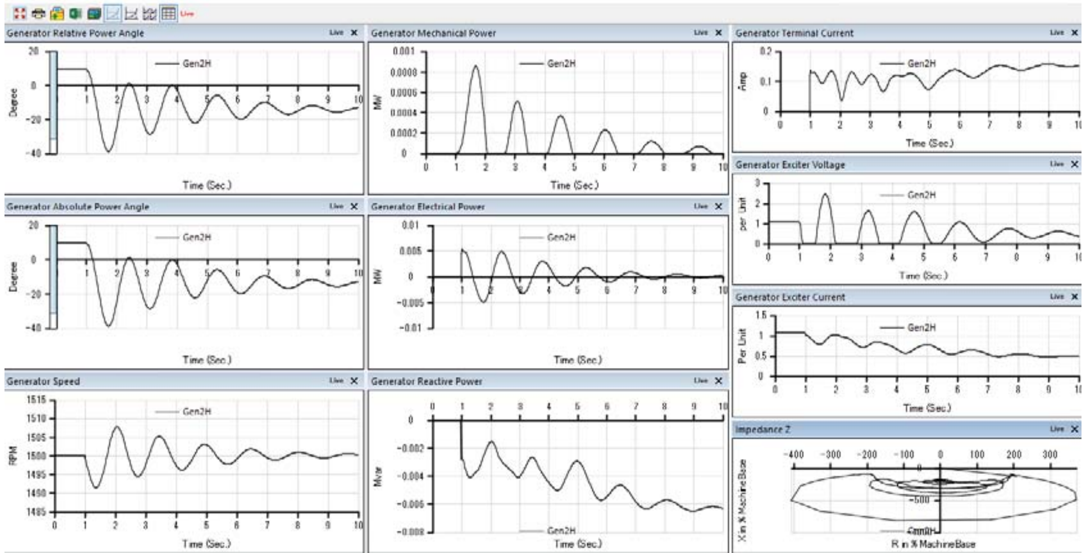
Calculated by ETAP



Transient Analysis of Current Grid Model
Generator of node 2 after 100MW Wind Turbine Trip

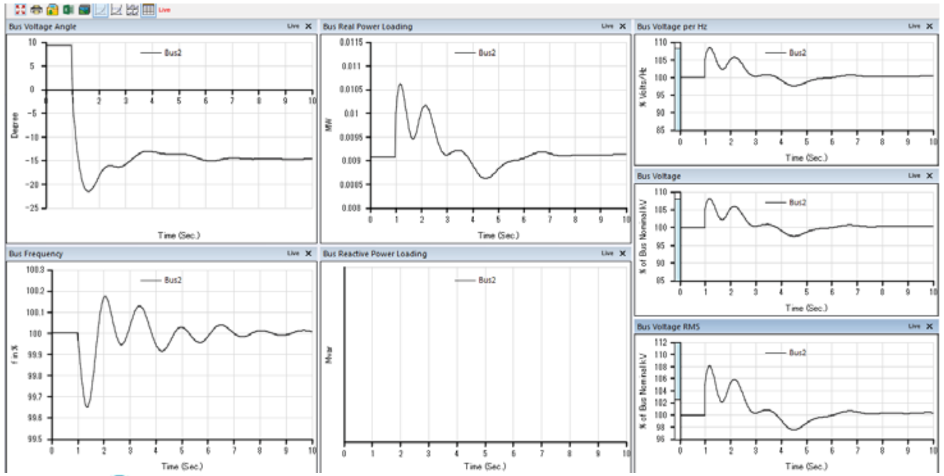
The transient analysis result shows that the system comes back to steady state after the trip

Calculated by ETAP



Transient Analysis of Current Grid Model
Bus Voltage and Power of node 2 after 100 MW Wind Turbine Trip

The transient analysis result shows that the system comes back to steady state after the trip



5. Analysis Result and Countermeasure of Grid Stability

Magnitude of node voltage in south area is high.
BLPC did some measurements, but additional measurement will be recommended especially at node 6, 7, 11, 12 and 13, south coast area.

Current of transmission lines is over its rated values.
The upgrade of transmission line voltage will be recommended to decrease the impedance to obtain enough transmission capacity in south area and city area.

For penetration of renewable energy,
(1)Battery is effective to decrease fluctuation of voltage and frequency.
(2)STATCOM and SCO at city area and residence area including microgrid are effective to keep voltage within its rated value.

4th Seminar on Grid Stability and Large RE

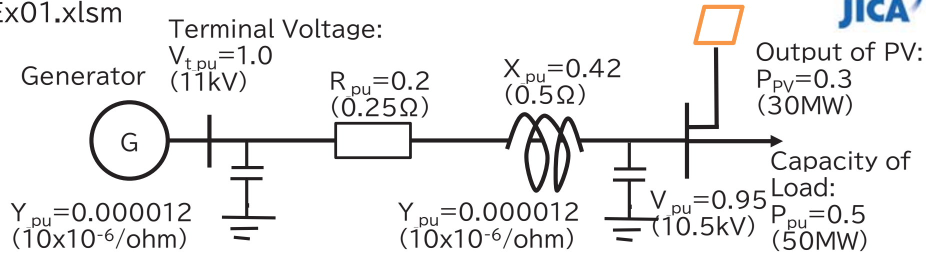
Day-2 Session
Exercises

- Exercise 1: Simple Grid
- Exercise 2: Case A and B Grid
- Exercise 3: Simple Grid with RE
- Exercise 4: Coverley Villages Microgrid (53nodes)
- Exercise 5: Coverley Villages Microgrid(100nodes)
- Exercise 6: Current Barbados Grid (2023)
- Exercise 7: Future grid of IRRP Scenario 3 (2030)
- Exercise 8: Proposed Energy Mix Scenario (2030)
-
  - Grid structure for Barbados is drawn based on Google map.
  - Generation capacity, load capacity, line impedance, battery, capacity of renewable energy are assumed.

Exercise 1

Per Unit & Load Flow Analysis

4thREGS_Ex01.xlsm

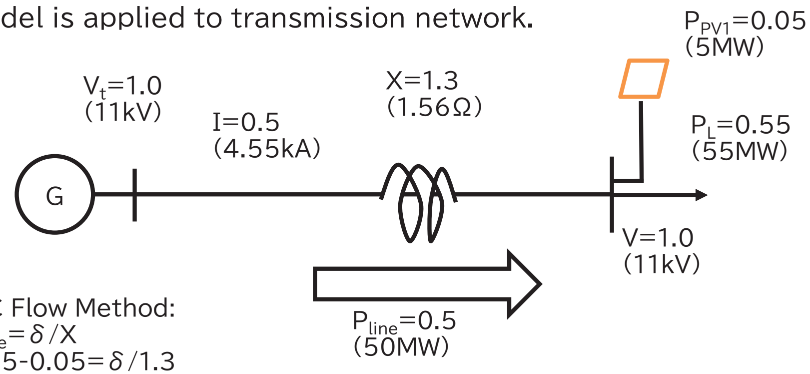


(1) Calculate base value of capacity, voltage, current, impedance and admittance
 (1) Vbase=11kV
 (2) (VA)base=100MVA
 (3) Ibase=100/11=9.1kA
 (4) Zbase=Vbase2/(VA)base=112/100=1.2 ohm
 (5) Ybase=1/Zbase=1/1.21=0.83 1/ohm
(2) Calculate distribution line impedance and node admittance
 (1) {0.05[ohm/km] +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]ˉ0+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.



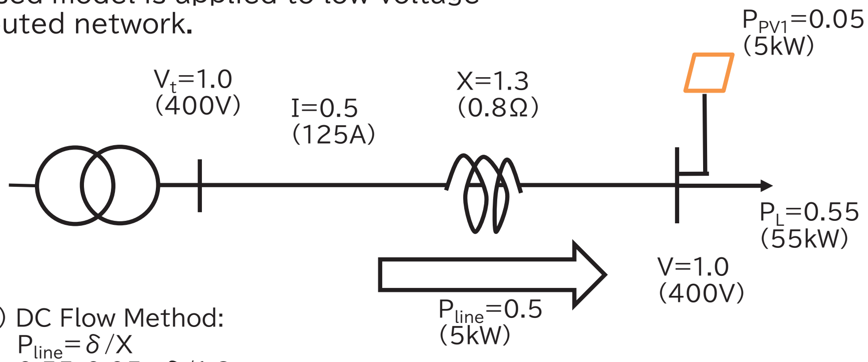
(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
$I=(P_L-P_{PV1})/V$=0.5/1.0=0.5=4.55A

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.

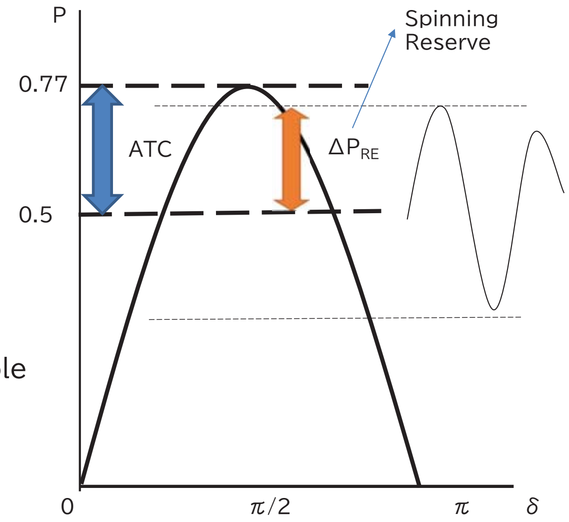


(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
I=(PL-PPV1)/V=0.5/1.0=0.5=125A

P-δ Curve and Stability Evaluation

Evaluation step (2)-(5)

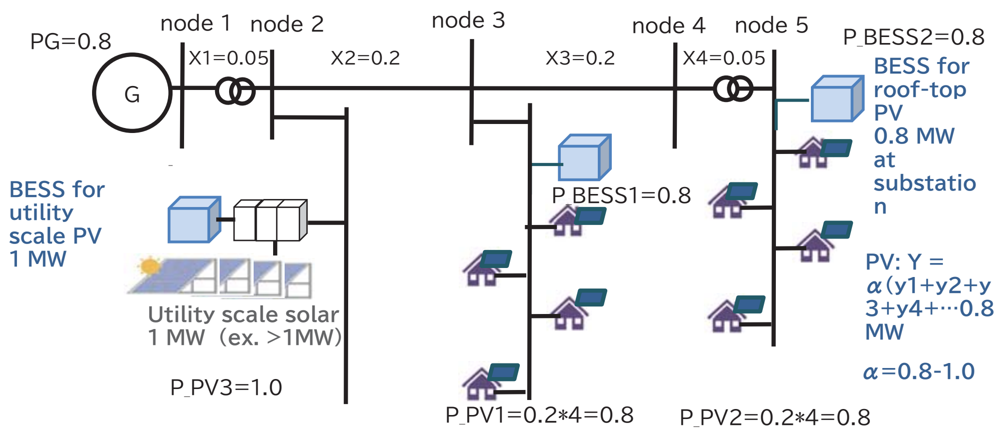
(2) Pmax=1*1/1.3=0.77
(3) Pop=0.5
 (a) Currently ΔP_{RE}= 0.15
  -> Stable
 (b) If ΔP_{RE}> 0.27
  -> Unstable
 SCR=Pop/ΔP_{RE}
 should be over 3
  =(a) 3.33 -> Stable
  =(b) 1.85 -> Unstable
(4) ATC=0.27 -> If ΔP_{RE}> 0.27
  -> Unstable
(5) Spinning Reserve should be more than ΔP_{RE}
  =0.15



Exercise 3 4thREGS_Ex03.xlsm

Simple Grid Model with RE

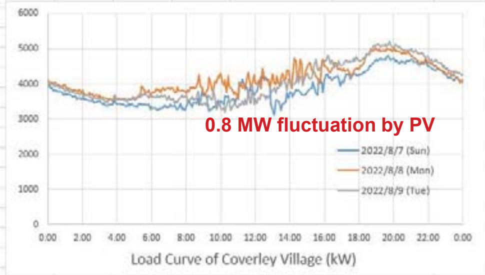
To see the effect of Battery and Large PV



X=X1+X2+X3+X4=0.05+0.2+0.2+0.05=0.5

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 rool area	31080	m2
Rooftop PV Capacity	3108	kWp
Specific PV Generation	4.917	kWh/kW/day
PV Generation by Rooftop	15,282	kWh/day
Current peak demand	5191	kW
Current energy demand	99,637	kWh/day

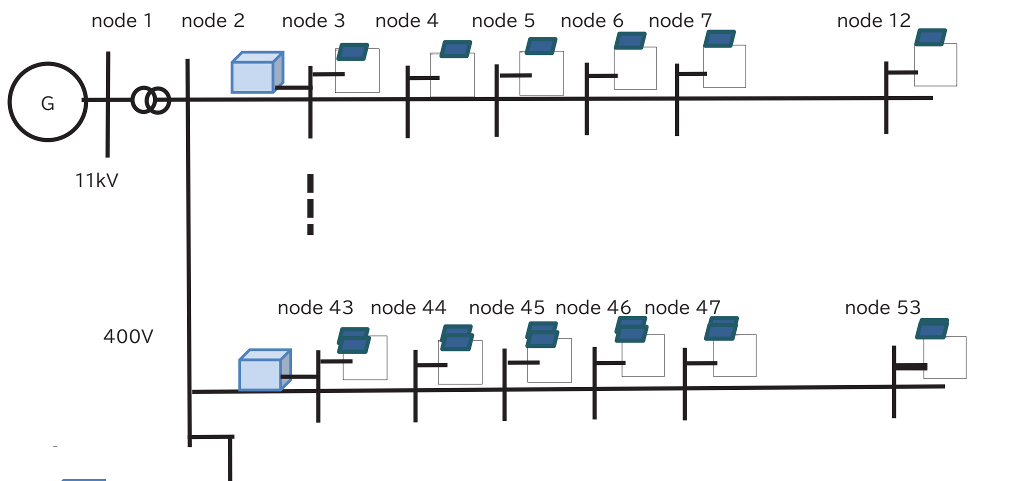
Exercise 4 4thREGS_Ex04-*_CoverleyVillage_53_2022.xlsm

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

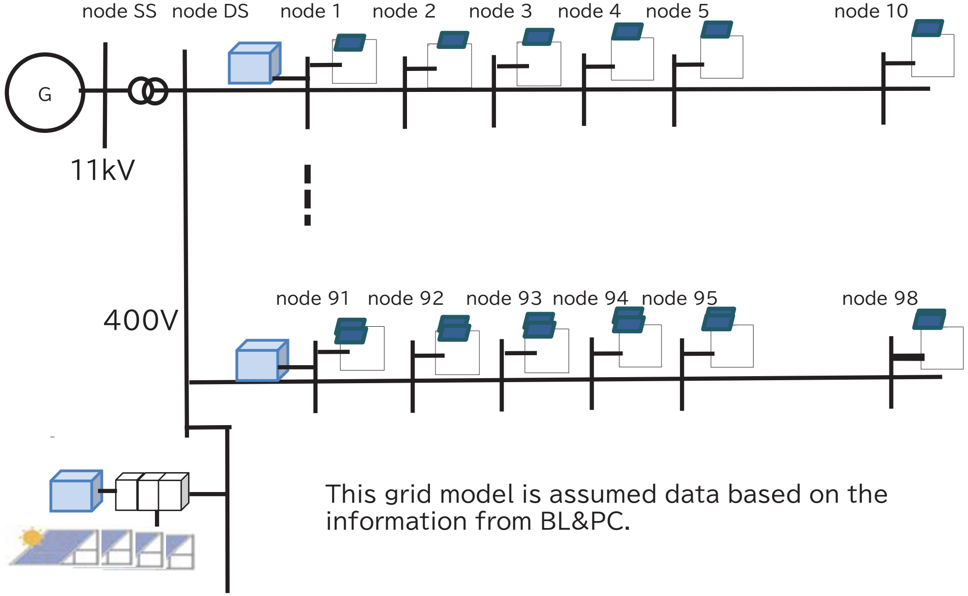
Coverley Village Microgrid Model for Load Flow Analysis



This grid model is assumed based on provided data by BL&P.

Exercise 5 4thREGS_Ex05_CoverleyVillage_100_2022.xlsm

Coverley Village Microgrid Model of 100 node

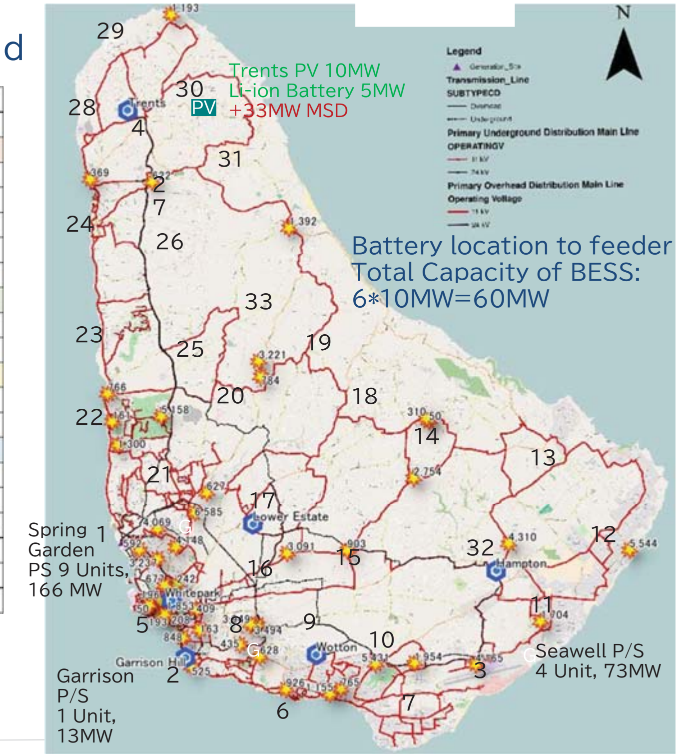


This grid model is assumed data based on the information from BL&PC.

Barbados 33 nodes Grid

	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

Barbados grid model is based on BL&P GIS map opened to public and information.



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Exercise 6 4thREGS_Ex06-*_Barbados_33_VREscenario.xlsm

Current Barbados Grid

Power resources of synchronous generators are set to P-V node.
Others are load. Renewable energy is modelled as negative load. They are set to P-Q node.
Capacity of generators and RE are as follows. Total demand is 150MW.

- Capacity of near future

Power Resources	Capacity[MW]	Node
– Thermal Generator	150*	1,2,3,4
– Utility PV	52+7	13
– Distributed PV	(65->91->) 100	1-33 (listed)
– West to Energy	30*	25
– WT	100+50	13, 19
– BESS	60 (->200)	2, 4, 5, 9, 17, 32
– Hydrogen Storage	20	25
• Total	514.05 (->654.05)	

Input data is per unit value.
(VA)base is defined as 100MW in the load flow analysis.

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Exercise 7 4thREGS_Ex07-*_Barbados_33_IRRPScenario3 .xlsm

Barbados Future Grid (IRRP Scenario 3)

Power resources of synchronous generators are set to P-V node.
Others are load. Renewable energy is modelled as negative load. They are set to P-Q node.
Capacity of generators and RE are as follows. Total demand is 250MW.

- Capacity in 2030 from IRRP Report

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

Input data is per unit value.
1.0PU is defined as 100MW in the load flow anslysis.

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Exercise 8 4thREGS_Ex08-*_Barbados_33_IRRPScenario3_EnergyMix.xlsm

Barbados Future Grid (Proposed Energy Mix Scenario)

Power resources of synchronous generators are set to P-V node.
Others are load. Renewable energy is modelled as negative load. They are set to P-Q node.
Capacity of generators and RE are as follows. Total demand is 250MW.

- Capacity in 2030 from proposed energy mix scenario
  Capacity/hour = Total MWh in 2030 / 365/24 =976.94/365/24=111MW
  Re capacity = Capacity/hour * ratio * capacity factor

Power Resources	Ratio	Capacity factor	Capacity [MW]
PV	60%	0.15	444.4
Wind	20%	0.4	55.5
Biofuel	20%	0,5	44.4
(Battery			203.37)
Total			543.9

Input data is per unit value.
1.0PU is defined as 100MW in the load flow analysis.

4th Seminar on Grid Stability and Large RE for St. Kitts and Nevis (Day-2)

Recommendation for Future RE and Grid Plan

Item	Description	Remark
Storage for smoothing output and peak shift	- Mandatory installation of BESS, for example, more than 80% (or 100%) of Peak MW and storage (ex. 4hrs) 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	In case 100% geothermal, not necessary
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 & 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.)	

Discussion for Policy and Grid Code

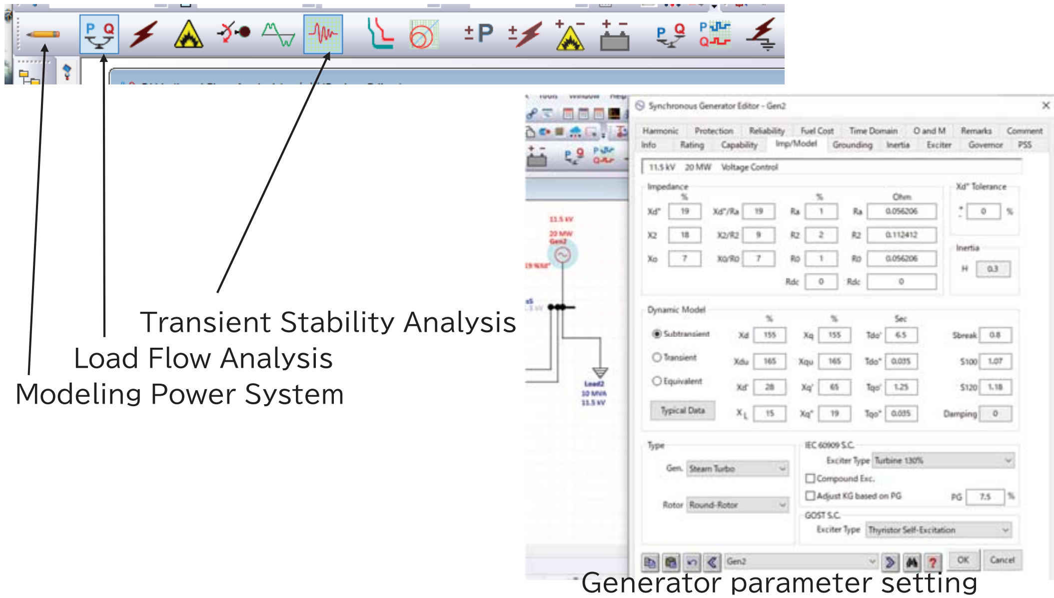
Item	Question	Discussion
BESS replacement	- How do you plan and how to share cost for energy storage at the time of replacement?	
Data platform	- How to share data for grid, PV, Wind, Storage, and demand . - Regular meeting? (MEB, BLPC, BREA, FTC, BMS, etc)	MEB provides dashboard
IRRP review	- Who and how to review according to actual progress - Grid plan, including upgrade (i.e., specific lines of 69kV)	
Tariff	- Current situation affect on tariff? - What organization initiate for tariff change? What is the procedure? (Applied to FTC?)	Time of Use setting for EV (lower charge in daytime) Demand side management
What Japan can do?	For example, feasibility study of hydrogen and storage alternative, demonstration of GFM, etc.	For future cooperation

4th Seminar on Grid Stability and Large RE

Day-3 Session

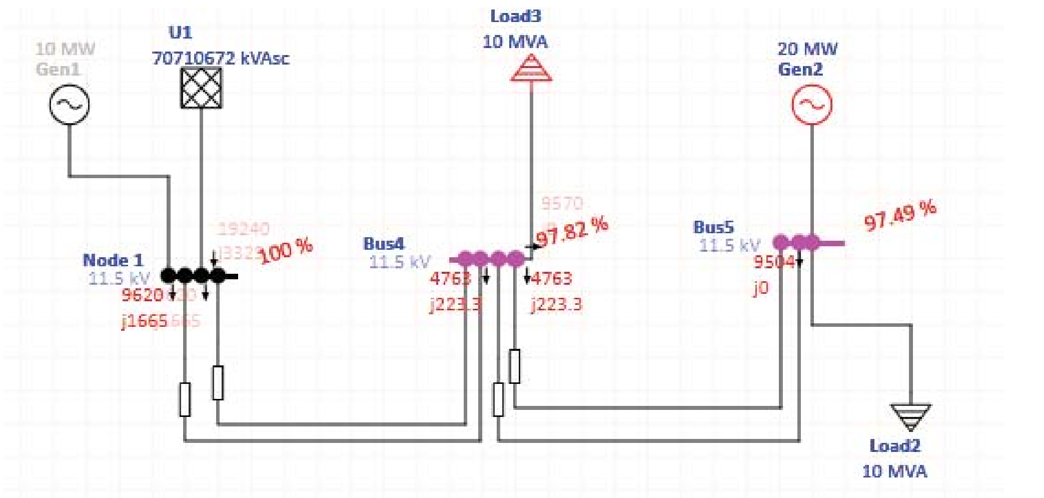
- ETAP Simulation
  - Modeling
  - Load Flow Analysis
  - Transient Stability Analysis
- Prepared Data
  - 3 node system
  - 5 node system
  - 25 node system
  - 50 node system
  - BLPC model
  - Coverley Villages (TBD)

Screen of ETAP



Case 1

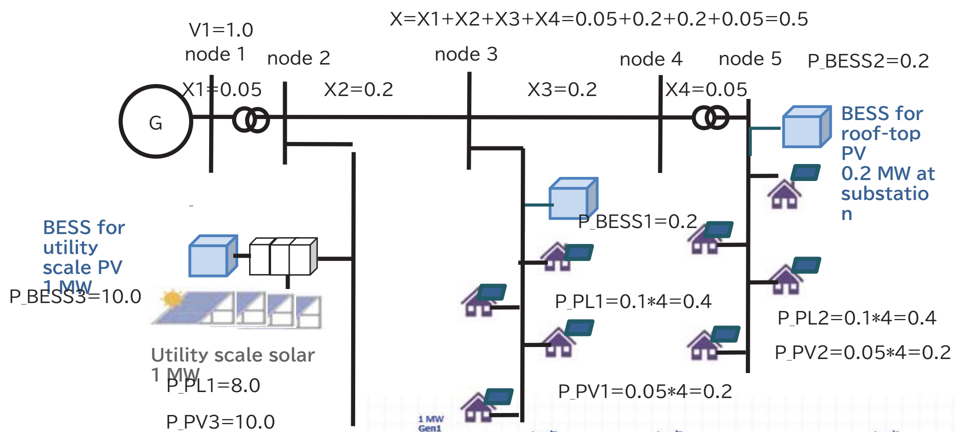
3 Bus Grid
Load Flow Analysis by ETAP



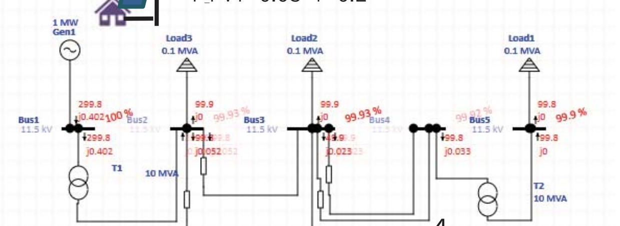
Calculated by ETAP

Case 2

5 node Simple Grid Model for RE



Calculated by ETAP

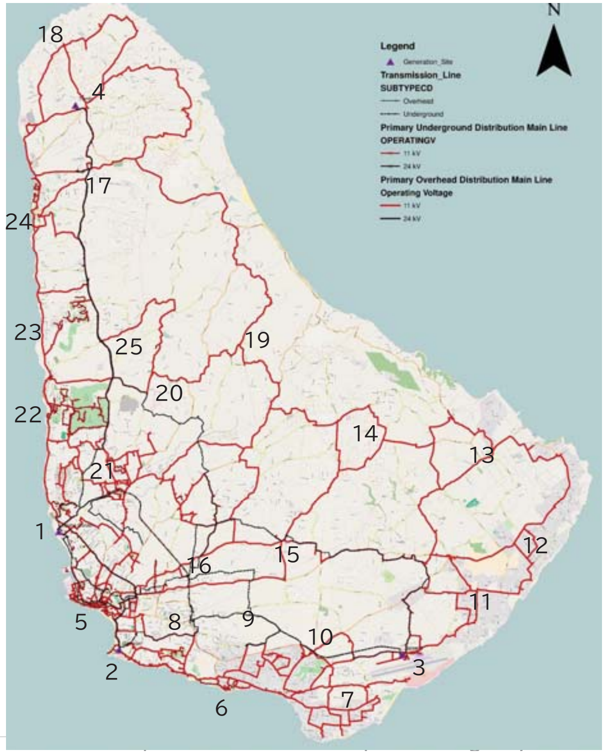


Case 3

Barbados Grid

25 nodes

Barbados grid model is based on BL&P GIS map opened to public.



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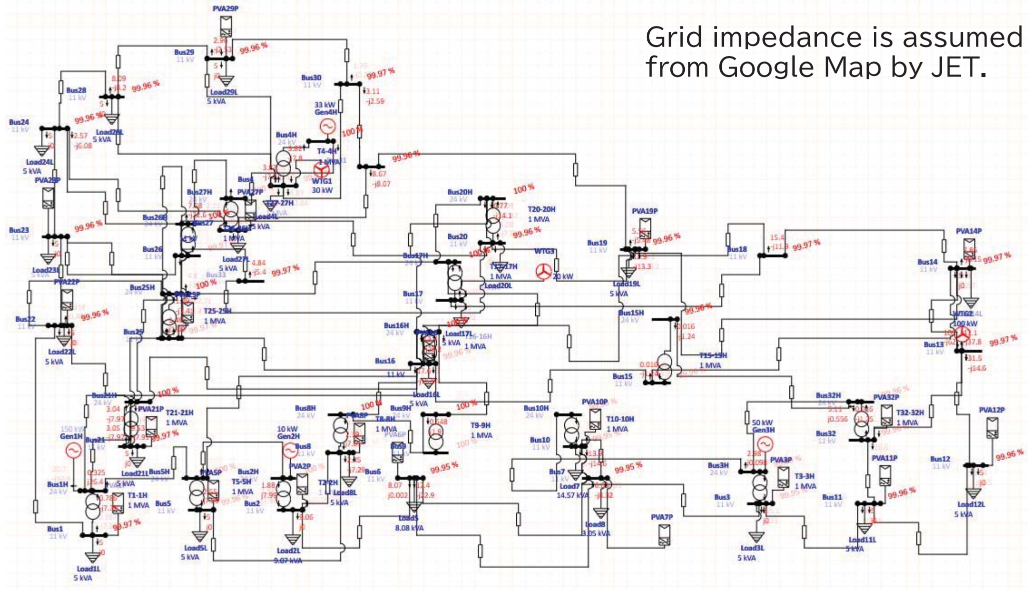
Case 4

Barbados 50 nodes grid map in ETAP

Grid impedance is assumed from Google Map by JET.



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Appendix 4-6-2 Attendant list, and Q&A, of the 4th RE & Grid Stability Seminar (Barbados)

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

4th Seminar on Grid Stability and Large RE in 25-26 Jan 2023 (Barbados): Q&A

No	Item	Content	Name	Answer
	Day-1			
1	Comment	The purported costs are maybe based on large systems. In addition, the cost for biofuels vary according to specific biofuels.	Mr. William Hinds, MEB	Yes, cost of biofuel is volatile, and highly depends on its composition as well as market availability and political situation.
2	Comment	It is now 73 MW in Jan 2023 plus the 10 MW for the utility.	Mr. William Hinds, MEB	Thank you for the information.
3	Question	Will GFM significantly reduce the need for battery storage? If so, to what extent?	Mr. Robert Goodridge, BREA	GFM is not the one to reduce the amount of battery storage but is necessary when VRE percentage becomes increased (like 50% above). When VRE with conventional inverter becomes majority, inertia and synchronous force shortage issue will occur. GFM will provide inertia and synchronous force with battery.
4	Question	What is expected to be the minimum size for Grid Forming Inverters? What I meant by this question, are they expecting to produce GFM's for smaller systems as low as 10 kW or are these likely to be for Utility scale systems?	Mr. Stephen Worme, BREA	There is no threshold for size of GFM. GFM can be applied to both rooftop and utility scale.
5	Question	I have heard several persons refer to SMART Inverters. How is this different to Grid Forming Inverters?	Mr. Stephen Worme, BREA	Smart inverter has a lot of meaning and definition is changing year by year. Conventionally, smart inverter has several function such as fault ride thought (FRT) and/or voltage compensation, but it does not support frequency and synchronizing force like GFM. However, nowadays, Smart inverter sometimes includes function of GFM. We try to avoid the word of smart inverter since it is confusing, and we use the word GFL and GFM in this seminar.
6	Question	Because GFM's will help with frequency control, would that help reduce the cycling of batteries and hence improve their life cycle?	Mr. Stephen Worme, BREA	GFM will support frequency and synchronizing force, but will not reduce charge-discharge amount of battery. Thus, GFM will not affect life cycle of battery.
7	Question	What was the procedure for black start when there was not batteries ?	Mr. William Hinds, MEB	For a black start, the system needs to wait until battery is charged by PV or wind if battery is empty. If there is no battery installed, a self-excitation generator is necessary.
8	Comment	Currently in Barbados some of the generating stations have Black Start Generators which have battery banks that allow them to start and once started they provide the power needed to start other generators.	Mr. Stephen Worme, BREA	Thank you for the information.
9	Question	I assume that the hydrogen storage is not used regularly given that it has relatively low efficiency compared to the other technologies?	Mr. Horace Archer, MEB	It is correct, at this moment. H_2 storage have lower efficiency than battery but technical development will improve in future.
10	Question	What is the relative cost compared to storage by battery?	Mr. William Hinds, MEB	It depends on situation. A survey will need to be conducted.
11	Question	Can we get the spread sheet to get the cost of battery and H_2?	Mr. William Hinds, MEB	Since it is referenced to other project, we will not be able to provide the spread sheet. Sorry.
12	Question	For the ISC to work successfully, the utility will have to have full sight (status and state of charge) and control of PV and Battery systems. Is that correct?	Mr. Stephen Worme, BREA	Utility can control substation but can not control customer. Operation of substation will be done by ISC system. Not all customer meter are monitored.
13	Question	How would an ISC work on a Network like Barbados where there are so many PV systems on the Distribution System where, when a feeder is tripped you are tripping both Generation and Load?	Mr. Stephen Worme, BREA	Not all the distributed system is considered but calculated with aggregated data obtained at substation, generally. Japanese system before operation every 30 min transient stability is calculated and estimated at substation base.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

4th Seminar on Grid Stability and Large RE in 25-26 Jan 2023 (Barbados): Q&A

No	Item	Content	Name	Answer
14	Question	What type of ISC load control is best for grids with high levels of renewable energy (Variable)?	Mr. William Hinds, MEB	Chubu has controlling RE, but function is total amount of RE. ISC is required for substation. For local, each house equipment with relay or circuit breaker will be suitable.
15	Question	Is a 1 minute delay in tripping a feeder be short enough to avoid failure of the system? And wouldn't this delay time depend on the communication network used?	Mr. Stephen Worme, BREA	It depends. After fault, we need to calculate within millisecond scale and within 10 millisecond operation is necessary. It is not communication but computing. Communication needs dedicated fiber system.
16	Question	Are there Grid Code in Japan with assuming as large RE?	Mr. William Hinds, MEB	We have association of PV and suggests grid code, but we have not have official grid code for large RE. It is still under discussion,
17	Question	What investment should be put as priority for Barbados to achieve 100% RE?	Mr. William Hinds, MEB	Battery according to penetration is necessary at present. According to increase of RE %, another measurement such as SCO is necessary. Higher voltage transmission line is also necessary.
18	Question	Can installation of smart inverter reduce SCO? Should we set standard of smart inverter?	Mr. Stephen Worme, BREA	If smart inverter with voltage support is installed, SCO can be reduced. Setting standard for inverter is preferred.
19	Question	What was peak demand for 100 MW PV system?	Mr. William Hinds, MEB	It is not clear. It is supposed to be 50%, but considered to be increased. It become mandate new PV IPP shall provide battery to reduce fluctuation.
20	Question	What is the difference of NaS and LiB?	Mr. Stephen Worme, BREA	NaS battery capacity is large and speed is fast, but operation is difficult with temperature of 300 degree-C. The cost is high compared with LiB.
Day-2				
21	Question	Can we understand that slack node is main generator and P-V node is distributed generators?	Mr. Stephen Worme, BREA	Yes. But for distributed PV generator, it needs to be input as negative load.
22	Question	How does Microgrid Designer compar4e with other tools like ETAP which is used in Barbados?	Mr. Stephen Worme, BREA	Microgrid Designer is based on load flow analysis. It das not include transient stability
23	Question	Is smart inverter and PV system set as P-V node?	Mr. Stephen Worme, BREA	In case GFM is installed, it can be P-V node but with conventional inverter it should be P-Q node. This is because GFL controls current, which is power.
24	Question	What if phase balance is unbalanced? Can Microgrid Designer simulate for zero-sequence?	Mr. Robert Harewood, BL&P	Microgrid Designer can not calculate three-phase difference. ETAP will do.
25	Question	For every 5 min data, why multiplied by 5/60 to get hourly data, not 60/5?	Mr. Stephen Worme, BREA	Because we calculate kWh data as hourly average. If we total all 5 min data for one hour, it will be 12 times hourly average.
26	Question	For load data, which data should be input, day or night?	Mr. Robert Goodridge, BREA	Since we need to study for most severe case to assess grid capacity, most severe data of the day should be input.
27	Question	How can we assume the case of battery charge and discharge status in power flow analysis?	Mr. William Hinds, MEB	Single Stage Power flow analysis assumes steady state condition, and most severe time of the day is assumed. Multi-stage analysis can assume demand and charge/discharge condition every hour and see the result.
28	Question	What is load area for voltage drop and fluctuation area?	Mr. William Hinds, MEB	Load area is city center. Fluctuation area is large PV installed area.
29	Question	What is maximum BESS capacity?	Mr. William Hinds, MEB	Ideally, 100% of VRE capacity. However, it is depending on smoothing effect. Based on historical data, considering smoothing, it can be reduced.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

4th Seminar on Grid Stability and Large RE in 25-26 Jan 2023 (Barbados)

List of Participants for Grid Stability and Large RE seminar						
No	**Org.**	**Participants**	**Position**	**25**	**26**	**Comments**
1	MEB	William Hinds	CECO	x	x	
2	MEB	Horace Archer	Senior Technical Officer	x	x	
3	MEB	Frank Branch	Technical Officer	x	x	
4	UWI	Natasha Corbin	Project Officer	x		
5	BREA	Robert Goodridge	President	x	x	
6	BREA	Stephen Worme	Vice-President	x	x	
7	JET	Tomoyasu Fukuchi	Project Leader	x	x	
8	JET	Yuka Nakagawa	RE Specialist	x	x	
9	JET	Hisao Taoka	Microgrid Specialist	x	x	
10	JET	Tomoaki Tsuji	Energy Specialist	x	x	
11	JET	Alex Harewood	Tech. Assistant	x	x	
12	BLPC	Robert Harewood	System Engineer	x	x	
13	BLPC	Cyprian Moore	Utilities	-	x	
14	GEED	Tyrone White		x		
15	GEED	Heather Sealy		x	x	
16	CCREEE	Giovanni Buckle	Junior Engineer	x	-	
17	CCREEE	Justin Taylor	Junior Engineer	x	-	
18	CCREEE	Felicia Whyte	Project Development Officer	x	-	

Appendix 4-7 All Feedbacks of RE & Grid Stability Seminars (Barbados)

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Feedbacks for Seminars on Large Renewable Energy and Grid Stability in Barbados

2nd seminar	
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 - Most economical way to compensate fluctuations caused by the intermittent energy from PV Generation. Concern: Spinning Reserves still need a energy source as the Battery Storage Systems lack inertia, Bio Fuels can work but may cause areas reserved for crops, converted to produce fuels. - 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 - We need a mix of more biomass resources, (liquid or gaseous to provide transition from quick response BESS to solid biomass generation)
What you would like to know more details in the seminar components	-Where to add storage (On Transmission or Distribution System)? How much storage? -Load Flow; Frequency Control -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. -The effect of hurricanes on small island states that is 100% renewable when everything is destroyed? -What systems can the customers implement to improve the power fed to the utility to improve grid stability.
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 -Where to add storage (On Transmission or Distribution System)? How much storage? applicable technology that can be used for implantation -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 -Bus Admittance Matrix and Newton Raphson Method -To expand more about grid stability and large scale renewables. Using a model for grid stability and RE penetration -Changes/additions that can be made to existing RE installations to improve the Grid Stability. -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.
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. - 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.
3rd seminar	
To achieve 100% renewable energy, what generation source combination with percentage or MW do you want to try for the grid stability for trial	Solar 70% Wind 10% biofuel 20 percent 60% PV, 20% wind, 20% biomass 65% PV 20% Biomass 15% wind 70% PV (including CSP), 12% Wind, 18% WTE/Biomass 60% PV, 30% Wind, 10% other RE baseload 65% PV 25%Biomass, 10%wind. 70% PV, 20% Wind and 10% is suitable for Barbados 65% PV, 35%wind.
Why you want to test the scenario in Q1	- To see how a combination of RE would work in this environment - The investors have a greater interest in solar investment than wind. Solar is also now cheaper than wind since 2017. Wind has moving parts and significant site specificity - Additional rotating machines required. - 25 MW WTE/Biomass Generator is presently being planned. Need to cnsider another option of 60% PV 22% Wind and 18% WTE/Biomass. - Based on availability of resource and cost of technology - This will allow biomass to provide the spinning reserve also put in the circuit achiving stability
Please suggest what is necessary for grid stability	- Battery, Synchronous condensers, bi-directional relays and controls. - There should also have Ramp-Rates for RE. - The also needs to be very short-term wind and solar forecasting based on locating 100 solar measurements stations around the island and at least 20 wind measuring systems - Batteries, grid forming inverters, demand response, microgrid integration - Include pumped storage, Hydrogen and Inverters that provide reactive power. - Battery can be used in replace of spinning reserve and Blackstart - The energy and power capacity recommended such be analysed on a case by case basis, and cost should be taken into account. - Utility company's installation of Synchronous condenser. Grid forming inverters can be part of the solution once they become commercially available. - Combination of SCO batteries and grid forming inverters (if commercially available) to create multiple micro grids which can interconnect
Please suggest if any other requests to consider in grid model and simulation.	- IRRP suggests 300 MW of solar and 300 MW wind and 20 MW biofuel - Flywheels for larger battery installations - simulation of different types of BESS services coupled with inverter curtailment - Short circuit analysis. - RE generation over 150% of the maximum demand and how to efficiently storage or curtail the excess energy

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Feedbacks for Seminars on Large Renewable Energy and Grid Stability in Barbados

What is the most challenging for achieving 100% RE?	- Grid stability by storage and spinning reserves - Technology availability at appropriate cost - The cost of the equipment with the appropriate technology maybe out of reach f of the existing population to obtain without financial and or governmental assistance. - Capital, lack of technical expertise - Cost of implementation. The use of IPP result in an increase cost of energy to the consumers. - Who will bear the responsibility for grid stability. And if distributed who will be responsible for determining the distribution - Control of grid voltages and frequencies
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 not be changed. We may have 2 interruptions/yr, 1hr per year - 1 to 1.5 hours per year - it should be better than 24 hours per year. - RE mix of PV and wind will result in numerous outages during the year. Interruptions should not exceed 1 week (168hrs) per year. -The public will accept minimal interruptions when 100% RE is established. - Zero
For achieving RE target 100% with sufficient grid stability, who and how to cover the cost of grid stability?	- IPPs should be required to minimise impact on stability. - IPP producer should install stability measurement and should have the responsibility of minimizing the impact on grid stabiity. - I believe the IPP should pay up for control & stabilizing equipment which would be specified by the owner of the distribution network. - Special selling rates should be given these IPPs who invest in not only provide RE by control & stabilizing equipment (SCO, batteries etc)
ditto	- Subsidy by government - It will be picked up by the consumers, as whoever pays it will need to pass it on to consumers if it were to be sustainable. Whoever pays upfront, it will be necessary to find ways to incentivise them to minimise what they need to pay. - The feed in tariff rate will have to be increased such that the Return On Investment (ROI) for RE system investors is reasonable and bankable.
ditto	- Overall having the utility pay it and pass it on through tariffs is likely to be cheaper unless have some alternative form of competitive procurement that will allow IPPs to get the lowest costs. - The cost of grid stability will have to be shared between the utility, IPPs and customers. - For a small grid the IPP intervention would lead to an increase cost to the consumers. The utility can implement the RE target and cover the grid stability cost with a small tariff increase in conjunction with government subsidy - The savings to the grid in producing RE at lower than cost of fossil fuel - From the studies depending on if the project is "scaled up" the project, we may reduce the tariff
Please provide your comment or additional suggestion, if any, for the Recommendation that JET made in Session-1	- We need to offer incentive/tariffs for other types of grid improvement beyond the storage - Weather prediction (LIDAR/satellite/etc; 15 min. ahead) required, along with microgrids, BESS. Ideally long duration storage should also be implemented. Multiple energy sources should be included (biogas, liquid biofuels, solid biomass, VREs). - Managed curtailment should be considered. - With the cost of diesel spinning reserve gets expensive, battery will be the best option as it is used for spinning reserve and smooth out the curve - Addition of BESS and flywheel will aid the conversion to 100%RE.
Questions that you would like to know more details in the seminar	- Cost of grid stability based on various mix of renewable energy - the overall cost impacts of the various technology mixes as the amount of PV penetration increases. - The approach to building the model. What do you consider when using lumped parameters? In ETAP, I noticed that the alliance cable is rated for 395A, but in the calculations the alliance cable is derated and 255A is used. How to do I over this hurdle when doing power flow studies? - Hormonics or less distortion -The impact of load shedding at various times of day of feeders which have PV penetration and complications that result when tripping occurs. - Safety considerations of Grid forming inverters, which seem to be able to continue operating when power is lost from the grid. - Prefer engineering calculations or model/algorithm development in open source software e.g. Octave, Python, etc.
Particular challenges of grid stability, RE, and others that you would like JICA Team to include in the next Seminar opportunity	-Biofuel generation - more specific discussion of synchronous condensers, more worked examples, modelling in open source software - Solar without storage - using BESS for black start. Using a BESS for frequent discharge on the system - what is the effect in battery degradation and the life of the battery. - 1) Impact of load shedding, 2) impact on the life of batteries and ultimate costs due to constant cycling of batteries. - harmonic distortion and frequency stabilization
Please advise JICA Team if there is necessary improvement	- More discussion and longer sessions - The review was a bit too extensive and there were no new problems worked. - 5 or 10 minutes break to stretch - The addition of new technology as well was very effective. An explanation of the new technology should be added to the next seminar. - Having the reading material in advance is a great help.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Feedbacks for Seminars on Large Renewable Energy and Grid Stability in Barbados

Please input what is the best finding during the seminar	- Storage practices - Excellent summary table on different interventions. Interesting maps of Jamaica and Barbados - Grid modelling - Storage and how it can help in achieving more renewable energy penetration - it was good to see the model of the Barbados system. I would like to see the solution to the system and the implementation of the solution to the model done to the physical system. - The impacts that the increasing penetration of PV will have on Grid Stability and cost of maintain Grid Stability was very compelling. It is disappointing that this study has taken so long to be done and is being done at the initiative of JICA and that the original report done by GE for BL&P should have been followed up, revised periodically and communicated as you are doing now.
4th Seminar	
How the components contributed to enhance your organizational capacity	-Better understand the issues with added more RE to the grid. -Great information of power system analysis The discussion on microgrids was helpful to understand the considerations for implementation and challenges. -Impact of RE penetration on grid stability, details of how the grid is impacted by different loads and power generations on the grid
Matters should be included in policy / grid code based on findings in Seminars	-Standards for BESS installation and Operation, Functional and Technical Specification for Grid Code. -Frequent updating of IRRP, Information sharing process Key stakeholder think-tank committee -Curtailment Control -Setup of Virtual Power Plants and Vehicle to Grid - Policy objective for sustainability of RE sector such that it encourages economic growth beyond RE 100% implementation and further drives the need for energy through creation of industry and commerce.
Needs of any further particular projects to request to Japan concerning RE & grid stability.	-Standards for hydrogen and LiB, Safety, Environment, electrical integration -Green Hydrogen, One-month full time attachment in grid modelling -Cost effective communications networks to oversee RE, inverters and battery -Localized management in particular at connection at solar PV site. How to rectify high voltage pockets created by PV. Approach to determining measure to address voltage rise caused by PV interconnection. -Provision of equipment and technical assistance on weather measurement of at least 50 locations for solar and wind on the stability of the grid. -Study for : -Review and Update of IRRP -Cost effective short-term alternatives for grid stability -Concentrated Solar Power (CSP) -Optimize generation mix -Wind resource assessments. -anaerobic digestion, waste-to-energy, hydrogen