Energy Efficiency & Conservation (EEC) Materiel Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

- Energy Consumption Analysis & EEC Roadmap -

Barbados, January 2023

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PADECO Co., Ltd.

Contents

1. Energy Consumption Analysis from Energy Balance Table

Energy Consumption Analysis from Energy Balance Table

- **Current situation :Energy consumption outlook by sector and energy source**
  - **Transportation is the largest energy consuming sector (33%) followed by Commercial & public service sector (28%) and residential sector (19%).**
  - **Electricity is the largest energy source (52%)** followed by oil (43%).

Energy consumption by sector and energy source on primary energy basis (2019, ktoe)

	Industry	Commercial & public	Residential	Other	Transportation	Total	
Oil	20	15	8	1	141	185	43%
Natural gas	1	10	2	0	0	12	3%
Bio/waste	7	0	0	1	0	8	2%
Charcoal	0.0	0.0	0.2	0.0	0.0	0.2	0%
Electricity (Primary energy basis)	28	97	72	26	0	223	52%
Total	55	122	83	27	141	428	100%
	13%	28%	19%	6%	33%	100%	

Note 1: Primary energy conversion factor of electricity is utilized to evaluate the effect of energy saving by reduction of 1kWh of electricity consumption at demand side.

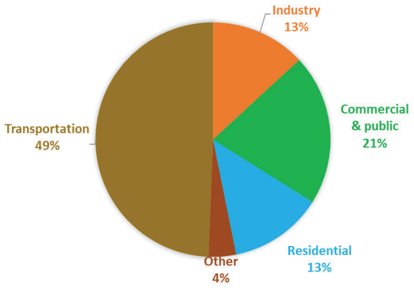
Note 2: To calculate primary energy consumption of electricity, energy efficiency at end use (36.3%) was used based on the material by Government of Barbados.

Source: JET with reference to energy balances (2019) by United Nations Statistics Division for overall energy balance and the material above mentioned (Note 2) for primary energy conversion factor calculation of electricity.
https://unstats.un.org/unsd/energystats/dataPortal/

Energy Consumption Analysis from Energy Balance Table

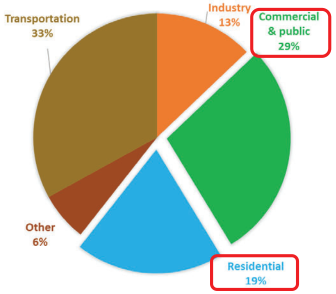
- Energy consumption should be evaluated on primary energy basis.
- Commercial & residential sectors share about half of the primary energy consumption.

Energy consumption by sector on final consumption basis (2019)



1 kWh consumption corresponds to 2.75 kWh as primary energy supply.
- 1 kWh / 0.363 =2.75 kWh

Energy consumption by sector on primary energy basis (2019)

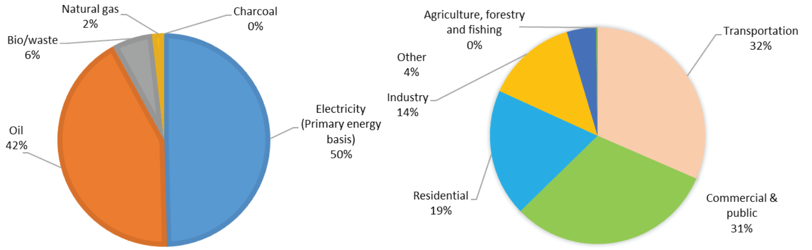


Source: JET with reference to energy balances (2019) by United Nations Statistics Division for overall energy balance.

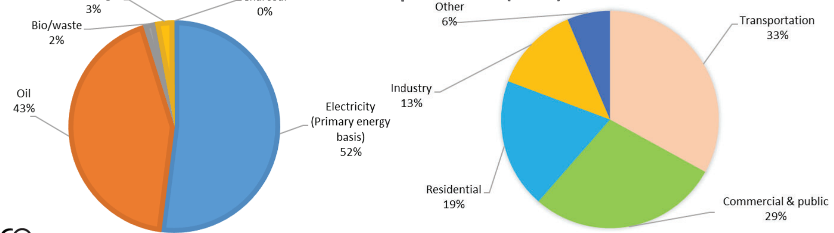
Energy Consumption Analysis from Energy Balance Table

- No particular change has been observed in energy consumption by fuel nor by sector between 2010 and 2019 on primary basis.

Energy Consumption by Fuel (left) and by Sector (right) on Primary Energy Consumption Basis (2010)



Energy Consumption by Fuel (left) and by Sector (right) on Primary Energy Consumption Basis (2019)



Energy Consumption Analysis from Energy Balance Table

Energy Consumption by Fuel and by Sector on Primary Energy Consumption Basis (2010)

	Industry	Commercial & public	Residential	Other	Transportation	Agriculture, forestry and fishing	Total	
Oil	820	723	487	25	6,045	47	8,147	42%
Natural gas	25	240	80	0	0	0	345	2%
Bio/waste	1,146	0	11	29	0	0	1,186	6%
Charcoal	0	0	0	0	0	0	0	0%
Electricity (Primary energy basis)	623	5,036	3,077	785	0	0	9,521	50%
Total	2,614	5,999	3,655	839	6,045	47	19,199	100%
	14%	31%	19%	4%	31%	0%	100%	

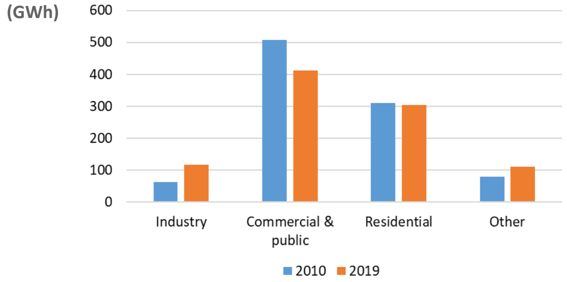
Energy Consumption by Fuel and by Sector on Primary Energy Consumption Basis (2019)

	Industry	Commercial & public	Residential	Other	Transportation	Total	
Oil	821	616	351	36	5,937	7,761	43%
Natural gas	22	402	94	0	0	518	3%
Bio/waste	312	0	0	27	0	339	2%
Charcoal	0	0	9	0	0	9	0%
Electricity (Primary energy basis)	1,163	4,091	3,019	1,085	0	9,358	52%
Total	2,318	5,109	3,473	1,148	5,937	17,985	100%
	13%	28%	19%	6%	33%	100%	

Energy Consumption Analysis from Energy Balance Table

- Electric power consumption was reduced by 2% between 2010 and 2019, some changes have been observed by sector:
  - ➢ Industry: Increased by 87%
  - ➢ Commercial: Decreased by 19%
  - ➢ Residential: Decreased by 2%

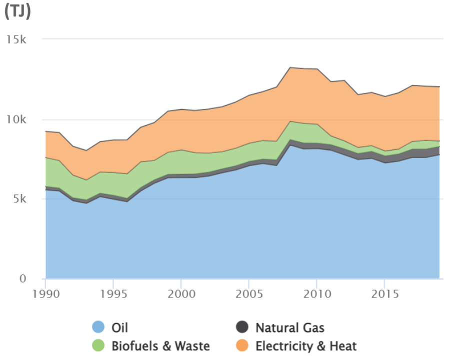
Changes in Electric Power Consumption by Sector from 2010 to 2019



Energy Consumption Analysis from Energy Balance Table

- Electricity and oil consumption have decreased slightly while natural gas consumption have been increasing during 2010 – 2019.
- Biofuel & waste consumption has decreased significantly.
- As total, final consumption was reduced by 1.0 % during 2010 – 2019.

Final Consumption by Fuel



Trend of Final Consumption by Fuel (2010 – 2019)

(TJ)

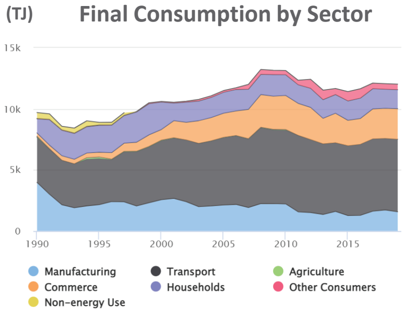
	2010	Share	2019	Share	AAGR
Electricity	3456	26%	3398	28%	-0.2%
Biofuels & Waste	1186	9%	348	3%	-12.7%
Natural Gas	346	3%	518	4%	4.6%
Oil	8148	62%	7761	65%	-0.5%
Total	13136	100%	12025	100%	-1.0%

Note: AAGR = Annual Average Growth Rate

Energy Consumption Analysis from Energy Balance Table

- Most of major sectors reduced final energy consumption and the industry sector is the largest among all (AAGR = -3.9%) during 2010 – 2019.

Final Consumption by Sector



Trend of Final Consumption by Sector (2010 – 2019)

	2010	Share	2019	Share	AAGR
Transport	6045	46%	5937	49%	-0.2%
Commerce	2791	21%	2503	21%	-1.2%
Households	1695	13%	1550	13%	-1.0%
Industry	2217	17%	1557	13%	-3.9%
Agriculture	47	0%	0	0%	-100.0%
Other consumers	340	3%	457	4%	3.3%
Total	13135	100%	12004	100%	-1.0%

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2. Energy Efficiency & Conservation Roadmap -Residential Sector-

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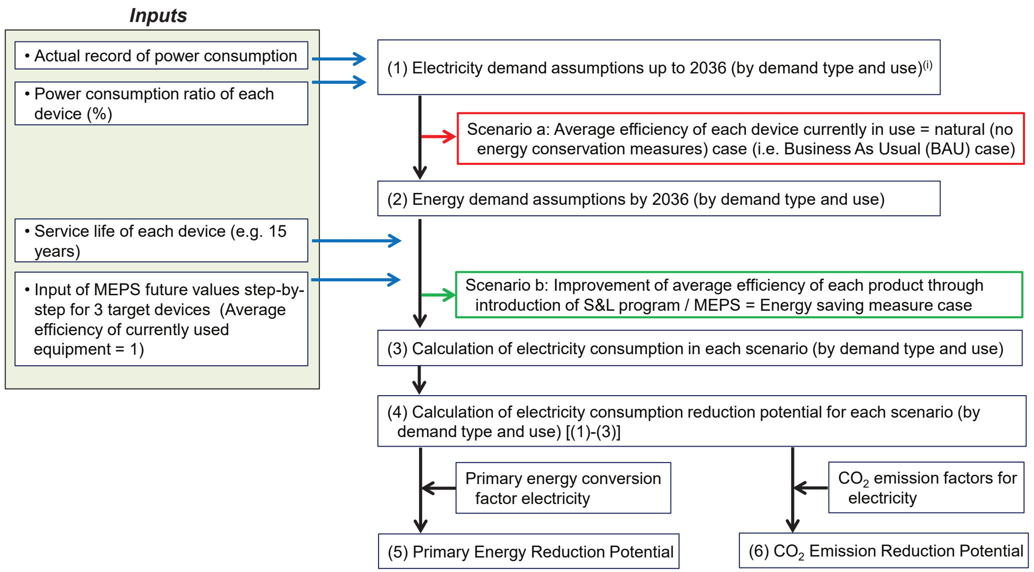
Energy Efficiency & Conservation (EEC) Roadmap



Inputs

- Actual record of power consumption
- Power consumption ratio of each device (%)
- Service life of each device (e.g. 15 years)
- Input of MEPS future values step-by-step for 3 target devices (Average efficiency of currently used equipment = 1)

(1) Electricity demand assumptions up to 2036 (by demand type and use)[(i)]

Scenario a: Average efficiency of each device currently in use = natural (no energy conservation measures) case (i.e. Business As Usual (BAU) case)

(2) Energy demand assumptions by 2036 (by demand type and use)

Scenario b: Improvement of average efficiency of each product through introduction of S&L program / MEPS = Energy saving measure case

(3) Calculation of electricity consumption in each scenario (by demand type and use)

(4) Calculation of electricity consumption reduction potential for each scenario (by demand type and use) [(1)-(3)]

Primary energy conversion factor electricity

CO_2 emission factors for electricity

(5) Primary Energy Reduction Potential

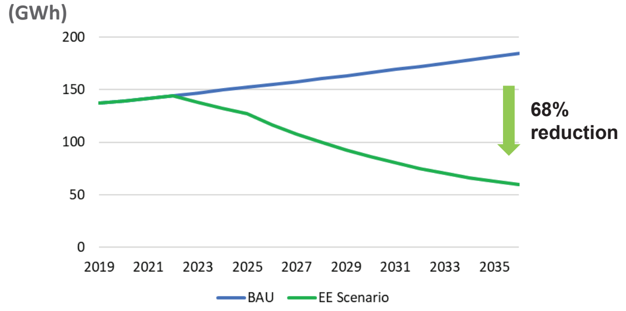
(6) CO_2 Emission Reduction Potential

(i) Source:1 Barbados Country Energy Balance Table (UN),
Source 2: Long-Term Peak Power Outlook: Report submitted to Prime Minister's Office, Government of Barbados (Mar 2017),
Note: the report does not present EEC measure scenarios.

Energy Efficiency & Conservation (EEC) Roadmap

- Electric power consumption of refrigerator has been estimated to be **reduced by 68%** with EE Scenario compared with BAU Scenario.
- Energy efficiency of refrigerator in use at households will be **3.1 times more efficient** compared with that of currently used in 2036 in EE Scenario with Introduction of MEPS.

Electric Power Consumption by Refrigerator up to 2036 (BAU and EE Scenario)



Assumed MEPS (EE Index) introduction for refrigerator in EE Scenario

EE index	
Present	1
2023	2
2026	3
2029	3.5
2032	4

Average EE index currently used at all households

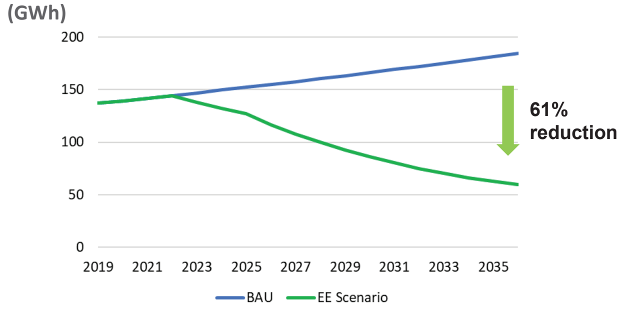
Assumed stepwise introduction of MEPS

Average EE index will be 3.1 in 2036 used at all households

Energy Efficiency & Conservation (EEC) Roadmap

- Electric power consumption of air conditioner has been estimated to be **reduced by 61%** with EE Scenario compared with BAU Scenario.
- Energy efficiency of air conditioner in use at households will be **2.6 times more efficient** compared with that of currently used in 2036 in EE Scenario with Introduction of MEPS.

Electric Power Consumption by Air Conditioner up to 2036 (BAU and EE Scenario)



Assumed MEPS (EE Index) introduction for air conditioner in EE Scenario

EE index	
Present	1
2023	2
2026	2.5
2029	3

Average EE index currently used at all households

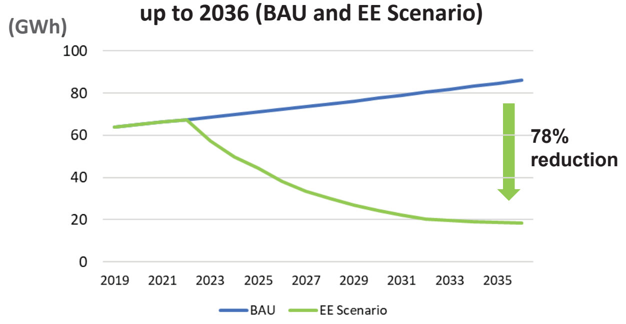
Assumed stepwise introduction of MEPS

Average EE index will be 2.6 in 2036 used at all households

Energy Efficiency & Conservation (EEC) Roadmap

- Electric power consumption of lighting equipment has been estimated to be **reduced by 78%** with EE Scenario compared with BAU Scenario.
- Energy efficiency of lighting equipment in use at households will be **4.7 times more efficient** compared with that of currently used in 2036 in EE Scenario with Introduction of MEPS.

Electric Power Consumption by Lighting Equipment up to 2036 (BAU and EE Scenario)



Assumed MEPS (EE Index) introduction for lighting equipment in EE Scenario

EE index	
Present	1
2023	3
2026	4
2029	4.5
2032	5

Average EE index currently used at all households

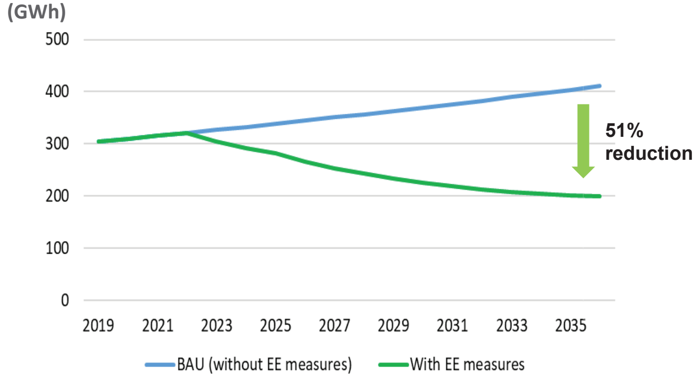
Assumed stepwise introduction of MEPS

Average EE index will be 4.65 in 2036 used at all households

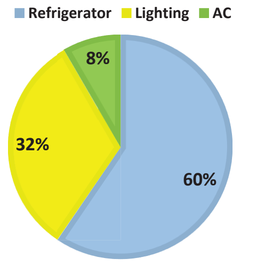
Energy Efficiency & Conservation(EEC) Roadmap

- With MEPS introduction targeting refrigerator, lighting equipment and air conditioner, it has been estimated power consumption will be **reduced by 51% in 2036.**

Energy Saving Potential in Residential Sector up to 2036 (BAU and EE Scenario)



Energy Saving Ratio by Appliance in 2036 (EE Scenario)



3. Energy Efficiency & Conservation Roadmap -Commercial Sector-

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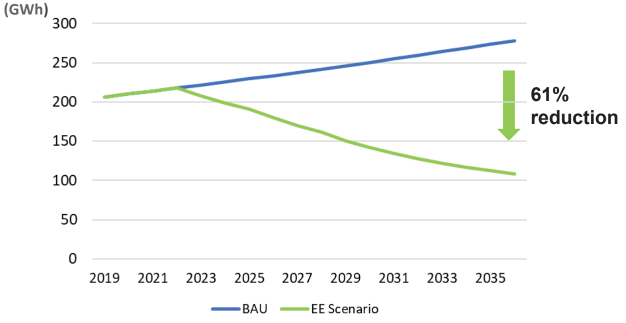
Energy Efficiency & Conservation Roadmap -Commercial-

- Electric power consumption of air conditioner has been estimated to be reduced by 61% with EE Scenario compared with BAU Scenario.
- Energy efficiency of air conditioner in use at households will be 2.6 times more efficient compared with that of currently used in 2036 in EE Scenario with Introduction of MEPS.

Electric Power Consumption by Air Conditioner up to 2036 (BAU and EE Scenario)



Assumed MEPS (EE Index) introduction for air conditioner in EE Scenario

EE index	
Present	1
2023	2
2026	2.5
2029	3

Average EE index currently used in commercial field

Assumed stepwise introduction of MEPS

Average EE index will be 2.6 in 2036 used in commercial field

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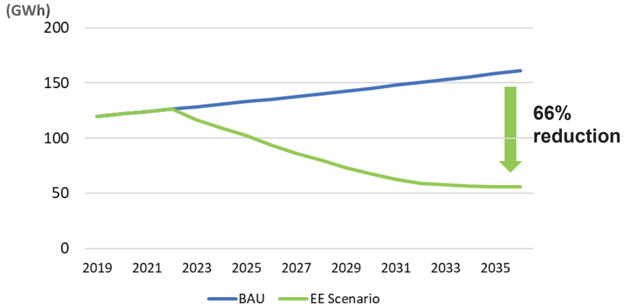
Energy Efficiency & Conservation Roadmap -Commercial-

- Electric power consumption of lighting equipment has been estimated to be reduced by 66% with EE Scenario compared with BAU Scenario.
- Energy efficiency of lighting equipment in use at households will be 2.9 times more efficient compared with that of currently used in 2036 in EE Scenario with Introduction of MEPS.

Electric Power Consumption by Lighting Equipment up to 2036 (BAU and EE Scenario)



Assumed MEPS (EE Index) introduction for lighting equipment in EE Scenario

EE index	
Present	1
2023	2
2026	2.5
2029	3

Average EE index currently used in commercial field

Assumed stepwise introduction of MEPS

Average EE index will be 2.9 in 2036 used in commercial field

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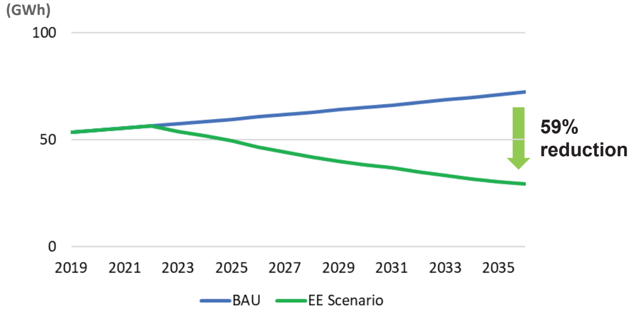
Energy Efficiency & Conservation Roadmap -Commercial-

- Electric power consumption of refrigerator has been estimated to be reduced by 59% with EE Scenario compared with BAU Scenario.
- Energy efficiency of refrigerator in use at commercial field will be 2.5 times more efficient compared with that of currently used in 2036 in EE Scenario with Introduction of MEPS.

Electric Power Consumption by Refrigerator up to 2036 (BAU and EE Scenario)



Assumed MEPS (EE Index) introduction for refrigerator in EE Scenario

EE index	
Present	1
2023	2
2026	2.5
2032	3

Average EE index currently used in commercial field

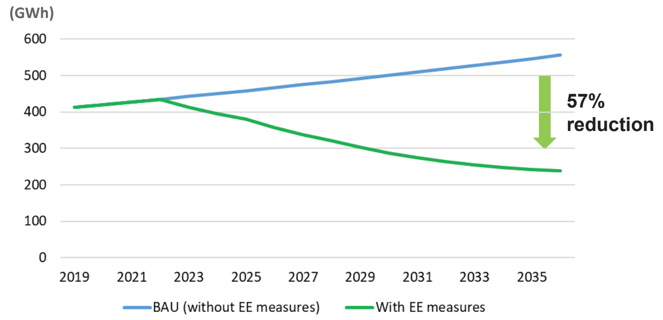
Assumed stepwise introduction of MEPS

Average EE index will be 2.5 in 2036 used in commercial field

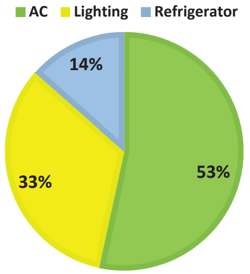
Energy Efficiency & Conservation Roadmap -Commercial-

- With MEPS introduction targeting refrigerator, lighting equipment and air conditioner, it has been estimated power consumption will be reduced by 57% in 2036.

Energy Saving Potential in Commercial Sector up to 2036 (BAU and EE Scenario)



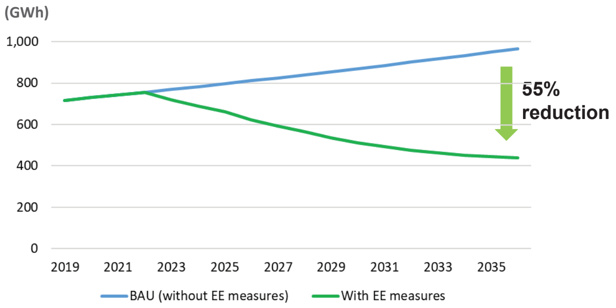
Energy Saving Share by Equipment in 2036 (EE Scenario)



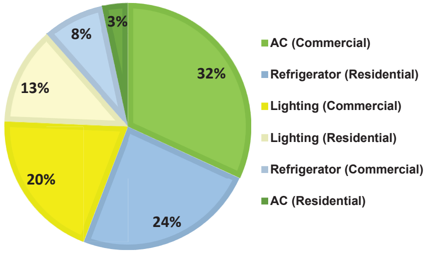
EE&C Roadmap -Residential + Commercial Sectors-

- With MEPS introduction targeting refrigerator, lighting equipment and air conditioner, it has been estimated power consumption will be reduced by 55% in residential and commercial sectors in 2036.

Energy Saving Potential in Residential + Commercial Sector up to 2036 (BAU and EE Scenario)



Energy Saving Share by Equipment and Sector in 2036 (EE Scenario)

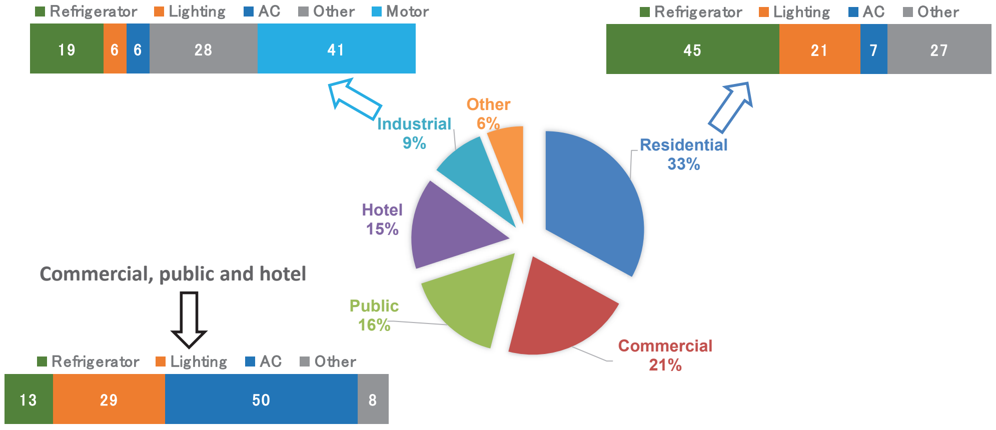


AC (R+C)	35%
Lighting (R+C)	33%
Refrigerator (R+C)	32%

Energy Efficiency & Conservation(EEC) Roadmap

- Current situation: Electricity consumption by sector and end-use

Electricity sales by demand group (last 10 years) and end-use



Source: JET with reference to Barbados NATIONAL ENEGY POLICY (2019-2030) and material by the Government of Barbados

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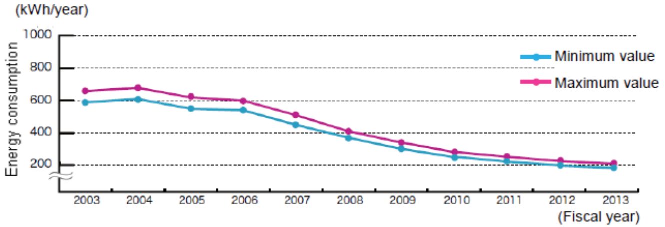
4. Promising Energy Efficient Technologies in non-industrial sectors

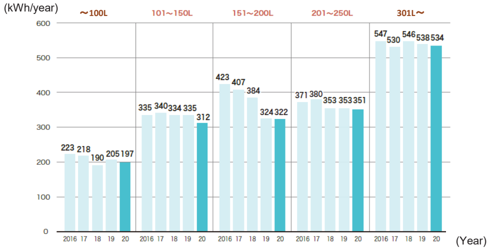
Trends of EE Improvement of Refrigerator (Res), Japan

Trends in Annual Energy Consumption of Refrigerator (401 –450ℓ, 2003 - 2013)



Source: Energy Saving Catalogue 2014 Summer (METI)

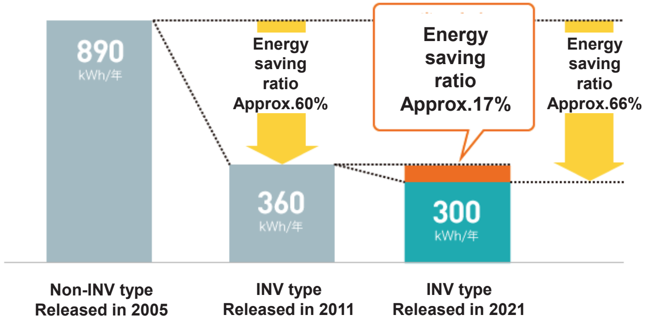
Trends in Annual Energy Consumption (2016 – 2020)



Source: Energy Saving Catalogue 2021 (METI)

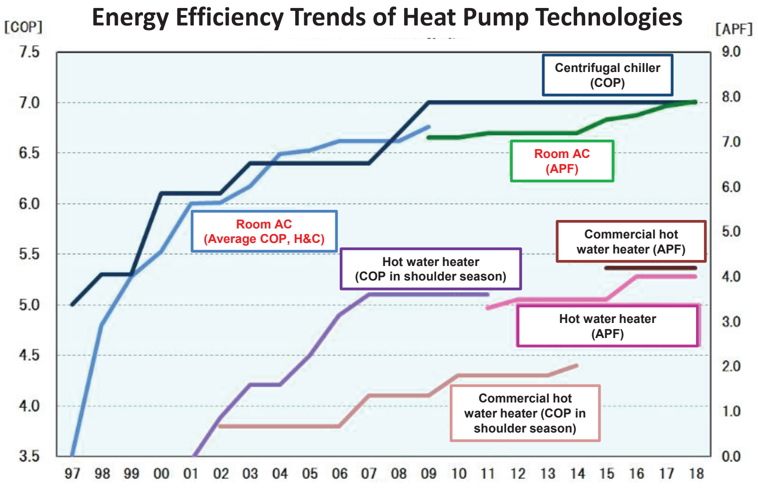
EE Improvement of Refrigerator (Commercial), Japan

Comparison of Annual Energy Consumption of Refrigerator (Commercial)



Source: HOSHIZAKI CORPORATION

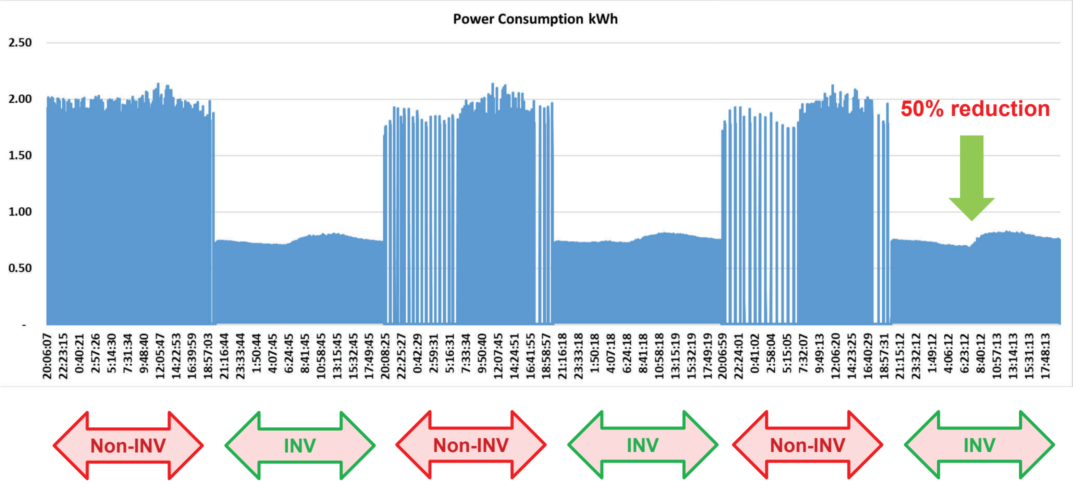
Trends of EE Improvement of various ACs, Japan



Source: Manufactures' Catalogue, Energy Saving Catalogue (METI)

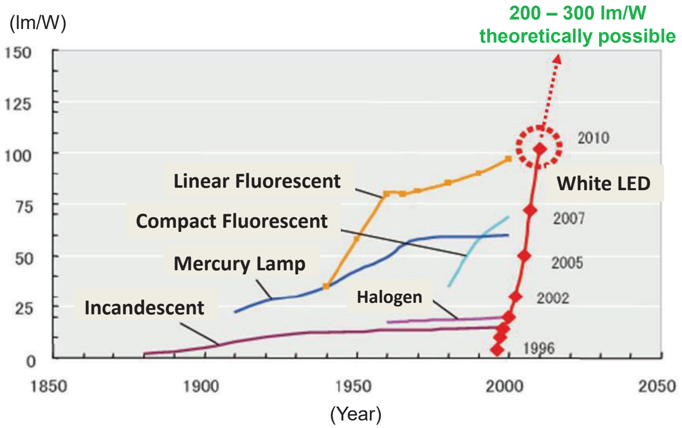
Note 1: COP stands for Coefficient of Performance, energy efficiency at rated operation (kWh/kWh)
Note 2: APF stands for Annual Performance Factor, energy efficiency throughout a year (kWh/kWh)

Results of Comparison Experiment, INV vs Non-INV AC



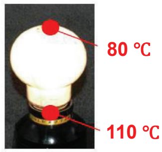
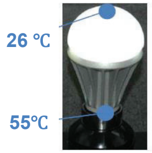
Trends of EE Improvement of Lighting Equipment, Japan

Trends of Luminous Efficiency



Source: Ministry of Economy and Trade and Industry, METI

Comparison of heat generation (Incandescent lamp vs LED lamp)

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

Contributes less AC demand

Introduction Examples of LED streetlamps (1)

Daytime view

Road width	4.8 m
Installation interval	Approx. 35 m
Installation height	Approx. 4.5 m

Before refurbishment: Mercury lamp 80W

Horizontal plane (average)		2.75 Lux
Vertical plane (Min.)	Road center	0.41 Lux
	Both sides of the road	0.39 Lux

After refurbishment: LED 33W

Horizontal plane (average)		7.09 Lux
Vertical plane (Min.)	Road center	1.59 Lux
	Both sides of the road	1.49 Lux

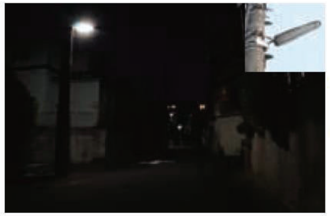
Source: Japan security systems association

Introduction Examples of LED streetlamps (2)

Daytime view

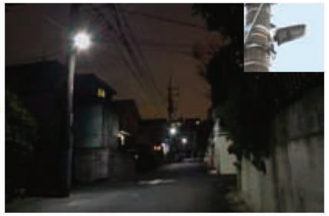
Road width	5.1 m
Installation interval	Approx. 30 m
Installation height	Approx. 5.0 m

Before refurbishment: CFL 20W



Horizontal plane (average)		1.76 Lux
Vertical plane (Min.)	Road center	0.17 Lux
	Both sides of the road	0.12 Lux

After refurbishment: LED 17W



Horizontal plane (average)		5.56 Lux
Vertical plane (Min.)	Road center	0.78 Lux
	Both sides of the road	0.64 Lux

Source: Japan security systems association

Introduction Examples of LED on Highways

Source: IWASAKI ELECTRIC CO., LTD.

5. References

EEC Implementation Best Practice - Commercial Sector -

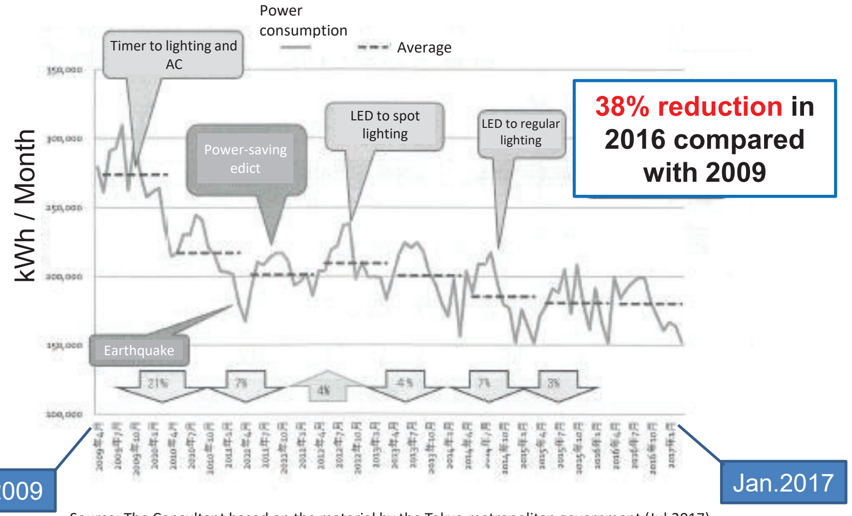
- **Outline of the building**
  - **Location: Tokyo**
  - **Floor area: 19,550m^2**
  - **Building structure: RC (Basement 1F – 4 floors)**
  - **AC system: DHC (District Heating and Cooling) + AC units (partially)**
  - **Number of workers: Approx.200 persons**

- EEC approaches (STEP by STEP)
  - Introduction of auto timer to lighting and AC in 2009. (ON/OFF switch was operated manually in the past)
  - Introduction of LED to spot lighting equipment (approx. 1,000 units) in 2012
  - Introduction of LED to regular lighting equipment (approx. 2,000 units) in 2014

EEC Implementation Best Practice - Commercial Sector -

Trend of Power Consumption Reductions

(approx.8years: Apr.2009-Jan.2017)

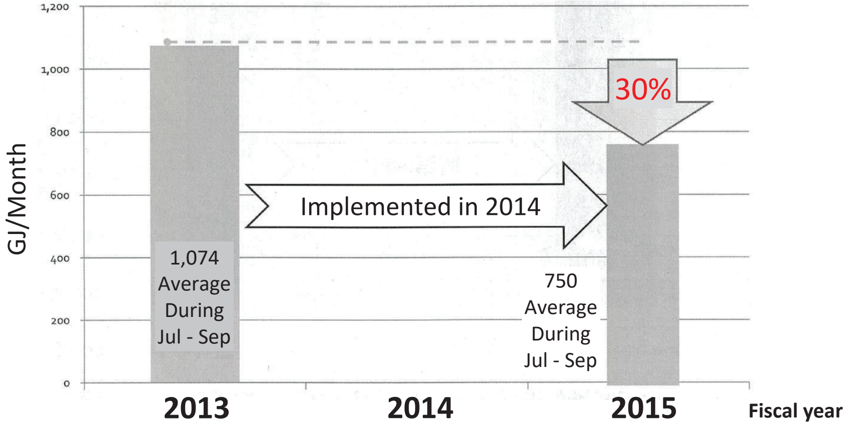


38% reduction in 2016 compared with 2009

Source: The Consultant based on the material by the Tokyo metropolitan government (Jul.2017)

EEC Implementation Best Practice - Commercial Sector -

Effects on Cooling Demand Reductions with Introduction of LED to Regular Lighting System



Source: JET based on the material by the Tokyo Metropolitan government (Jul.2017)

Introduction of LED realized reductions of waste heat from lighting equipment and achieved cooling demand reductions (30%) in summer.

EEC Implementation Best Practice - Commercial Sector -

Evaluation of Energy Consumption Reductions on Primary Energy Basis

	Before		After		Primary energy consumption reductions
Energy	2009	2013	2015	2016	
Electric power consumption	275 MWh x 12 = 3,300 MWh/year			171 MWh x 12 = 2,052 MWh/year	
Primary energy consumption	3,300 x 9.97 = **32,901** GJ/year			2,052 x 9.97 = **20,458** GJ/year	32,901 – 20,458 = **12,443 GJ/year**
Cooling& heating demand		445 GJ x 12 = 5,340 GJ/year	325 GJ x 12 = 3,900 GJ/year		
Primary energy consumption		5,340 GJ x 1.36 =**7,262** GJ/year	3,900 GJ x 1.36 =**5,304** GJ/year		7,262 – 5,304 = **1,958 GJ/year**
Total	32,901 + 7,262 = 40,163 GJ/year		20,458 + 5,304 = 25,762 GJ/year		**14,401 GJ/year (36%)**

Note1: Calculation was made by JET
Note2: Conversion factors for electric power and DHC were based on the guide for completing periodical report regarding EE law . (METI, Aug.2017)
Note3: Changes of both heating and cooling demands by the introduction of LED are taken into account.
Source: JET based on the material by the Tokyo Metropolitan government (Jul.2017)

Thank you very much for your kind attention !

Energy Efficiency & Conservation (EEC) Materiel Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

- Energy Efficiency Building Code -

Barbados, January 2023

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

Contents

1. Outline of EE Regulations in Residential Building

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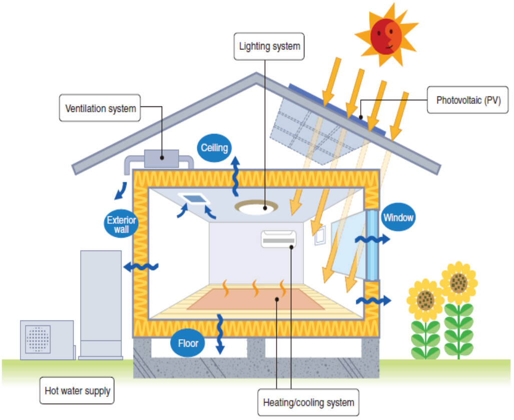
1. Outline of EE Regulations in Residential Building

- **Overview of the Energy Efficiency Standards for Residential Buildings**

The evaluation of energy efficiency (EE) performance for residential buildings uses the following two standards:

- ➢ Standards to evaluate envelope performance (e.g. windows, exterior walls of residential buildings
- ➢ Standards to evaluate the primary energy consumption amount of equipment and appliances etc.



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1. Outline of EE Regulations in Residential Building

- **Envelope performance**
  - ➢ Average outer shell heat transmission coefficient (U_A)

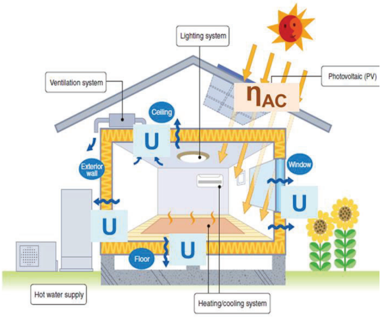
$$\underset{(W/m^2\cdot K)}{U_A} = \frac{\text{Amount of total heat loss per unit of temperature difference}}{\text{Total surface area of exterior}}$$

➢ U_A

✓ An indicator of the ease of heat transfer between indoor and outdoor air.

✓ When the temperature difference between the inside and outside of the building is 1 °C, the amount of heat released per unit time from the inside of the building to the outside of building is divided by the total surface area of exterior.

✓ The smaller the value, the more difficult it is for heat to enter and exit, and the higher the insulation performance.



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1. Outline of EE Regulations in Residential Building

- **Envelope performance**
  - ➢ Average solar heat gain coefficient during cooling period (η_{AC})

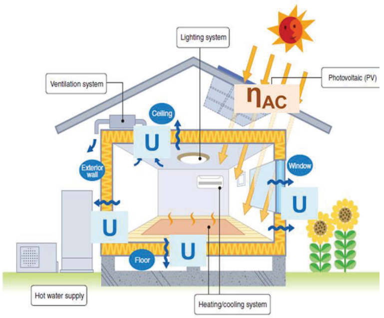
$$\underset{(-)}{\eta_{AC}} = \frac{\text{Amount of total solar heat gain per unit of solar radiation intensity}}{\text{Total surface area of exterior}} \times 100$$

➢ η_{AC}

✓ An indicator of how easily solar radiation enters the room.

✓ Amount of heat acquired inside the building from solar radiation per unit of solar radiation intensity averaged by the cooling season and divided by the total surface area of exterior.

✓ The smaller the value, the less sunlight enters and the higher the shielding performance.



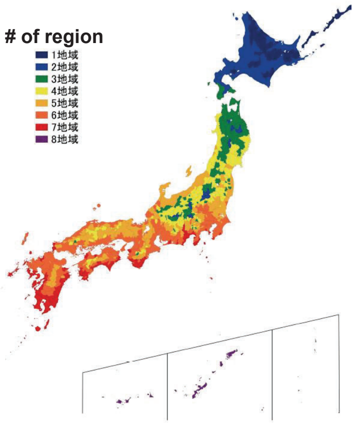
1. Outline of EE Regulations in Residential Building

☐ **Envelope performance**

U_A Design Value ≦ Standard Value

η_{AC} Design Value ≦ Standard Value

✓ **Standard values of U_A and η_{AC} are defined by region by region. (regions are classified in 8 regions in Japan)**



Region	1&2	3	4	5	6	7	8
Standard Value of U_A	0.46	0.56	0.75	0.87	0.87	0.87	-
Standard Value of η_{AC}	-	-	-	3.0	2.8	2.7	6.7

Revised in Apr.2020 as previous value was too strict (3.2)

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1. Outline of EE Regulations in Residential Building

- **Primary energy consumption amount**

+ heating/cooling system primary energy consumption amount
+ ventilation system primary energy consumption amount
+ lighting system primary energy consumption amount
+ hot water supply primary energy consumption amount
+ other (household appliances) primary energy consumption amount
- reduction amount of primary energy consumption through PV, etc

= **primary energy consumption amount**

☐ **Evaluation of primary energy consumption amount**

$$\frac{\text{Design value (excludes home appliances etc.)}}{\text{Standard value (excludes home appliances etc.)}} \leqq 1.0$$

---

1. Outline of EE Regulations in Residential Building

☐ **Promulgated on June 17, 2022 (Ministry of Land, Infrastructure, Transport and Tourism Housing Bureau**

- Mandate that **all new residential and nonresidential buildings** comply with EEC standards
- Conducted as part of the building permit process, integrated with the structural safety regulation conformity assessment.
- **Enforcement will be made by FY2025**, while ensuring a sufficient preparation period in consideration of small and medium-sized construction firms and the development of the screening system.

	current	
	Non-residential	Residential
large-scale 2,000m^2 or more	Compliance obligation	Notification obligation
mid-scale	Compliance obligation	Notification obligation
Less than 300m^2 small scale	Explanation obligation	Explanation obligation

➡

	revision	
	Non-residential	Residential
large-scale 2,000m^2 or more	Compliance obligation	Compliance obligation
mid-scale	Compliance obligation	Compliance obligation
Less than 300m^2 small scale	Compliance obligation	Compliance obligation

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

2. Examples of Simplified Calculation in Residential Building (6 Region)

Simplified Calculation

Envelope performance

Region	Legend of sheet number
6 **Region**	6 － 1 － 1
wooden	Category 1: Wooden 2: Reinforced Steel, Steel, etc.

1: Floor-insulated dwelling (Bathroom floor insulation)
2: Floor-insulated dwelling (Bathroom foundation insulation)
3: Floor-insulated dwelling (no bathroom floor in contact with outside air, etc.)
4: Foundation-insulated dwelling

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

Average heat transmission coefficient U_A

Please fill in the values in the bold frame below.

In the case where a single part has several different specifications, the heat transfer coefficient shall be that of the specification with the largest heat transfer coefficient. If the area of a window is less than or equal to the total floor area of the unit dwelling multiplied by 0.02, the window specification concerned may be excluded.

				Heat transmission coefficient U		Result	
Roof or ceiling		0.194	×	0.258	=	0.051	(1)
Outer wall	general section	0.489	×	0.430	=	0.211	(2)
	Foundation wall (Entrance)	0.004	×	4.11	=	0.017	(3)
Floor	Bathroom	0.009	×	3.34	=	0.031	(4)
	Other Floors	0.121	×	0.492	=	0.060	(5)
Window		0.107	×	2.91	=	0.312	(6)
Door		0.014	×	3.49	=	0.049	(7)

↑Rounded up to the fourth decimal place

				Linear thermal transmittance ψ		Result	
Periphery of dirt floor, etc.	Entrance etc.	0.021	×	0.99	=	0.021	(8)

↑Rounded up to the fourth decimal place

Average heat transmission coefficient of envelope: U_A [W/(m^2·K)] Sum of (1)-(8) = 0.76

*Rounded up to the third decimal place (Conforming if the standard value is 0.87 [W/(m^2·K)] or less)

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

Average solar heat gain during cooling season η_{AC}

Please fill in the values in the bold frame below.

If a site has several different specifications, the thermal transmittance of the specification with the largest thermal transmittance should be used.
If a window has several different specifications, the vertical solar heat gain shall be the vertical solar heat gain of the specification with the largest vertical solar heat gain. If the area of a window is less than or equal to the total floor area of the unit dwelling multiplied by 0.04, the window specification concerned may be excluded.

				Heat transmission coefficient U		Result	
Roof or ceiling		0.659	×	0.258	=	0.171	(9)
Outer wall	General section	0.762	×	0.430	=	0.328	(10)
	Foundation Wall (Entrance)	0.004	×	4.11	=	0.017	(11)
Door		0.020	×	3.49	=	0.070	(12)

↑Rounded up to the fourth decimal place

			Coefficient of Vertical Surface Solar Heat Gain Coefficient η_d		Results	
Window	4.356	×	0.32		1.394	(13)

↑Rounded up to the fourth decimal place

Average solar heat gain during cooling season η_{AC} [-] Sum of (9)-(13) = 2.0

*Rounds up to the second decimal place (Conforming if the standard value is 2.8 [-] or less)

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

Average solar heat gain during the heating season η_{AH}

Please enter the values in the bold boxes below.

If a site has several different specifications, the thermal transmittance of the specification with the largest thermal transmittance should be used.
If a window has several different specifications, the vertical surface solar heat gain shall be that of the specification with the lowest vertical surface solar heat gain. If the area of the window is less than or equal to the total floor area of the unit dwelling multiplied by 0.04, the window specification concerned may be excluded.

				Heat transmission coefficient U		Result	
Roof or ceiling		0.658	×	0.258	=	0.169	(14)
Outer wall	general section	0.882	×	0.430	=	0.379	(15)
	Foundation Wall (Entrance)	0.002	×	4.11	=	0.008	(16)
door (Western-style)		0.014	×	3.49	=	0.048	(17)

↑Rounded down to the fourth decimal place

			Coefficient of Vertical Surface Solar Heat Gain Coefficient η_d		Results	
window	4.786	×	0.32	=	1,531	(18)

↑Rounded down to the fourth decimal place

Average solar heat gain during the heating season η_{AH} [-] Sum of (14)-(18) = 2.1

*Rounded down to the second decimal place (Reference value: None)

2. Examples of Simplified Calculation in Residential Building (6 Region)

Simplified Calculation
Primary energy consumption performance

6
Region

Sheet No.	Principal living space	Other living space
6-ENE-1	Not installed	
6-ENE-2	Room air conditioner	
6-ENE-3	Hot water floor heating (Oil latent heat recovery hot water heater)	Room air conditioner
6-EN-4	Hot water floor heating (Gas latent heat recovery hot water heater)	Room air conditioner

---

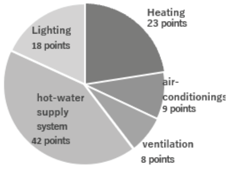
2. Examples of Simplified Calculation in Residential Building (6 Region)

Please fill in the envelope performance.

Please fill in the figures in the bold frame below.

Average heat transmission coefficient U_A [W/(㎡・K)]	0.76
Average solar heat gain during cooling season η_{AC} [-]	2.0
Average solar heat gain during the heating season η_{AH} [-]	2.1

From the Point Listing page, post the points you selected in (1) through (5) in the bolded box below and calculate the total.



Reference] Approximate points for each facility (excluding other facilities)

Please fill in the points in the bold frame below.

heating facilities	Transcribe the numbers in (1)	=	29	(a)
air-conditioning facilities	Transcribe the numbers in (2)	=	10	(b)
ventilation equipment	Transcribe the numbers in (3)	=	8	(c)
hot-water supply system	Transcribe the numbers in (4)	=	36	(d)
Lighting equipment	Transcribe the numbers in (5)	=	10	(e)

Primary energy consumption performance points Total of (a)-(e) = 93

(Conforming If less than or equal to 100 points)

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

(1) Envelope performance and heating system

*Confirm the average heat transmission coefficient and the average solar heat gain during the heating season for the house in question, and check the points of the heating equipment with ☑ the relevant envelope performance value. (However, only if the average solar heat gain during the heating season is 1.8 or higher.

Average heat transmission coefficient U_A [W/(㎡・K)]	Average solar heat gain during the heating season η_{AH} [-]	point
☑ Greater than 0.69 0.78 or less	☑ 1.8 or higher Less than 2.3	29
	☐ 2.3 or higher Less than 2.8	28
	☐ 2.8 or higher Less than 3.3	26
	☐ 3.3 or higher Less than 3.8	25
	☐ 3.8 or higher Less than 4.3	24
	☐ 4.3 or higher	21

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

(2) Envelope performance and cooling system

*Confirm the average heat transfer coefficient of the external envelope of the house in question and the average solar heat gain during the cooling season, and check the points of the cooling system with ☑ the relevant external envelope performance value. (However, only if the average solar heat gain during the cooling season is 4.3 or less.

Average heat transmission coefficient U_A [W/(㎡・K)]	Average solar heat gain during the cooling season η_{AC} [-]	point
☑ 0.69 or more Less than 0.78	☐ 1.8 or less	9
	☑ 1.8 Larger 2.3 or less	10
	☐ 2.3 Larger 2.8 or less	11
	☐ 2.8 Larger 3.3 or less	13
	☐ 3.3 Larger 3.8 or less	14
	☐ 3.8 Larger 4.3 or less	16

(3) Ventilation equipment

*Please check the points by ticking the appropriate ones.

type	point
☐ Ducted Type 1 Ventilation System	13
☐ Ducted Type 2 ventilation equipment or ducted Type 3 ventilation equipment	10
☐ Wall-mounted Type 1 ventilation equipment	10
☑ Wall-mounted Type 2 ventilation equipment or Wall-mounted Type 3 ventilation equipment	8

2. Examples of Simplified Calculation in Residential Building (6 Region)

(4) Hot-water supply system

*Please check the points by ticking the appropriate ones.

type	Hot water-saving faucet*.1		point
☐ Not installed	-		43
☐ Conventional gas water heater	☐	No	47
	☐	Yes	44
☐ Gas latent heat recovery water heater	☐	No	40
	☐	Yes	38
☐ Conventional oil water heaters	☐	No	42
	☐	Yes	39
☐ Oil latent heat recovery water heater	☐	No	40
	☐	Yes	38
☐ Electric heat pump water heater (CO_2 refrigerant)	☑	No	36
	☐	Yes	34

*1: "Yes" can be selected for hot water-saving faucets when faucets with the following functions are installed in all "kitchen", "bathroom shower", and "washbasin" areas.
Kitchen": water shut-off function or priority water dispensing function
Bathroom shower: Hand-held shut-off function or low-flow discharge function
Washbasin": Priority water dispensing function

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2. Examples of Simplified Calculation in Residential Building (6 Region)

(5) Lighting equipment

*Check the points for all fixtures in the main living room and all other living rooms by ☑ in the appropriate combination. However, lighting fixtures in non-occupied rooms must be non-incandescent.

type		point
Lighting fixtures in principal living rooms*.2	Lighting fixtures in other living rooms *.2	
☐ Not installed	☐ Not installed	9
	☐ LED	9
	☐ Other than incandescent lamps	10
	☐ Incandescent lamp	13
☑ LED	☐ Not installed	9
	☐ LED	9
	☑ Other than Incandescent lamps	10
	☐ Incandescent lamp	13
☐ Other than incandescent lamps	☐ Not installed	11
	☐ LED	11
	☐ Other than incandescent lamps	11
	☐ Incandescent lamp	14
☐ Incandescent lamp	☐ Not installed	15
	☐ LED	15
	☐ Other than incandescent lamps	16
	☐ Incandescent lamp	18

2: "LED": LEDs are used in all devices.
"Non-incandescent": All equipment uses non-incandescent lamps.
"Incandescent": Incandescent lamps are used in any of the devices.

---

2. Examples of Simplified Calculation in Residential Building (6 Region)

Primary energy consumption calculation results (residential version)

1. Design primary energy consumption etc.

(1) Name of housing type	○○○○ residence (detached house)			
(2) Floor area.	Principal living space	Other living space	Non-living space	Total
	29.81 m2	51.34 m2	38.93 m2	120.08 m2
(3) Regional classification	6 Region		**********	
(4) Primary energy consumption (per dwelling)			Design primary [MJ].	Standard Primary [MJ].
	heating facilities		17236	15382
	air-conditioning facilities		5390	5611
	ventilation equipment		4583	4542
	hot-water supply system		20940	25091
	lighting equipment		5964	10763
	Other equipment.		21241	21241
	On-site consumption of electricity generated by power generation facilities *1		--	--
	Deductions related to the amount of electricity sold from cogeneration facilities *2		--	--
	total amount		75353	82629
(5) BEI	Primary energy consumption (excluding others) [GJ/(unit/year)].		54.2	61.4
	BEI		0.89	

*1: Power generation facilities include cogeneration facilities and photovoltaic facilities. *2: This is the amount of primary energy consumption required to generate the electricity sold by the cogeneration facility.

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3. Examples of Simplified Calculation in Residential Building (8 Region)

3. Examples of Simplified Calculation in Residential Building (8 Region)

Simplified Calculation

Envelope performance

Region	Legend of sheet number
8 Region	8 – 1 – 1 Category 1: Wooden 2: Reinforced Steel, Steel, etc. 1: Floor-insulated dwelling (Bathroom floor insulation) 2: Floor-insulated dwelling (Bathroom foundation insulation) 3: Floor-insulated dwelling (no bathroom floor in contact with outside air, etc.) 4: Foundation-insulated dwelling
wooden	

---

3. Examples of Simplified Calculation in Residential Building (8 Region)

Average heat transmission coefficient U_A Please fill in the values in the bold frame below.

In the case where a single part has several different specifications, the heat transfer coefficient shall be that of the specification with the largest heat transfer coefficient. If the area of a window is less than or equal to the total floor area of the unit dwelling multiplied by 0.02, the window specification concerned may be excluded.

				Heat transmission coefficient U		Result	
Roof or ceiling		0.194	×	0.99	=	0.192	(1)
Outer wall	general section	0.489	×	0.430	=	0.211	(2)
	Foundation wall (Entrance)	0.004	×	4.11	=	0.017	(3)
Floor	Bathroom	0.009	×	3.34	=	0.031	(4)
	Other Floors	0.121	×	0.492	=	0.060	(5)
Window		0.107	×	6.0	=	0.642	(6)
Door		0.014	×	3.49	=	0.049	(7)

↑ Rounded up to the fourth decimal place

				Linear thermal transmittance ψ		Result	
Periphery of dirt floor, etc.	Entrance etc.	0.021	×	0.99	=	0.021	(8)

↑Rounded up to the fourth decimal place

Average heat transmission coefficient of envelope: U_A [W/(m^2·K)] Sum of (1)-(8) = 1.22

Note 1: U_A of roof /ceiling was adopted the standard value in region 8 while other values are set at same value as region 6 (there is no standard values for them).

Note 2: For window, adopted coefficient of vertical surface solar heat gain of single-layer glass.

---

3. Examples of Simplified Calculation in Residential Building (8 Region)

Average solar heat gain during cooling season η_{AC} Please fill in the values in the bold frame below.

If a site has several different specifications, the thermal transmittance of the specification with the largest thermal transmittance should be used.

If a window has several different specifications, the vertical solar heat gain shall be the vertical solar heat gain of the specification with the largest vertical solar heat gain. If the area of a window is less than or equal to the total floor area of the unit dwelling multiplied by 0.04, the window specification concerned may be excluded.

				Heat transmission coefficient U		Result	
Roof or ceiling		0.959	×	0.99	=	0.949	(9)
Outer wall	General section	0.762	×	0.430	=	0.330	(10)
	Foundation Wall (Entrance)	0.004	×	4.11	=	0.016	(11)
Door		0.019	×	3.49	=	0.066	(12)

↑Rounded up to the fourth decimal place

			Coefficient of Vertical Surface Solar Heat Gain Coefficient η_d	Results	
Window	4.55	×	0.63	2.867	(13)

↑Rounded up to the fourth decimal place

Average solar heat gain during cooling season η_{AC} [-] Sum of (9)-(13) = 4.2

*Rounds up to the second decimal place
(Conforming if the standard value is 6.7 [-] or less)

Note : For window, adopted coefficient of vertical surface solar heat gain of single-layer glass.

---

3. Examples of Simplified Calculation in Residential Building (8 Region)

Simplified Calculation

Primary energy consumption performance

8
Region

Sheet No.	Principal living space	Other living space
8-ENE-1	Not installed	
8-ENE-2	Room air conditioner	

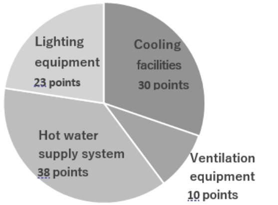
3. Examples of Simplified Calculation in Residential Building (8 Region)

Please fill in the envelope performance.

Please fill in the figures in the bold frame below.

Average heat transmission coefficient U_A [W/(㎡ · K)]	1.22
Average solar heat gain during cooling season η_{AC} [-]	4.2

From the Point Listing page, post the points you selected in (1) through (4) in the bolded box below and calculate the total.



Reference] Approximate points
for each facility (excluding other facilities)

Please fill in the points
in the bold frame below.

air-conditioning facilities	Transcribe the numbers in (1)	=	35	(a)
ventilation equipment	Transcribe the numbers in (2)	=	10	(b)
hot-water supply system	Transcribe the numbers in (3)	=	26	(c)
Lighting equipment	Transcribe the numbers in (4)	=	12	(d)

Primary energy consumption performance points Total of (a)-(d) = 83

(Conforming If less than or equal to 100 points)

---

3. Examples of Simplified Calculation in Residential Building (8 Region)

(1) Envelope performance and cooling system

*Confirm the average heat transfer coefficient of the external envelope of the house in question and the average solar heat gain during the cooling season, and check the points of the cooling system with ☑ the relevant external envelope performance value. (However, only if the average solar heat gain during the cooling season is 8.7 or less.

Average heat transmission coefficient U_A [W/(㎡ · K)]	Average solar heat gain during the cooling season η_{AC} [-]	point
☑ 1.05 or more Less than 1.50	☐ 1.7 or less	19
	☐ 1.7 Larger 2.7 or less	25
	☐ 2.7 Larger 3.7 or less	30
	☑ 3.7 Larger 4.7 or less	35
	☐ 4.7 Larger 5.7 or less	40
	☐ 5.7 Larger 6.7 or less	45
	☐ 6.7 Larger 7.7 or less	50
	☐ 7.7 Larger 8.7 or less	55
☐ 1.50 or more Less than 1.95	☐ 1.7 or less	17
	☐ 1.7 Larger 2.7 or less	22
	☐ 2.7 Larger 3.7 or less	26
	☐ 3.7 Larger 4.7 or less	30
	☐ 4.7 Larger 5.7 or less	35
	☐ 5.7 Larger 6.7 or less	40
	☐ 6.7 Larger 7.7 or less	45
	☐ 7.7 Larger 8.7 or less	49

---

3. Examples of Simplified Calculation in Residential Building (8 Region)

(2) Ventilation equipment

*Please check the points by ticking the appropriate ones.

type	point
☐ Ducted Type 1 Ventilation System	16
☐ Ducted Type 2 ventilation equipment or ducted Type 3 ventilation equipment	13
☐ Wall-mounted Type 1 ventilation equipment	13
☑ Wall-mounted Type 2 ventilation equipment or Wall-mounted Type 3 ventilation equipment	10

(3) Hot-water supply system

*Please check the points by ticking the appropriate ones.

type	Hot water-saving faucet*.[1]	point
☐ Not installed	-	38
☐ Conventional gas water heater	☐ No	42
	☐ Yes	39
☐ Gas latent heat recovery water heater	☐ No	36
	☐ Yes	33
☐ Conventional oil water heaters	☐ No	38
	☐ Yes	35
☐ Oil latent heat recovery water heater	☐ No	36
	☐ Yes	33
☐ Electric heat pump water heater (CO_2 refrigerant)	☑ No	26
	☐ Yes	25

---

3. Examples of Simplified Calculation in Residential Building (8 Region)

(4) Lighting equipment

*Check the points for all fixtures in the main living room and all other living rooms by ☑ in the appropriate combination. However, lighting fixtures in non-occupied rooms must be non-incandescent.

type		point
Lighting fixtures in principal living rooms*.[2]	Lighting fixtures in other living rooms *.[2]	
☐ Not installed	☐ Not installed	11
	☐ LED	11
	☐ Other than incandescent lamps	12
	☐ Incandescent lamp	16
☑ LED	☐ Not installed	11
	☐ LED	11
	☑ Other than Incandescent lamps	12
	☐ Incandescent lamp	16
☐ Other than incandescent lamps	☐ Not installed	13
	☐ LED	13
	☐ Other than incandescent lamps	14
	☐ Incandescent lamp	17
☐ Incandescent lamp	☐ Not installed	19
	☐ LED	19
	☐ Other than incandescent lamps	20
	☐ Incandescent lamp	23

2: "LED": LEDs are used in all devices.
“Non-incandescent": All equipment uses non-incandescent lamps.
“Incandescent": Incandescent lamps are used in any of the devices.

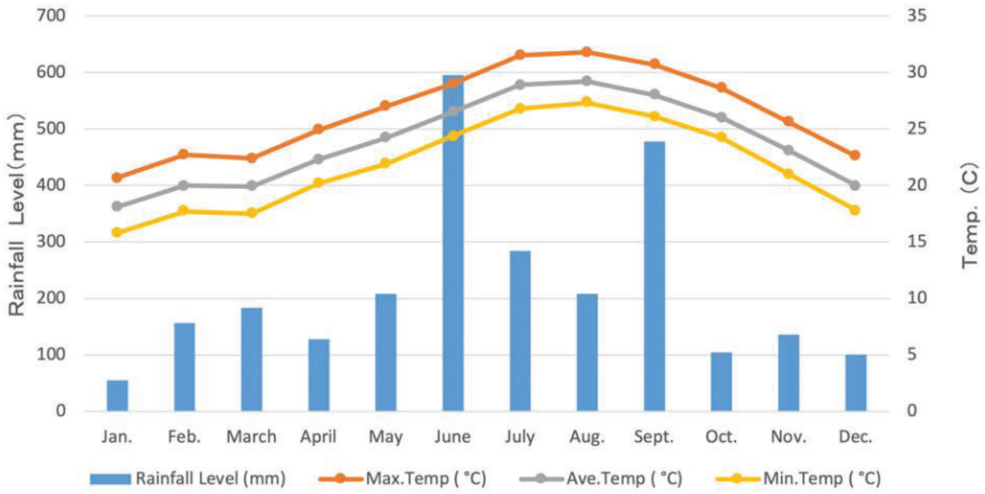
3. Examples of Simplified Calculation in Residential Building (8 Region)

1. Design primary energy consumption etc.

(1) Name of housing type	OOOO residence (detached house)			
(2) Floor area.	Principal living space	Other living space	Non-living space	Total
	29.81 m2	51.34 m2	38.93 m2	120.08 m2
(3) Regional classification	8 Region		**********	
(4) Primary energy consumption (per dwelling)			Design primary [MJ].	Standard Primary [MJ].
	heating facilities		0	0
	air-conditioning facilities		15483	21289
	ventilation equipment		4583	4542
	hot-water supply system		12338	17922
	lighting equipment		5964	10763
	Other equipment.		21241	21241
	total amount		59609	75756
(5) BEI	Primary energy consumption (excluding others) [GJ/(unit/year)].		38.4	54.6
	BEI		0.71	

*1: Power generation facilities include cogeneration facilities and photovoltaic facilities. *2: This is the amount of primary energy consumption required to generate the electricity sold by the cogeneration facility.

[Ref] Rainfall level & average temperature in Okinawa, 8 Region, 2019



Data source: Japan Meteorological Agency

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4. EEC Unique Approaches in Residential Building, Okinawa, Japan

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4. EEC Unique Approaches in Residential Building, Okinawa

Energy Reduction Effects by Applying Efficient Technologies in Okinawa

Use	Energy consumption standard value (GJ)	Efficient technology		Energy consumption rate (standard value is set at 1.0) more efficient →			
				Level 1	Level 2	Level 3	Level 4
Cooling	**10.3 (15%)**	**Use and control of natural wind**		0.96	0.91	0.88	
		Solar radiation shielding method		0.9	0.8	0.75	0.7
		Cooling system plan (efficient AC, etc.)		0.9	0.8	0.75	0.65
Ventilation	3.1 (5%)	Ventilation equipment	ducted	0.7	0.5		
	2.8		wall-mounted	0.8			
Hot water supply	**13.8 (21%)**	**Solar hot water supply**		0.9	0.7	0.5	0.3
		Hot water supply system		0.9	0.8	-	0.6
Lighting	**13.6 (20%)**	**Daylight use**		0.97～0.98	0.95	0.9	
		Lighting Equipment planning		0.85	0.8	0.7	
Appliances	**21.4 (32%)**	**Introduction of high-efficiency appliances**		0.8	0.6		
Other (Cooking)	4.4 (7%)						
Total amount	66.6						
	66.3						

Source: Energy efficient house guidelines (Okinawa prefecture, 2015)

4. EEC Unique Approaches in Residential Building, Okinawa

Adopted EE Methods and Estimation of Energy Saving Effects - Example of the Model House - (1)

Use	Efficient technologies	Evaluation level	Energy consumption rate	Adopted EE methods
Cooling	Use of natural wind	3	0.88	• Openings on ventilation paths • Openings with consideration of the prevailing wind direction • Use of high windows
	Solar radiation shielding method	4	0.7	• Thermal barrier paint • Thermal barrier block
	Cooling system planning	3	0.75	• High-efficiency air conditioner (COP 4 or higher) + fan
Hot water supply	Hot water supply system planning	4	0.6	• CO2 heat pump water heater
Ventilation	Ventilation system planning	1	0.8	• Simplified ventilation system
Lighting	Daylight use	2	0.95	• LD and individual rooms
	Lighting Equipment Planning	3	0.7	• High efficiency, control, and design ingenuity
Appliances		2	0.6	• Efficient products + reduced standby power

---

4. EEC Unique Approaches in Residential Building, Okinawa

Adopted EE Methods and Estimation of Energy Saving Effects - Example of the Model House - (2)

Use	Standard value (GJ)	A	B	C	Design value (GJ)	Energy saving rate (%)	Note
Cooling	10.3	0.88	0.7	0.75	4.76	53.7	4.76 = 10.3 X 0.88 X 0.7 X 0.75
Hot water supply	13.8	0.6			8.28	40.0	8.28 = 13.8 X 0.6
Ventilation	3.1	0.8			2.48	20.0	2.48 = 3.1 x 0.8
Lighting	13.6	0.95	0.7		9.04	33.5	9.04 = 13.6 x 0.95 x 0.7
Appliances	21.4	0.6			12.84	40.0	12.84 = 21.4 x 0.6
Other	4.4				4.4	0	
Total	66.6				41.8	37.2	

Energy saving rate

---

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

● **Methods to shield sunshine**

- ✓ It is basic to keep the building skeleton close to the ambient temperature, not to heat it.
- ✓ The strong sunshine of Okinawa should be blocked outside.

Sunshine Shield in Urban Area

Sunshine Shield in Suburban Area

---

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

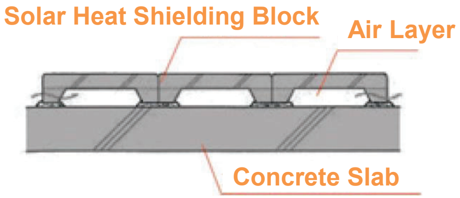
- ➢ Green roof

- ➢ Solar Heat Shielding Paint

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

- **Solar Heat Shielding Block**



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4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

- **HANA Block**

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4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

- **Wall-surface Greening**

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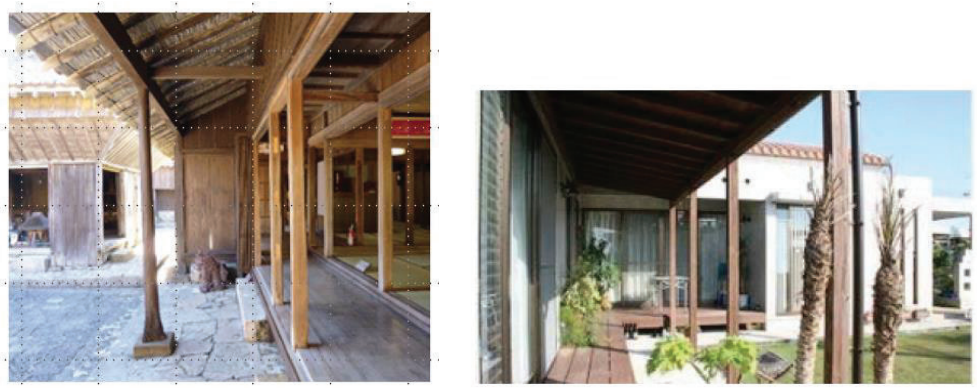
4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

- **AMAHAJI**



AMAHAJI is Okinawa's traditional eaves where customers are welcomed as there is not entrance in Okinawa's unique houses.

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

- ➢ **Eaves**

---

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

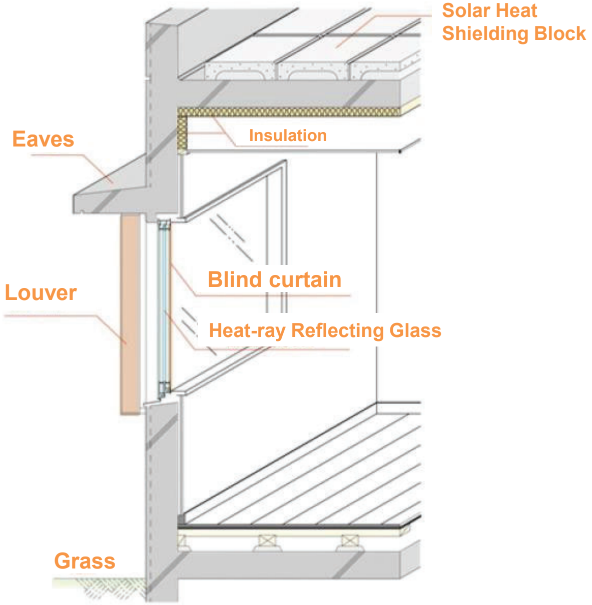
- ➢ **Louver**

---

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 1: Sunshine Shield

Example of Solar Heat Shielding Measures for Opening and Roof ⇨



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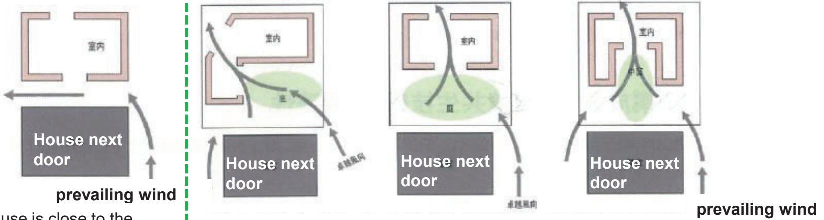
4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 2: Create Cool Breeze, Bring Cool Breeze

●**Methods to Create Cool Breeze, Bring Cool Breeze**

- ✓ **It is basic to bring cool breeze in rooms**
- ✓ **Ingenuity in building layout and window positions**
  - ➢ **In summer, cool breezes are drawn into the building from the south.**
  - ➢ **In winter, the wind from the north should be blocked.**



If the house is close to the house next door, the wind will blow parallel to the window. It will be difficult to have wind into the room.

Wind can be taken in effectively if a certain space (e.g. garden) is provided without being in close contact with the house next door.

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 2: Create Cool Breeze, Bring Cool Breeze

- ➢ **Windows at high position**

Windows at high position (from outside)

Windows at high position (from inside)

---

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 2: Create Cool Breeze, Bring Cool Breeze

- ➢ **Security-friendly small window**

---

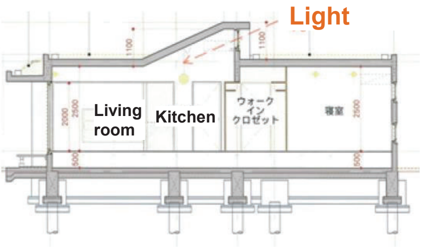
4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 3: Make good use of daylight

●**Methods to Make good use of daylight**

- ✓ It is basic to **allow light to enter a room while blocking direct sunshine.**
- ✓ Utilization of **inner court, high sidelight (windows on high position) and louver**, etc.

- ➢ **High Sidelight**



High Sidelight

High Sidelight (sunshine enters indirectly)

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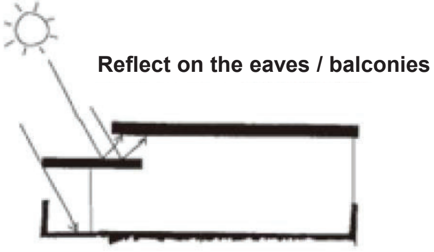
4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 3: Make good use of daylight

- ➢ **Introduction of light shelf concept**



- If the eaves on the south side of the building are made two-tiered, the eaves blocks direct sunshine from entering the window.
- The light reflected on the upper part of the eaves is diffusely reflected on the ceiling of the room and light up the back of the room.

4. EEC Unique Approaches in Residential Building, Okinawa

Key Points 3: Make good use of daylight

- **HANA Block**

Lighting with utilization of HANA block

Thank you very much for your kind attention !

Energy Efficiency & Conservation (EEC) Materiel
Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

- Energy Audit including Walk Through Survey -

Barbados, January 2023

Nippon Koei Co.
PADECO Co.

Contents

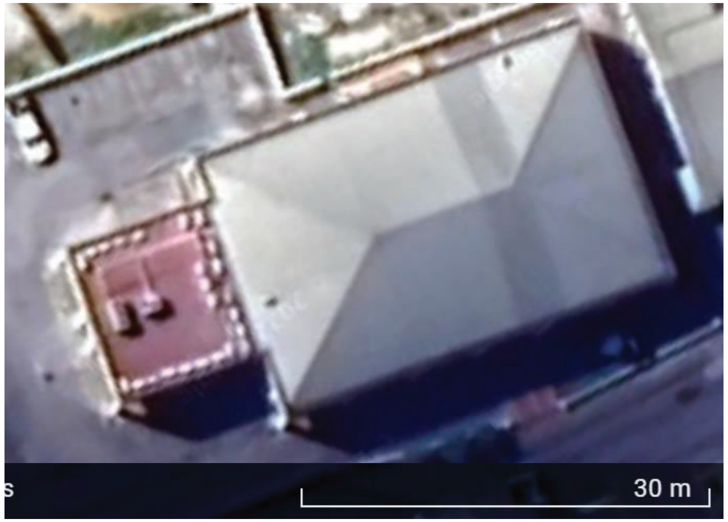
1. **Overview of MEB Building (energy division) in Bridgetown**
2. **Current Situation on Power Consumption**
3. **Comparison with Other Buildings in Tropical Weather**
4. **Examination of Energy Savings Opportunities**

Overview of MEB (energy division) Building in Bridgetown, Barbados (entrance)

Basic Data of the Building

Item	Basic Data
Number of floors	2
Floor area	966 m2
Building use	Government
Annual power consumption	167,635 kWh
Annual power consumption per floor area	174 kWh/m2

Bird 'eye view of MEB (energy division) Building



1. Overview of MEB Building (energy division) in Bridgetown, Barbados

Bird 'eye view of MEB (energy division) Building

Parking lot

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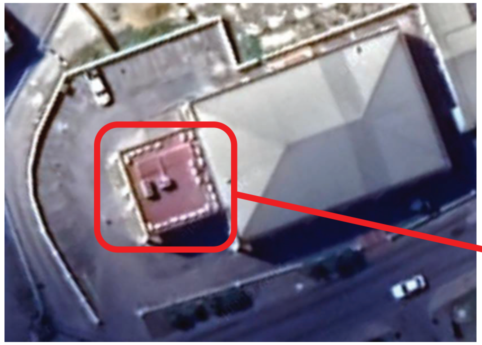
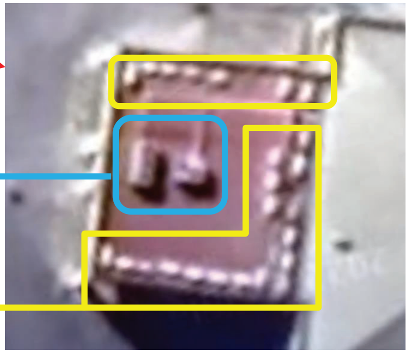
1. Overview of MEB Building (energy division) in Bridgetown, Barbados

Bird 'eye view of MEB (energy division) Building



More than 20 outdoor units of mini split air-conditioners and couple of outdoor units of central air-conditioners are observed.



Outdoor units of roof top air-conditioners

Outdoor units of mini split air-conditioners

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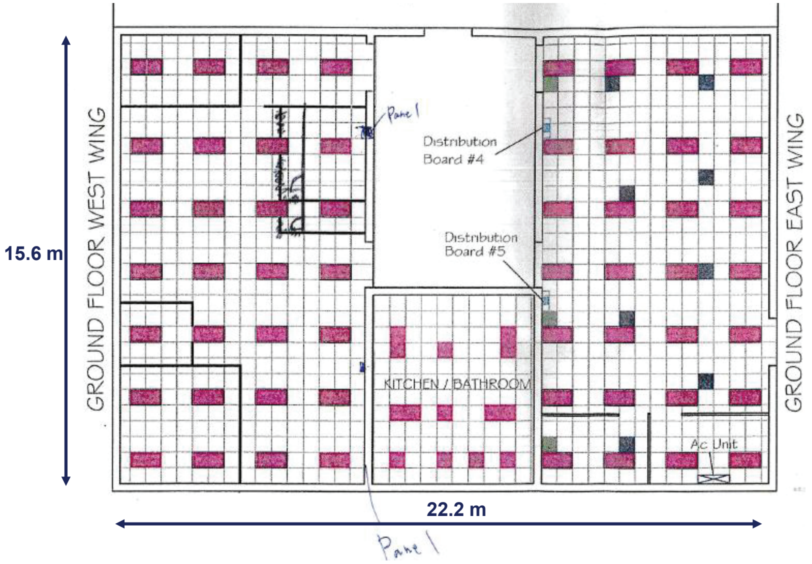
1. Overview of MEB Building (energy division) in Bridgetown, Barbados

- **Floor plan of the building (ground floor)**



Floor area of ground floor = 346 m2

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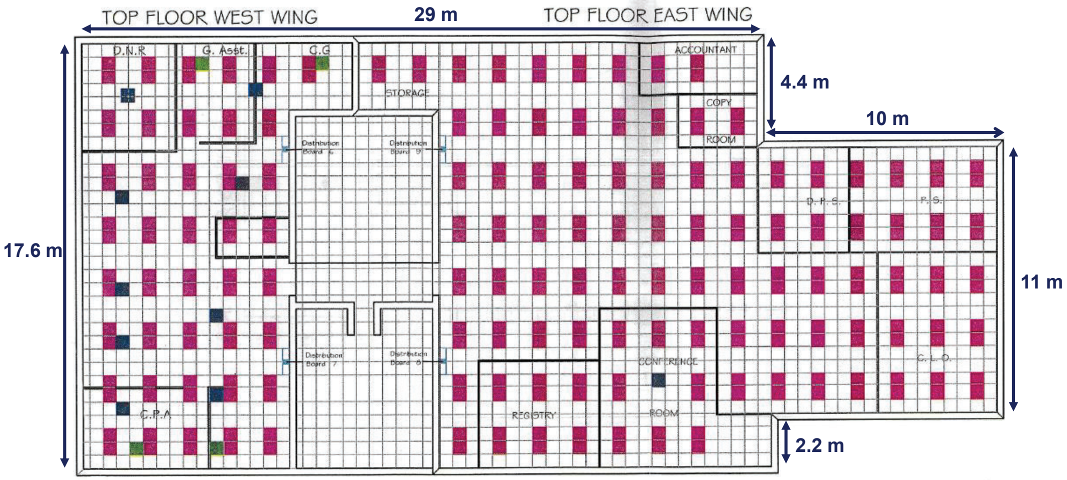
1. Overview of MEB Building (energy division) in Bridgetown, Barbados

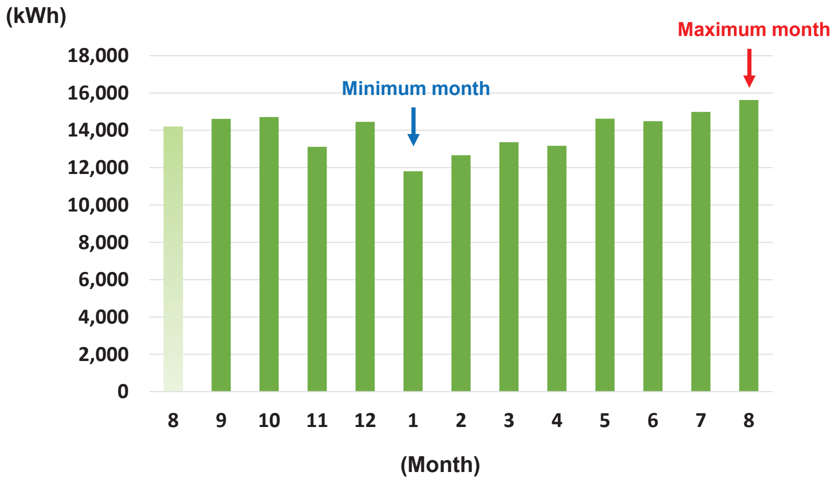
- **Floor plan of the building (top floor)**



Floor area of top floor = 620 m2 ➡ **Total floor area of the building = 966 m2**

2. Current Situation on Power Consumption

Monthly Power Consumption Trends at MEB Office Building (actual data, Aug.2021 - Aug.2022)



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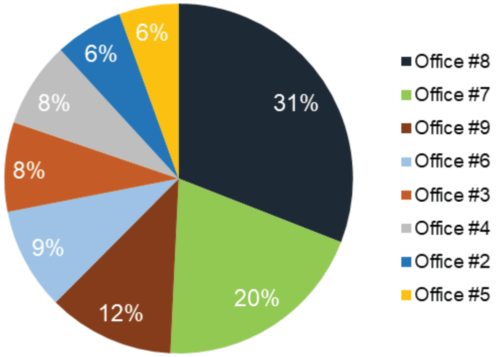
2. Current Situation on Power Consumption

Annual Power Consumption Share by Each Office (actual data, Sep.2021 - Aug.2022)



Office #8 is the largest power consumer and Office #8 and #7 share more than half of the total power consumption.

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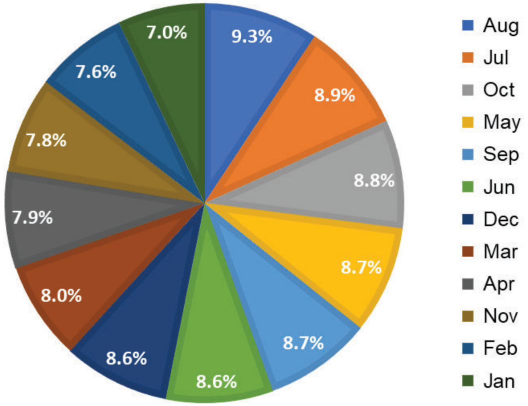
2. Current Situation on Power Consumption

Annual Power Consumption Share by Month (actual data, Sep.2021 - Aug.2022)



Power consumption in August is the largest month through a year. However, there is no significant difference by months.

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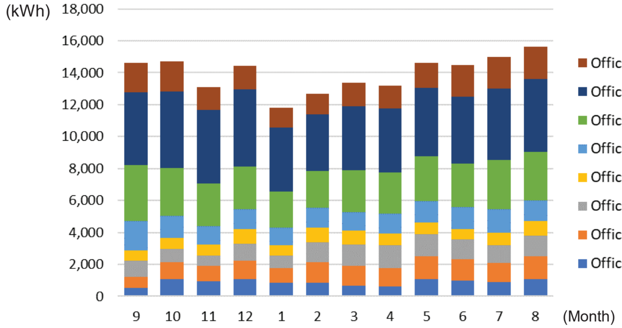
2. Current Situation on Power Consumption

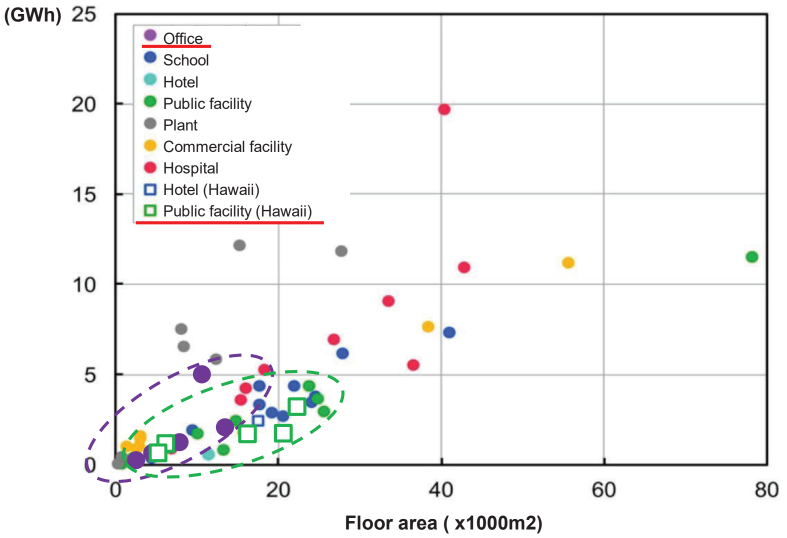
Power Consumption Trends at the Building (actual data, Sep.2021 - Aug.2022)



	9	10	11	12	1	2	3	4	5	6	7	8	TOTAL	AVE	MAX	MIN
Office #2	540	1,070	943	1,082	846	840	680	596	1,055	977	911	1,068	10,608	884	1,082	540
Office #3	695	1,055	978	1,136	929	1,275	1,209	1,186	1,455	1,342	1,166	1,442	13,868	1,156	1,455	695
Office #4	987	839	620	1,060	756	1,243	1,355	1,409	1,383	1,239	1,135	1,277	13,303	1,109	1,409	620
Office #5	650	692	677	928	676	958	851	758	707	661	767	927	9,252	771	958	650
Office #6	1,854	1,402	1,186	1,233	1,091	1,236	1,169	1,215	1,335	1,384	1,453	1,310	15,868	1,322	1,854	1,091
Office #7	3,506	2,993	2,655	2,662	2,268	2,302	2,615	2,611	2,819	2,725	3,090	3,008	33,254	2,771	3,506	2,268
Office #8	4,562	4,760	4,600	4,862	3,986	3,523	4,026	3,984	4,311	4,188	4,468	4,575	51,845	4,320	4,862	3,523
Office #9	1,820	1,905	1,456	1,490	1,252	1,290	1,463	1,410	1,560	1,973	1,998	2,020	19,637	1,636	2,020	1,252
Total	14,614	14,716	13,115	14,453	11,804	12,667	13,368	13,169	14,625	14,489	14,988	15,627	167,635	13,970	15,627	11,804

2. Comparison with Other Buildings in Tropical Weather

Annual Power Consumption Data (Okinawa & Hawaii)



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2. Comparison with Other Buildings in Tropical Weather

Summary Table of Annual Power Consumption per Floor Area

Location	Building use	Data number of buildings	Floor area (m2)	Annual power consumption (kWh)	Annual power consumption per floor area (kWh/m2)
Okinawa	Office	5	7,807 (average)	7,678,185	197
Hawaii	State gvrnt office 1	1	15,989	1,641,600	103
	State gvrnt office 2	1	5,442	618,920	114
	State gvrnt office 3	1	6,140	942,400	153
	State gvrnt office 4	1	22,146	3,184,800	144
	State gvrnt office 5	1	20,688	1,828,400	88
Barbados	MEB office	1	966	167,635	174

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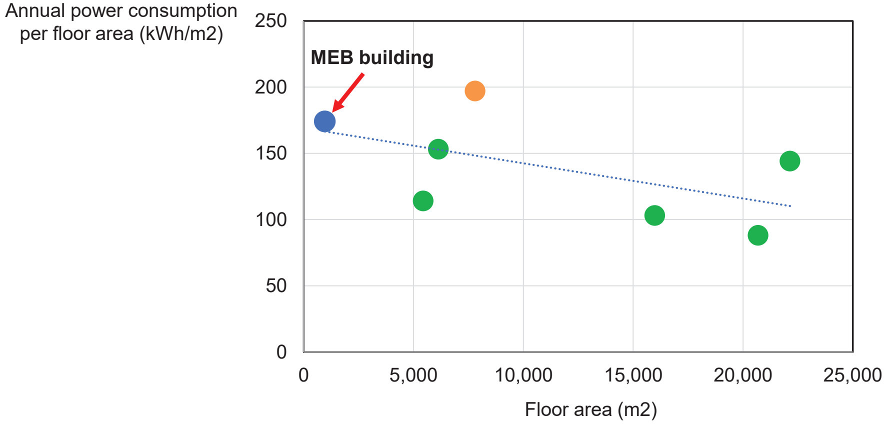
2. Comparison with Other Buildings in Tropical Weather

Graph of Annual Power Consumption per Floor Area



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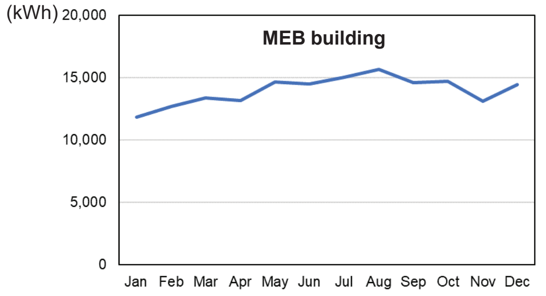
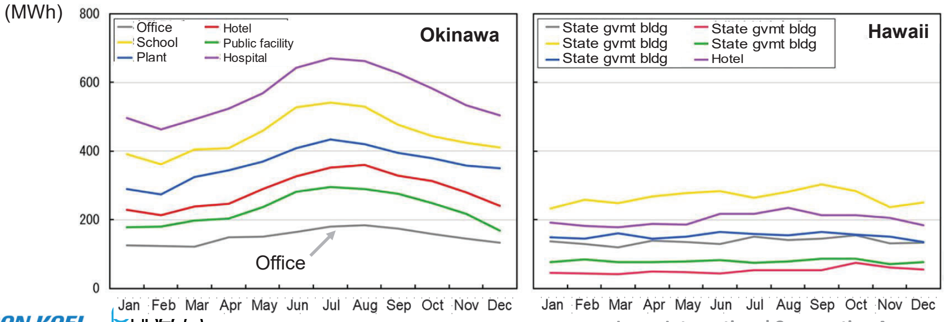
2. Comparison with Other Buildings in Tropical Weather

Monthly Power Consumption

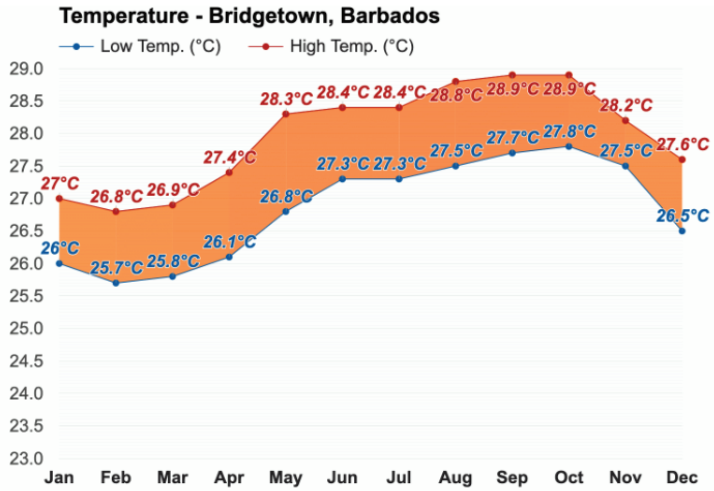
- A bit larger difference has been observed in MEB building by season than those in Okinawa and Hawaii.





2. Comparison with Other Buildings in Tropical Weather

Average Temperature Bridgetown, Barbados



Source: Weather Atlas

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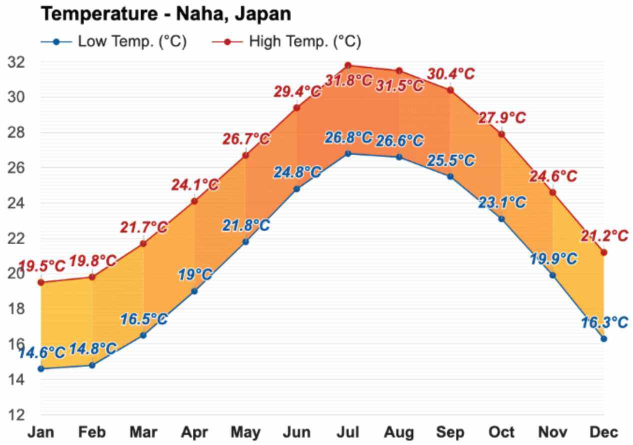
2. Comparison with Other Buildings in Tropical Weather

Average Temperature Naha (Okinawa), Japan



Source: Weather Atlas

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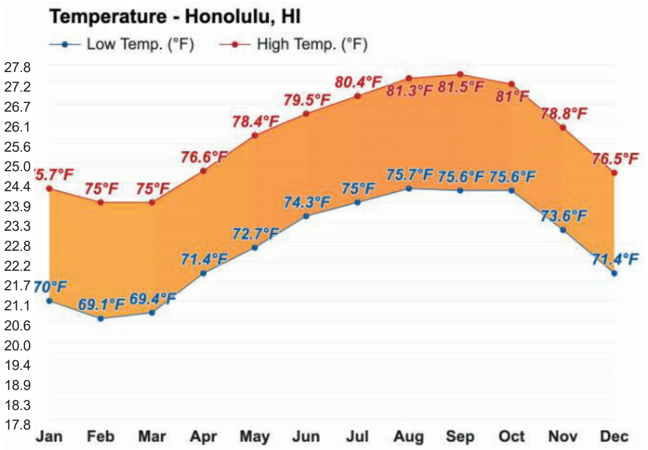
2. Comparison with Other Buildings in Tropical Weather

Average Temperature Honolulu (Hawaii), USA



Source: Weather Atlas

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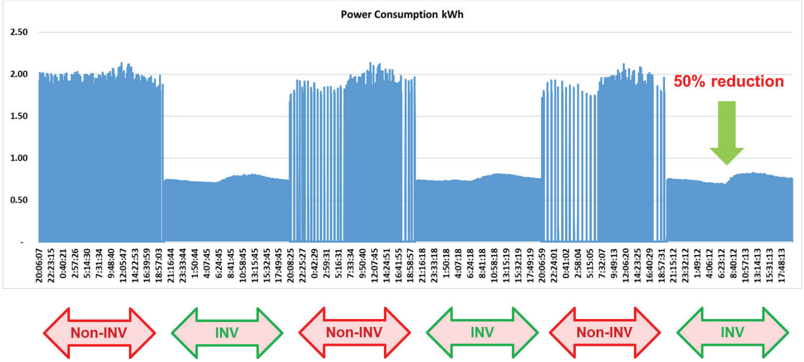
3. Examination of Energy Savings Opportunities

- ☐ **Examination of energy savings by adopting efficient air conditioning technologies and approaches**

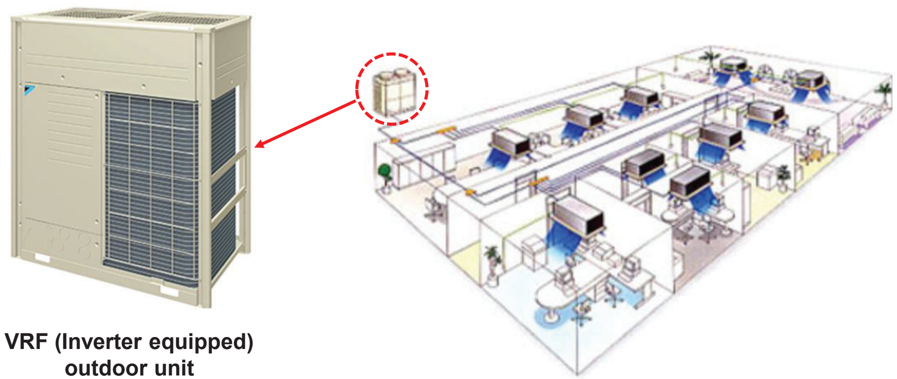
  (i-a) Adoption of Inverter mini split air conditioners
  - ➢ **Reduction of 50% power consumption**

Ref: Results of power consumption measurement of Inverter vs Non-Inverter AC



3. Examination of Energy Savings Opportunities

(i-b) Adoption of Variable Refrigerant Flow (VRF, Inverter always equipped) as an alternative of roof top air conditioners (Non-Inverter)



VRF (Inverter equipped) outdoor unit

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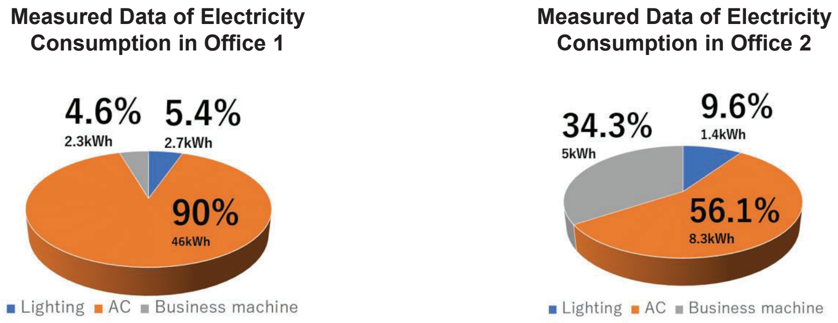
3. Examination of Energy Savings Opportunities

Ref: Measured power consumption data in 2 office rooms on Jun.12.2022 (24 hours, highest temp: 32.2 °C, lowest temp: 26.1 °C)



Note: All lighting equipment is LED.

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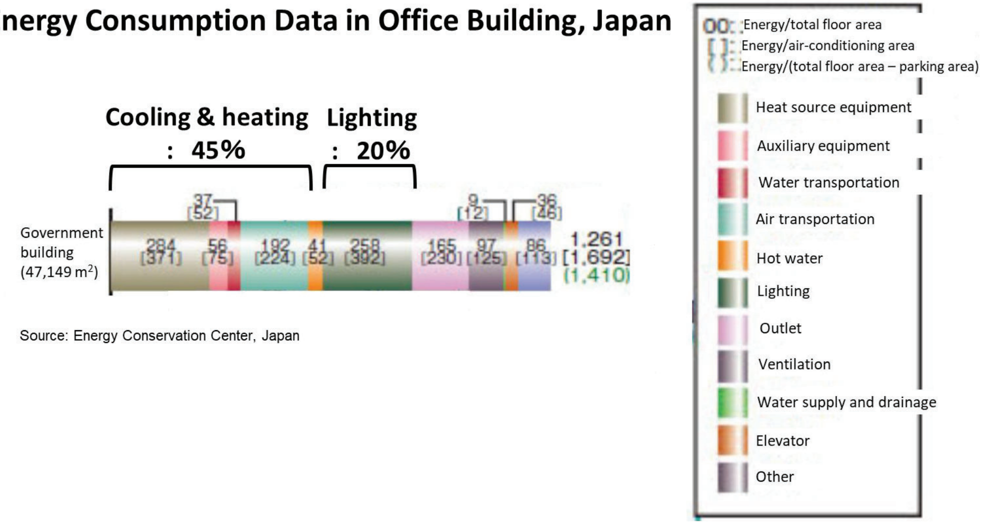
3. Examination of Energy Savings Opportunities

Ref:

Energy Consumption Data in Office Building, Japan



Source: Energy Conservation Center, Japan

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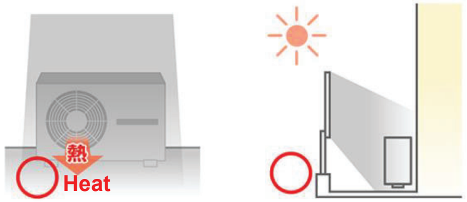
3. Examination of Energy Savings Opportunities

(ii) Heat shielding of outdoor units

- **10 % power reduction was observed by heat shielding**

← **Construction of heat shielding**

	Room A inv [kWh]	Room B inv [kWh]	Effect of EE&C [%]
Jan.14	150	164	-9%
Jan.16	207	202	3%
Jan.20	93	86	8%
Jan.22	115	84	27%
Jan.28	146	122	16%
Jan.30	129	116	10%
Feb.3	148	141	4%
Feb.5	119	107	10%
Feb.9	152	132	13%
Feb.11	129	100	22%
Feb.13	126	103	18%
Feb.17	108	108	1%
ave.	135	122	10%



Source: "Data collection survey on energy efficiency in the D.R. final report" (Jan. 2016, JICA)

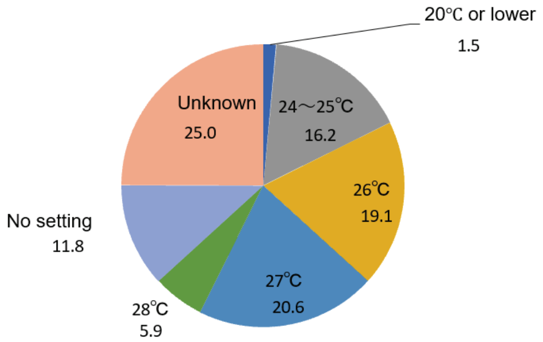
3. Examination of Energy Savings Opportunities

(iii) Lower temperature setting of air conditioner

- **10 % power reduction by setting 1 ºC higher temperature**

Note: 13 % of power reduction with setting 1 ºC higher temperature (by Ministry of Environment)

Ref: Setting temperature of air conditioner in Okinawa



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3. Examination of Energy Savings Opportunities

❑ Results of Examination (1) : power & cost savings

		Present situation		
Annual power consumption for cooling	kWh	83,818		
Power consumption by INV AC	kWh	27,939		
Power consumption by Non-INV AC	kWh	55,879		
Cooling loads by INV AC	kWh	139,697		
Cooling loads by Non-INV AC	kWh	139,697		
Total cooling loads	kWh	279,393		
		EE measure (i)	EE measure (i)+(ii)	EE measure (i)+(ii)+(iii)
Power consumption after EE measures	kWh	55,879	50,291	45,262
Power savings per year	kWh	27,939	33,527	38,556
Power saving ratio	%	33	40	46
Cost savings per year	$	17,881	21,457	24,676
Annual power consumption per floor area	kWh/m2	145	139	134

Assumption:
- **50% of ACs are INVERTER at present**
- **Efficiency of INV AC = 5 in kW/kW**
- **Efficiency of Non-INV AC = 2.5 in kW/kW**

Note: Unit rate of power (customer charge + demand charge + energy charge + fuel charge) = $0.64/kWh

---

3. Examination of Energy Savings Opportunities

❑ Results of Examination (2) : Investment in INVERTER ACs

Estimation of cooling capacity of existing Non-INV ACs

Item	Unit	Value
Total power capacity of building	kVA	85
Power factor	%	90
Total power demand of building	kW	76.5
Power demand of ACs	kW	38.3
Power demand of INV ACs	kW	12.8
Power demand of Non-INV ACs	kW	25.5
Cooling capacity of Non-INV ACs	**kW**	**63.8**

Item	Unit	Value
INV AC cost (5.27 kW in cooling capacity)	$	1,700
Necessary number of AC	Unit	13
Total investment cost of INV AC	**$**	**22,100**

Note: AC market survey conducted in Barbados by JET in 2019

Simple payback year = 22,100 / 17,881 = 1.2 year

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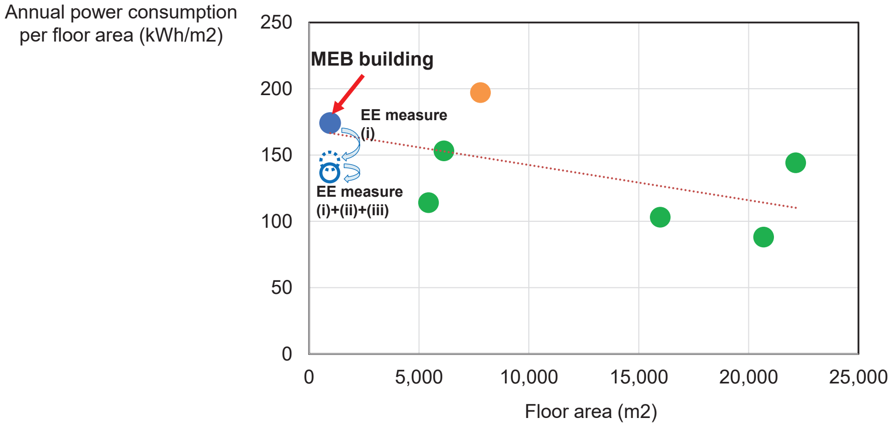
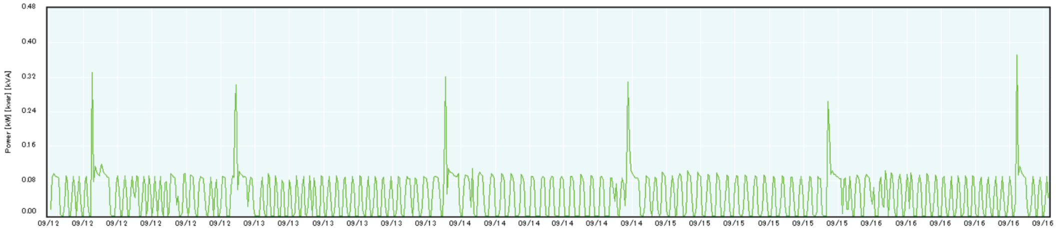
3. Examination of Energy Savings Opportunities

Graph of Annual Power Consumption per Floor Area with EE Measures



4. References: Power Consumption Data of Refrigerator

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



➡ **Existing refrigerator (Non-INVERTER) can be replaced with efficient one with INVERTER**

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4. References: Illuminance standards for offices

Illuminance standards for offices in Japan (JIS Z 9110)

Illuminance (lux)	Place	Work
2000		—
1500		● design ● drawing ● type ● calculation ● keypunch
1000	office (a)(*) , sales room, design room, entrance hall (daytime)(**)	
750		

(Note)
(*) In the event that the office is used for **detailed visual work** or where daylight makes the room feel dark inside and bright outside the window, (a) should be selected.
(**) In the entrance hall, the illuminance should be high because the interior of the hall appears dark when the eye is applying the tens of thousands of lux from outdoor natural light during the day. The entrance hall (nighttime) and (daytime) may be adjusted with staged flashing.

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4. References: Illuminance standards for offices

Illuminance (lux)	Place			Work
750				
500	—	Office (b), boardroom, conference room, printing room, computer room, control room, clinic room • switchboards and instrument panels in electrical and machine rooms, etc. • reception (desk)		—
300	reception room, waiting room, dining room, cooking room, recreation room, guard room, entrance hall (at night), elevator hall	warehouse, electrical room, auditorium, machine room, miscellaneous workroom, elevator	—	
200	—		washing area, hot water heating area, bathrooms, corridors, stairs, lavatories	
150	coffee room, rest room, lodging room, changing rooms, storage, entrance (porch)			
100			—	
75				
50	indoor emergency staircase			
30				

Source: JET based on EEC guidebook for building, 2022 (Energy Efficiency and Conservation Center of Japan)

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4. References: EEC Check Items

EEC Promotion System

- ✓ Do you have a mechanism for continuous EEC (e.g. EEC committee, etc.)?
- ✓ Are PDCA cycles for EEC activities being implemented with management participation?
- ✓ Have you designated a person or leader responsible for promoting EEC?
- ✓ Have you set EEC targets?
- ✓ Are energy consumption statuses posted for employees to see?
- ✓ Have you established a policy and implementation plan for EEC measures?
- ✓ Do you conduct personnel training and EEC awareness activities?
- ✓ Do you have the time and budget for EEC efforts?

Source: JET based on EEC guidebook for building, 2022 (Energy Conservation Center of Japan)

4. References: EEC Check Items

Measurement, Recording and Maintenance

- ✓ Do you maintain equipment ledger, drawings and other documents?
- ✓ Have you identified equipment that should be intensively managed for EEC?
- ✓ Do you have operation records (daily, monthly, etc.) for major facilities?
- ✓ Have you set values to be managed and their ranges to check operating conditions?
- ✓ Do you perform daily inspection and maintenance of equipment?
- ✓ Are there management standards for major facilities (air conditioning, ventilation, lighting, production facilities, etc.)?
- ✓ Do you perform periodic calibration and inspection of measuring instruments?
- ✓ Are filters, strainers, etc. cleaned and replaced regularly?
- ✓ Do you conduct periodic repairs and leak inspections (water, steam, compressed air, etc.) of piping, etc.?

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4. References: EEC Check Items

Energy Management

- ✓ Do you tabulate (graphs, etc.) and visualize energy consumption by month/year?
- ✓ Is energy consumption measured and recorded by type and use, and constantly monitored?
- ✓ Do you measure hourly power usage and manage peak power?
- ✓ Do you analyze energy consumption taking into account outside temperatures and other factors?

Management of Energy Intensity, etc.

- ✓ Have you calculated a common energy unit cost for the office (e.g. $/kWh, $/litre, $/m3)?
- ✓ Do you manage intensity ("energy use/floor area", "energy cost/floor area", etc.)?
- ✓ Do you manage energy intensity / expenses by each department?

Management Cycle -PDCA-

- ✓ Are you reviewing your EEC targets?
- ✓ Are you verifying the effectiveness of improvement measures implemented to date?
- ✓ Are you reviewing your plans for implementing future facility improvements and measures?

Source: JET based on EEC guidebook for building, 2022 (Energy Efficiency and Conservation Center of Japan)

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4. References: EEC Check Items

Improvements of Air Conditioning Efficiency

- ✓ Are outdoor units shaded and watered during the summer months?
- ✓ Are window blinds utilized to reduce heat gain through windows?
- ✓ Are filters cleaned regularly?
- ✓ Are shading films attached to window glass, and has plantings near windows implemented?
- ✓ Is air introduced into the room at night when the outside temperature is cooler (**night purge**)?
- ✓ Can we reduce the size of the air-conditioned area (partitions, high ceiling linings, etc.)
- ✓ Are spot coolers used when the air-conditioned area is large and the number of people is small?
- ✓ Are air-conditioned areas blocking drafts?
- ✓ Are you updating to high-efficiency air conditioners?

---

4. References: EEC Check Items

Lighting Fixture Management and EEC

- ✓ Is the illuminance standard for each room determined and controlled?
- ✓ Are window lights turned off (using daylight)?
- ✓ Are lights turned off when not needed, such as in unoccupied rooms or during lunch breaks?
- ✓ Do you adjust the lighting hours and number of exterior lights according to the hours of daylight?
- ✓ Have you cleaned the lamps and replaced old lamps?
- ✓ Are motion sensors used in restrooms, warehouses, etc.?
- ✓ Is the installation position (height and placement) of the lighting fixture appropriate for the required brightness?
- ✓ Are lighting circuits subdivided so that lights can be turned off in unoccupied areas, etc.?
- ✓ Are lights dimmed or turned off by automatic control?
- ✓ Are you updating to LED lighting?
- ✓ Have you considered task ambient lighting (all room lighting => overall + hand lighting)?

Thank you very much for your kind attention !

Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

Information Sharing Material
- Energy Efficiency Policy in Japan -

Barbados, January 2023

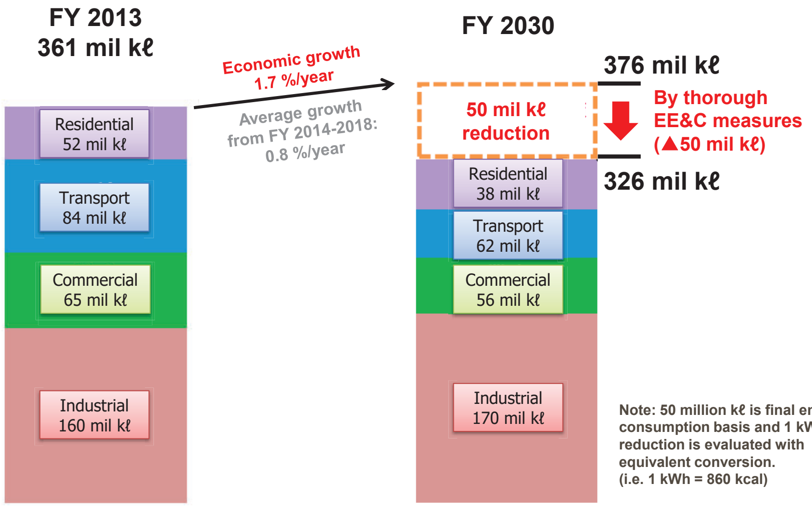
Nippon Koei Co., Ltd.
PADECO Co., Ltd.

Energy Efficiency - Energy Policy incl. EE&C in Japan -

Year	Policy
2002	**Basic Act on Energy Policy**
2003-2014	**Released Basic Energy Policies 4 times in 2003, 2007, 2010, 2014**
2015	**Long-term outlook for energy demand and supply** ●**Energy Mix** in 2030 (ratio of power sources): RE: 22-24%, Nuclear: 20-22%
2018	**5th Basic Energy Policy** ●2030: To achieve Energy Mix surely ●2050: Challenge to energy conversion and decarbonization
Oct.2020	**Prime Minister's speech** ●Greenhouse gas emissions to zero by 2050 ●Establishment of a stable energy supply by thorough EE as well as introducing RE to the maximum extent.

Energy Efficiency - EE&C Targets in Energy Mix -

EE&C Target for 2030 in Long-term Outlook for Energy Demand and Supply (energy mix)



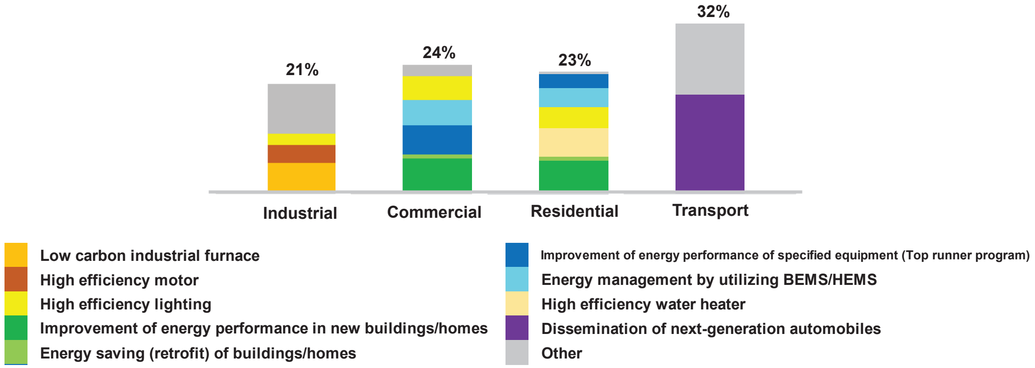
Note: 50 million kℓ is final energy consumption basis and 1 kWh reduction is evaluated with equivalent conversion. (i.e. 1 kWh = 860 kcal)

Source: JET based on the Ministry of Economy, Trade and Industry's (METI) material. Mar.2021

Energy Efficiency - EE&C Targets in Energy Mix -

- **EE&C 2030 targets were developed sector by sector as well as technology by technology (bottom-up approach)**

EE&C 2030 Targets by Sector (in Energy Mix)



Energy Efficiency - EE&C Targets in Energy Mix -

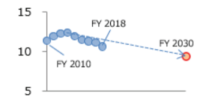
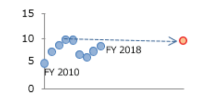
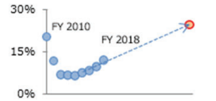
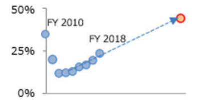
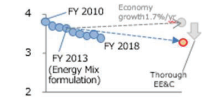
- **Various EE&C technologies / approaches could be applied across the sectors, and these exceeded 40% of the energy-saving target amount.**

Cross Sectorial EE&C Approaches (in Energy Mix targets)

(%)

	Industrial	Commercial	Residential	Total
🟩 Improvement of energy performance in new buildings/homes		6.6	6.2	12.8
🟨 High efficiency lighting	2.1	4.5	4	10.6
🟦 Energy management by utilizing BEMS / HEMS		4.7	3.5	8.2
🟦 Improvement of energy performance of specified equipment (Top runner program)		5.5	2.7	8.2
🟩 Energy saving (retrofit) of buildings/homes		0.8	0.8	1.6
Total	2.1	22.1	17.2	41.4

Energy Efficiency - Progress of Energy Mix -

	FY 2018 results	Targets in FY 2030	Progress
1. Energy-originated CO_2 emissions (total GHG emissions)	1.06 billion Ton (GHG:1.24 billion Ton)	0.93 billion Ton (GHG:1.04 billion Ton)	
2. Electricity cost (fuel cost + FIT purchase cost)	8.5 Tera Yen • Fuel cost : 5.7 Tera Yen (Crude oil cost: 63$/bbl) • FIT cost : 2.8 Tera Yen	9.2~9.5 Tera Yen • Fuel cost : 5.3 Tera Yen (Crude oil cost: 128$/bbl) • FIT cost : 3.7~4.0 Tera Yen	
3. Energy self-sufficiency rate (whole primary energy)	12%	24%	
4. Zero emission power supply ratio	23% • RE: 17% • Nuclear: 6%	44% • RE: 22~24% • Nuclear: 22~20%	
5. EE&C (final energy consumption in crude oil equivalent)	339 mil kℓ • Commercial/industry : 210 • Residential : 50 • Transport:80	326 mil kℓ • Commercial/industry : 230 • Residential : 40 • Transport:60	

Source: JET based on METI's material. Jul.2020

Energy Efficiency - Energy Efficiency & Conservation Policy in Japan -

- **Energy savings achieved in FY 2018 = ▲13.4 mil kℓ**
  - **Progress rate = 26.6%   # Average progress rate = 33.3% (2013-2030)**

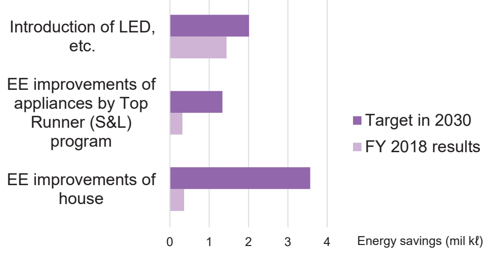
Progress of Energy Savings by Sector

Sector	FY 2018 results			
	Energy savings	Progress rate	Progress rate by EE&C measure	
Residential	▲2.9 mil kℓ	24.9%	• Introduction of LED, etc. • EE improvements of appliances • EE improvements of house	72% 24% 10%
Commercial	▲3.3 mil kℓ	27.1%	• Introduction of LED, etc. • Energy management by BEMS, etc. • Introduction of efficient refrigerator -freezer and router / server, etc.	63% 25% 18%
Industrial	▲2.8 mil kℓ	26.3%	• Introduction of LED, etc. • Energy management by FEMS, etc. • Introduction of efficient motor • Introduction of industrial heat pump	66% 18% 9% 8%
Transport	▲4.4 mil kℓ	27.6%	• Other measures in transport sector • Diffusion of next generation vehicle	47% 14%

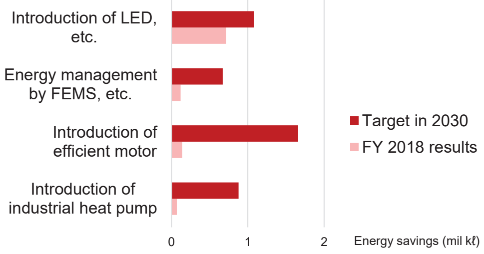
Source: JET based on METI's material, Mar.2021

Energy Efficiency - Energy Efficiency & Conservation Policy in Japan -

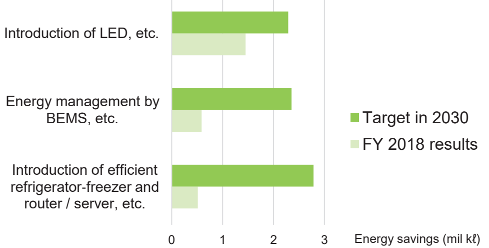
Progress of Major EE&C Measures in Residential Sector



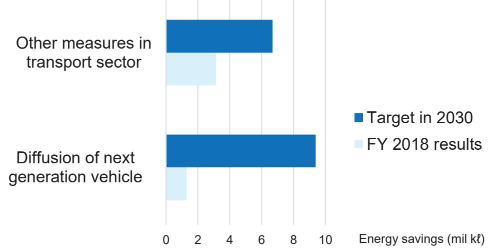
Progress of Major EE&C Measures in Industrial Sector



Progress of Major EE&C Measures in Commercial Sector



Progress of Major EE&C Measures in Transport Sector

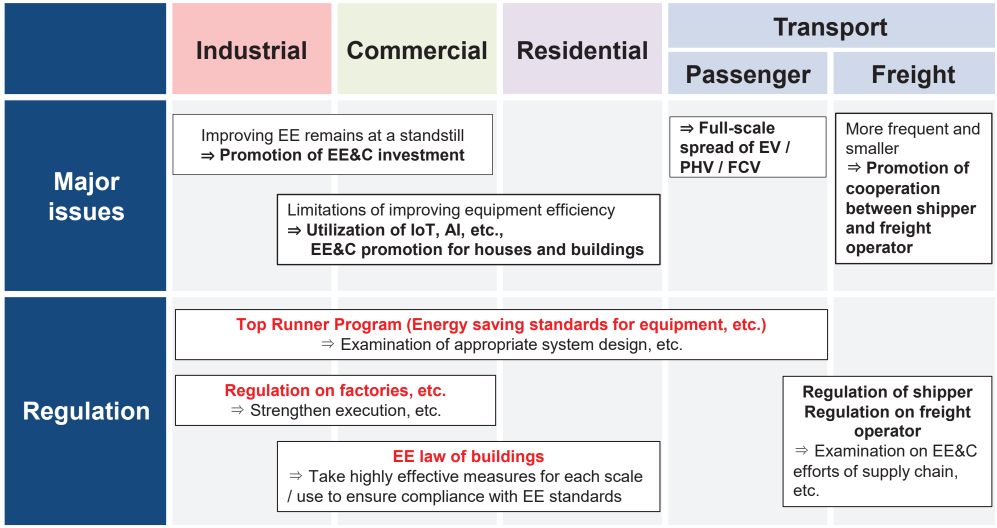


NIPPON KOEI PADECO

Source: JET based on METI's material, Mar.2021

Energy Efficiency - Energy Efficiency & Conservation Policy in Japan -

Major Issues and EE&C Regulations by Sector



Industrial | Commercial | Residential | Transport (Passenger, Freight)

Major issues

- Improving EE remains at a standstill **⇒ Promotion of EE&C investment**
- Limitations of improving equipment efficiency **⇒ Utilization of IoT, AI, etc., EE&C promotion for houses and buildings**
- **⇒ Full-scale spread of EV / PHV / FCV**
- More frequent and smaller **⇒ Promotion of cooperation between shipper and freight operator**

Regulation

- **Top Runner Program (Energy saving standards for equipment, etc.)** ⇒ Examination of appropriate system design, etc.
- **Regulation on factories, etc.** ⇒ Strengthen execution, etc.
- **EE law of buildings** ⇒ Take highly effective measures for each scale / use to ensure compliance with EE standards
- **Regulation of shipper Regulation on freight operator** ⇒ Examination on EE&C efforts of supply chain, etc.

NIPPON KOEI PADECO

Source: JET based on METI's material, Mar.2021

Energy Efficiency - Energy Efficiency & Conservation Policy in Japan -

- **Top runner program started in 1998 which was defined in EE law (establishment: 1979)**
  - **Standards for performance of appliances, etc. are set at the top runner performance in that year.**
  - **Other products (runner-up, etc.) are required to catch up and qualify the top runner level in designated duration.**

Current Target Products of Top Runner Program (32 products)

Passenger Vehicles	Video Tape Recorders	Vending Machines	Printers
Freight Vehicles	Electric Refrigerators	Transformers	Heat Pump Water Heaters
Air Conditioners	Electric Freezers	Electric Rice Cookers	AC Motors
TV Sets	Space Heaters (Gas/Oil)	Microwave Ovens	Bulbs
Copying Machines	Gas Cooking Appliances	DVD Recorders	Refrigerating Showcases
Computers	Gas Water Heater	Routers	Insulation Materials
Magnetic Disk Units	Oil Water Heaters	Switches	Sashs
Lighting equipment	Electric Toilet Seats	Multi-function Printers	Double Glazing

Source: JET based on METI's homepage

NIPPON KOEI PADECO

Thank you very much for your kind attention !

NIPPON KOEI PADECO

Energy Efficiency & Conservation (EEC) Materiel
Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

Information Sharing Material - Energy Audit Best Practice at Aquarium & Amusement Park in Japan -

Barbados, January 2023

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

Outline of the Aquarium & Amusement Park

- ✓ The company was Established in 1990.
- ✓ The amusement park was opened in 1993.
- ✓ Annual number of visitors; 4 to 5 million (Top 5 in Japan).
- ✓ The park is type-1 designated energy management factory under "the law concerning the Rational Use of Energy".

◆ Three-story aquarium with thousands of fish which is one of the largest in Japan.
⇒ A lot of cold energy & heat (chilled & hot water) are necessary to maintain water temperature in water tanks constant all year around as well as space heating & cooling for visitors.

◆ Other attractions
- ➢ Vertical fall amusement (BLUE FALL) with 107 meters high.
- ➢ Japan's first roller coaster that swings out over the ocean.
- ➢ World famous Merry-Go-Round with thousands of lights glittering.

Outline of the Aquarium & Amusement Park

---

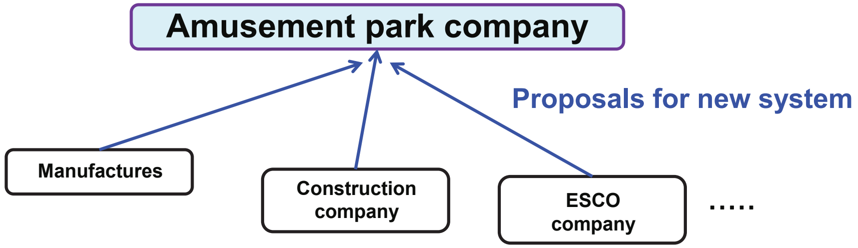
4 WANTS in the Company

1. Cut energy cost
2. Improve the efficiency of maintenance and operation of facilities
3. Promote further energy savings and environmental measures
4. Asset-light business operation by reducing investments

Two major backgrounds in Japan

- ✓ Increasing interests in energy savings by the law concerning the Rational Use of Energy.
- ✓ Increasing interests in CO_2 emissions reduction.

Toward the Realization of 4 WANTS



Amusement park company

Proposals for new system

Manufactures

Construction company

ESCO company

.....

- Several companies proposed new system.
- Amusement park company itself analyzed and examined each proposal for more than a year.
- In the process of examination, the responsible person was appointed by the company played an important role on;
  - ➢ Providing suggestion to management from technical angle.
  - ➢ Verification of various figures indicated in proposals such as consumption of electric power, city gas, water.

Key Point 1 for Realization of 4 WANTS

1. Reduction of maintenance fee for co-generation
2. High efficiency system which contributes to energy savings and CO_2 reductions
3. Simple system toward the realization of efficient operation

⬇

Stop operation of co-gen (2 units) and introduction of high efficiency air-source heat pumps instead.

➢ In case of air-source HPs, cooling water necessary in the existing system will not become necessary by air-source HPs.

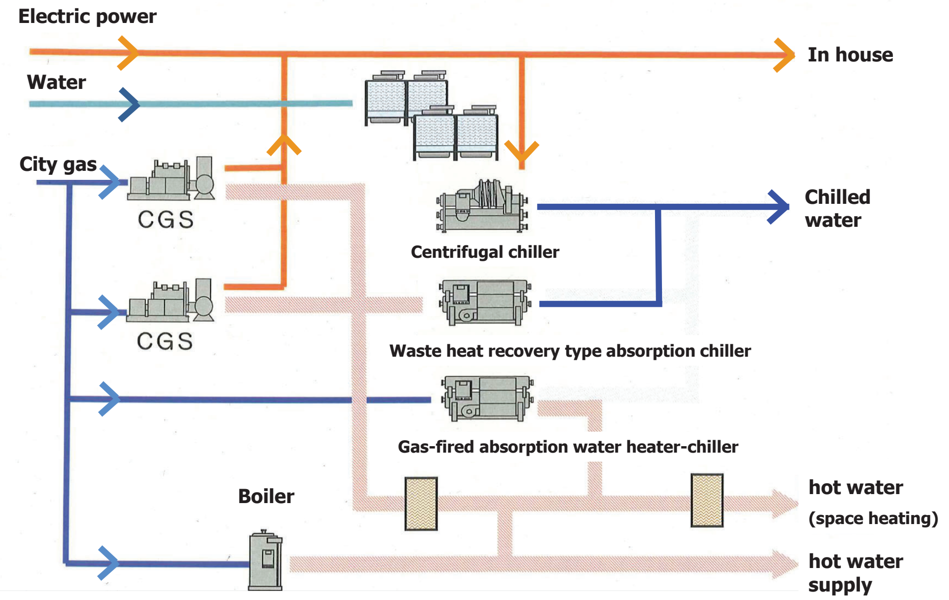
Key Point 2 for Realization of 4 WANTS

Adoption of high efficiency heat pumps

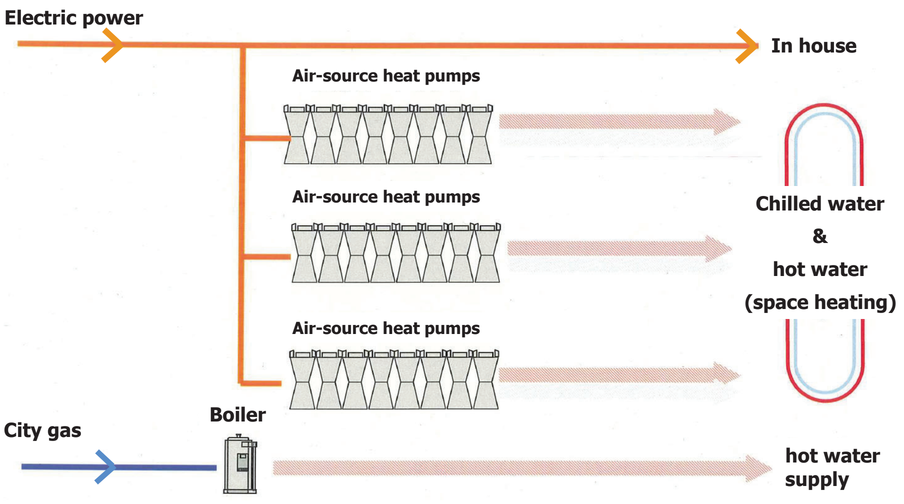
- ➢ The industry's first large-scale heat pumps with high efficiency.
- ➢ This heat pump won the Minister of Economy, Trade and Industry Prize at the Energy Conservation Awards.

Picture of high efficiency heat pumps

System Comparison – existing system -

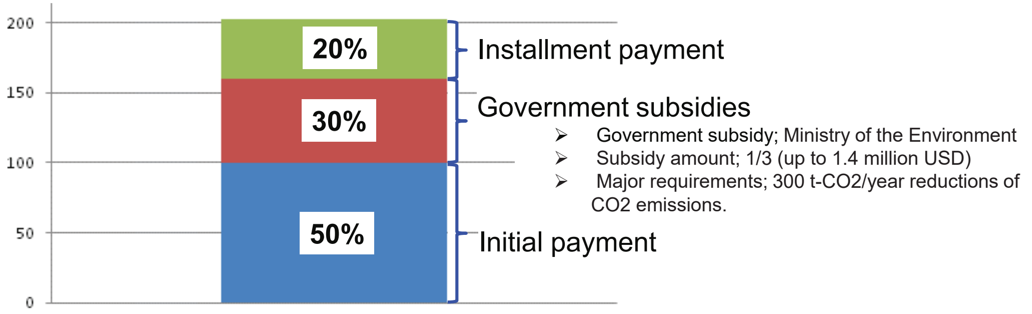


System Comparison – renewed system -



New system is more simple.
⇒ Needs no water and less space.

Construction Cost

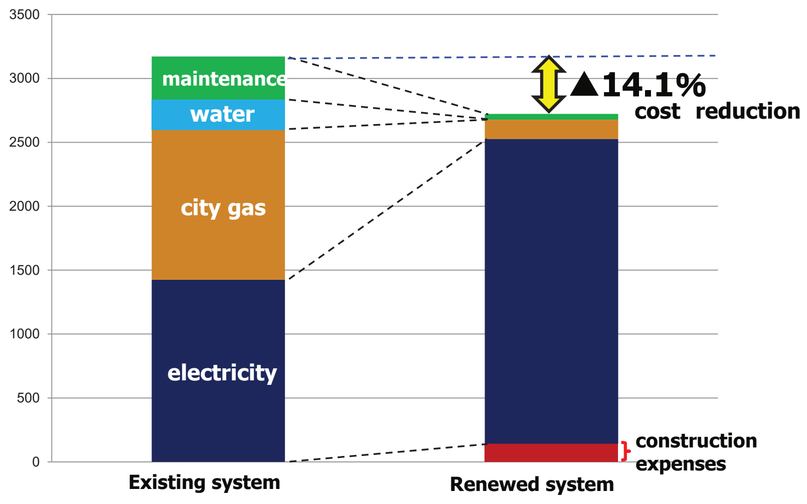


- Government subsidy; Ministry of the Environment
- Subsidy amount; 1/3 (up to 1.4 million USD)
- Major requirements; 300 t-CO2/year reductions of CO2 emissions.

Composition on payment for construction cost

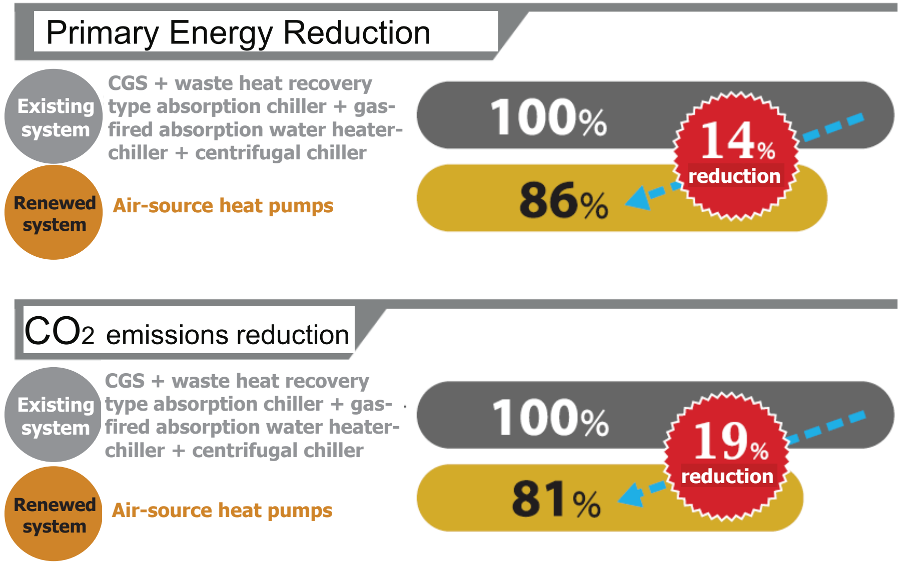
- 10% out of total cost are interests.
- Term of installment payment is 15 yrs.

Comparison of Life Cycle Cost



Comparison of LCC (15yrs)

Primary Energy & CO_2 Emissions Reduction



Primary Energy Reduction

Existing system CGS + waste heat recovery type absorption chiller + gas-fired absorption water heater-chiller + centrifugal chiller

Renewed system Air-source heat pumps

CO_2 emissions reduction

Existing system CGS + waste heat recovery type absorption chiller + gas-fired absorption water heater-chiller + centrifugal chiller

Renewed system Air-source heat pumps

Through 2 Years Operation

- ■ **Operational cost reduction**

➡ **Approx. 70 million JPY (0.5 million USD) was reduced annually.**

⬇

Construction cost was already recovered within 2 years.

- ■ **CO_2 emissions reductions**

  - ➢ **Obligated amounts of reductions by MOE**
    = Approx. 600 t-CO_2/year

➡ **Approx. 1,800 t-CO_2 was reduced within 2 years.**

⬇

CO_2 emissions clears the designated level by MOE.

Thank you very much for your kind attention !

The Technical Cooperation Project to Promote
Energy Efficiency in Caribbean Countries

Organizational Management

Energy Efficiency Workshop

January 2023

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

Organizational Management

Organizational structure
- How to make organization
- Acquisitions, mergers, divestitures
- Decision making process…

Human resource management
- Recruitment of employees
- Trainings
- Assessment of employees …

Organizational management

Organizational strategy
- Set visions, targets, plans
- Budgeting, finance, accounting
- How to improve sales & profits…

Organizational communication
- How to keep good relationship
- Internal & external communication
- Formal or informal communication
- Negotiations
- Information sharing …

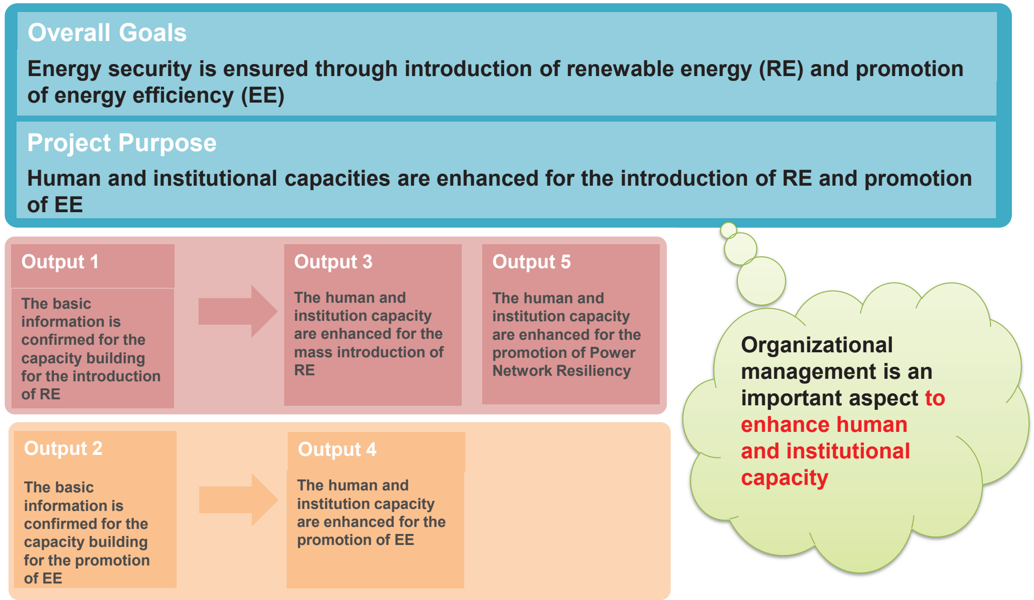
Essential functions of organization

By Chester I. Barnard

1. **Common purpose**
2. **Willingness to cooperate***Incentive and Persuasion
3. **Communication***to share common purpose/make organizational activities effective and efficient.

Review of JICA project & baseline survey

JICA project design & outputs



Overall Goals

Energy security is ensured through introduction of renewable energy (RE) and promotion of energy efficiency (EE)

Project Purpose

Human and institutional capacities are enhanced for the introduction of RE and promotion of EE

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 5

The human and institution capacity are enhanced for the promotion of Power Network Resiliency

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

Organizational management is an important aspect to enhance human and institutional capacity

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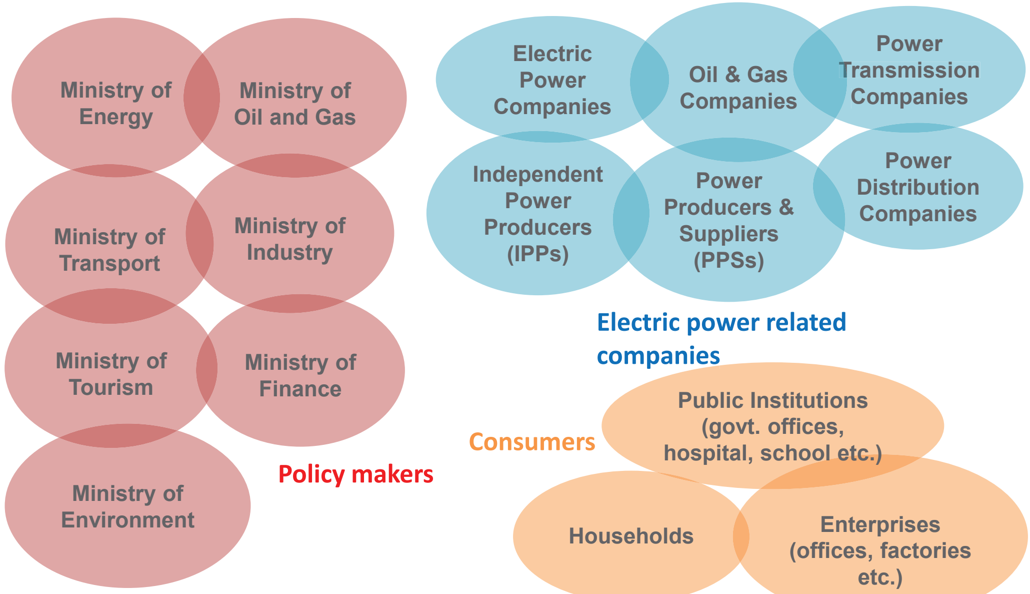
Various stakeholders in energy sector

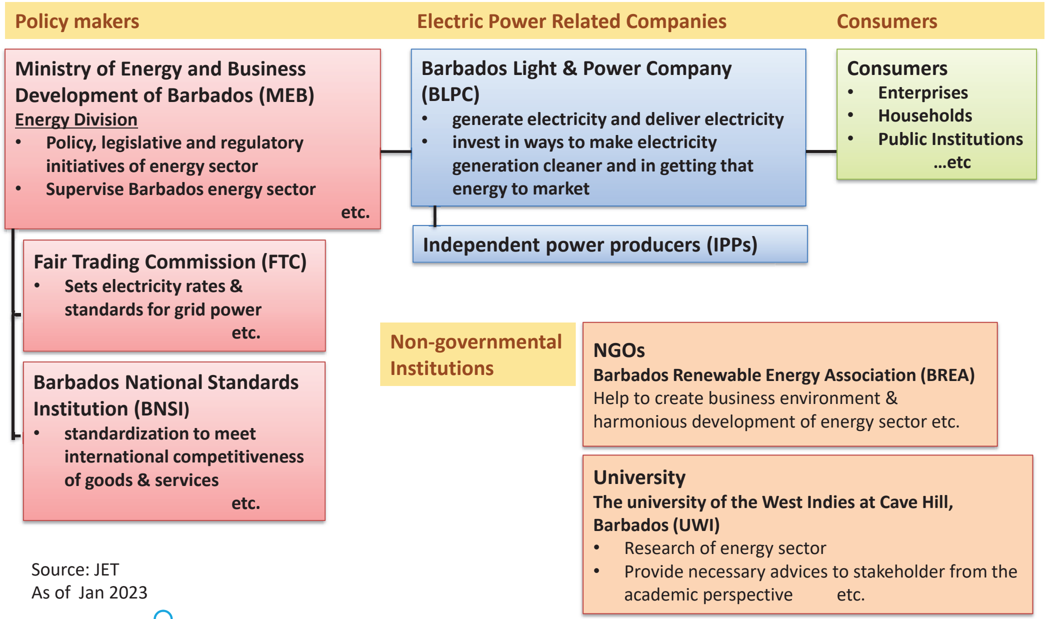


Stakeholders of JICA project

Barbados: MEB, BNSI, BLPC, BREA, UWI
St. Kitts & Nevis: MPI, SKELEC, NIA, NEVLEC
Jamaica: MSET, JPS

Red: policy makers
Blue: electric power related companies
Black: non-governmental institutes

Barbados: Energy sector



Policy makers

Ministry of Energy and Business Development of Barbados (MEB)
Energy Division
- Policy, legislative and regulatory initiatives of energy sector
- Supervise Barbados energy sector

etc.

Fair Trading Commission (FTC)
- Sets electricity rates & standards for grid power

etc.

Barbados National Standards Institution (BNSI)
- standardization to meet international competitiveness of goods & services

etc.

Electric Power Related Companies

Barbados Light & Power Company (BLPC)
- generate electricity and deliver electricity
- invest in ways to make electricity generation cleaner and in getting that energy to market

Independent power producers (IPPs)

Consumers

Consumers
- Enterprises
- Households
- Public Institutions

…etc

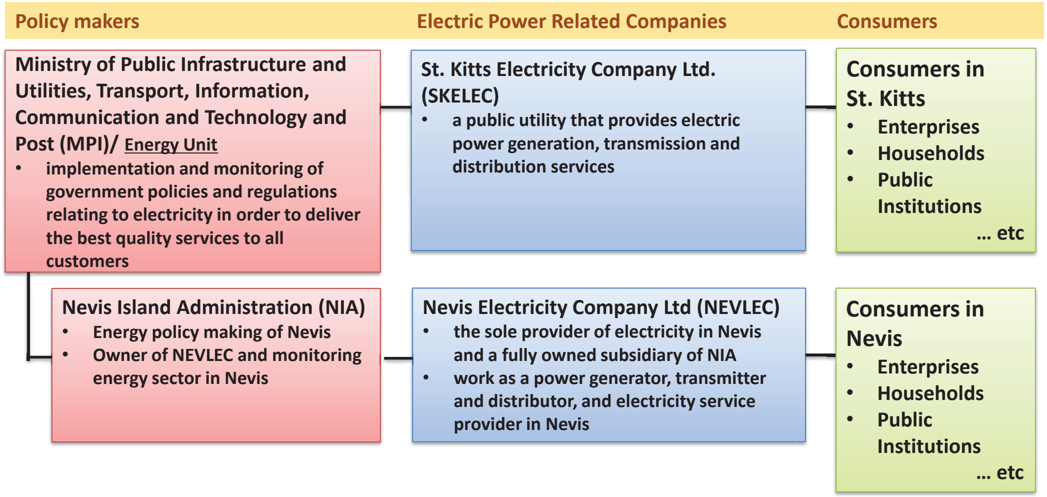
Non-governmental Institutions

NGOs
Barbados Renewable Energy Association (BREA)
Help to create business environment & harmonious development of energy sector etc.

University
The university of the West Indies at Cave Hill, Barbados (UWI)
- Research of energy sector
- Provide necessary advices to stakeholder from the academic perspective etc.

Source: JET
As of Jan 2023

St. Kitts & Nevis: Energy sector



Policy makers

Ministry of Public Infrastructure and Utilities, Transport, Information, Communication and Technology and Post (MPI)/ Energy Unit
- implementation and monitoring of government policies and regulations relating to electricity in order to deliver the best quality services to all customers

Nevis Island Administration (NIA)
- Energy policy making of Nevis
- Owner of NEVLEC and monitoring energy sector in Nevis

Electric Power Related Companies

St. Kitts Electricity Company Ltd. (SKELEC)
- a public utility that provides electric power generation, transmission and distribution services

Nevis Electricity Company Ltd (NEVLEC)
- the sole provider of electricity in Nevis and a fully owned subsidiary of NIA
- work as a power generator, transmitter and distributor, and electricity service provider in Nevis

Consumers

Consumers in St. Kitts
- Enterprises
- Households
- Public Institutions

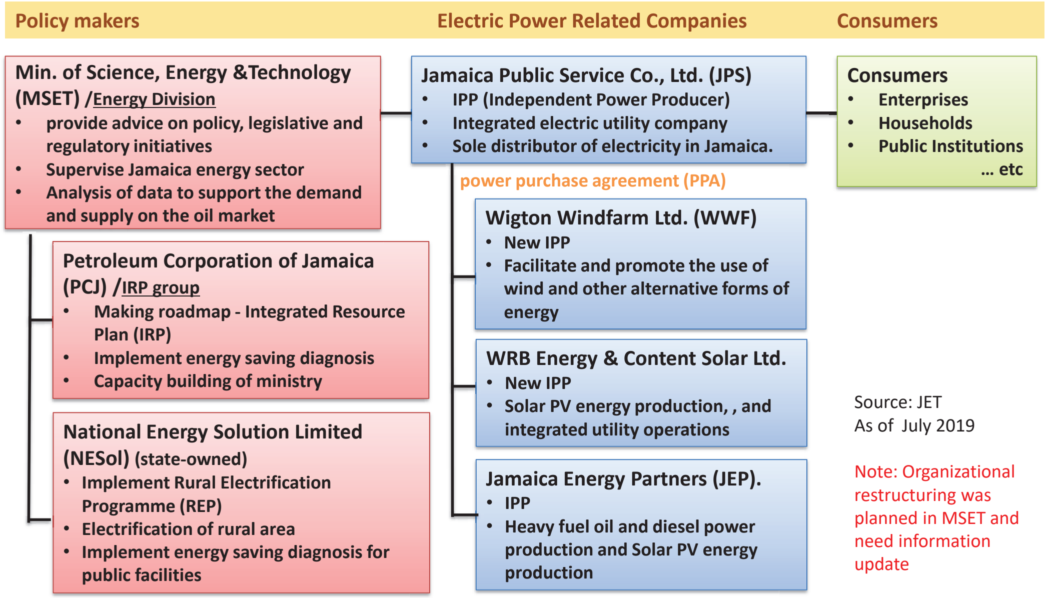
… etc

Consumers in Nevis
- Enterprises
- Households
- Public Institutions

… etc

Source: JET
As of Jan 2023

Jamaica: Energy sector



Policy makers

Min. of Science, Energy &Technology (MSET) /Energy Division
- provide advice on policy, legislative and regulatory initiatives
- Supervise Jamaica energy sector
- Analysis of data to support the demand and supply on the oil market

Petroleum Corporation of Jamaica (PCJ) /IRP group
- Making roadmap - Integrated Resource Plan (IRP)
- Implement energy saving diagnosis
- Capacity building of ministry

National Energy Solution Limited (NESol) (state-owned)
- Implement Rural Electrification Programme (REP)
- Electrification of rural area
- Implement energy saving diagnosis for public facilities

Electric Power Related Companies

Jamaica Public Service Co., Ltd. (JPS)
- IPP (Independent Power Producer)
- Integrated electric utility company
- Sole distributor of electricity in Jamaica.

power purchase agreement (PPA)

Wigton Windfarm Ltd. (WWF)
- New IPP
- Facilitate and promote the use of wind and other alternative forms of energy

WRB Energy & Content Solar Ltd.
- New IPP
- Solar PV energy production, , and integrated utility operations

Jamaica Energy Partners (JEP).
- IPP
- Heavy fuel oil and diesel power production and Solar PV energy production

Consumers

Consumers
- Enterprises
- Households
- Public Institutions

… etc

Source: JET
As of July 2019

Note: Organizational restructuring was planned in MSET and need information update

Findings from baseline survey

Common challenges from the perspective of organizational analysis

- Limited human resources & qualified staffs (1 staff covered wide area)
- Limited human resource development plan and training opportunities
- Communication gaps between organizations (including data & information sharing)

Organizational management can improve these challenges

Organizational structure

-How to improve organization-

Different types of organizational structure

- ✓ To destroy tangible and intangible organizational barriers
- ✓ To collect and share information
- ✓ To realize speedy / right decision making

- Committee organization
- Matrix organization
- Project organization
- Network organization
  - internal network - IT, different hierarchy
  - external network
- Flat organization
- Small organization

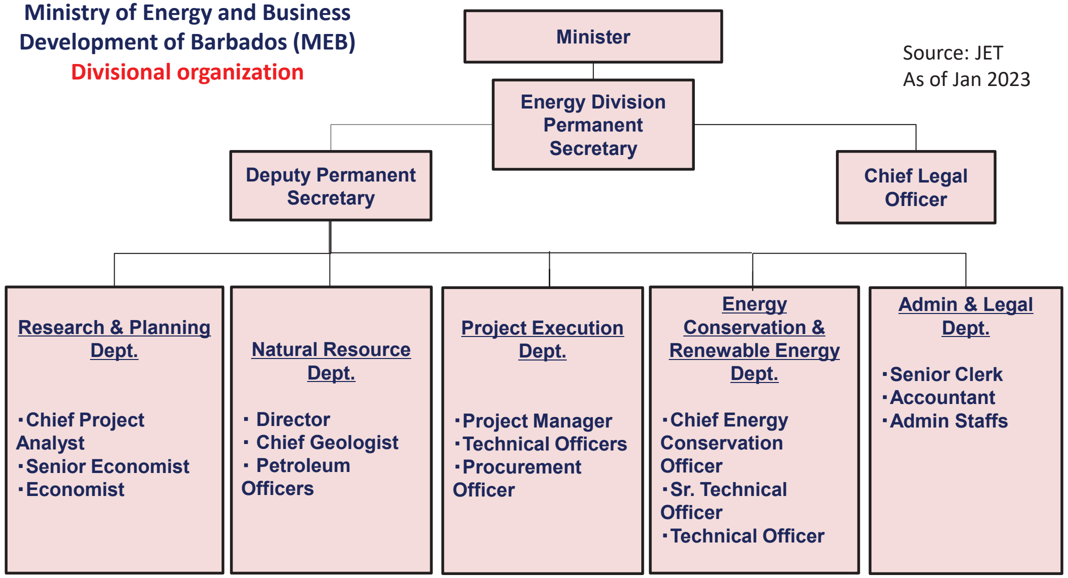
Strengthen horizontal networking

Optimization and diversification of information route

Communication of hierarchical relationship

Source: Masatake Ushiro (2002)

Barbados: MEB organizational chart

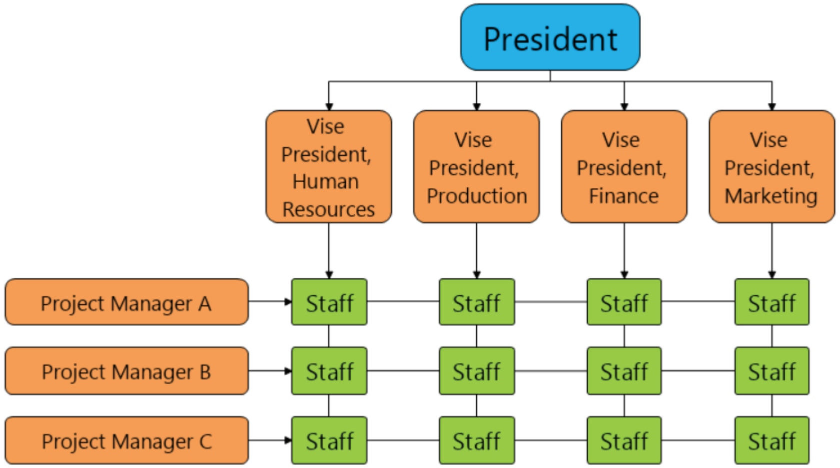


Ministry of Energy and Business Development of Barbados (MEB)
Divisional organization

Source: JET
As of Jan 2023

- Minister
  - Energy Division Permanent Secretary
    - Deputy Permanent Secretary
      - Research & Planning Dept.
        - Chief Project Analyst
        - Senior Economist
        - Economist
      - Natural Resource Dept.
        - Director
        - Chief Geologist
        - Petroleum Officers
      - Project Execution Dept.
        - Project Manager
        - Technical Officers
        - Procurement Officer
      - Energy Conservation & Renewable Energy Dept.
        - Chief Energy Conservation Officer
        - Sr. Technical Officer
        - Technical Officer
      - Admin & Legal Dept.
        - Senior Clerk
        - Accountant
        - Admin Staffs
    - Chief Legal Officer

Matrix organization - Strengthen horizontal networking



President

Vise President, Human Resources

Vise President, Production

Vise President, Finance

Vise President, Marketing

Project Manager A

Project Manager B

Project Manager C

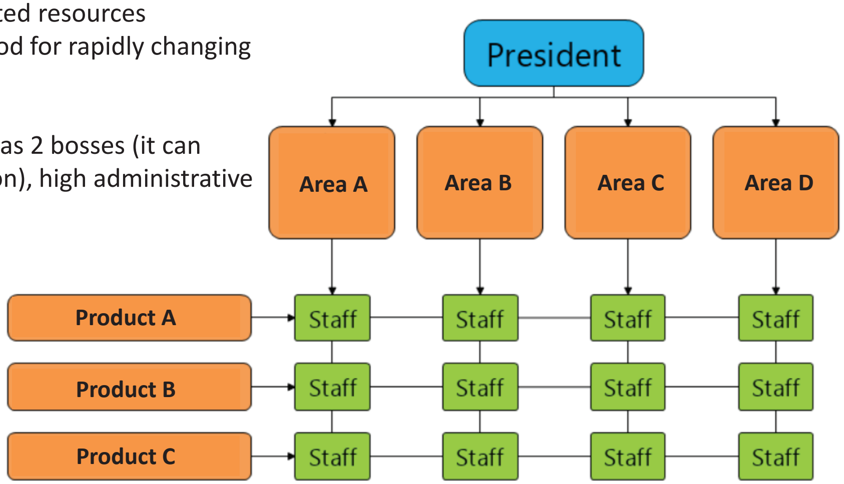
Staff

Source: Masatake Ushiro (2002)

Matrix organization - Strengthen horizontal networking

Pros: Use limited resources effectively, good for rapidly changing environment

Cons: 1 staff has 2 bosses (it can make confusion), high administrative cost



President

Area A

Area B

Area C

Area D

Product A

Product B

Product C

Staff

Source: Masatake Ushiro (2002)

Project organization - Strengthen horizontal networking

Project based organization

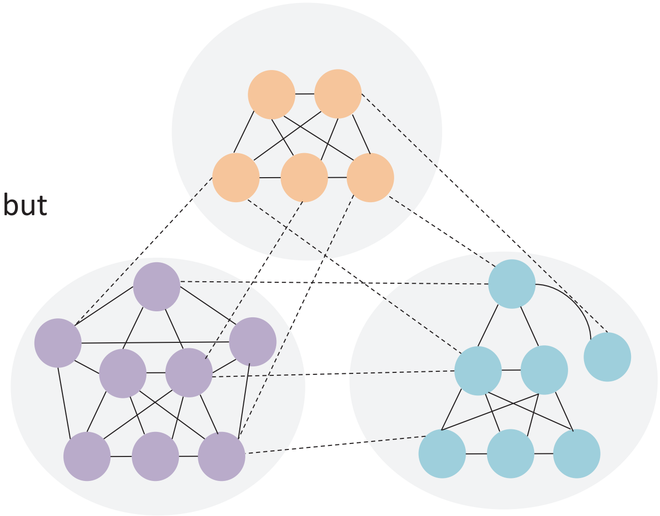
- **Short time/small people**
- **Gathering expert** of each division (better to recruit those who are interested in the project)
- **Clear purpose/direct linkage with top management**
- **Top priority**
- **Close communication** within members
- **Visualization of result/feedback**

Source: Masatake Ushiro (2002)

Network organization

- Optimization and diversification of information route

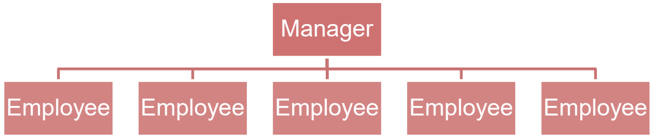
- Between members
  departments
  organizations
- **Functional relationship**, but no hierarchy
- **Independence**
- **Variety of information networks**
- **Variety of learning opportunities**



Source: Masatake Ushiro (2002)

Flat organization

- Communication of hierarchical relationship



- **Quick decision making**
  - ✓ simplification of information route and decision-making process
- **Reduce administrative cost**

Source: Masatake Ushiro (2002)

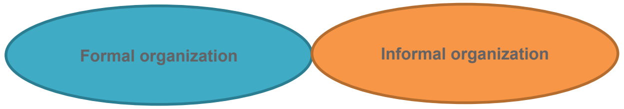
Point of excellent company

Excellent company

Informal organizations are developed, and their activities **support formal organization** to achieve common purpose

Non-excellent company: Informal organizations work against common purpose

Source: Masatake Ushiro (2002)



Organizational communication

-How to keep good relationship/improve relationship-

Dealing with cultural differences

1. Ignore differences
- be physically or mentally isolated/separated
- deny

2. Recognise differences but Evaluate them Negatively
- denigrate others
- feel superior
- place others on a pedestal

3. Recognise differences but Minimise their Importance
- trivialize
- fail to notice uniqueness « We are all the same »

Source: Philippe Rosinski (2022)
Bennett: « Towards Ethnorelativism: A Developmental Model of Intercultural Sensitivity. » 1993
Rosinski: « Beyond Intercultural Sensitivity: Leveraging Cultural Differences . » 1999

Dealing with cultural differences

4. Recognise and Accept differences
- acknowledge, appreciate, understand
- acceptance agreement, surrender
- acceptance needs to be instinctual and emotional as much as intellectual

5. Adapt to differences
- move outside one's comfort zone
- empathy (temporary shift in perspective)
- adaptation adoption, assimilation

6. Integrate differences
- hold different frames of reference in mind
- analyse and evaluate situations from various cultural perspectives
- remain grounded in reality essential to avoid becoming dazzled by too many possibilities

7. Leverage differences
- make the most of differences, strive for synergy
- proactively look for gems in different cultures
- achieve unity through diversity

Effective communication

Intercultural communication – Being able to rely on various forms of communication: explicit and implicit, direct and indirect, affective and neutral, formal and informal

Source: Philippe Rosinski (2022)

Mindset for differences

Differences in response due to high homogeneity and high heterogeneity

	high homogeneity	high heterogeneity
communication	Responsibility of listeners	Responsibility of speakers
relationship	Staging vertical relationships	Staging horizontal relationships
thinking	Seeking for a right answer	Seeking for optimized answer

It is important to develop positive mindset for differences.

Source: Shinji Kawakami (2017)

Effective negotiation

Distributive negotiation

- Only one party "wins"
- Focus on outcomes; not the relationship
- Outcomes seen as fixed
- Goals mutually exclusive
- Emphasize differences
- Emphasize positions
- Short-term perspective
- Key: preparation & tactics
- Guarded communication
- Distrust

Integrative negotiation

- Both parties "win"
- Concerned with mutual outcomes and relationship
- Outcomes can be maximized
- Goals not mutually exclusive
- Emphasize similarities & differences
- Emphasize interests
- Long-term perspective
- Key: cooperation & creativity
- Open communication
- Trust

How to keep good relationship?

Source: Dr. Ahmad Siddiquei (2022)

Communication tools

✓ Information sharing

report, presentation, chat, interview
mailing list, message board, SNS, group chat
newsletters, operational manuals, circulation of documents
cloud storage (share file/folder)…

✓ Meeting

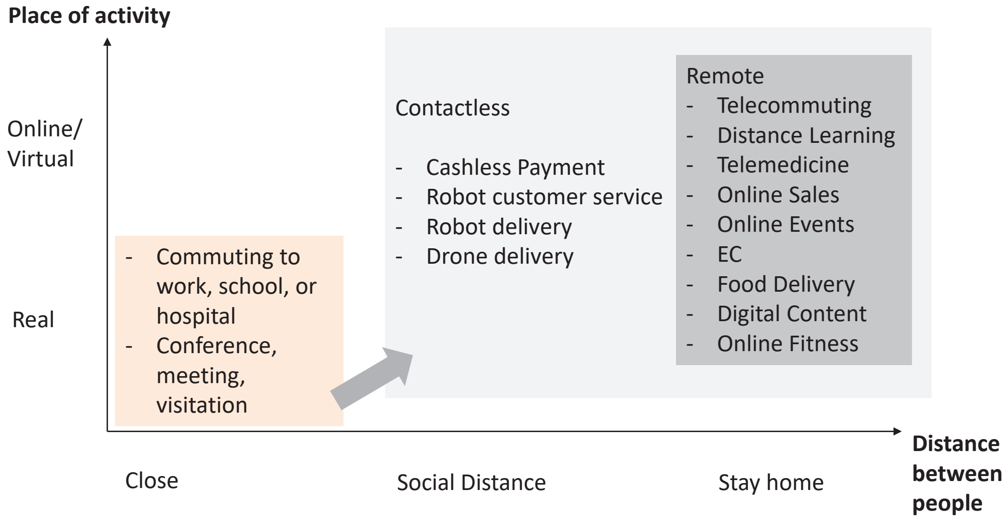
frequency of meeting - monthly, weekly, daily… regular or irregular
face to face, online…

✓ Training

Internal- OJT, OFF-JT, mentor, workshop, group work…
External- trainings for civil servant, college courses, seminars, online trainings…

Information technology & DX

Shift from real to online with information technology and digital transformation (DX)



Ref) Kenichi Ohmae (2021)

Discussion

How can you improve organizational communication in your work?

Summary

Various stakeholders and common challenges

- There are policy makers, electric power related companies and consumers in energy sector.
- Result of baseline survey shows limited resources, budget & time to enhance human and institutional capacity…

Optimize organizational structure & communication

- There are different types of organizational structure
- Good use of informal organization helps formal organization to achieve a goal

Importance of organizational communication

- Accept, adapt, integrate and leverage difference and develop positive mindset for difference
- There are different negotiation styles and what do you select?
- There are many communication tools. How do you maximize use of information technology and DX?

Thank you!

Anna Miyaura (Ms.)
JICA Expert of Human Resources Development/Monitoring
Project Consultant @PADECO
[redacted]

Appendix 4-2-2 Attendant list, and Q&A, of the 2nd Energy Efficiency Workshop (Barbados)

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

2nd EE Workshop: Attendant Day-1 (23 Jan 2023)

Total 9

No.	Name	Position	Org.	How to participate	Count
1	Horace Archer	Senior Technical Officer	MEB	Physical	OK
2	Frank Branch	Technical Officer	MEB	Physical	OK
3	Fabian Scott	Chief Technical Officer	BNSI	Physical	OK
4	Renate Lynn Sealy	Technical Officer	BNSI	Physical	OK
5	Jonathan Platt	Technical Officer	BNSI	Physical	OK
6	Damien Prescott	Technical Officer	BNSI	Physical	OK
7	Robert Goodridge	President	BREA	Physical	OK
8	Felicia Whyte	Project Development Officer	CCREEE	Physical	OK
9	Ayanna Evelyn	Knowledge Management Associate	CCREEE	Physical	OK
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

2nd EE Workshop: Attendant Day-2 (24 Jan 2023)

Total **8**

No.	Name	Position	Org.	How to participate	Count
1	Horace Archer	Senior Technical Officer	MEB	Physical	OK
2	Frank Branch	Technical Officer	MEB	Physical	OK
3	Fabian Scott	Chief Technical Officer	BNSI	Physical	OK
4	Jonathan Platt	Technical Officer	BNSI	Physical	OK
5	Damien Prescott	Technical Officer	BNSI	Physical	OK
6	Robert Goodridge	President	BREA	Online	OK
7	Felicia Whyte	Project Development Officer	CCREEE	Physical	OK
8	Ayanna Evelyn	Knowledge Management Associate	CCREEE	Physical	OK
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

EE Workshop on 23 Jan: Q&A

No	Item	Content	Name	Answer
1	Question	Why is there an increase in the industry sector?	R. Goodridge	The increase is related to more companies working or factory working hours
2	Comment	The industry increase when compared to the overall energy use is quite small. The commercial decrease can be attributed to decrease in economic activity in that sector.	H. Archer	We agree.
3	Comment	It takes about 3 joules of fossil fuel produces only 1 joule of electricity.	W. Hinds	Thank you for this comment.
4	Question	In terms of industry, are standard a/c units still being made as inverter technology is more efficient? Is it being phased out?	H. Archer	Small scale, inverter tech is popular in mini splits. But VRF, and large chillers have no MEPS. These medium and large scale chillers are used in 10,000-30,000 m^2 buildings and have water piping. They intake fresh air and expel heated air from building via an air handler. VRF and mini-split a/c just control temperature of the room.
5	Comment	There are examples of inefficient LED installations in Barbados that needs to suit the Street lighting application.	W. Hinds	The correct reflective materials are needed as LED shine at 120 degrees where conventional mercury/CFL bulbs are 360 degrees.
6	Question	What are the costs for adding in the LED lighting initiatives for commercial industry? So a proper Cost Benefit Analysis can be conducted.	R. Goodridge	The details are not available, but the reduction of the energy use correlated to the amount of chilled water the case study was billed each month. LED payback periods are usually 2-3 years.
7	Comment	In 2009, India's Govt started something similar for lighting, where they dimmable lighting on streets and highways and it saved them money. Something like this can be done in commercial spaces.	F.Hinds	This happens in commercial buildings since the 1990's where timing and proximity sensors were used to decrease energy demand and control lighting. Now with the advent of LED lighting, the energy savings can be enhanced significantly. The LED lighting we have installed have the capacity to be dimmable, but those modules wasn't installed.
8	Question	The total value for the box and the windows are added for our building requirement calculations?	W. Hinds	Yes we add them in the calculations.
9	Question	Would we have similar values for our windows to calculate our heat gain?	W. Hinds	These values were given by the Japanese Gov't, but some of the values are provided from the window manufacturers catalogue.
10	Question	Can a Household Energy Efficiency calculation sheet be developed for Barbados? And can the solar water heater be added to our special revision?	W. Hinds	Yes it can be developed, and the solar water heating is the most efficient method- for heating in this region.
11	Question	Have you discovered the law is now accelerating EE measures, i.e. an increase of EE installations in Japan?	F.Hinds	EE measures an installations have increased due to the tightening EE laws in Japan as most regulations are mandatory.
12	Comment	The CREEBEC is quite similar to this simplified calculation method.	J.Platt	Yes we have this standard in our possession and we reviewed it.
13	Comment	The CREEBEC is very complex and this approach is simple and easy to use	J.Platt	Thank you for this comment.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

EE Workshop on 23 Jan: Q&A

No	Item	Content	Name	Answer
14	Comment	Passive Cooling is something we as Barbadians should look into, primarily insulation of roofs	W. Hinds	This is something we can see as very beneficial to Barbadian homes, especially in decreasing the cooling requirement.
15	Comment	Large eaves can't work in Barbados as we are in the Hurricane Belt, so we can use paints etc.	J.Platt	Thank you for this comment.
16	Comment	Need to introduce an Energy Efficiency Standard for houses in Barbados. Might have to be like European Standards and not like the Japanese approach that does a calculation.	W. Hinds	The simplified version can work for Barbados.
17	Comment	There is still a need to ensure the EE measures are done correctly in Barbados, despite the lack of resources.	J.Platt	Agreed, even in Japan planning for verification is still ongoing and checking will start in 2025.
18	Question	What energy reduction can we see in the residential and commercial sector?	W. Hinds	Half of the demand for a/c, refrigerator and lighting will be achieved by 2050

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

EE Workshop on 24 Jan: Q&A

No	Item	Content	Name	Answer
1	Question	Shading of the a/c units are beneficial, but what can we do to minimize the impact of salt mist in the air as it corrodes the outdoor unit	J. Platt	Shielding can assist with that, but salt spray is very corrosive.
2	Question	We have a mall here in Barbados and the installers placed PV panels over the units and quoted 20%, is it true?	H. Archer	Yes, as some manufactures say 20% reduction , so our 10% reduction is conservative.
3	Comment	For companies renting buildings, there is no incentives to invest in energy savings as this doesn't benefit the landlord. If there is a mechanism where the tenant and landlord both benefit.	W. Hinds	This has been identified as a barrier to improve the EE measures in tenanted buildings, even in Japan. For reference, there are cases in US that tenants bring in the AC equipment and monthly power bill is also paid by tenants. This is one of the models for tenant buildings to raise incentive to introduce efficient equipment.
4	Comment	LEED and other energy efficient building certifications can be used to incentivize energy efficiency measures.	H. Archer	We thank you for this comment.
5	Comment	There are about 4 buildings that are focused on energy efficiency in Barbados and use this as a selling point for their tenanted buildings.	J. Platt	Thank you for this comment
6	Comment	The office of the MEB can have a reduction in lighting requirements as the light levels are about 900 Lux.	H. Archer	The retrofit from fluorescent to LED caused an increase of Lux in the office, and due to the lighting layout, it might be best to decrease the amount of lights installed .
7	Comment	The temperature variation is the highest from late night till midday. If we utilize the variations in temperature during the night and weather variations, we can boost energy efficiency in cooling in Barbados. (night parge)	W. Hinds	Thank you for this comment
8	Question	The CREEBC recommends motion sensors to further improve efficacy, what is JICA's take on sensors?	J. Platt	Sensors can be utilize to advance the progress of building control management to a greater efficiency.
9	Question	With reference to your presentation, what category would you place JICA in? The structure of BNSI is old and needs revamping. BNSI has changed into a project based company and would like to see examples of how to make government agencies more flexible to meet the energy goals of Barbados.	F.Scott	We are part of JICA's approach as we are executing a Joint-Venture project here with the project. We cannot speak directly about JICA's organization directly.
10	Comment	The avoidance of being dazzled by several possibilities is one key measure BNSI takes to progress the national standards.	J. Platt	We thank you for this comment.
11	Question	What is the purpose of communication?	H. Archer	The purpose of communication in this aspect is to boost relations between Government and Non-Governmental Organizations, and to promote energy efficiency and climate change mitigation.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

EE Workshop on 24 Jan: Q&A

No	Item	Content	Name	Answer
12	Comment	The advent of COVID-19 globally has transformed the way in which we communicate in order to be more effective.	J. Platt	This is true, as it provides a myriad of ways to communicate.
13	Comment	There isn't a framework for communication as all of this tools that are available. Having a protocol for effective communication in organizations.	F.Scott	Having a framework for communication via a set suite of platforms would ensure efficacy.
14	Comment	There is a need for high level protocols for meetings to streamline lengthy meetings.	W. Hinds	Thank you for this comment
15	Comment	What is the structure for EV infrastructure in Japan? We at the BNSI would like to see what we can glean from JICA. BNSI was like to get information on battery standards and performance, along with information for a secondary battery market.	J. Platt	Thank you for this comment
16	Question	What information is available for SWAC for district level cooling in government buildings.	F.Scott	SWAC is not used in Japan, but has been demonstrated for district cooling in places like Hawaii. We do not have detailed information.
17	Comment	Energy Storage standards to ensure safety.	H. Archer	We thank you for this comment.
18	Question	What are the industry standards for module replacement as this is important for safety standards. We need to establish V2G tech standards as well.	F.Scott	The standards are highly dependent on the type of battery and can vary.

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

Progress and Discussion for RE and Grid Stabilization in Barbados

Jul 2022

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

RE Team Agenda and Objective in Jul 2022 in Barbados

Agenda

- Activity and overall project schedule
- RE target, challenges, and activity of Technical Assistance
- Grid with large RE penetration
- Microgrid Concept for resilience

Objective of the visit in July 2022

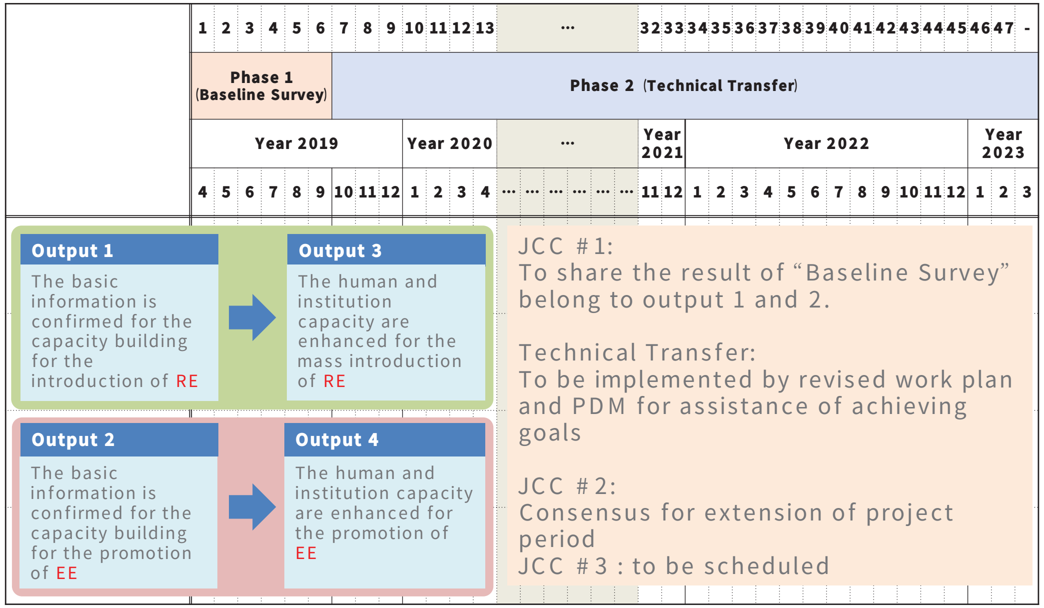
- To confirm and update generation & grid plan/status in Barbados
- To collect data for grid analysis and microgrid concept
- To conduct Workshop-1 (introduction) for grid analysis
- To discuss about recommendation about grid code and promotion policy for RE

Agenda for Workshop for Grid Stability with Large RE Penetration

Date/time: 13:00-15:00 27 Jul 2022
Venue: MEBD/ Online hybrid

13:00-13:10	Opening Remarks and Introduction
Session-1	General session
13:10-13:40	RE target in Barbados and Challenges, Recommendation for resilience (Microgrid and Asset Management)
13:40-14:00	Grid Stability: for Future Grid in Barbados
Session-2	Special session
14:00-14:45	Grid Stability: analysis method, tools
14:45-15:00	Discussion

Overall Project Schedule



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

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

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

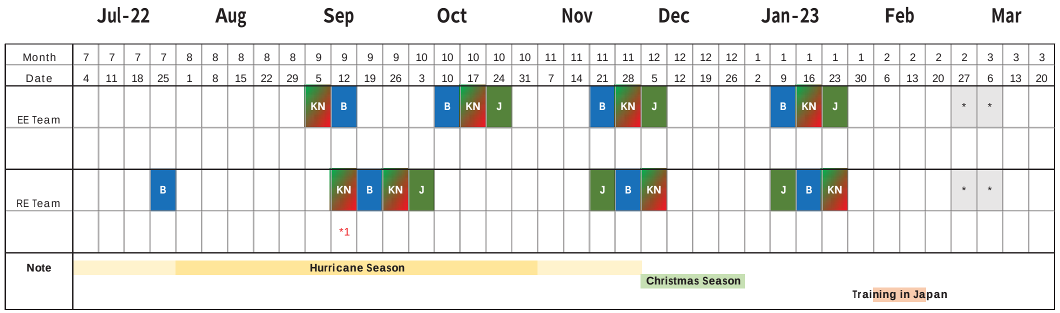
Output 4
The human and institution capacity are enhanced for the promotion of EE

JCC #1:
To share the result of "Baseline Survey" belong to output 1 and 2.

Technical Transfer:
To be implemented by revised work plan and PDM for assistance of achieving goals

JCC #2:
Consensus for extension of project period
JCC #3 : to be scheduled

Tentative Overall Schedule



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	J		
RE Team				B							KN	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		B	KN	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.

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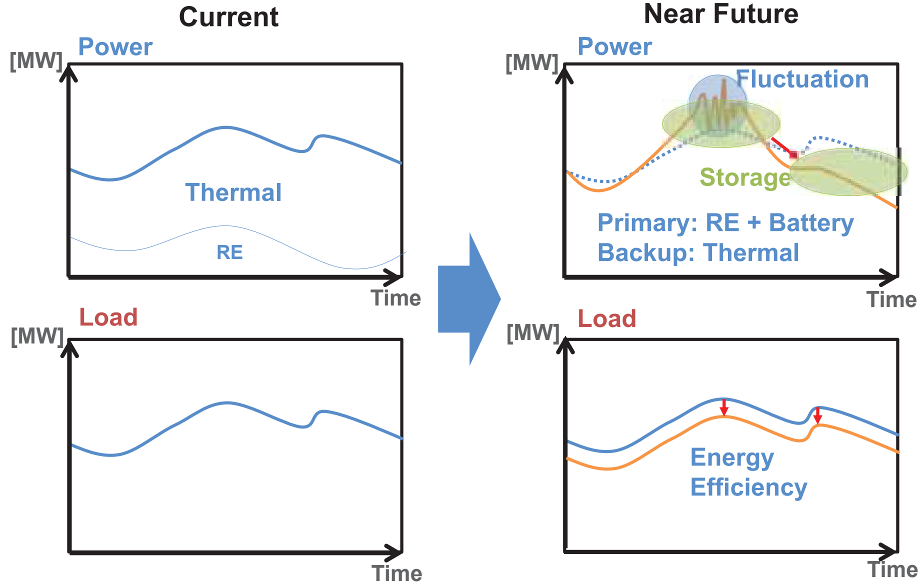
1. Project Outline

Challenges



RE: Key T/C Activities for RE

Barbados

- Training for Grid stability analysis and simulation
- Micro-grid concept study at Coverley Village

Jamaica

- Training for grid simulation
- Introduction of network asset management
- 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**

✓ **Suggestion for policy and RE target with reviewing affordability of RE**

---

2. Baseline Survey Report- Summary

Summary

B

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 + 12 MW Roof top	Confirmation of affordability and feasibility of 100% RE target Future project IP confirmation Training for grid simulation Micro-grid concept study
3. Grid Stabilization	• 5MW, 20 MWh BESS, 400 USD/MWh • 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 • Predictive Maintenance: Conducted twice a year	-
5. Human Resources and Capacity Building	• MEWE's Energy Conservation and Renewable Energy Unit: 3 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

Barbados Grid and PS

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

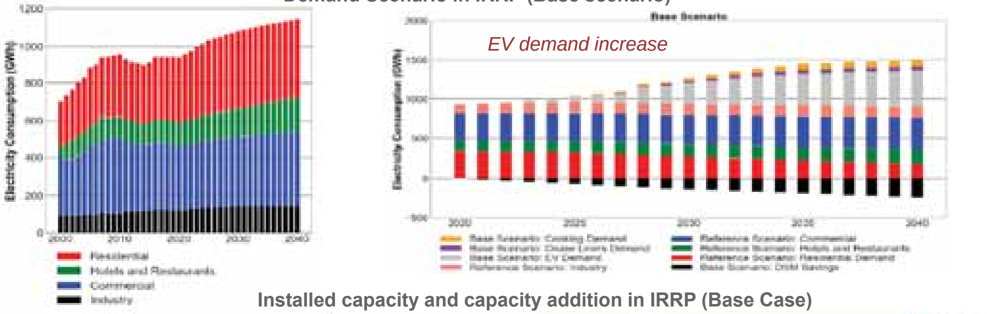
	Location	MW/u	Qy	MW	Remark
Existing					
Total thermal power				**232**	
	Spring Field	12	3	36	LSD Engine
	Spring Field	12.5	1	12.5	LSD Engine
	Spring Field	30	2	60	LSD Engine
	Spring Field	20	2	40	Steam Turbine
	Spring Field	17.5	1	17.5	Gas Tubine
	Spring Field Total		9	166	
	Garrison	13	1	13	Gas Tubine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

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

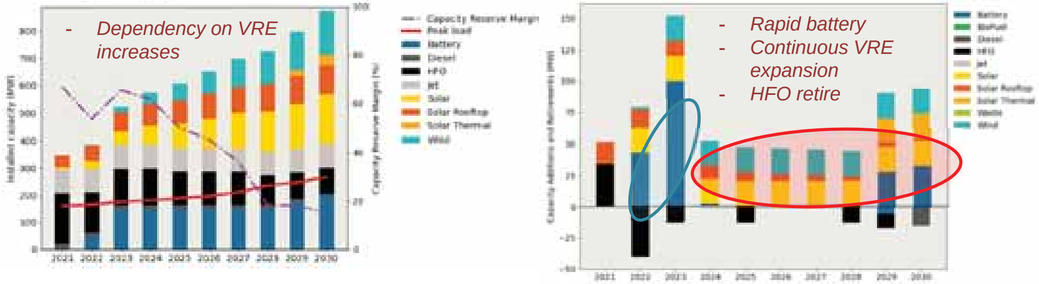
Barbados Demand&Installed capacity in IRRP

Source: IRRP Draft 2021, MottMacDonald

Demand Scenario in IRRP (Base scenario)



Installed capacity and capacity addition in IRRP (Base Case)



Challenges indicated in IRRP

#	Item	Challenges	Solution/mitigation
1	Technical, reliability, operation	- Insufficient system reserve, diversification of generation, distribution generation& Storage, resilience and islanding - Lack of mid-term storage, smart EV system, - future asynchronous generation	Biomass, BESS, Incentive for distributed generation & storage, CAES, smart system
2	Land	Balancing competing users for land given for RE	Integrated town/land use planning
3	Fiscal	Large outflow of forex for oil	Diversify RE and BESS, storage
4	Environmental	- Decarbonization of energy system - Environmental impact of RE, cruise liners	Ditto, low-grad land utilization, RE to electrify cruise liners
5	Socio-economic	- Balancing socio-economic benefit, education and marketing benefits of customer RE	Tariff & financial incentives, market policy
6	Market/ regulatory	- Lack of market design, regulatory framework for fair RE industry, data access	GIS and data gathering
7	Capacity & resource	Capacity of IRRP transmission studies, skill in large bioenergy, on/off-shore wind,	Generation and transmission studies, university and experts
8	Cost	High cost of electricity	Diversify generation, increase energy storage

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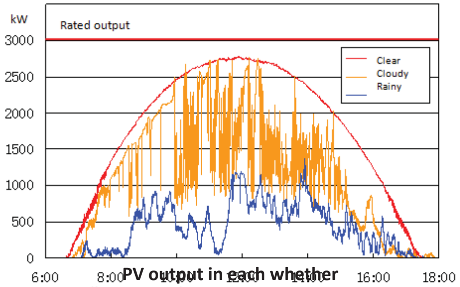
JICA T/C Items for RE and Grid Stability

IRRP #	Item	Details	Solution
1, 6, 7	Recommendation for Grid Stability with large RE penetration	Insufficient system reserve, spinning reserve and inertia, grid instability	- Planning with grid simulation, renewable synchronous generator/BESS, and new technology such as gird forming inverter - System stability cost sharing
1, 2, 4, 6, 7	Policy Recommendation for RE and grid stability, grid code	- Distributed RE - Investment plan, IPP, private - Grid code	- Smoothing effect by installation distributed PV at various places - Incentive for energy storage - SCR, inverter, etc.
1, 2, 5, 6	Recommendation for Demand side management	Demand increase especially due to EV and battery charging	- Incentive for demand side management for EV, efficient charging system
1, 4, 6, 8	Recommendation for Resilience and micro-grids	Damage to power system due to hurricane	Micro-grid, utilization of EV for V2H, asset management

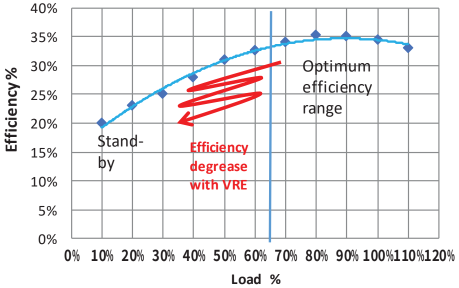
With Large RE Penetration

- VRE causes frequency and voltage fluctuation
- Load shedding due to fluctuation:
- Efficiency reduction
  - 10% DG efficiency reduction offsets 30% RE output in micro-grid without grid stabilization method
  - Increasing fuel consumption



PV output in each whether

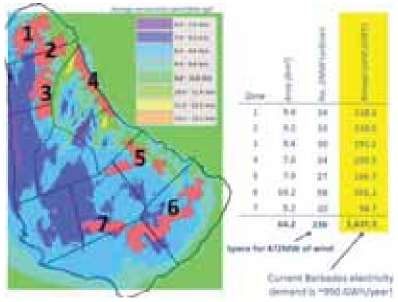
Source: http://www.kyuden.co.jp/effort_renewable-energy_photovoltaic.html



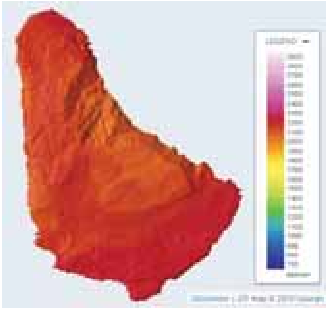
Load and efficiency of typical diesel generator

Status in Barbados

B



Measuring and mapping wind energy in Barbados 2016



Source: ESMAP

RE Potential

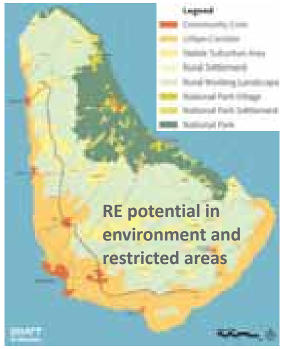
- ✓ Irradiation 4.4-4.7 kWh/kW, 2050-2240 kWh/m2/yr
- ✓ 472 MW wind potential identified but constrained by land availability

RE Projects

	Location	MW/u	Qy	MW	Remark
Existing					
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	
	St Lucy	10	1	10	Wind Planned
	St Tomas	30	1	30	Vaucluse Biomass

Challenges for RE

- ✓ Project implementation plans for 100% RE target for all energy
- ✓ Grid stability
- ✓ Bottle neck : land availability and environment
- ✓ Diversifying options: Biofuel, CSP



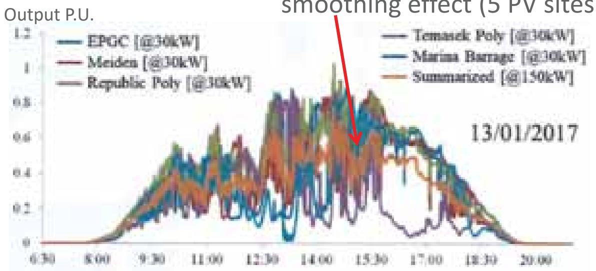
Recommendation for BESS cost reduction

1) Output smoothing by overlaying different PV/wind locations
2) Battery at each site → Centralized battery storage system

Battery cost reduction, but still high cost

Cost reduction Example in Singapore

67% of battery capacity can be reduced by output smoothing effect (5 PV sites)



Source: Meidensha, Autonomous Micro-grid Conference, 2019

To reduce cost:

- Smoothing effect needs to be considered with distributed RE locationa
- Data analysis with solar irradiation/wind speed short interval necessary at several locations
- Speedy communication system advanced EMS control is necessary

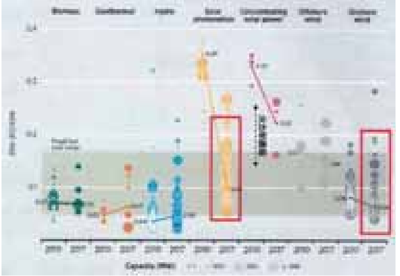
Battery & control cost should be considered in Tariff

Way Forward for Large RE Penetration

Paradigm Shift

- VRE generation is low cost, promoted by market but cost is without stabilization
- Grid stabilization is necessary for large scale
- **Inertia** needs to be considered
  - Biomass, Biofuel, Biogas, CS
  - Grid-forming inverter
- Large cost for energy storage

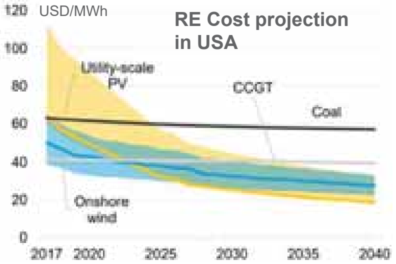
→ **Who owns the stabilization cost?**



Source: Mitsubishi Electrics, IRENA RE cost database

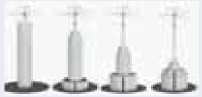
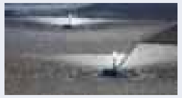
Necessary consideration in project activity

1) Grid Stabilization
2) Cost reduction of energy storage
3) Resiliency
4) Microgrid



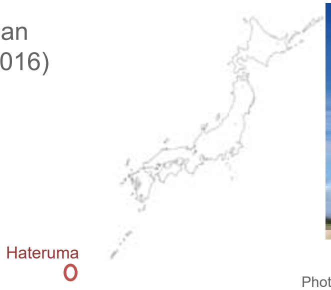
Source: Power Markets Today, Broomberg 2018/ METI, Japan

Emerging technology for large RE with Grid stabilization : Promotion recommended

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: FRT, VRT, voltage support)	- Under development - (Smart inverter by IEEE1547, Mandatory in Hawai)

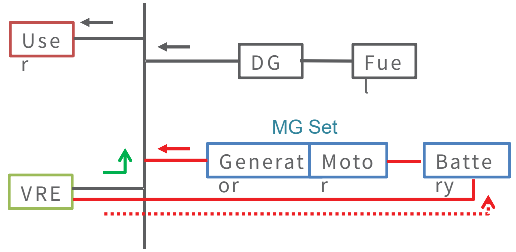
Diversification of Technology: Battery Motor Generator set (MG Set)

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**

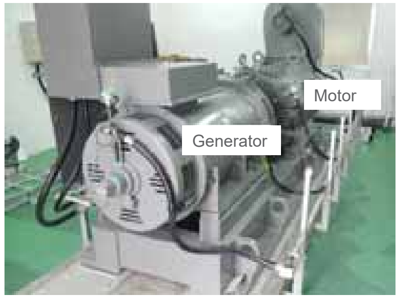


Wind generator

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

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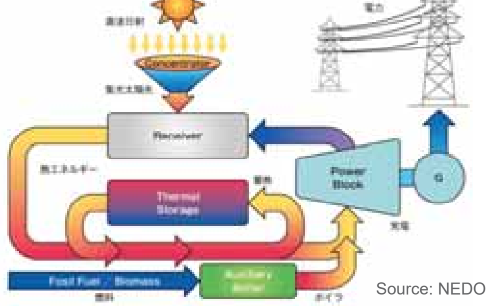
Diversification of Technology : CSP

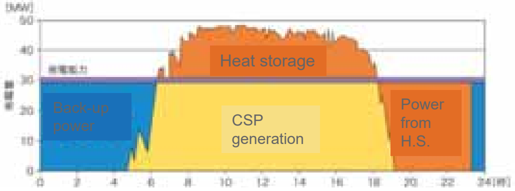
Concentrating Solar Thermal Power (CSP)



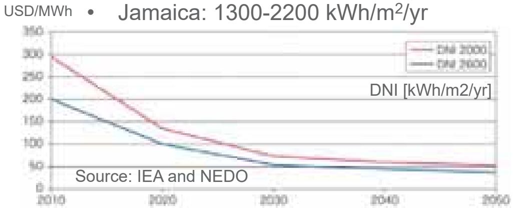
Source: NEDO

Photo: blog.eco-megane.jp/

- Inertial power can be supplied
- Combination with molten-salt heat storage
- Inertial power can be supplied
- Combination with molten-salt heat storage



- 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

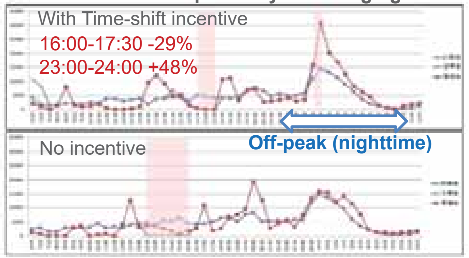


Source: IEA and NEDO

Recommendation for EV

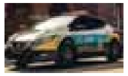
(1) TOU or Unit charge rate according to load curve and weather and PV output with EMS
(Ex.) Range-1 : Daytime, sunny , lowest
Range-2 : Daytime, sunny/cloudy / off-peak, middle
Range-4: Rain and evening, peak-time highest

Demand Response by EV Charging

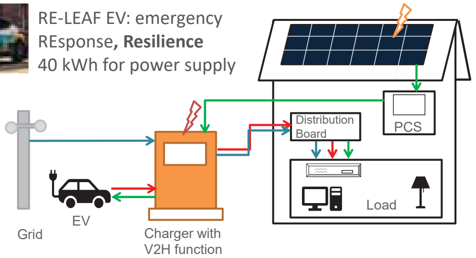


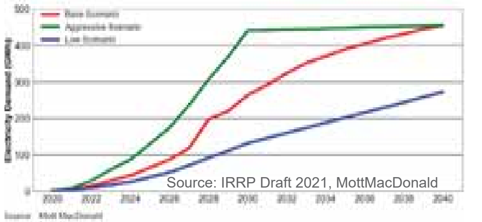
https://xtech.nikkei.com/dm/article/FEATURE/20150120/399714/?P=5

(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





Source: IRRP Draft 2021, MottMacDonald

(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/

Resilience of 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

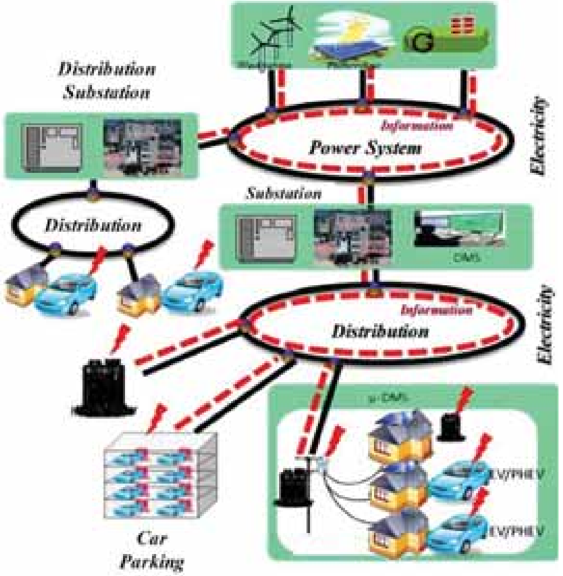
9 Sep 2019 Kanto, Japan
@kadowaki_kozo
Damage of roof-top structure by high speed wind

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
✓ Compensation, third party Insurance coverage
✓ Safety Education for shock
✓ Fast recovery with **GIS and Asset management**
✓ **Micro-grid**

Recommendation for Micro-grid Concept

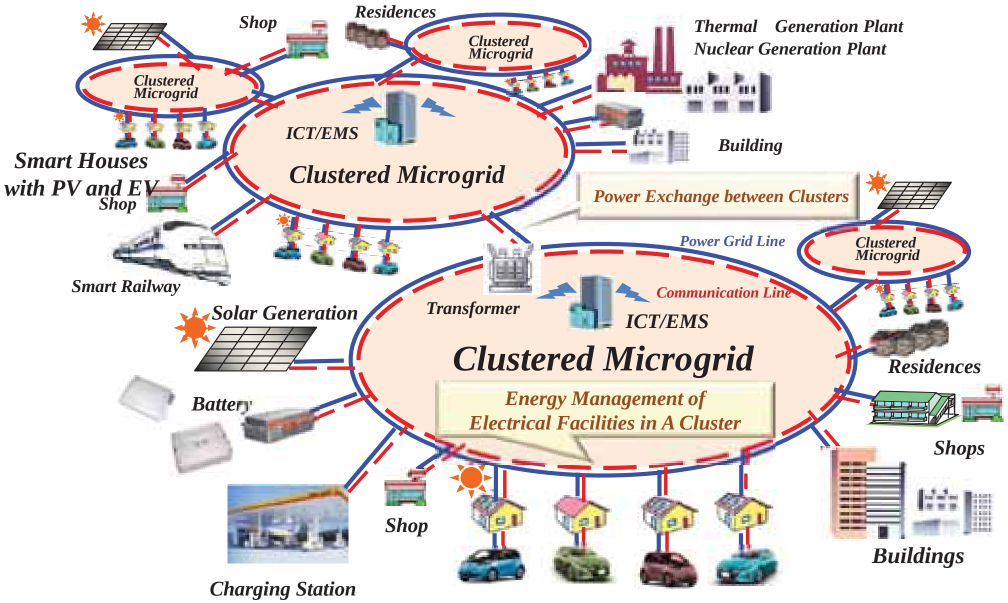


Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

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

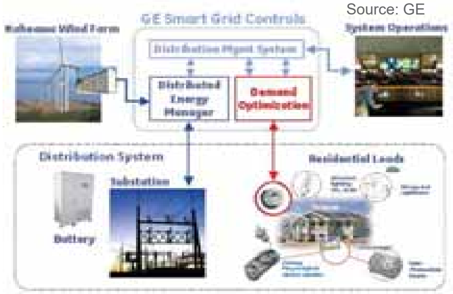


RE: Large RE Example in Islands

40% RE: Hawaii

Hawaiian Electric Company: Expansion of distributed power sources
Nos of customers: 462,225, total 1,795 MW, VRE 673 MW
- Energy storage
- Output suppression of wind and solar
- 15% peak load reduction

Source: GE



100% RE: Samoa (USA)

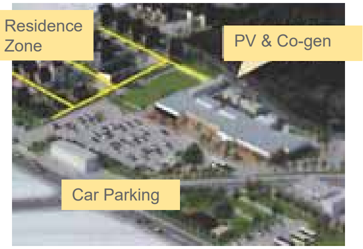
Source: JICA

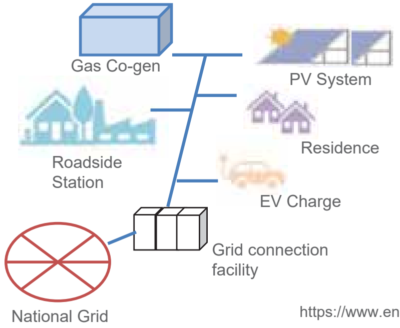
3 villages, 203 household, population 790
Peak **229kW**, Demand1300 MWh/yr, **3.6 MWh/day**)
RE: **1.4 MW PV (6.1 times than peak)**
Battery: **750kW**/**6 MWh** LIB, Tesla 20yrs guarantee
DG: 320kW✕3, 150kW✕1

Mon	Jan	Feb	Mar	Apr	May	Jun
RE%	98.4	97	99	91.2	89.9	99.6

Small demand, but huge RE and Battery
→ **Micro-grid**, Back-up DG is necessary

Microgrid for Resilience: Mutsuzawa Road Side Station





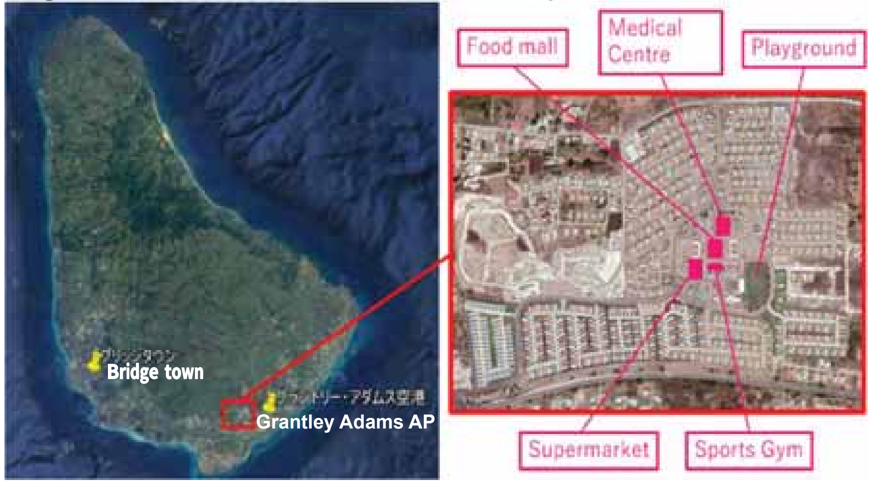
Mutsuzawa Road Side Station

- 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

Micro-grid Concept: Coverley Village

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



Item	Data
Population	2,000, of which 1,300 are student
Household	1,000 houses
Expansion Plan	+300 houses
RE Status	100% solar thermal, 10% PV Panel

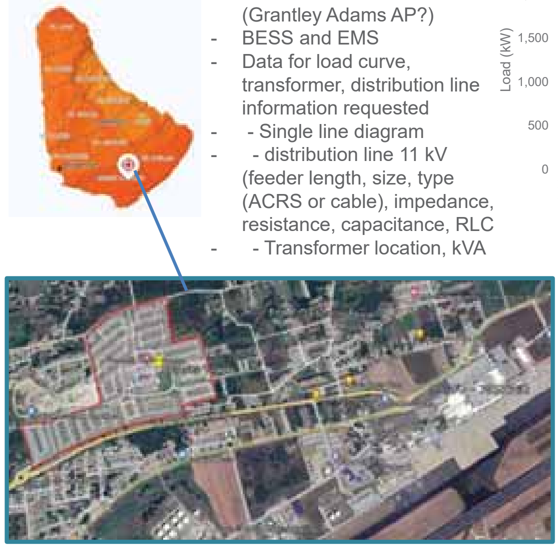
Requested Data

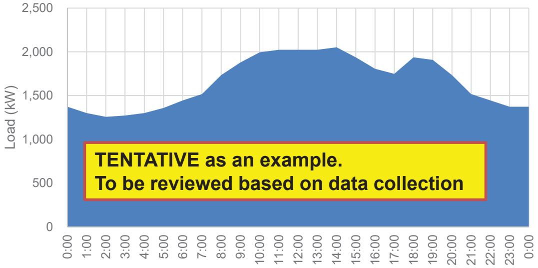
- **Demand and facility data from BL&P**
- **100%RE Scenario (RE source, BESS, EMS)**
- **Information for EV**

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





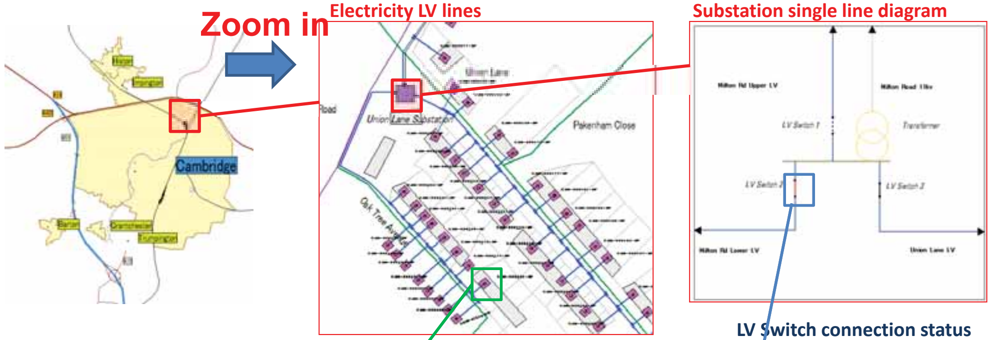
Load Curve in Coverly Village (assumed)

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

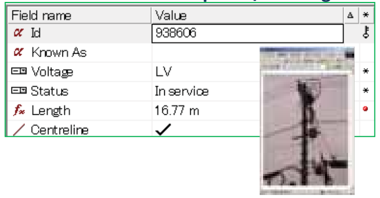
Resiliency Enhancement

System infrastructure: GIS and Digitalized Data Model



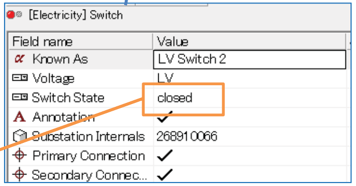
LV Switch connection status

Service wire status and photo/drawing



Field name	Value
Id	938606
Known As	
Voltage	LV
Status	In service
Length	16.77 m
Centreline	✓

The System judges if the feeder line is connected and power can be supplied with LV switch status in substation

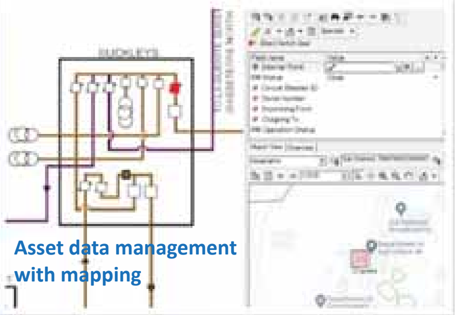


[Electricity] Switch

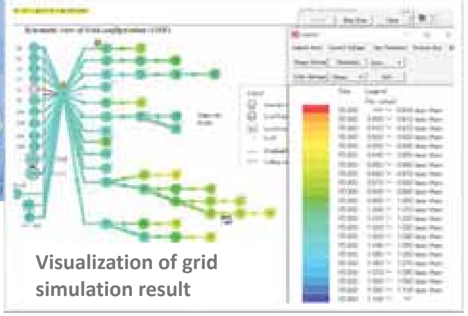
Field name	Value
Known As	LV Switch 2
Voltage	LV
Switch State	closed
Annotation	✓
Substation Internals	268910066
Primary Connection	✓
Secondary Connec...	✓

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

GIS mapping



Asset data management with mapping

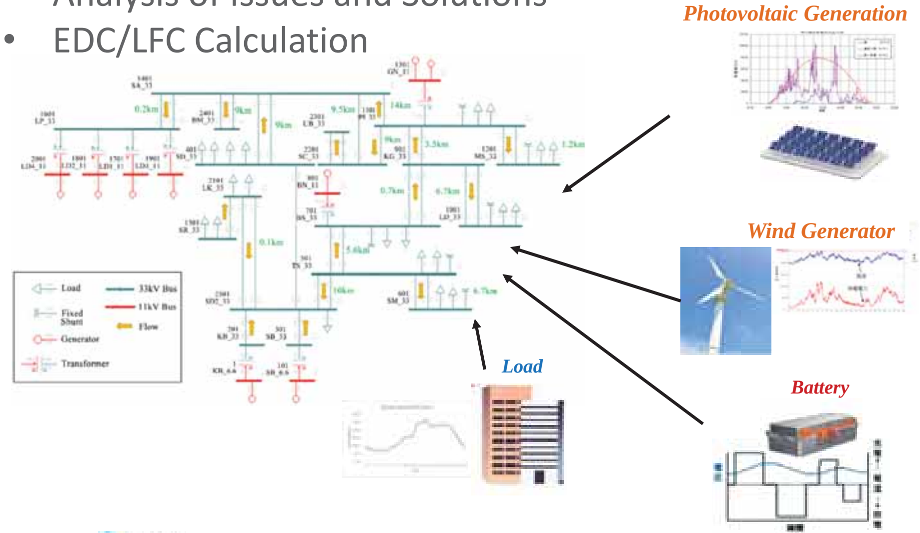


Visualization of grid simulation result

Appendix :
Grid Simulation

Grid Stabilization Simulation

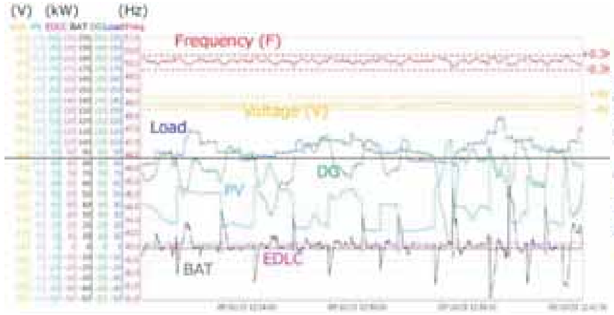
- Simulation of National Grid Model based on asset data
- Analysis of Issues and Solutions
- EDC/LFC Calculation



RE: Example of Grid Stabilization with RE and energy storage

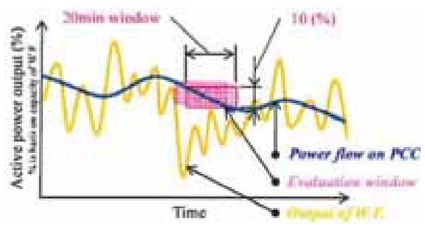
For Voltage and Frequency stabilization (below)

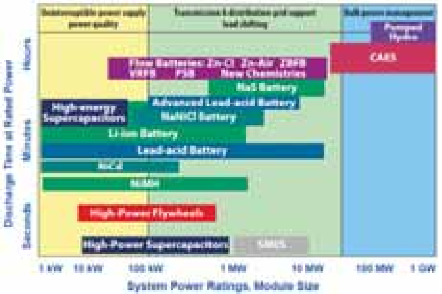
- ✓ Generation: PV, Wind, DG, GT, etc.
- ✓ Energy Storage: Battery (BAT), Capacitor (EDLC)
- ✓ Load /Demand control
- → **Grid Simulation is necessary**
- → **Various energy storage with inertia option needs to be considered**



Source: Meidensha, Autonomous Micro-grid Conference, 2019

Smoothing output





CAES: compressed air energy storage
Source: IRENA, Electricity Storage and Renewables, 2017

Grid Simulation: for Optimization of Power Flow Analysis

Microgrid Designer consists of tools of Economic Load Dispatch (ELD) and power 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 Power 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 Power 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.

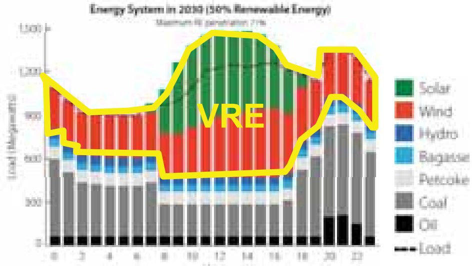
O&M of Thermal Power Generation(Barbados)

<List of Thermal Power Unit>

Country	Plant	Unit	Type	Fuel	Manufacture	Year Installed	Load	Rating Capacity(MW)
Barbados	Spring Garden	D10(Unit A)	LSD	HFO	MAN	1982	Base	12.0
		D11(Unit A)	LSD	HFO	MAN	1982	Base	12.0
		D12(Unit A)	LSD	HFO	MAN	1987	Base	12.0
		D13(Unit A)	LSD	HFO	MAN	1990	Base	12.5
		CG01	ST	heat from unit A	Peter Brotherhood	1985	Base	1.5
		D14(Unit B)	LSD	HFO	MAN	2005	Base	30.0
		D15(Unit B)	LSD	HFO	MAN	2005	Base	30.0
		CG02	ST	heat from unit B	SHINKO	2005	Base	2.0
		Unit S1	ST	HFO	GEC	1976	Base	20.0
		Unit S2	ST	HFO	GEC	1976	Base	20.0
			Olympos GT	Jet Fuel/ Diesel	CURTISS WRIGHT	1969-1970	Peak	17.5
	Garrison	G02	GT	Diesel	ABB	1990	Peak	13.0
	Seawell	G03	GT	Diesel	ABB	1996	Peak	13.0
		G04	GT	Jet Fuel	ABB	1999	Peak	20.0
		G05	GT	Jet Fuel	ABB	2001	Peak	20.0
		G06	GT	Jet Fuel	ABB	2002	Peak	20.0

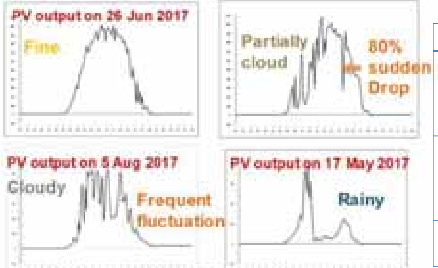
Total: 255.5MW

RE: Instability Caused by VRE



Source: Jamaica Sustainable Energy Roadmap 2013

Spinning reserve is necessary for RE fluctuation.



Grid instability
- Voltage and frequency fluctuation
- Shortage of Inertial power
- High cost for countermeasure

Fuel L/kW increase in diesel generator
- Low load operation
- Acceleration and deceleration
- Spinning reserve

→ EMS and Battery Storage are necessary for grid stability and economic operation (expensive)

→ It might need to optimize RE%

VRE %	< 20%	20-60%	> 60%
Issue	Response by thermal poser	Voltage and frequency fluctuation, power failure increase	(in addition to left) harmonic wave, phase balance, synchronization, supplement of reactive power
Equipment needed for grid stabilization	Output restrain by PCS, EMS	EMS and high-speed charge-discharge battery or capacitor, quick-response thermal power	Power factor control PCS is needed. Special arrangement according to site is necessary.
Cost	Low	High (battery replacement is necessary)	Very high. Specific technical arrangement is necessary

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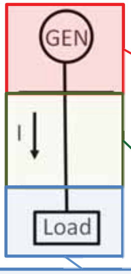
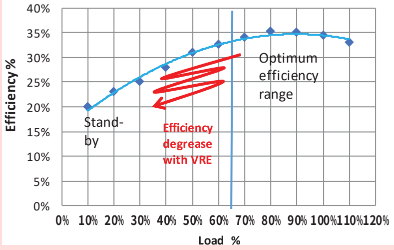
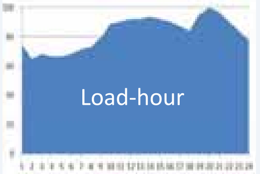
Input Data



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)



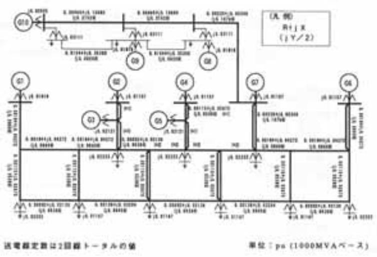
Transmission Line, Substation

[Common]
- Power flow limitation
- Voltage Magnitude

[Option 1]
- Impedance Map

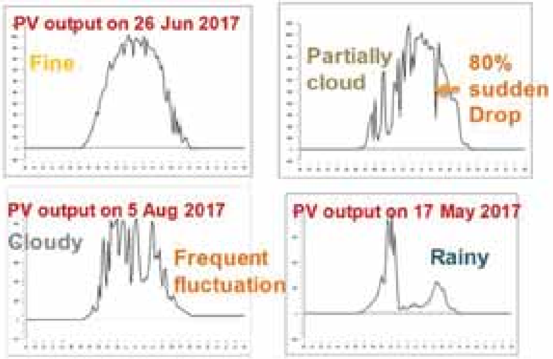
[Option 2]
- Shunt Capacitor
- Cable length
- Cable capacitance [μF/km]

Example of Impedance Map



Input Data

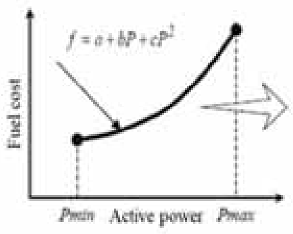
Necessary Data
- Fuel efficiency (heat rate) of each DG generator units at each load range
- PV generation 24 hr curve



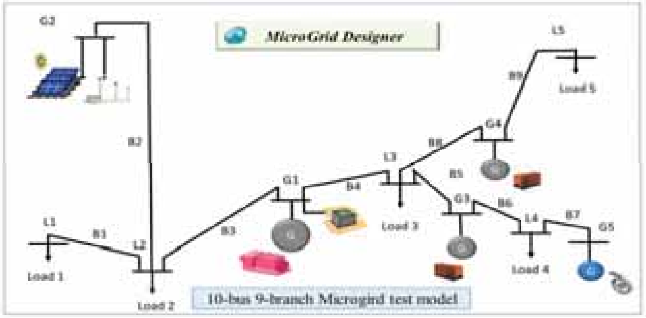
Battery
- Sum of MWh

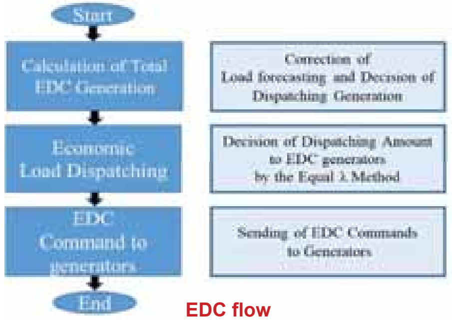
Battery A	5MWh
Battery B	3MWh
Battery C	1MWh
Sum of Battery Capacity	**9MWh**

EDC example with IEEE Microgrid Model

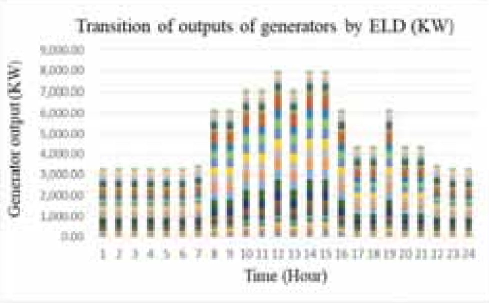


Load-fuel efficiency curve



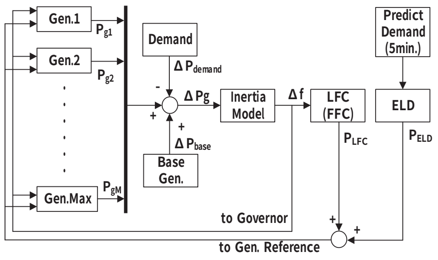


EDC flow

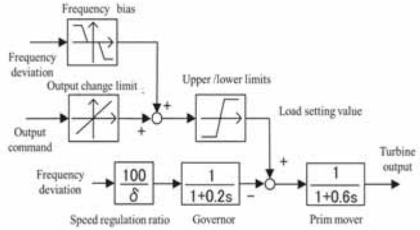


Optimum power output allocation of generators

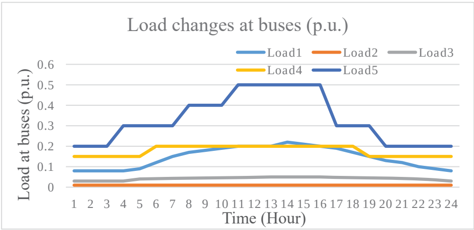
Load-flow Analysis



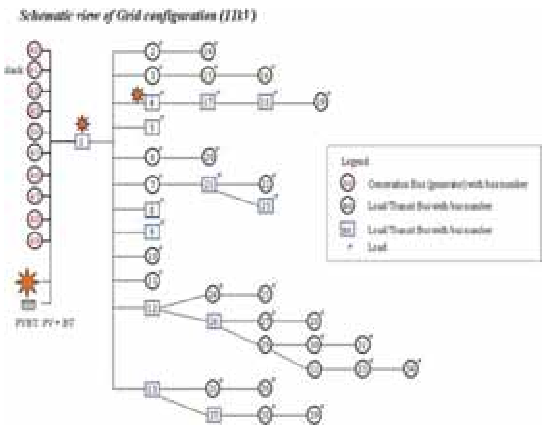
LFC model using EDC result



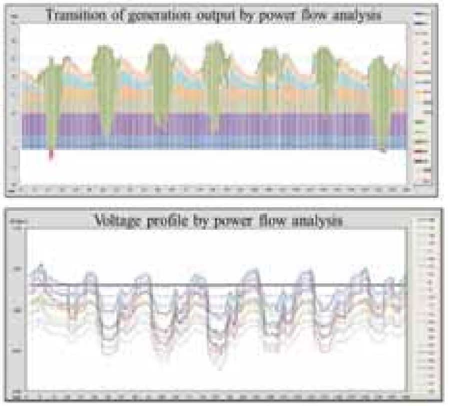
Output model of DG



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

Grid Stability: Future Grid in Barbados Brought by RE (Session-1 General)

Hisao Taoka

Why Grid Stability

- Responsibility of IBR(Inverter Based Resources) is faster than that of synchronous generator.
- The output of IBR can be controlled quickly.
- IBR has less or no inertia than synchronous generator.

↓

- Increase or add inertia function to IBR
  - Grid Forming Inverter
- Increase generator with large inertia.
  - Resources provided by Synchronous generators

Keywords for Grid Stability

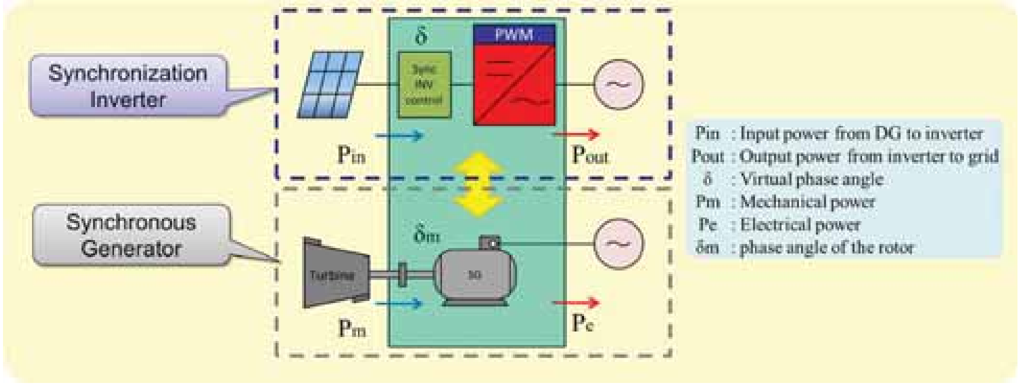
- **Virtual Inertia**
  - Grid Forming Inverter vs Grid Following Inverter
  - EV(Electric Vehicle) for V2G(Vehicle to Grid)
  - Virtual Power Plant
  - DR(Demand Response)
- Evaluation Index of Stability
  - **SCR**(Short Circuit Ratio)
  - **ATC**(Available Transmission Capacity)
- Grid Code from the Viewpoint of Stability

- Tools for Monitoring Power Grid
  - Load Flow Analysis
  - LFC(Load Frequency Control) and ELD(Economic Load Dispatching)
  - Stability Evaluation by EAC(Equal Area Criterion)
- Microgrid: One Solution for Stability
  - Decrease Power Flow of Utility Transmission Lines

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
  - Suppy Virtual Inertia to Grid
  - Source: PV, WP(Wind Power), EV(Electric Vehicle), Battery

Concept of Virtual Inertia



Pin : Input power from DG to inverter
Pout : Output power from inverter to grid
δ : Virtual phase angle
Pm : Mechanical power
Pe : Electrical power
δm : phase angle of the rotor

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

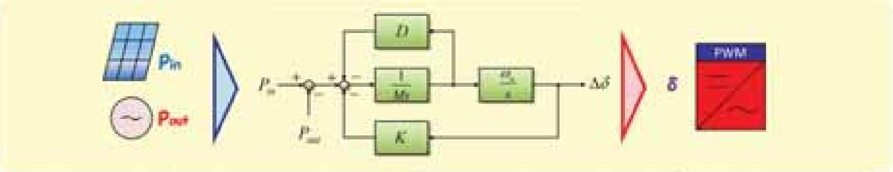
The control method of Synchronization Inverter is expressed by the swing equation. This equation is added damping term and synchronizing power term.

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

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

The transfer function of voltage value

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



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, WP) 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.
- Swing Equation
  - $P = \frac{V_i V_j}{X} sin\delta$
- Synchronizing Force
  - $\frac{dP}{d\delta} = \frac{V_i V_j}{X} cos\delta$
- Maximum Transmission Capacity
  - $P = \frac{V_i V_j}{X}$

    or $P_{loss} = R * (\frac{V_i}{X})^2$ $< P_{lossmax}$----- from heat capacity limit

---

Spinning Reserve

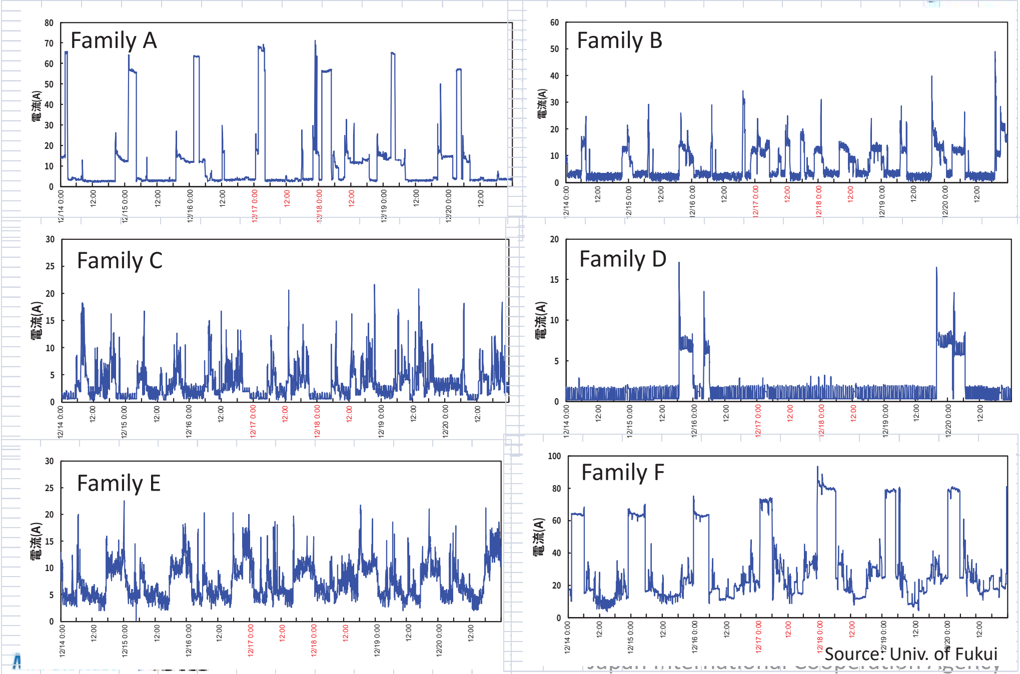
- In order to get electrical power under abnormal condition of grid, spinning reserve should be kept even if RE is installed. (under development)

- RE Sources for Spinning Reserve:
  - EV
  - Battery
  - Biofuel or Diesel Generator

etc.

Samples of Load (one week)

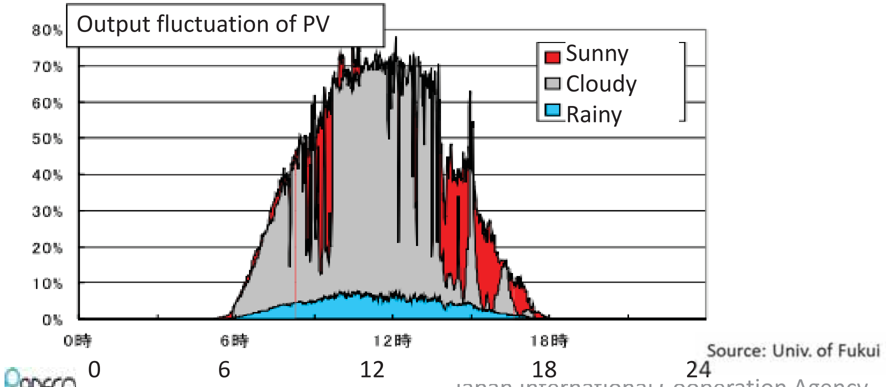
Confidential



Source: Univ. of Fukui

Generation Power of PV (Example)

- The range of PV output is 0 to max.
- Total power of renewable energy may be limited not to be over the spinning reserve of network.
- Battery and smoothing effect by PV in various place may cover short time fluctuation.



Source: Univ. of Fukui

Frequency and Voltage Control

- Frequency Control
  - Frequency Ride Through
  - Governor Control in Generation Side(PV, WP)
  - Load Frequency Control through Control Center/EMS
- Voltage Control
  - Voltage Ride Through
  - DVS(Dynamic Voltage Support) by Reactive Power in Generation Side (PV)

Recommendation for Grid Code

- The following items will be required from Grid Stability:
  - Virtual Inertia for IBR(Inverter Based Resources)
  - High SCR of Grid
  - Spinning Reserve from EV, Battery, etc.
- RE with these functions is key technology for grid stability.

Grid Code in EU and USA

- RfG(Requirements for Generators) : Grid Code in EU
  - The relevant TSO (Transmission System Operator) shall have the right to specify that power park modules [of type C and D] be capable of providing synthetic inertia during very fast frequency deviations.
- IEEE P2800 : Grid Code in USA
  - IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems

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Grid Code Committee in Japan

Under discussion

- Short Term Target:2023/4
  - Criterion for Generator
- Middle Term Target:2025/4
  - Voltage Ride Through
- Long Term Target:2030/4
  - Inertia Market
  - RoCoF8rate of Change of Frequency)
  - Virtual Inertia
  - Stability
  - Black Start

Operating State of Power System

- Total Generation Power is to be normally 60〜70%.
- The fluctuation of load is 10〜20%, if load prediction is operated well.
- The fluctuation of renewable energy has to be about 10%, but already over 30% in Barbados.
- If total demand of grid becomes to 90% over of rated capacity of grid,
  - Spinning reserve will be decreased.
  - Synchronizing power will be very small not to be returned to stable state.
- 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.

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

Grid Stability:
Future Grid in Barbados Brought by RE
-Tools for Grid Stability-
(Session-2 Special)

Hisao Taoka

Tools for Grid Stability

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

VPP: Virtual Power Plant

Load Flow Analysis

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

Stability Analysis

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

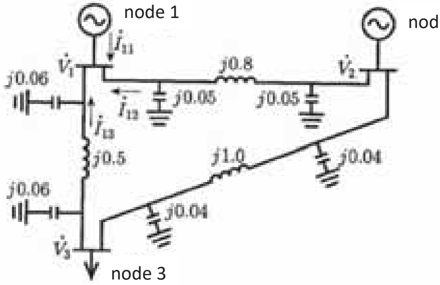
Load Flow(Power Flow) Analysis

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

- Slack (Swing) Bus
  - The magnitude and phase angle of the voltage are specified.
  - This bus makes up the difference between the scheduled loads and generated power that are caused by the losses in the network.
- P-V Buses (Generator Buses)
  - The real power and voltage magnitude are specified.
  - The phase angles of the voltages and the reactive power are to be determined.
- P-Q Buses (Load Buses)
  - The active and reactive powers are specified.
  - The magnitude and the phase angle of the bus voltages are unknown.

Node Admittance Matrix to Describe Grid

Calculation example of power flow in 3 nodes network



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

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

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

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

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

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

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

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

Power Flow Equation & Solution Method

Power Flow Equation of each node

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

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

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

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

Solution Methods:

- Gauss-Seidel Method
- Newton-Raphson Method
- Fast Decoupled Method
- DC Flow Method

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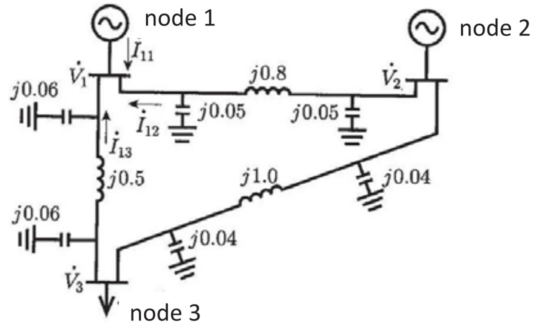
Power Flow Equation

(Example of 3 nodes network)



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

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

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

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

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

Newton Raphson Method

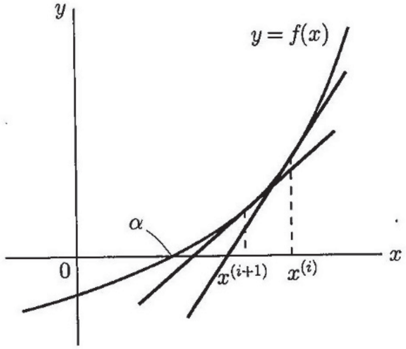
For computer model

This method is used in **Microgrid/VPP designer**.

This method can get solution, even if power flow is heavy.

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

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



DC Flow Method

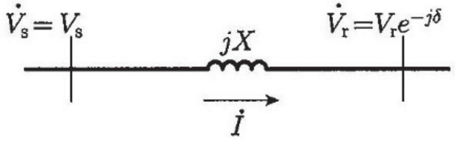
Manual method to calculate power flow.

Easy to calculate in manual.

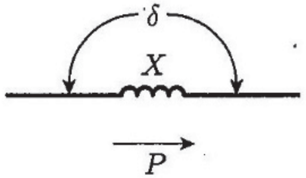
$$
\begin{aligned}
P_r + jQ_r &= V_r e^{-j\delta}\dot{I}^* \\
&= V_r e^{-j\delta}\left(\frac{V_s - V_r e^{-j\delta}}{jX}\right)^* \\
&= \frac{V_s V_r e^{-j\delta} - V_r^2}{-jX} \\
&= \frac{V_s V_r}{X}\sin\delta + j\frac{V_s V_r \cos\delta - V_r^2}{X}
\end{aligned}
$$

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

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

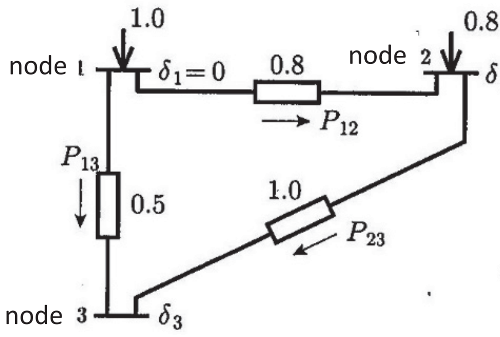


Simplified and Similar to DC circuit solution



DC Flow Method

(Example of 3 nodes network)



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

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

$$\delta_2 = 0.104$$

$$\delta_3 = -0.565$$

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

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

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

Per Unit Method:

Rated or base voltage and power in grid are set to 1.0

Microgrid/VPP Designer

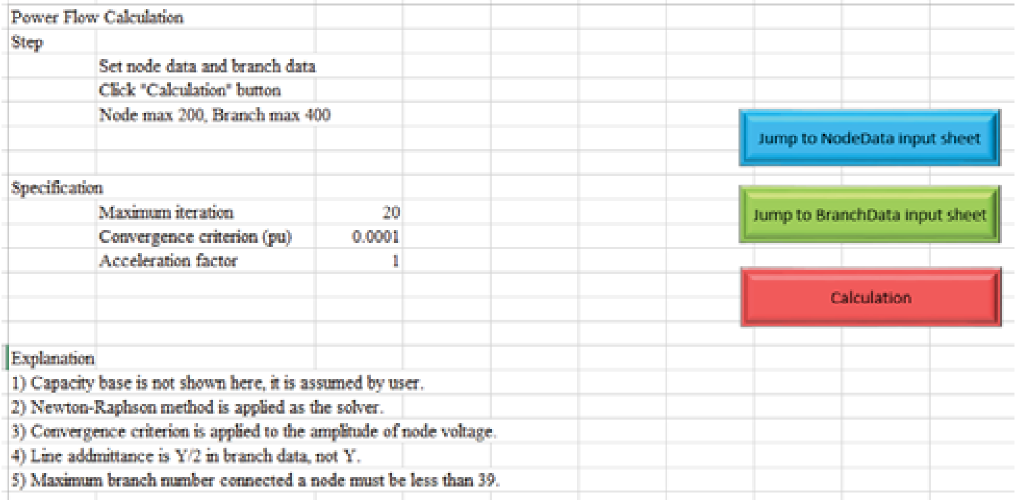
- Calculate large scale power grid including microgrid
- From power flow solution till demand and supply control
- Based on Microsoft Excel Macro
  - Easy to install into PC

<Functions>

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

VPP: Virtual Power Plant

Starting Window of Load Flow



Power Flow Calculation

Step

Set node data and branch data

Click "Calculation" button

Node max 200, Branch max 400

Specification

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

Explanation

1) Capacity base is not shown here, it is assumed by user.

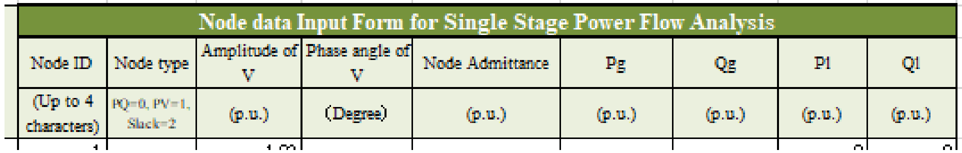
2) Newton-Raphson method is applied as the solver.

3) Convergence criterion is applied to the amplitude of node voltage.

4) Line addmittance is Y/2 in branch data, not Y.

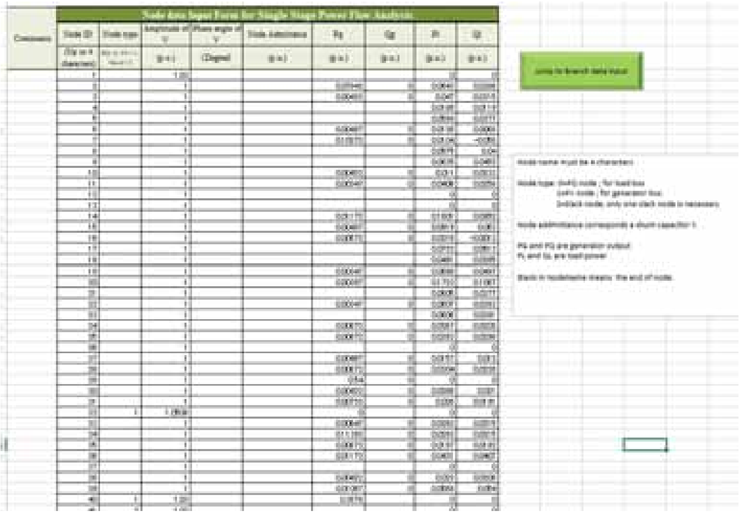
5) Maximum branch number connected a node must be less than 39.

Node Data

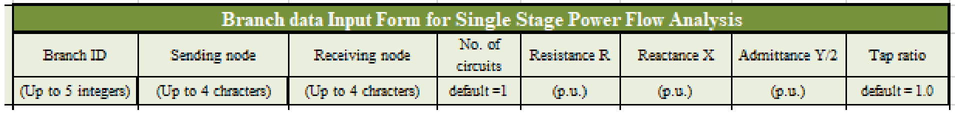


Node data Input Form for Single Stage Power Flow Analysis

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.)

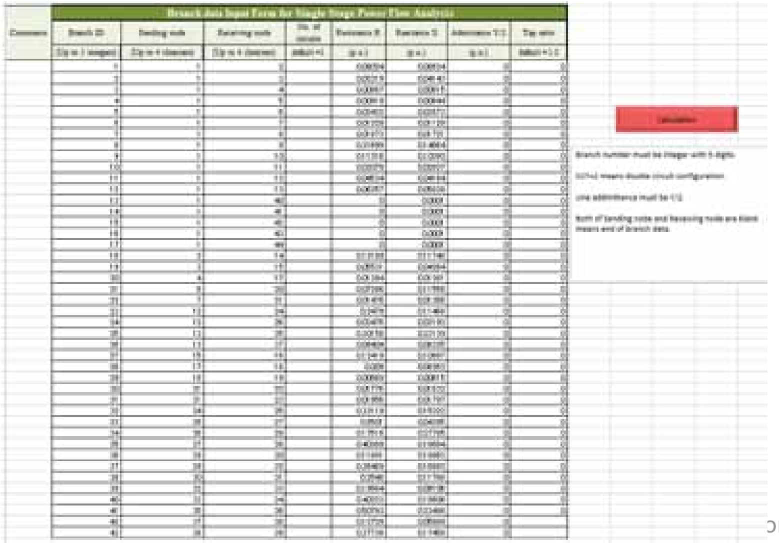


Branch Data

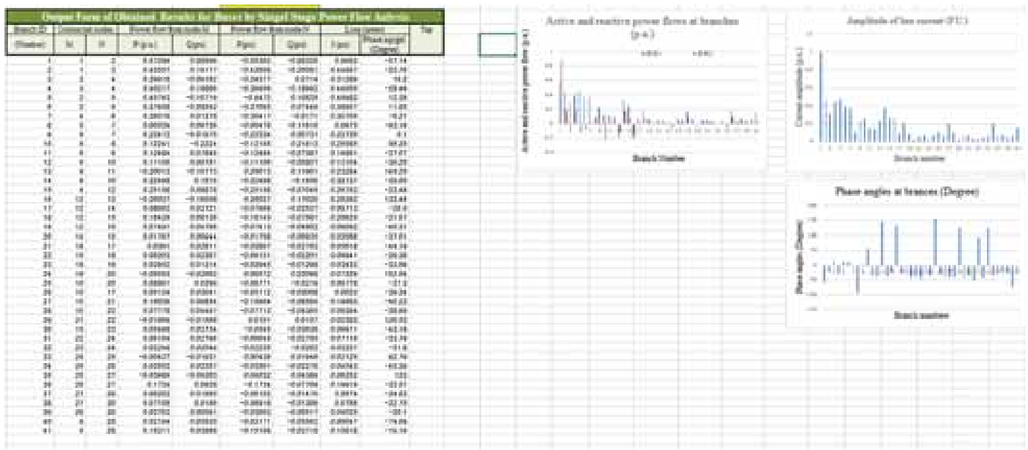


Branch data Input Form for Single Stage Power Flow Analysis

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



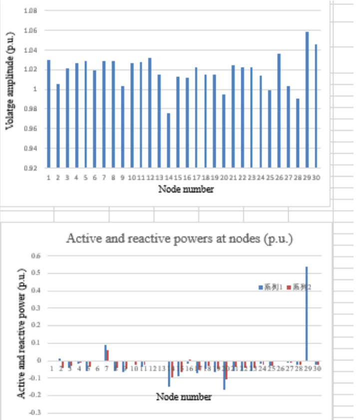
Calculation Results of Branch



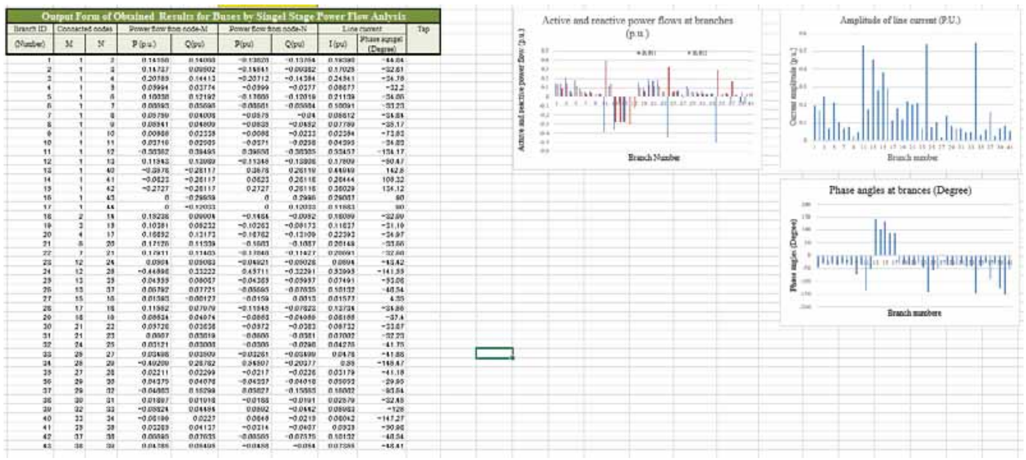
Calculation Results of Node

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

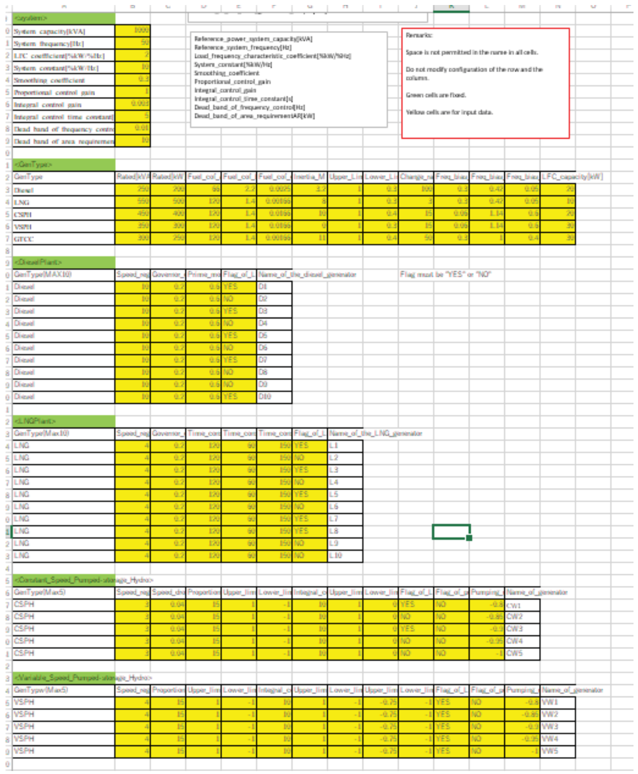
Node ID	Node type	Specified voltage	Obtaiened value		Specified P&Q		Obtained P&Q		Injection current	
(Up to 4 characters)	PQ=0, PV=1, Slack=2	V (p.u.)	V (p.u.)	(Degree)	P (p.u.)	Q (p.u.)	P (p.u.)	Q (p.u.)	I (p.u.)	Angel (Degree)
1	0	1.03	1.02997	0	0	0	-0.00002	-0.00181	0.00175	90.53
2	0	1	1.00576	0.03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



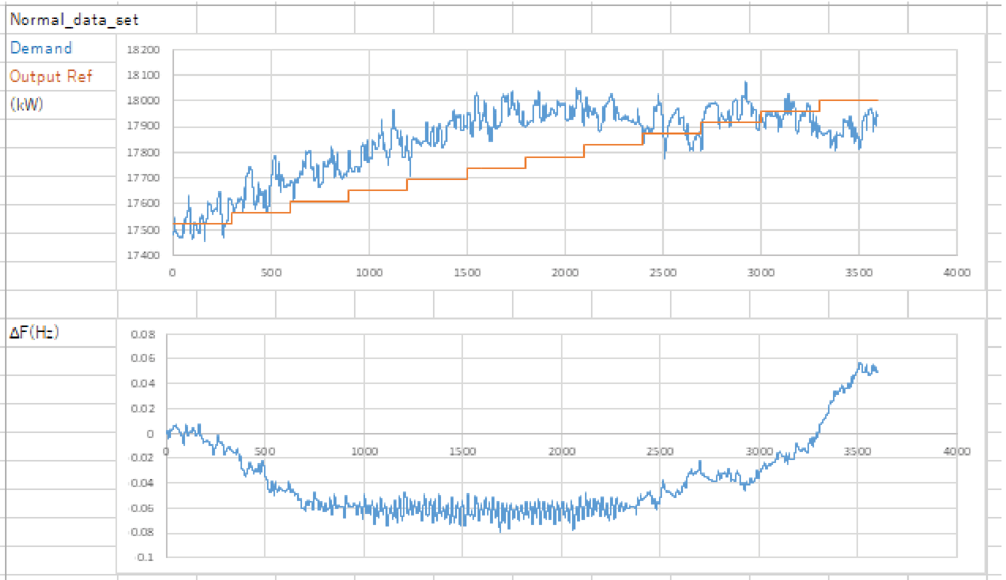
Calculation Results of Branch



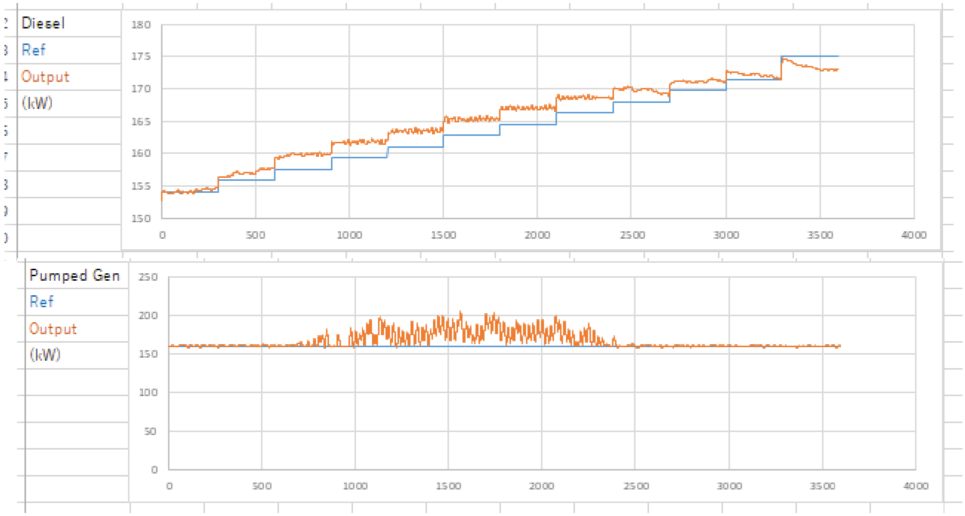
LFC Calculation -Input Data-



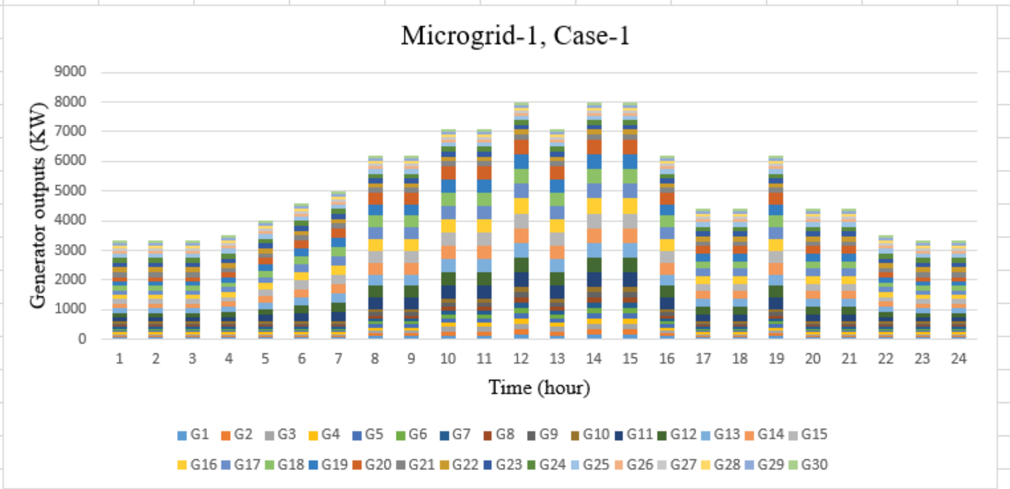
Demand and Frequency
-LFC result-



Generator Output
-LFC result-



ELD Calculation Results

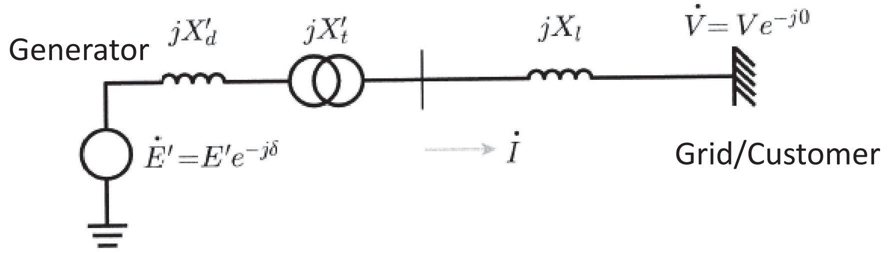


Stability Analysis
-Swing Equation-

M: Inertia capacity

- $M\ d^2\delta/dt^2=P_m-P_e=\Delta P$
  - This equation describes relationship between power and frequency.
  - Power will swing according to disturbances caused by unbalance between generation power and consuming load.
- P_m: Generation Power
  - Synchronous Generator: Controllable
  - Renewable Energy Generator:
    Uncontrollable? -> Control,,,
    Uncertainty? -> Predict,,,
- P_e: Load
  - Customer: Uncertainty-> Predict,,,
  - Fault: Uncertainty, Unpredictable (Of course)

Simplified Grid Model



P-δ Equation

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

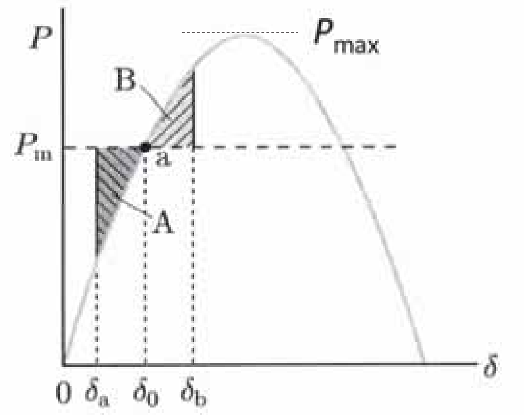
$$P + jQ = \dot V \dot I^*$$
$$= \dot V \left\{\frac{E'e^{-j\delta} - \dot V}{j(X'_d + X_t + X_l)}\right\}^*$$
$$= \frac{\dot V E'}{X'_d + X_t + X_l}\sin\delta + j\frac{\dot V E'\cos\delta - \dot V^2}{X'_d + X_t + X_l}$$

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

Equivalent Area Criterion for Stability Analysis

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

Pmax=>ATC



A: Acceleration Energy
B: Deceleration Energy

ATC(Available Transmission Capacity)

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

  or $P_{loss} = R * (\frac{V_i}{X})^2$ <P_{lossmax}----- from heat capacity limit

Operating State of Power System

- Total Generation Power is to be normally 60〜70%.
- The fluctuation of load is 10〜20%, if load prediction is operated well.
- The fluctuation of renewable energy has to be about 10%, but already over 30% in Barbados.
- If total demand of grid becomes to 90% over of rated capacity of grid,
  - Spinning reserve will be decreased.
  - Synchronizing power will be very small not to be returned to stable state.
- 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.

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

Appendix 4-3-2 Attendant list, and Q&A, of the 1st RE & Grid Stability Seminar (Barbados)

Workshop for RE and Grid Stability on 27 Jul 2022: List of Participants

	Name	Organisation	Position
1	Destine Gay	MEBD	Project Manager
2	Horace Archer	MEBD	Senior Technical Officer
3	William Hinds	MEBD	Senior Technical Officer
4	Robert Harewood	BLPC	
5	Rohan Seale	BLPC	
6	Johann Greaves	BLPC	
7	Stephen Worme	BREA	
8	Dr. Gary Jackson	CCREEE	Director
9	Jean-Michel Parle	CCREEE	
10	Danielle Evanson	CERMES, UWI	Researcher
11	Heather Sealy	GEED	
12	Baidy Diallo	HDF	Business Developer
13	Jeffrey Kiyoshi Chen	Massy	
14	Dwight Grannum	Willams Renewable Energy	
15	Gleeson Roach	Williams Solar	
16	Natasha Davis	Williams Solar	
17	Nida R	WREL	
18	Aria Goodridge		
19	D. Coombs		
20	Jamal J		
21	Lawson Benard		
22	Owen Reader		
23	Tyrone White		
24	Dudley Williams		
25	Ron Farley		
26	Prof. Hisao Taoka	JET	Energy Model Expert
27	Yuka Nakagawa	JET	
28	Alex Harewood	JET	Technical Assistant

Workshop for RE and Grid Stability on 27 Jul 2022: Question and Answers

	Question	Placed by	Response
1	Is this a project being done on behalf of the Ministry of Energy?	Stephen Worme	We are JICA (Japan International Cooperation Agency) team providing technical assistance to MEBD in this project. MEBD is our counterpart for this project.
2	Does the grid model presented incorporate RE production and energy consumption?	Rohan Seale	The model will incorporate RE production and demand. This is an introductory workshop and if we receive data from BLPC, we will produce accurate models based on BLPC data for the selected microgrid area.
3	Are these presentations going to be available to participants after this presentation.	Stephen Worme	We will provide the slides via chat.
4	Is Grid Forming Inverter technology at a point where it can be applied to a Grid the size of Barbados? Or are these only available at the Distributed Micro Grid Scale?	Jeffrey Kiyoshi Chen	The size of Grid Forming Inverter is from home size to utility size. But the cost will be high. So utility size including microgrid will be better.
5	This is very technical and even as an engineer, a lot of it is over my head. However, I gather these are all of the things you are going to be examining and will be advising on. A lot of PV has already installed. What is going to happen between now and when they come back with their final report?	Stephen Worme	Today is an introductory session. The detailed session for input and analysis with the simulator will be held in the next session in Sep 2022. Final Report will be submitted in Mar 2023.
6	Could you further discuss the fluctuation of renewable energy?	Horace Archer	Generally, acceptable fluctuation level is less than 10% of grid capacity, but in Barbados, it is already significantly beyond that figure as 30MW in demand swings are seen routinely while demand was 130 MW. According to IRRP, utility will need to install Synchronous Condensers , in addition to battery, to mitigate this problem.
7	My concern is that already our grid is unstable and we continue to add more PV and the expectation of PV owners is that their systems will be installed in a reasonable time frame. Is this going to be possible to continue installing systems and if we do what is going to be the impact on the grid?	Stephen Worme	According to increase of PV, the output fluctuation will be increased, while demand is kept same. Then, voltage and frequency goes up and down. In case of frequency drops due to sudden output decrease without any stabilization measurement, under frequency relay (UFR) operates at the source of feeder, and the feeder is tripped to cut the load, and power cut will happen for the feeder. At the worst case, it will bring black out of the country. Battery installation is needed as soon as possible. Large PV installations can work, but energy management system with weather prediction AI will be necessary. Some ideas to solve this problem are as follows. (1)Install Batteries to substations. It can control all PV at substations. (2)Utility controls output of PV's using smart meters or other metering and control equipments. (3)Install PV with Grid Forming Inverter (future application)
8	It is my understanding that the Utility will not be able to get batteries for many months. What do we do in the interim?	Stephen Worme	Black-outs is an significant issue as risk increases with a greater influx of variable PV. Significant PV curtailment can be a tentative solution. Utility should use some of current diesel generators as LFC generator to control and keep frequency in stable state.
9	The use of concentrated solar heat power	Horace Archer	IRRP suggests to introduce concentrated solar heat generation (CSP) after 2028 as base case. It can be used to mitigate issues with intermittency since it can provide inertia. A study indicates irradiation level more than 2000 DNI will result in cost range of 6-8 c/kWh. It is still not sure if it is economic as it has not been deployed in places like Barbados.

Appendix 4-4-1 Material for the 2nd RE & Grid Stability Seminar (Barbados)

Technical Cooperation to Promote
Energy Efficiency in Caribbean Countries

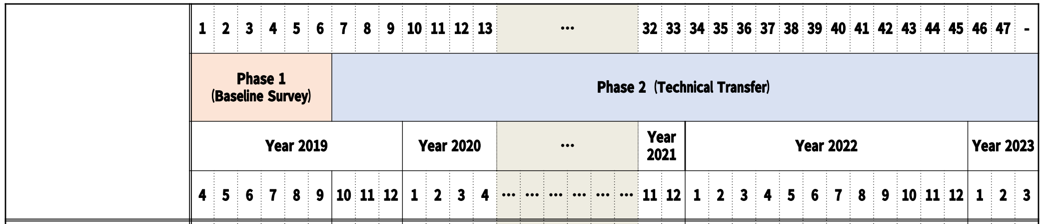
Consideration of Large VRE into Grid

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

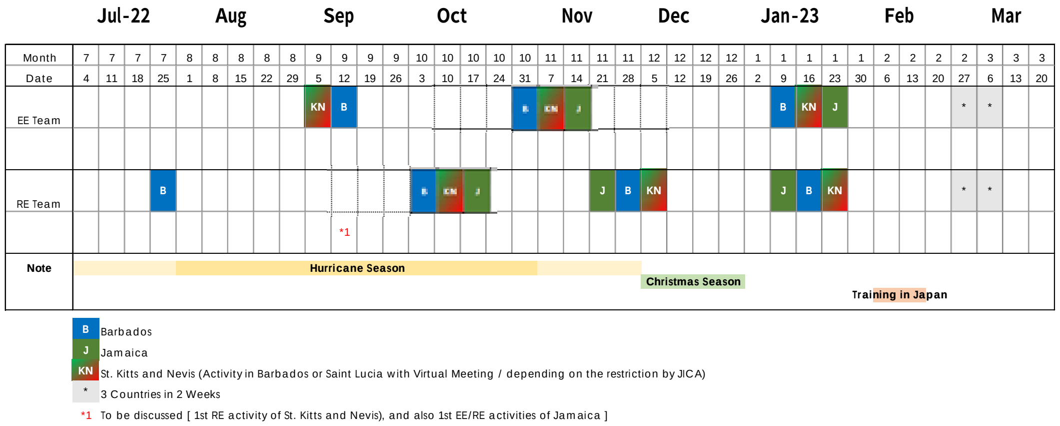
Barbados
- Training and Provision of Grid simulation software
- Micro-grid concept study at Coverley Village

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	11	11	11	12	12	12	12	1	1	1	1	1	2	2	2	2	3	3	3
Date	4	11	18	25	1	8	15	22	29	5	12	19	26	3	10	17	24	31	7	14	21	28	5	12	19	26	2	9	16	23	30	6	13	20	27	6	13	20
EE Team										KN	B							B	KN	J								B	KN	J					*	*		
RE Team				B										B	KN	J					J	B	KN					J	B	KN					*	*		
											*1																											

Note
Hurricane Season
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

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2. Baseline Survey Report- Summary

Summary: Barbados

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

Barbados Grid and PS

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

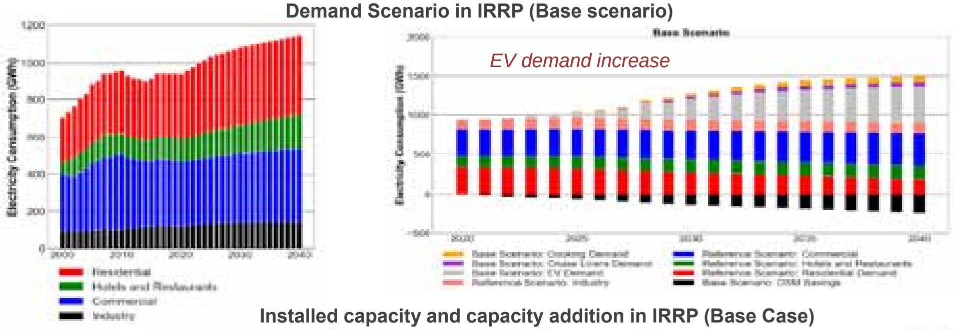
	Location	MW/u	Qy	MW	Remark
Existing					
Total thermal power				**232**	
	Spring Field	12	3	36	LSD Engine
	Spring Field	12.5	1	12.5	LSD Engine
	Spring Field	30	2	60	LSD Engine
	Spring Field	20	2	40	Steam Turbine
	Spring Field	17.5	1	17.5	Gas Tubine
	Spring Field Total		9	166	
	Garrison	13	1	13	Gas Tubine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

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

Barbados Demand&Installed capacity in IRRP

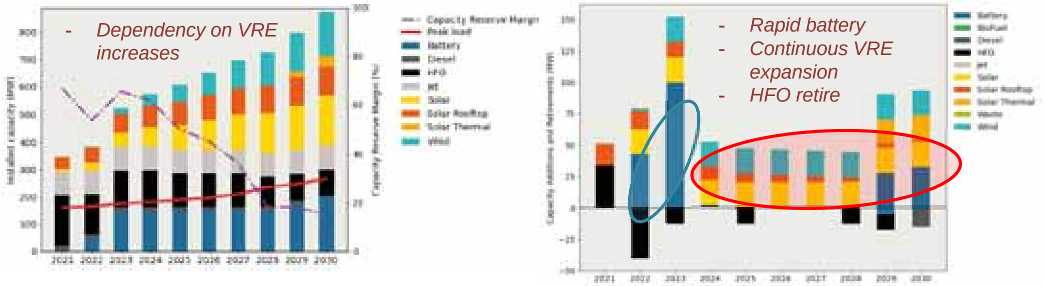
Source: IRRP Draft 2021, MottMacDonald

Demand Scenario in IRRP (Base scenario)



EV demand increase

Installed capacity and capacity addition in IRRP (Base Case)



- *Dependency on VRE increases*

- *Rapid battery*
- *Continuous VRE expansion*
- *HFO retire*

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

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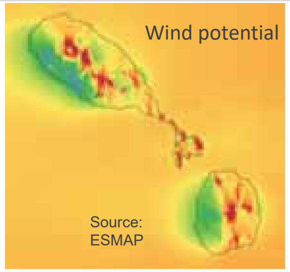
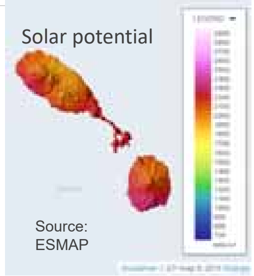
RE: Status in St.Kitts & Navis

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



Source: ESMAP



Source: ESMAP

Necessary consideration for future RE

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

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

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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

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RE Status in Jamaica

Challenges for RE & Grid:

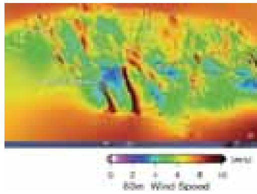
- ✓ Increasing RE capacity >15%. Grid stability and power cut issue
  - ✓ Feeder cut at 49.5 Hz
- ✓ System losses 26.3% (2018) →28.3% (2021)
- ✓ Large number of distributed PV, available database?
- ✓ Wind & PV potential unevenly distributed →less smoothing

Source: JPS, 2019

VRE Projects in Jamica

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

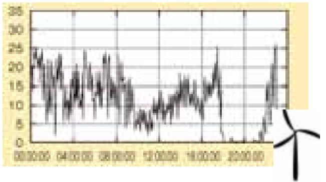
Source: Prepared by JET with several data sources



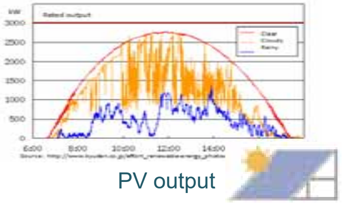
Wind Potential in Jamaica

Source: Sustainable Energy Roadmap 2013

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

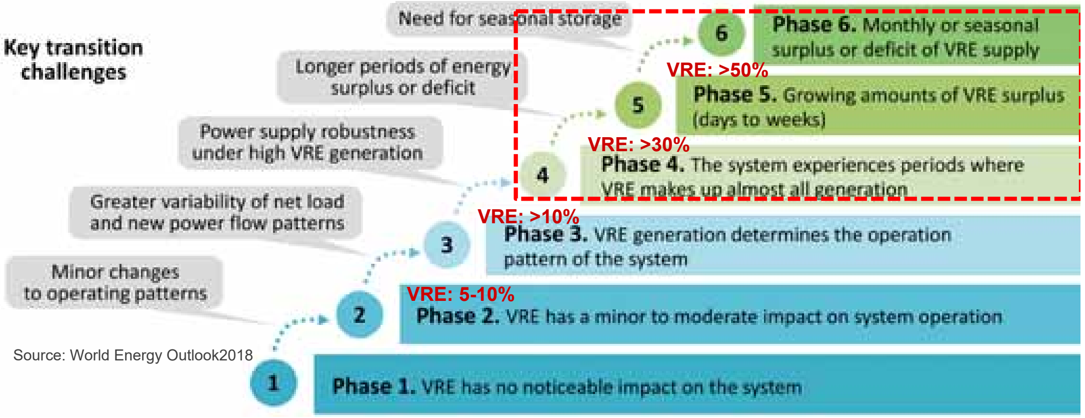
PV
- No output in night-time and rainy day
- Large fluctuation in tropical climate (likely to change 80% in a minute)

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

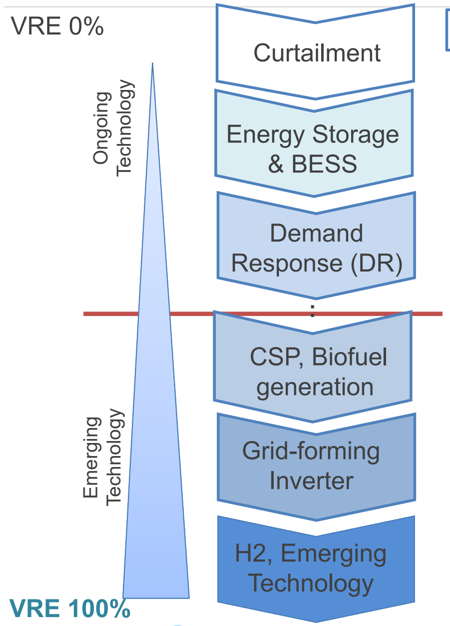
Transition Changes of RE Penetration



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

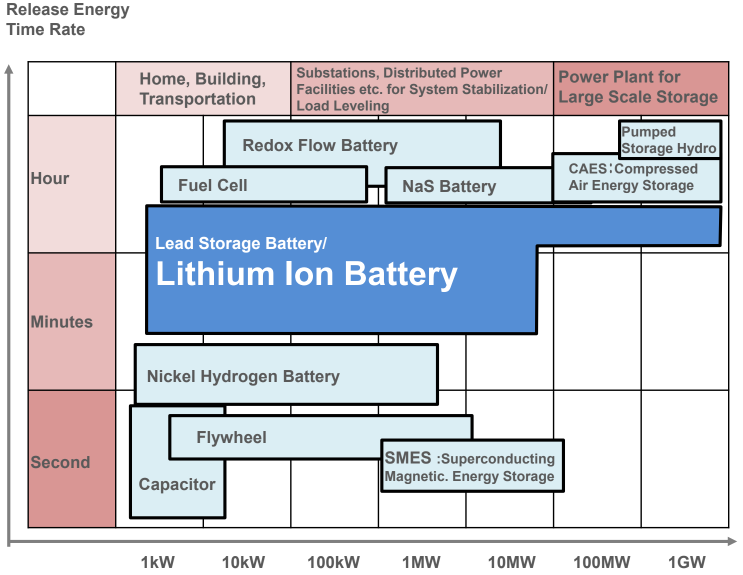


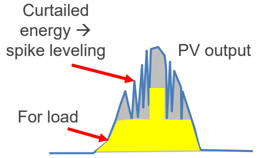
Voltage and frequency Stabilization
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- EV charging time shift
- Demand side management
- Regulatory framework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

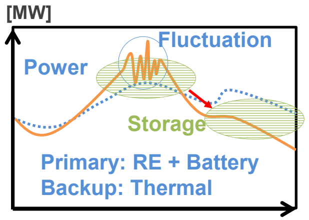
Insufficient Inertia, Synchronizing Force
- **Synchronous condenser, Statcom**
- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale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

Battery and Energy Storage

Positioning for Energy Storage Technology



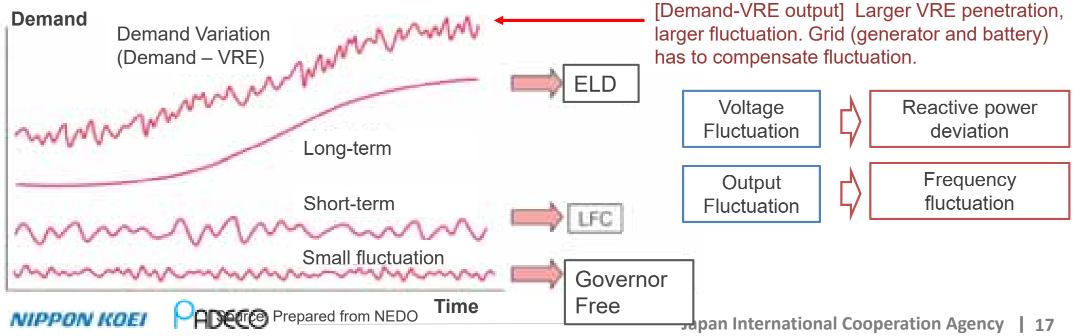




Source: NEDO Renewable Energy Technology White Paper Chapter 9

Grid Stabilization: GF, LFC, ELD

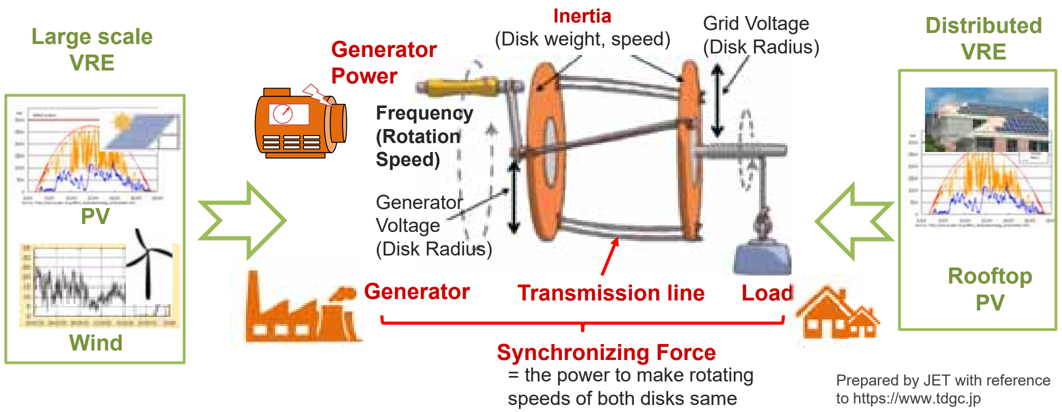
Control Type	Frequency	Description
Governor Free (GF)	Within one minute	Generator detects rotation fluctuation and automatically controls rotation so that frequency is kept at suitable level
Load Frequency Control (LFC)	Minutes-ten minutes	This involves the sensing of the bus bar frequency and compares 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.



[Demand-VRE output] Larger VRE penetration, larger fluctuation. Grid (generator and battery) has to compensate fluctuation.

Source: Prepared from NEDO

Inertia and Synchronizing Force with RE



Synchronizing Force
= the power to make rotating speeds of both disks same

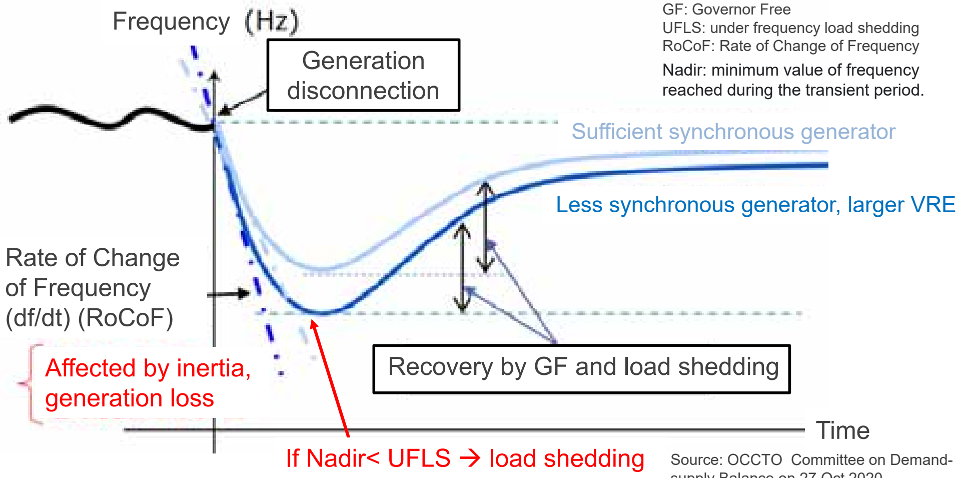
Prepared by JET with reference to https://www.tdgc.jp

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

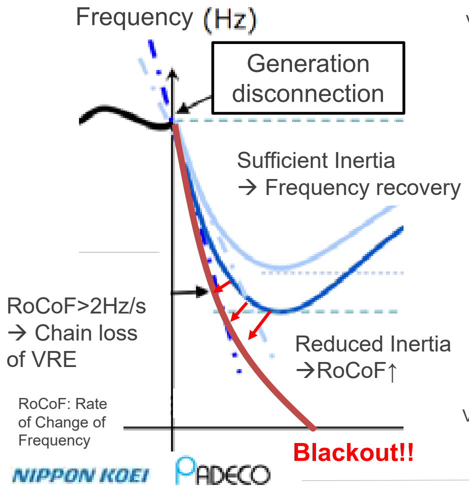


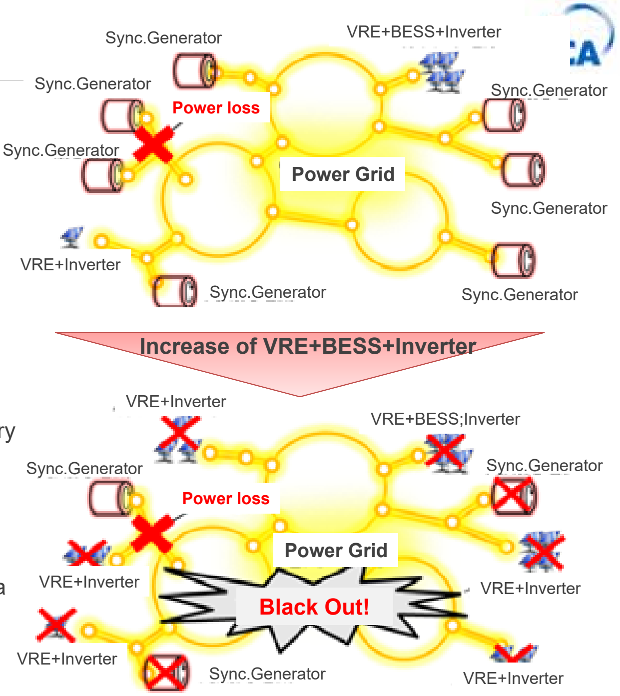
GF: Governor Free
UFLS: under frequency load shedding
RoCoF: Rate of Change of Frequency
Nadir: minimum value of frequency reached during the transient period.

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

Black-out when insufficient Sync. Gen.

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



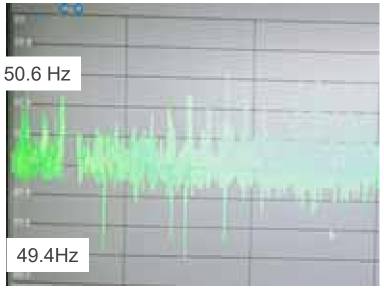


Source: Transmission and Grid Council, Japan

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?

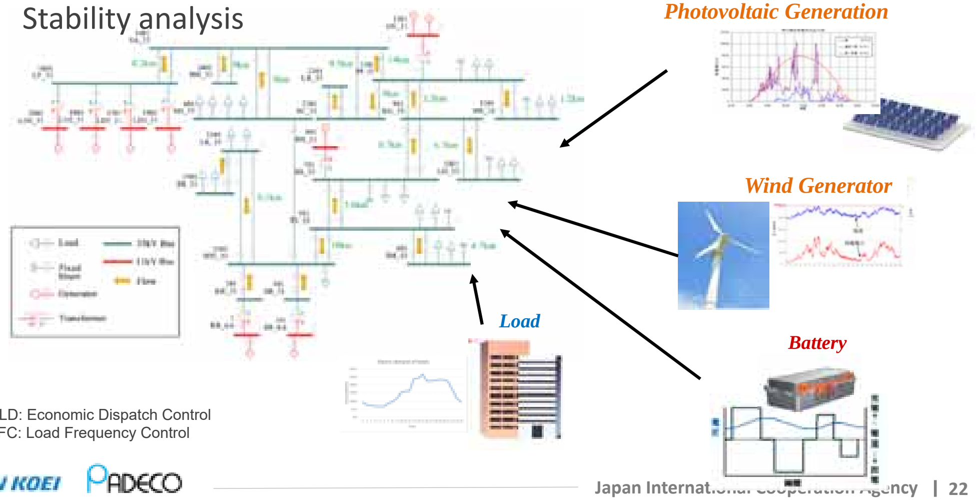
- Planning with **grid simulation** is necessary.
  - Load flow analysis
  - Stability analysis
- Grid code needs to be checked for condition of grid connection of VRE and BESS



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

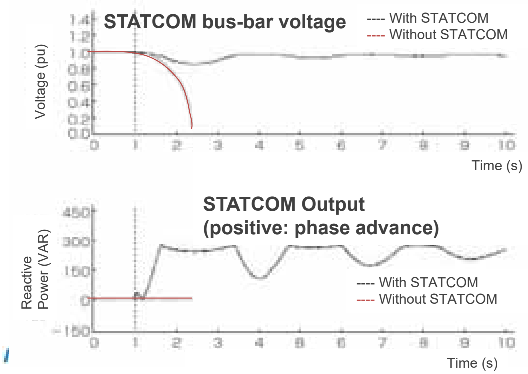
SCO (Synchronous Condenser) :

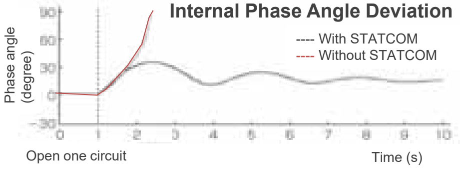
SCO is DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. Though changing field excitation, SCO adjusts reactive power and provides reactive power at the time of voltage drop.

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

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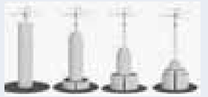
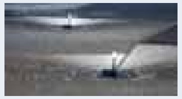
Emerging technology for large RE with Grid stabilization : Generation with Inertia and Synchronous Power

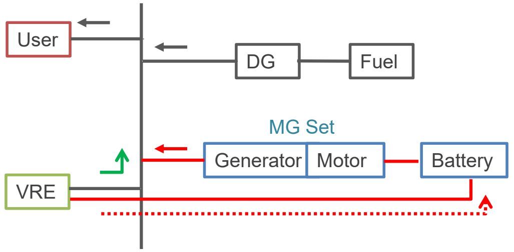
Type of Technology		Advantage	Develop stage
 Source: taiyo-electric	Motor generator (MG)	- Energy in battery provides synchronization and inertia - Small scale supply, for micro grid	- Used as frequency conversion - Commercial operation
 energyvault.com/gravity	Gravity Storage Battery	- Gravity of recycled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

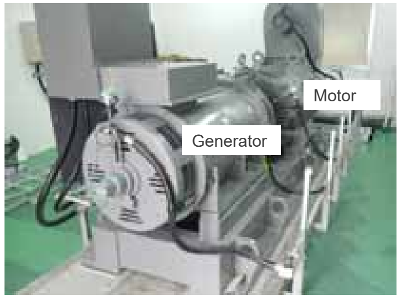
Hateruma Island: Southern most island in Japan
- Area：12.73 km2 , Population 527, hh 272 (2016)
- Peak power: 770 kW (2016)
- Generation: DG (Bunkar-A, total 1,250kW)
- Wind (245kW✕2, total 490kW)
- Lead-acid Batt (600kW/1,500kWh)
- **MG Set: Rated 300 kW**

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

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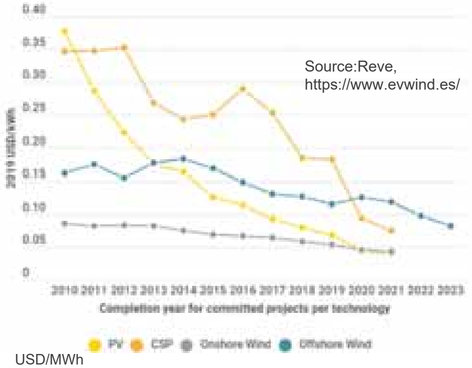
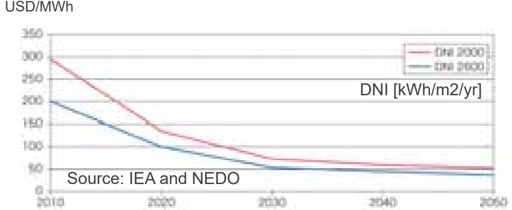
Option for 100% RE: CSP

Concentrating Solar Thermal Power (CSP)

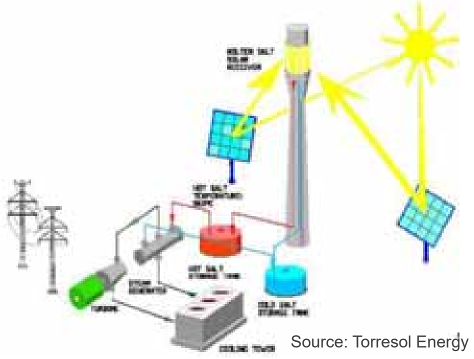


Source:Reve, https://www.evwind.es/



Source: IEA and NEDO

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



Source: Torresol Energy

- 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

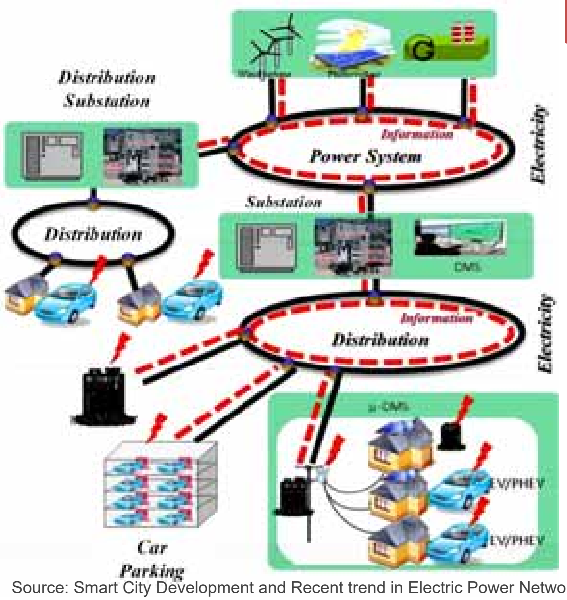
9 Sep 2019 Kanto, Japan
@kadowaki_kozo
Damage of roof-top structure by high speed wind

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

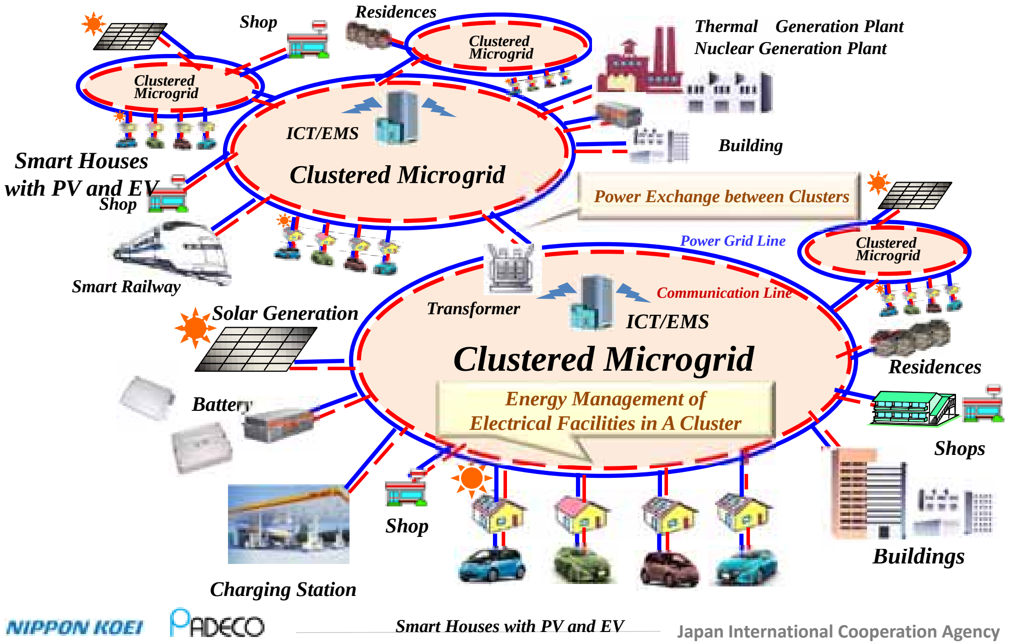


Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

Concept of Micro-grid

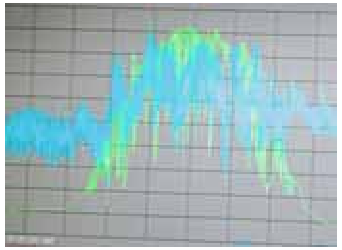
- ✓ Respective Micro-grid is connected each other, and each Micro-grid can work independently
- ✓ Local energy production for local consumption
  - ✓ Generation: PV, wind, biomass, DG, GT, battery, etc.
  - ✓ Demand: industry, commercial, home, EV, etc.
- ✓ No transmission → loss saving
- ✓ With IoT,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

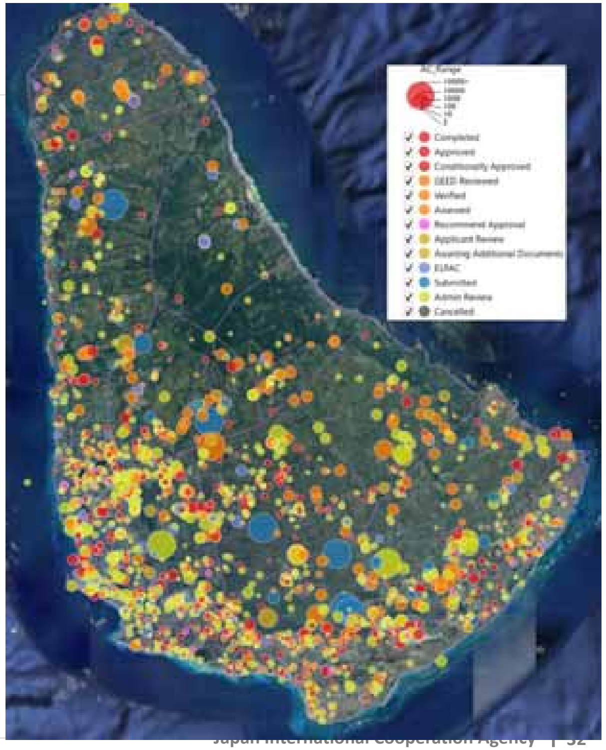
Microgrid for Resilient System
-- Autonomous Micro Grid



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

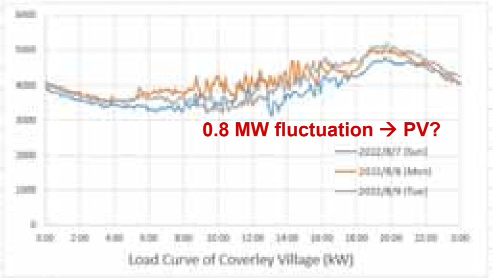
- Requested data: Location of transformer, existing PV, LV line alignment (GIS), location shunt capacitors(ShC) or static var compensators(SVC or STATCOM) if any
- Two autonomous Microgrid connecting Coverley Village Microgrid and Airport Microgrid can be preposed

---

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

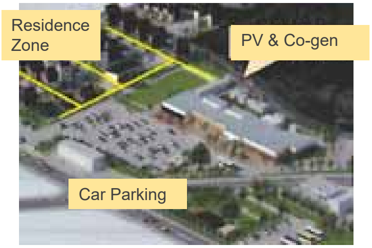


Load Curve of Coverley Village (kW)

Example of system, to be reviewed

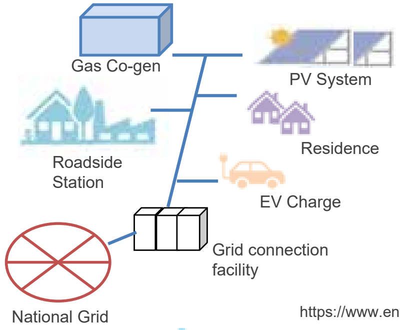
Nos of houses	1026	nos
Roof area for PV	30	m2/house
Commercial/official roof	300	m2 (6 facilities)
Total roof area	31,080	m2
PV Capacity	3108	kWp
Specific PV generation	4.917	kWh/kW/day
PV generation energy	15,282	kWh/day
Peak demand	4,104	kW
Electric energy demand	41,329	kWh/day
External PV	6,622	kWp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

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

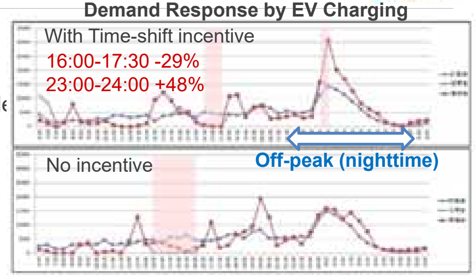
(1) TOU or Unit charge rate according to load curve and weather and PV output with EMS

(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

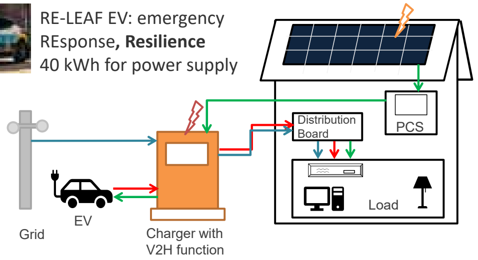


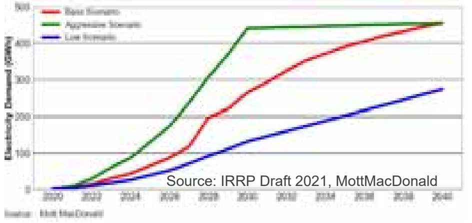
https://xtech.nikkei.com/dm/article/FEATURE/20150120/399714/?P=5

(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





Source: IRRP Draft 2021, MottMacDonald

(3) Promotion of solar assisted car

- 60 kWh, 400→725km , >47,600ASD (33,320 USD)
- Load to grid is mitigated

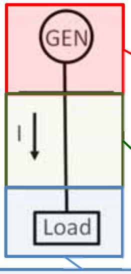
https://www.drive.com.au/

Grid Simulation: for Optimization of Load Flow Analysis

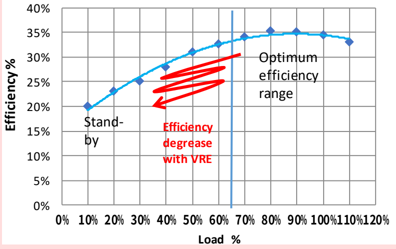
Microgrid Designer consists of tools of Economic Load Dispatch (ELD) and load flow analysis modules, developed by Energy & Environment Technology Research Institute, Japan (Venture company of Waseda Univ).

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.

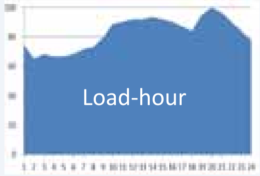
Input Data



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)



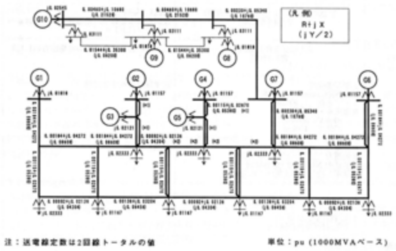
Transmission Line, Substation

[Common]
- Power flow limitation
- Voltage Magnitude

[Option 1]
- Impedance Map

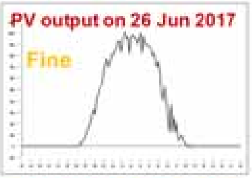
[Option 2]
- Shunt Capacitor
- Cable length
- Cable capacitance [μF/km]

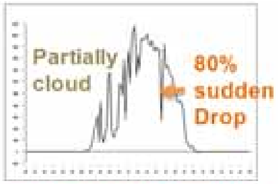
Example of Impedance Map

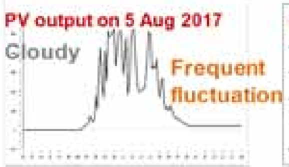


Input Data

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



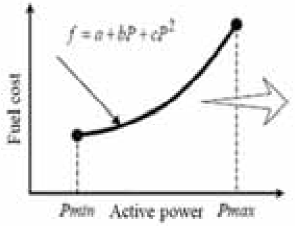




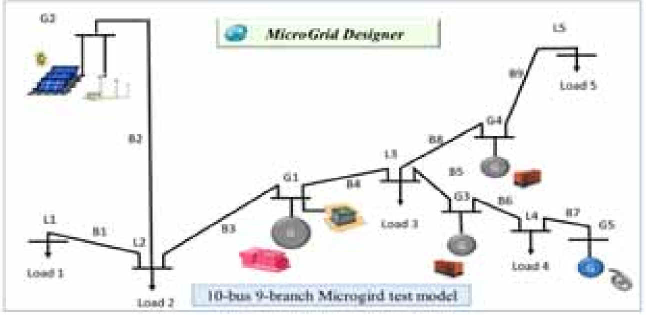
Battery
- Sum of MWh

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

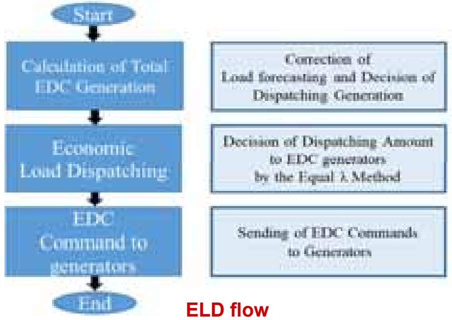
ELD example with IEEE Microgrid Model



Load-fuel efficiency curve



10-bus 9-branch Microgird test model



Start

Calculation of Total EDC Generation

Correction of Load forecasting and Decision of Dispatching Generation

Economic Load Dispatching

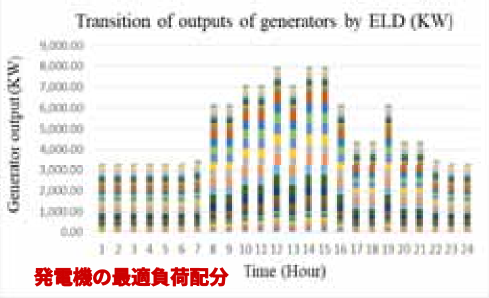
Decision of Dispatching Amount to EDC generators by the Equal λ Method

EDC Command to generators

Sending of EDC Commands to Generators

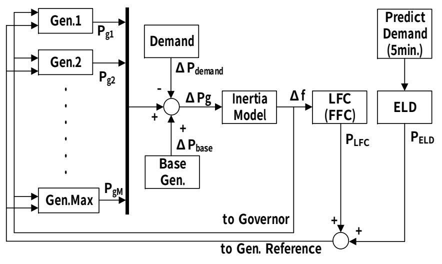
End

ELD flow

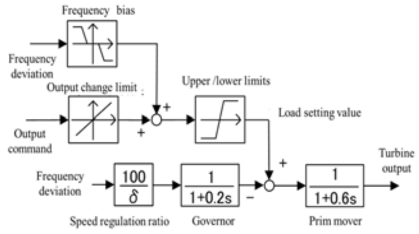


発電機の最適負荷配分

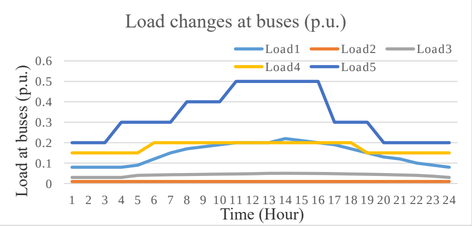
Load-flow Analysis

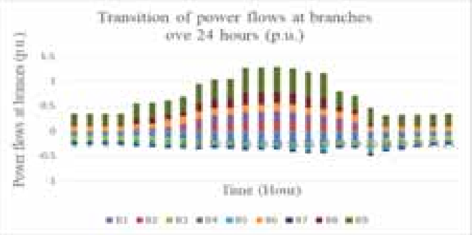


LFC model using ELD result

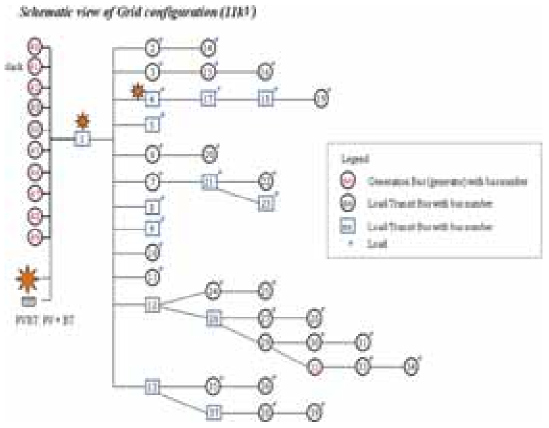


Output model of DG

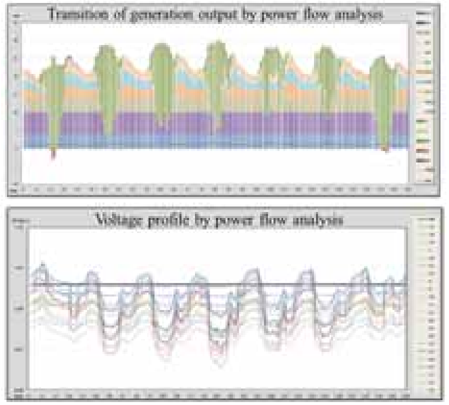




Grid Analysis Model of Microgrid in St. Kitts



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

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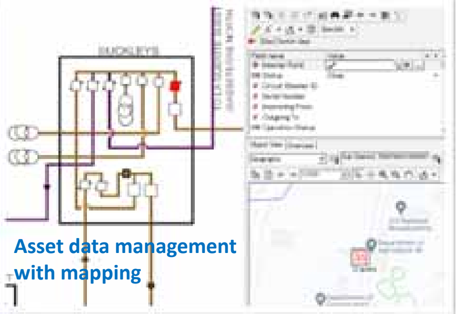
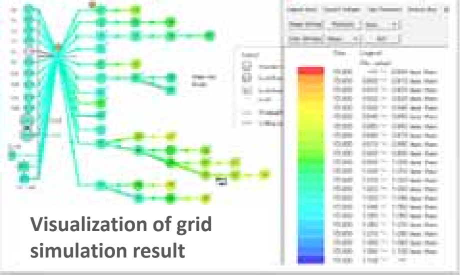
GIS, Asset Management with Grid Simulation Example of St. Kitts

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

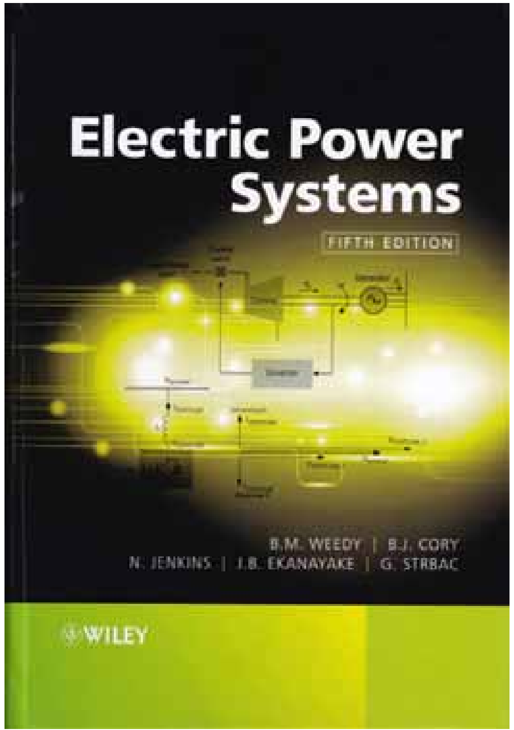
- Day 1
  1. What is Power System: Three-Phase AC, Single line network description
  2. Per Unit Method: Definition, Example
  3. Modeling of Power System Equipment: Transmission line, Transformer, Generator, Load
  4. Active Power & Frequency: Frequency control, Area requirement
  5. Reactive Power & 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. "

電気・電子工学ライブラリ
UKE 03
電力システム工学の基礎
加藤政一・田岡久雄 共著
数理工学社

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
B.M. WEEDY | B.J. CORY
N. JENKINS | J.B. EKANAYAKE | G. STRBAC
WILEY

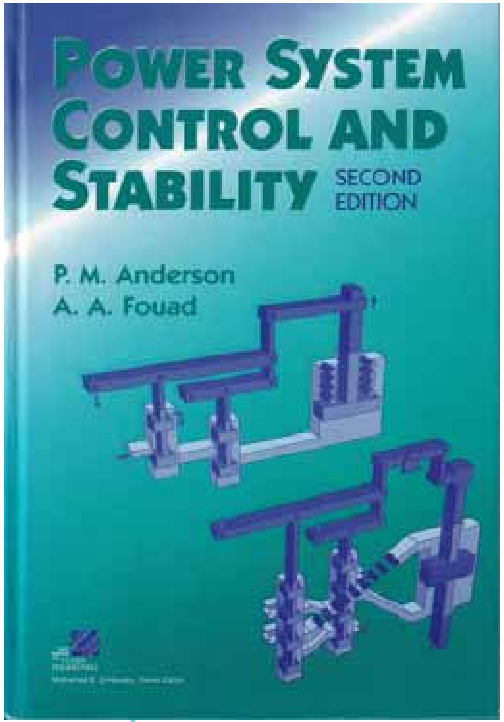
Electric Power Systems

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

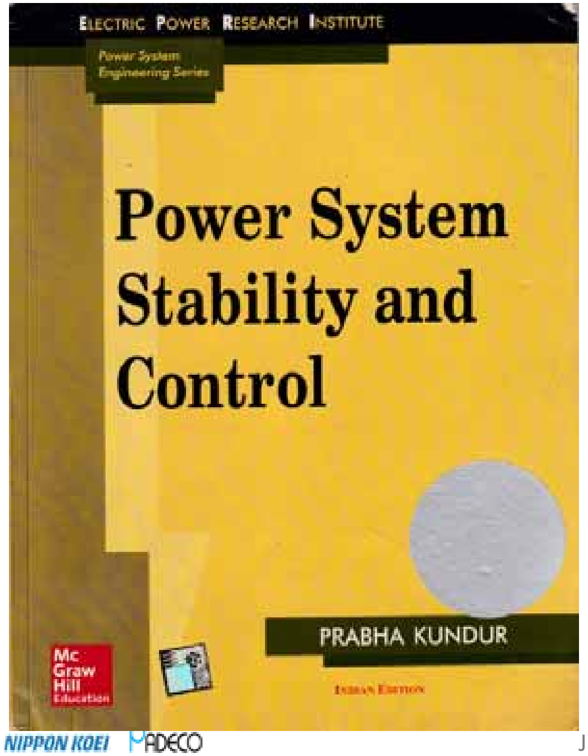
Classic Textbook of Stability

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

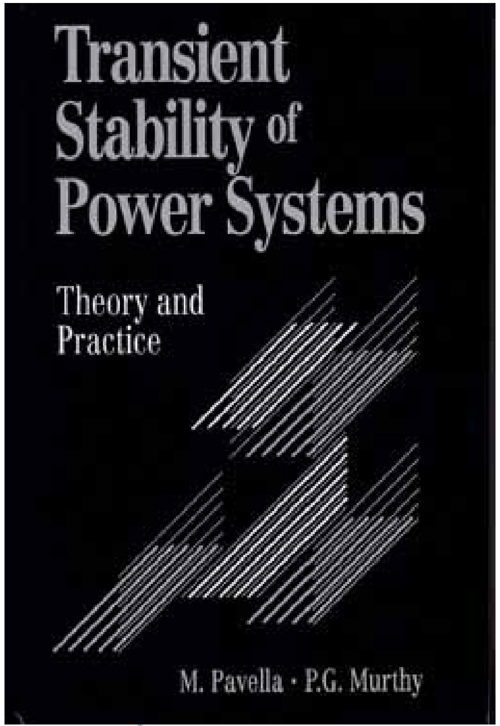
Widely Read Textbook

P. Kundur

McGraw-Hill,

New York, USA

1994



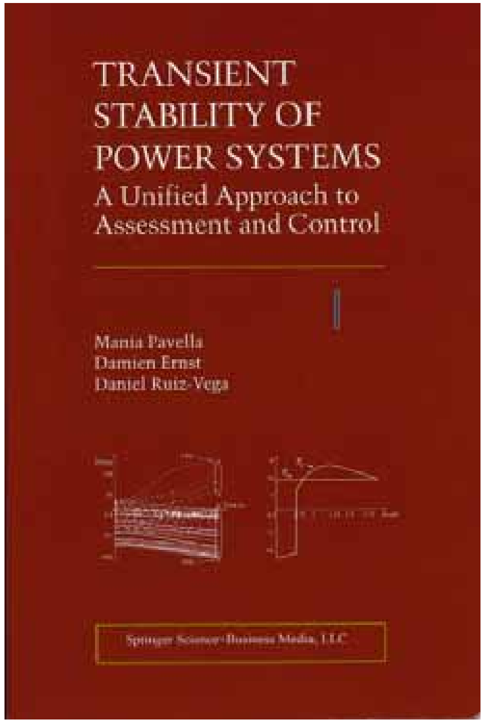
Transient Stability of Power Systems
Theory and Practice

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

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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

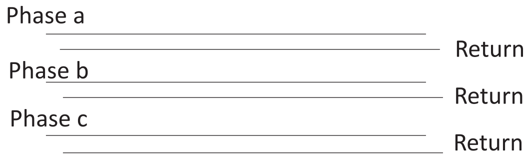
- Flow of Electricity
  - DC (Direct Current): Difficult to change voltage and switch off circuit
  - AC (Alternative Current): Stability problem
- AC
  - Single Phase & Three Phase
- Components of Power System
  - Transmission Line
  - Transformer & Switchgear (Substation)
  - Generator (Synchronous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

Methods of Power System Analysis

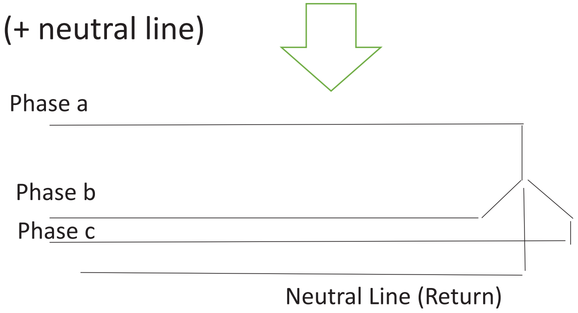
- Steady State: under Small Disturbance
  - Voltage, Power, Angle are constant at a certain time
  - It keeps the same state under small disturbance
  - ->Load Flow Analysis, Eigenvalue Analysis
- Transient State: under Large Disturbance
  - Voltage, Power, Angle are changing
  - ->Equal Area Criterion,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

Single-Phase to Three-Phase

- Single transmission line
  - Require 2 lines

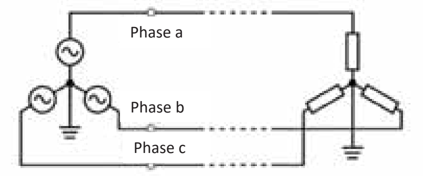


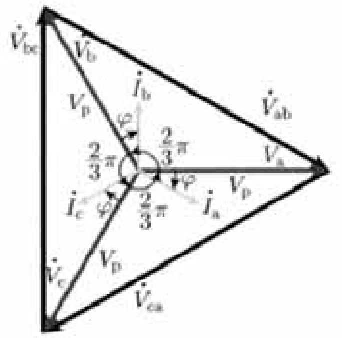
- Three-Phase transmission line
  - Require 3 or 4 lines (+ neutral line)
  - 3 times capacity



Three-Phase AC Circuit

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



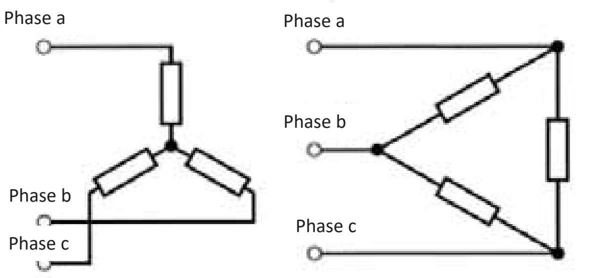


Va, Vb, Vc: Phase Voltage
Vac, Vbc, Vca: Line-to-Line Voltage
Ia, Ib, Ic: Phase Current
Iab, Ibc, Ica: Line Current

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

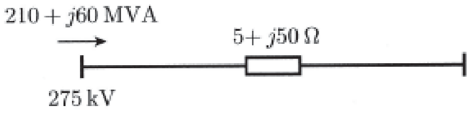
Example of Conversion to Per Unit

(1) Calculate Base Value

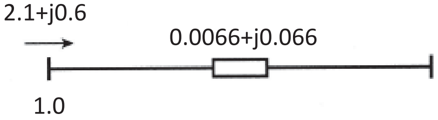
Vbase=275kV

(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



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

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

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

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

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

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

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

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

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

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

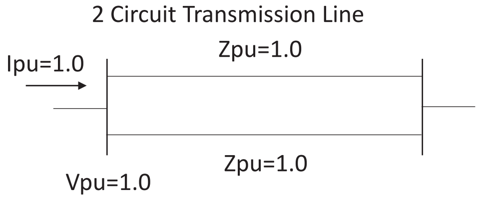
- The meaning:

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



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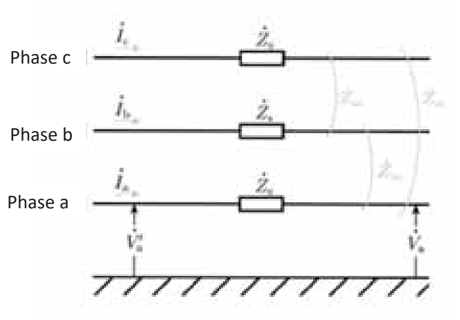
3. Modeling of Power System Equipment

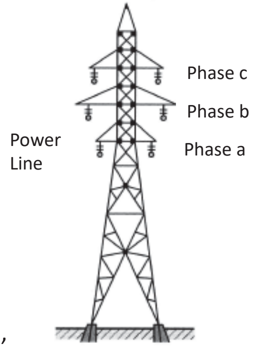
- Make it easy to analyze feature of power system equipment
- Modeling of Components of Power System
  - Transmission Line
  - Transformer & Switchgear (Substation)
  - Generator (Synchronous Generator, Photovoltaic, Wind Power)
  - Load

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.

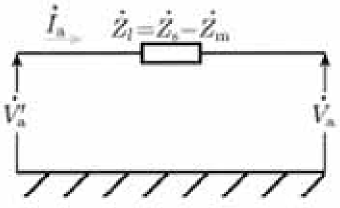
Impedance of Transmission Line

- Impedance of Transmission Line

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

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

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



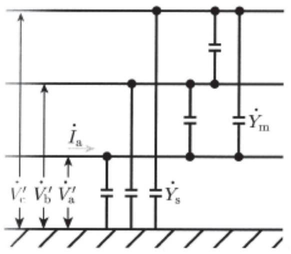
Zs: Self Impedance, Zm: Mutual Impedance
Z_l=Zs-Zm : Line Impedance, Sum of self and mutual impedance
R: Line Resistance
Ls: Self Inductance, Lm: Mutual Inductance
Ia, Ib, Ic: Phase Current
Va’, Va: Phase Voltage
(Sending Terminal Voltage, Receiving Terminal Voltage)

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

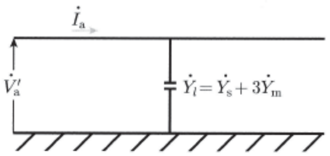
Admittance of Transmission Line

- 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

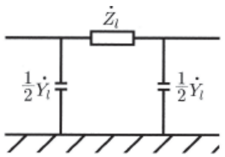


Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

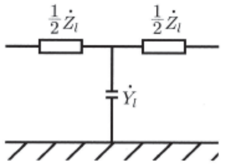
Equivalent Circuit of Transmission Line

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

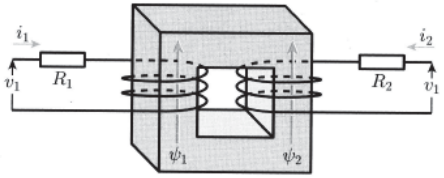
- Mathematical equations of transformer

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

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

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

$$r = \frac{M_{12}}{L_2}$$



$$\begin{cases} \dot{V}_1 = \dot{I}_1 R_1 + j\omega(L_1 \dot{I}_1 + M_{12}\dot{I}_2) = (R_1 + j\omega L_1)\dot{I}_1 + j\omega M_{12}\dot{I}_2 \\ \dot{V}_2 = \dot{I}_2 R_2 + j\omega(M_{21}\dot{I}_1 + L_2\dot{I}_2) = j\omega M_{21}\dot{I}_1 + (R_2 + j\omega L_2)\dot{I}_2 \end{cases}$$

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

Equivalent Circuit of Transformer

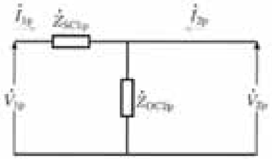
- Relationship of per unit base values

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

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

- 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

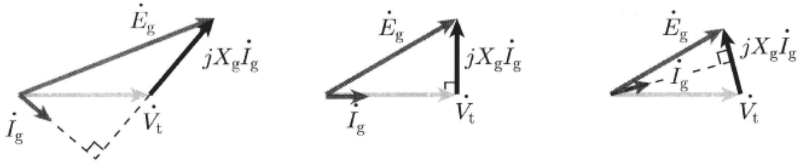
$$\frac{V_{1\mathrm{base}}}{V_{2\mathrm{base}}} = \frac{\dfrac{(VA)_{1\mathrm{base}}}{I_{1\mathrm{base}}}}{\dfrac{(VA)_{2\mathrm{base}}}{I_{2\mathrm{base}}}} = \frac{I_{2\mathrm{base}}}{I_{1\mathrm{base}}} = \frac{rI_{1\mathrm{base}}}{I_{1\mathrm{base}}} = r$$

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

---

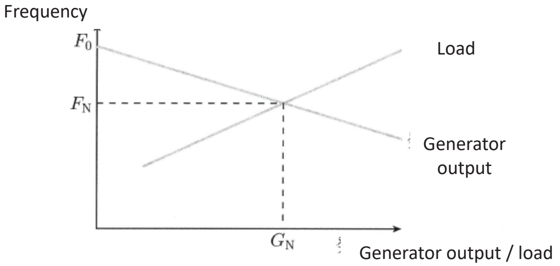
4. Active Power & Frequency

- 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

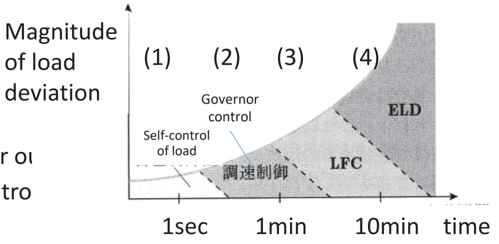
- Frequency Control Scheme is categorized to 4 stages.

(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.

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

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

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

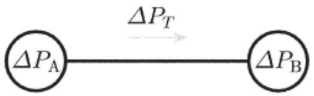
$$\Delta P + (\Delta G - \Delta L) = 0$$
$$\Delta P = (K_G + K_L)\Delta F$$

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

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

Power Systems Connected by a Tie-Line

- Two interconnected power systems



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

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

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

Frequency of Interconnected grids are collected as the following equations.

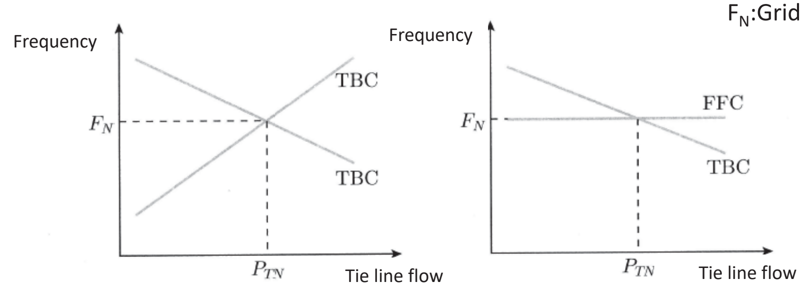
$$\begin{cases} \Delta F = \dfrac{\Delta P_A + \Delta P_B}{K_A + K_B} \\ \Delta P_T = \dfrac{K_B \Delta P_A - K_A \Delta P_B}{K_A + K_B} \end{cases}$$

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

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

Relationship between generator, load and frequency

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



F_N:Grid Freqency

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

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5. Reactive Power & Voltage

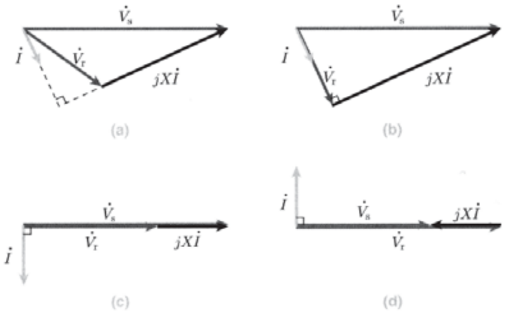
- Most of load consumes reactive power and its voltage will decrease.
- In order to keep voltage to a certain value, reactive power should be provided.
- Provider of reactive power
  - Synchronous generator
  - Synchronous Condenser/Capacitor (SC, SCO)
  - Static Var Compensator (SVC)
  - Static Synchronous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

Reactive Power & Voltage

- Relationship between Reactive Power and Voltage

$$\dot{V}_{\mathrm{r}} = \dot{V}_{\mathrm{s}} - jX\dot{I}$$

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



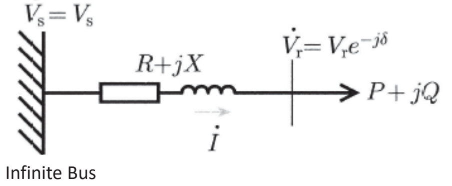
Vs: Sending Terminal Voltage, Vr: Receiving Terminal Voltage
I: Tiranssmission Line Curent
X: Transmission Line Impedance

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

Reactive Power

- Sensitivity of P & Q

$$P + jQ = \dot{V}_{\mathrm{r}}\dot{I}^{*}$$
$$= V_{\mathrm{r}}e^{-j\delta}\left(\frac{V_{\mathrm{s}} - V_{\mathrm{r}}e^{-j\delta}}{R + jX}\right)^{*}$$
$$= \frac{V_{\mathrm{s}}V_{\mathrm{r}}e^{-j\delta} - V_{\mathrm{r}}^{2}}{R - jX}$$
$$RP + XQ + V_{\mathrm{r}}^{2} = V_{\mathrm{s}}V_{\mathrm{r}}\cos\delta$$
$$RQ - XP = -V_{\mathrm{s}}V_{\mathrm{r}}\sin\delta$$
$$(RP + XQ + V_{\mathrm{r}}^{2})^{2} + (RQ - XP)^{2} = V_{\mathrm{s}}^{2}V_{\mathrm{r}}^{2}$$
$$\frac{\partial V_{\mathrm{r}}}{\partial P} = -\frac{(R^{2} + X^{2})P + RV_{\mathrm{r}}^{2}}{V_{\mathrm{r}}(2XQ + 2RP + 2V_{\mathrm{r}}^{2} - V_{\mathrm{s}}^{2})}$$
$$\frac{\partial V_{\mathrm{r}}}{\partial Q} = -\frac{(R^{2} + X^{2})Q + XV_{\mathrm{r}}^{2}}{V_{\mathrm{r}}(2XQ + 2RP + 2V_{\mathrm{r}}^{2} - V_{\mathrm{s}}^{2})}$$



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.

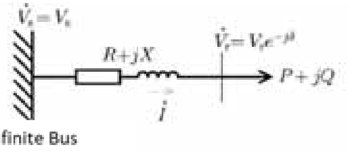
$$\begin{cases} \Delta V_{\mathrm{r},P} = \left(\dfrac{\partial V_\mathrm{r}}{\partial P}\right)\Delta P \\ \Delta V_{\mathrm{r},Q} = \left(\dfrac{\partial V_\mathrm{r}}{\partial Q}\right)\Delta Q \end{cases} \qquad \begin{aligned} \frac{\partial V_\mathrm{r}}{\partial P} &= -\frac{(R^2+X^2)P+RV_\mathrm{r}^2}{V_\mathrm{r}(2XQ+2RP+2V_\mathrm{r}^2-V_\mathrm{s}^2)} \\ \frac{\partial V_\mathrm{r}}{\partial Q} &= -\frac{(R^2+X^2)Q+XV_\mathrm{r}^2}{V_\mathrm{r}(2XQ+2RP+2V_\mathrm{r}^2-V_\mathrm{s}^2)} \end{aligned}$$

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

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

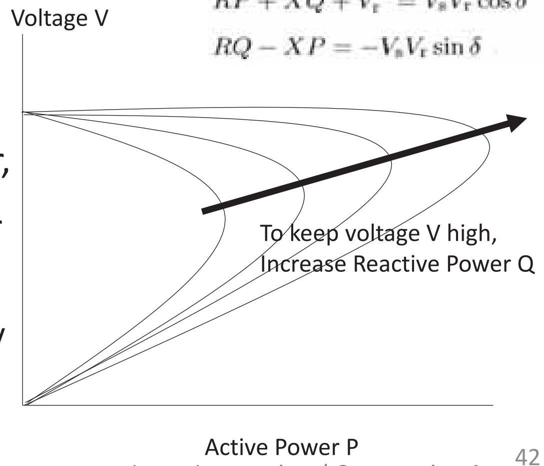
P-V Curve & Q(Reactive Power)

- 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.



$$RP + XQ + V_\mathrm{r}^2 = V_\mathrm{s}V_\mathrm{r}\cos\delta$$

$$RQ - XP = -V_\mathrm{s}V_\mathrm{r}\sin\delta$$



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

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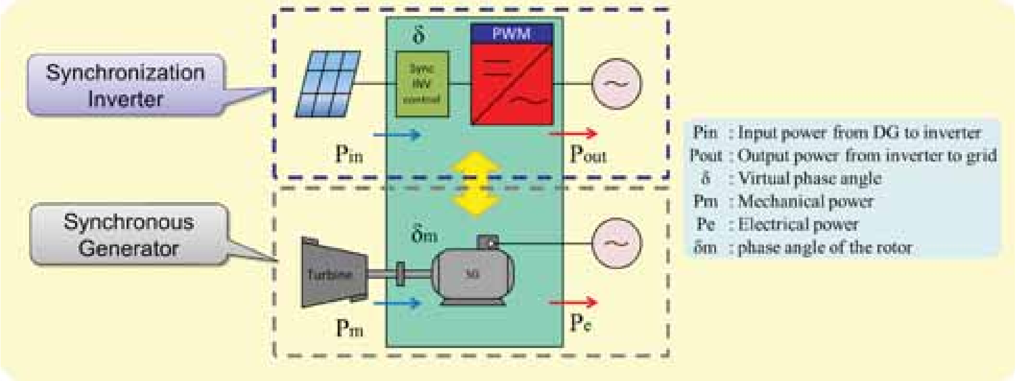
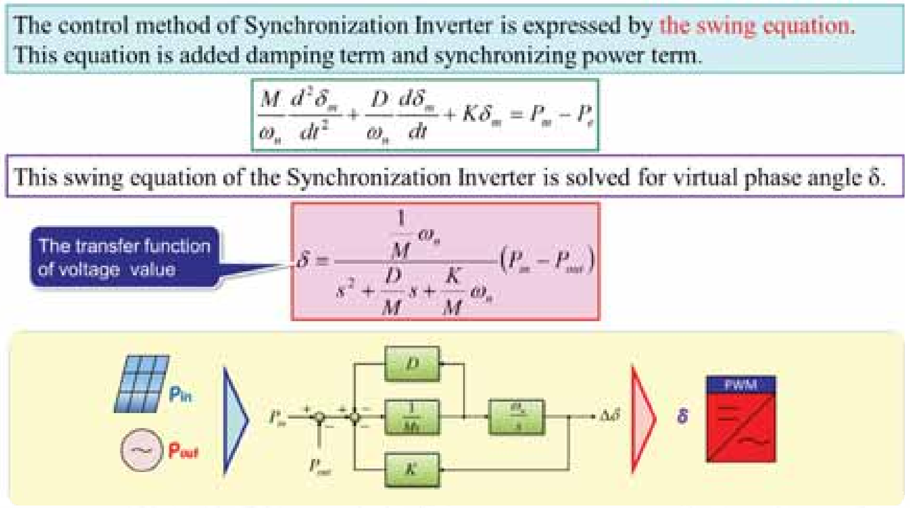
Concept of Virtual Inertia



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

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

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

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

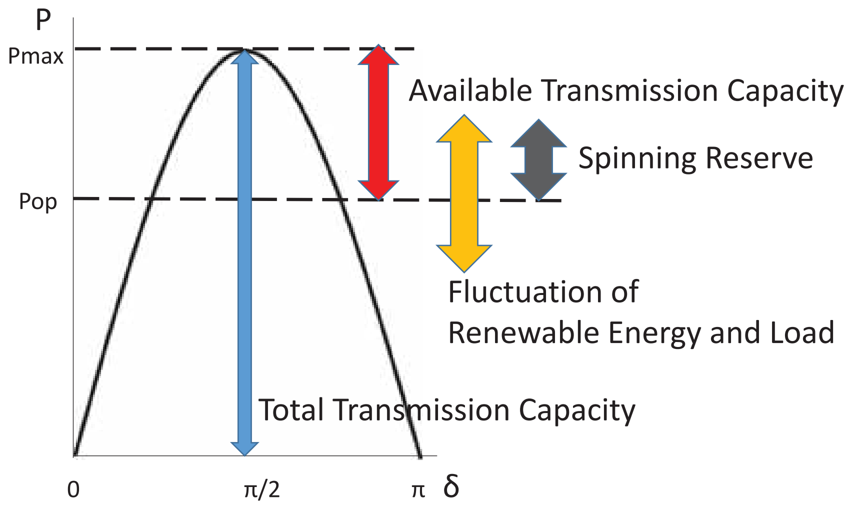
- Available Transmission Capacity from Transient Stability

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

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

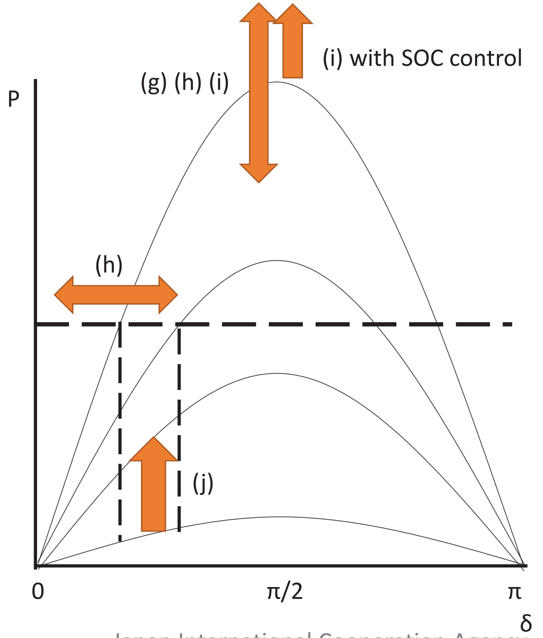
(i) Battery

Change Pmax

(j) SCO

(Synchronous Condenser)

Change P during fault



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6. Practice of Modeling Grid

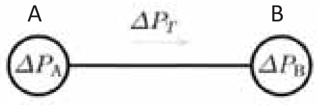
- Per Unit Calculation
  - Calculation of base current and impedance for several base voltage and base capacity
- Active Power - Frequency Relationship
  - Calculation of Area Requirement
  - The way to calculate Microgrid Interconnection
- Reactive Power - Voltage Relationship
  - Calculation of voltage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

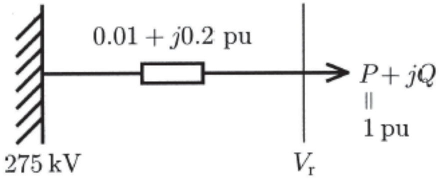


Exercise 3

- 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
   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

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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

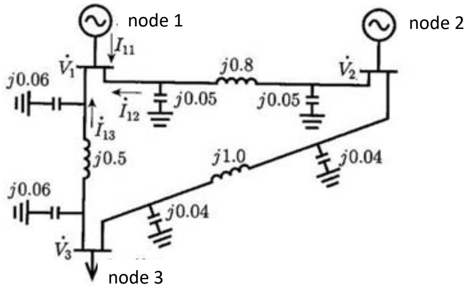
- DC Flow Method (manual calculation)
  - Simplified Load Flow Calculation of Three-phase AC Transmission Line
  - Solve relationship between power and voltage angle
- Newton Raphson Method
  - Solve relationship between power and voltage in vector

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

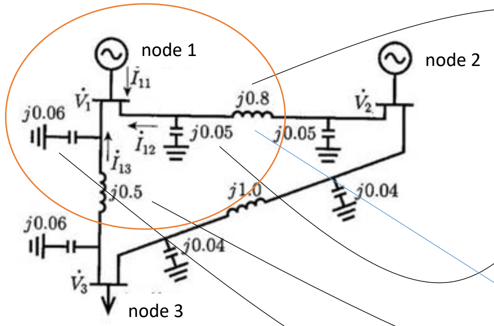


- Calculation example of power flow in 3 nodes network

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

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

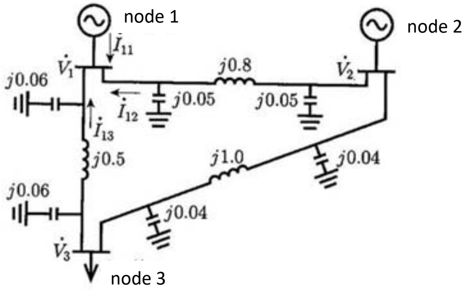
- Y11,Y22,Y33:
  - Driving Point Admittance
- Y12,Y21,Y13,Y31,Y23,Y32:
  - Transfer Admittance

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.

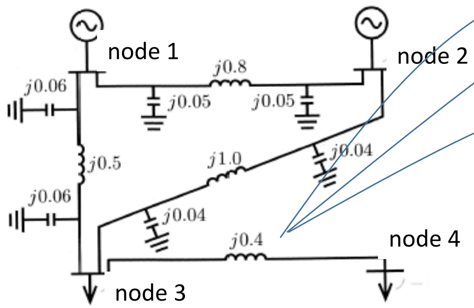
Node Admittance Matrix
- Adding new node

- 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

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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

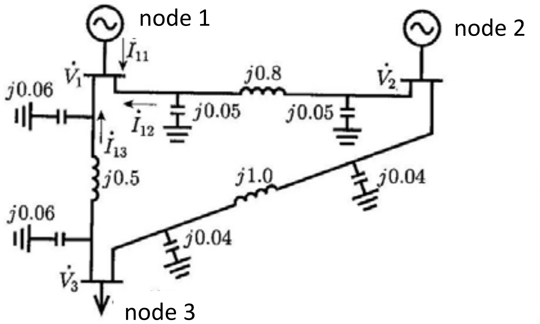
Necessary items to consider Load flow Analysis
Buses are categorized to the following 3 types.

- 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

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

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

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

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

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

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

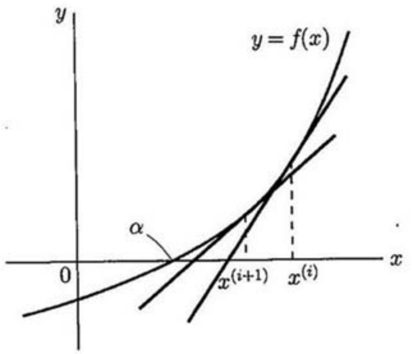


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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.

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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

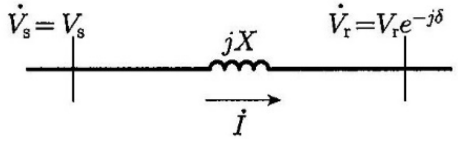
Manual method to calculate power flow.
Easy to calculate in manual.

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

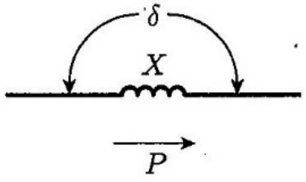
$$\begin{aligned}P_r + jQ_r &= V_r e^{-j\delta} \dot{I}^* \\ &= V_r e^{-j\delta} \left(\frac{V_s - V_r e^{-j\delta}}{jX} \right)^* \\ &= \frac{V_s V_r e^{-j\delta} - V_r^2}{-jX} \\ &= \frac{V_s V_r}{X} \sin\delta + j \frac{V_s V_r \cos\delta - V_r^2}{X}\end{aligned}$$

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

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



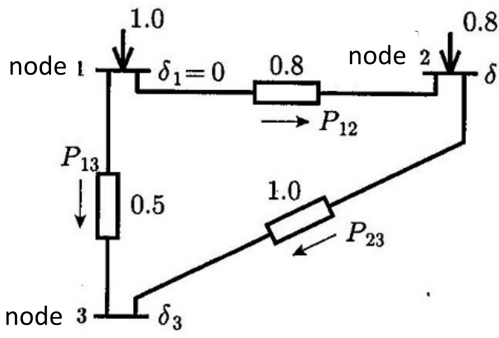
Simplified and Similar to DC circuit solution



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:

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

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

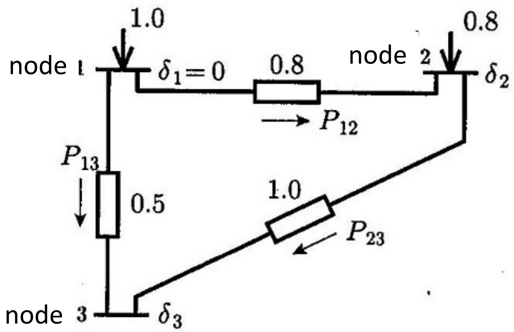
$$\delta_2 = 0.104$$

$$\delta_3 = -0.565$$

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.

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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.

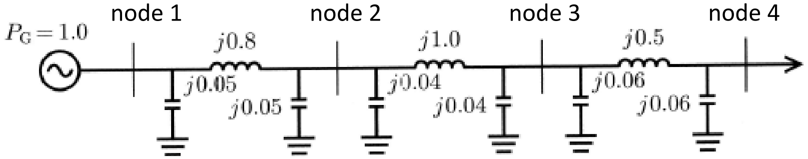
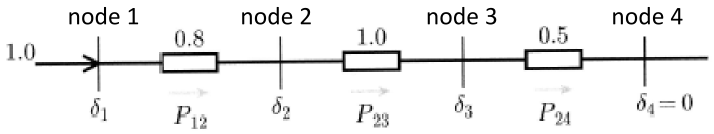


Figure is cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

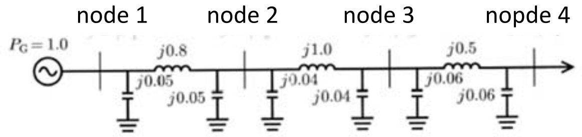
Exercise of DC Flow method

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

$$P_{1s} = \mathrm{Re}\left\{(-j1.20)^*(e_1+jf_1)^*(e_1+jf_1) + (j1.25)^*(e_2+jf_2)^*(e_1+jf_1)\right\}$$
$$= -1.25e_1f_2 + 1.25e_2f_1$$

$$V_{1s}^2 = e_1^2 + f_1^2$$

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

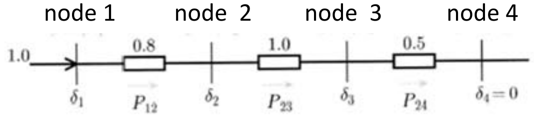
$$Q_{2s} = \mathrm{Im}\left\{(j1.25)^*(e_1+jf_1)^*(e_2+jf_2) + (-j2.16)^*(e_2+jf_2)^*(e_2+jf_2) + (j1.0)^*(e_3+jf_3)^*(e_2+jf_2)\right\}$$
$$= -1.25e_1e_2 - 1.25f_1f_2 + 2.16e_2^2 + 2.16f_2^2 - e_2e_3 - f_2f_3$$

$$P_{3s} = \mathrm{Re}\left\{(j1.0)^*(e_2+jf_2)^*(e_3+jf_3) + (-j2.9)^*(e_3+jf_3)^*(e_3+jf_3) + (j2.0)^*(e_4+jf_4)^*(e_3+jf_3)\right\}$$
$$= -e_3f_2 + e_2f_3 - 2.0e_3f_4 + 2.0e_4f_3$$

$$Q_{3s} = \mathrm{Im}\left\{(j1.0)^*(e_2+jf_2)^*(e_3+jf_3) + (-j2.9)^*(e_3+jf_3)^*(e_3+jf_3) + (j2.0)^*(e_4+jf_4)^*(e_3+jf_3)\right\}$$
$$= -e_2e_3 - f_2f_3 + 2.9e_3^2 + 2.9f_3^2 - 2.0e_3e_4 - 2.0f_3f_4$$

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

Exercise 3 Answer



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

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

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

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

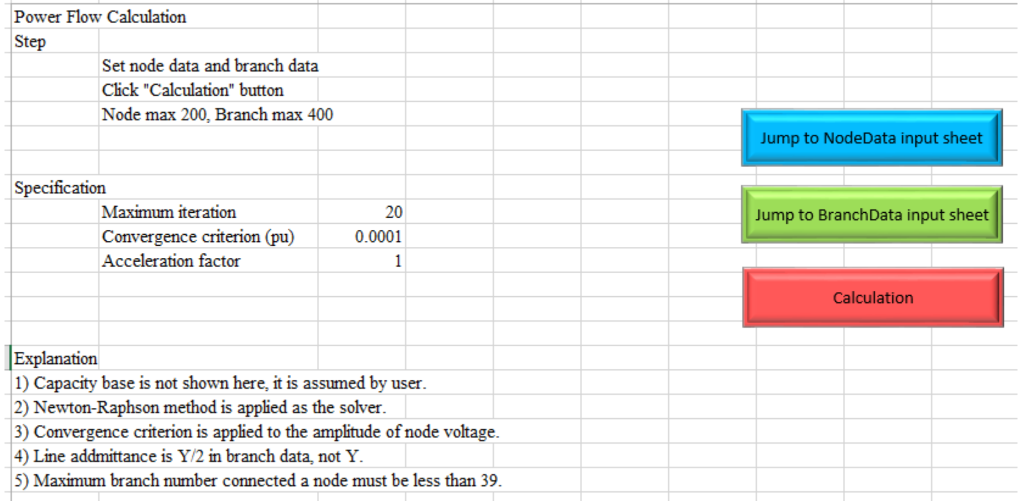
$$P_{12} = 1.0, \quad P_{23} = 1.0, \quad P_{34} = 1.0$$

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

Specification

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

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.

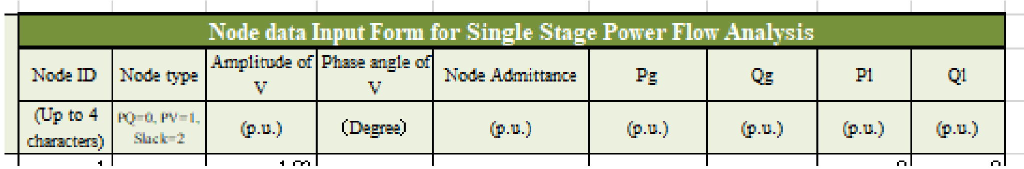
5) Maximum branch number connected a node must be less than 39.

Node Data

V: Voltage of Node

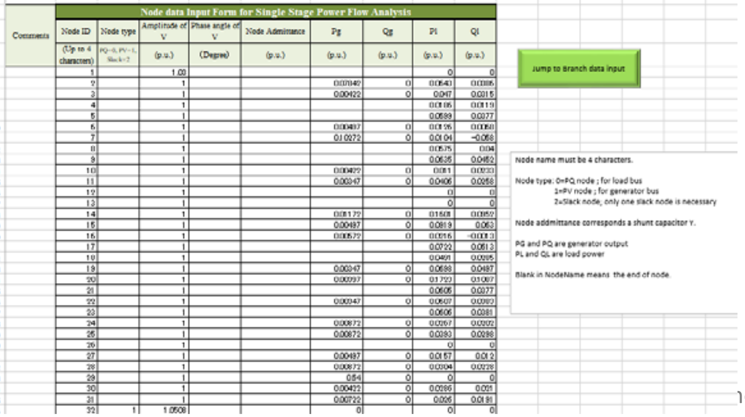
Pg: Active Power of Generator, Qg: Reactive Power of Generator

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.)



Node data Input Form for Single Stage Power Flow Analysis

Node name must be 4 characters.

Node type: 0=PQ node ; for load bus
1=PV node ; for generator bus
2=Slack node; only one slack node is necessary

Node addmittance corresponds a shunt capacitor Y.

PG and PQ are generator output
PL and QL are load power

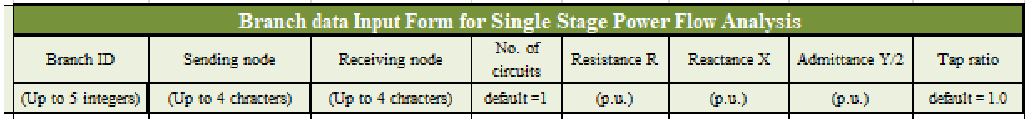
Blank in NodeName means the end of node.

Branch Data

R: Resistance of Line, X: Reactance of Line

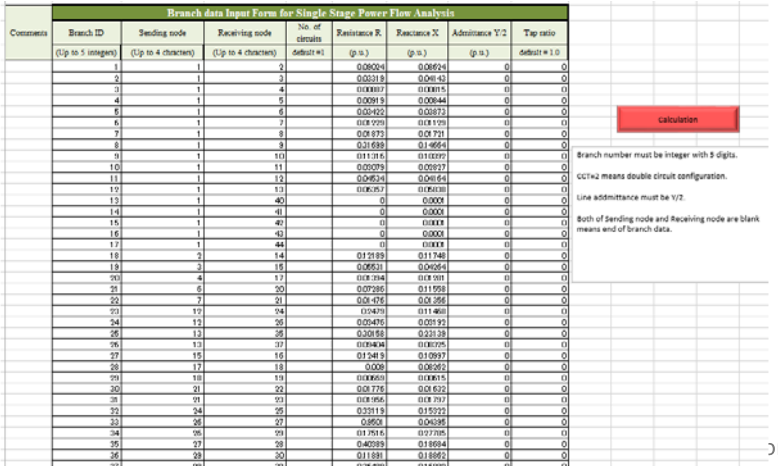
Y/2: Half of Admittance of Line

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



Branch data Input Form for Single Stage Power Flow Analysis

Branch number must be integer with 5 digits.

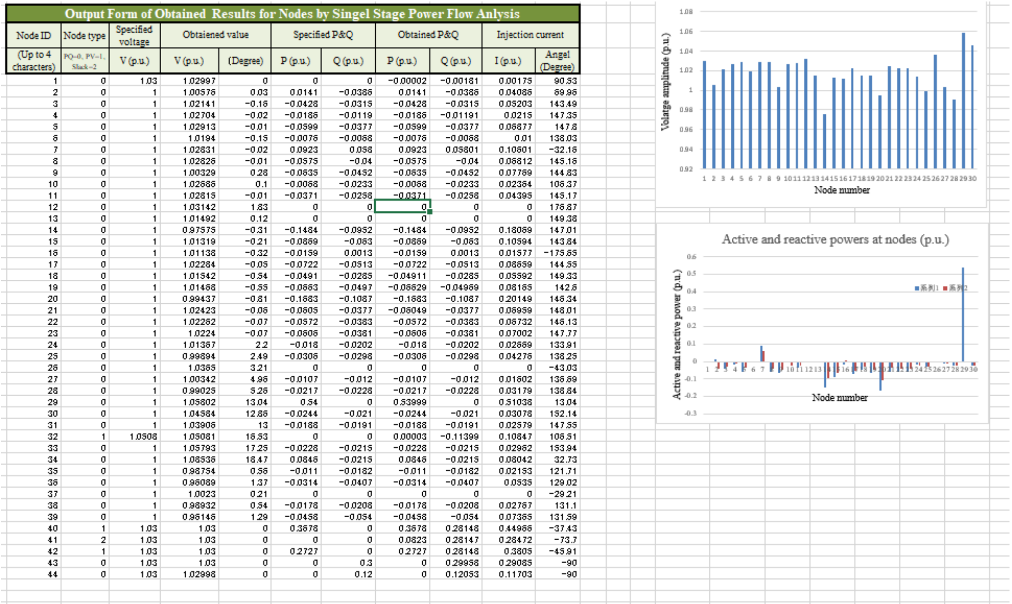
CCT=2 means double circuit configuration.

Line addmittance must be Y/2.

Both of Sending node and Receiving node are blank means end of branch data.

Calculation Results of Node

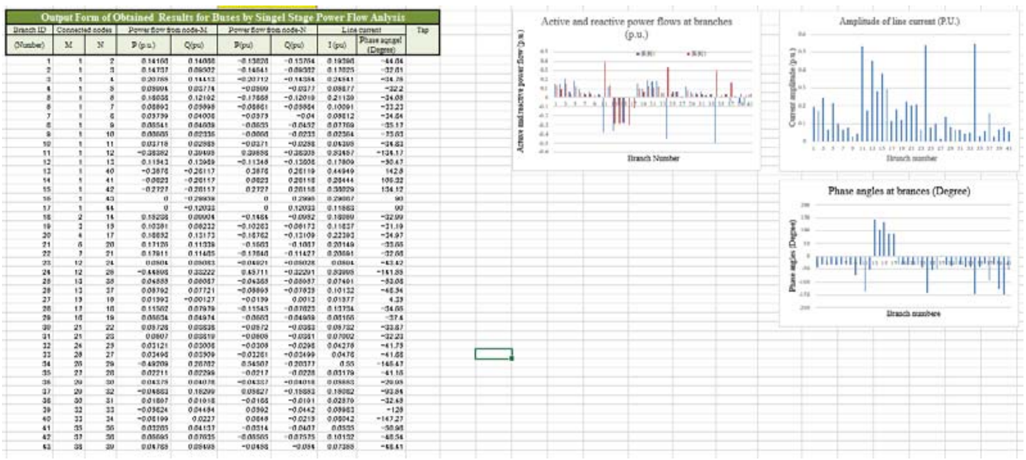
Specified value is initial value. Obtained value means value after calculation.



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

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

Calculation Results of Branch



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

6. Load Flow Analysis and Evaluation

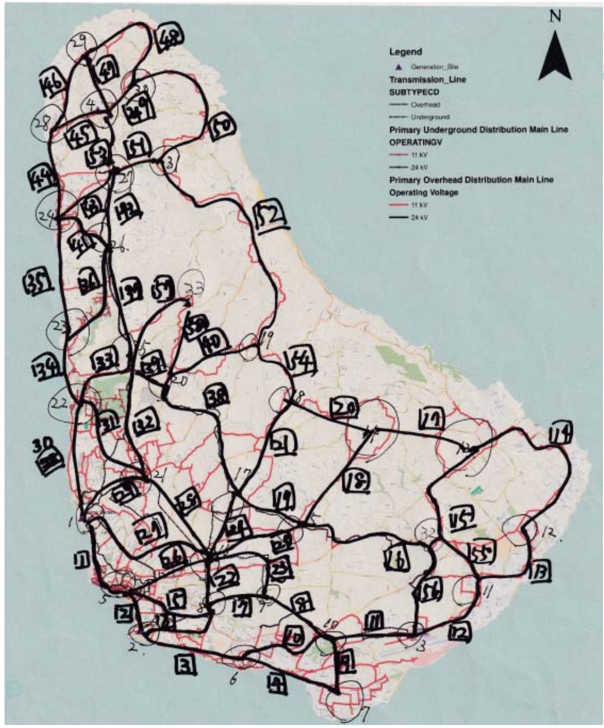
- DC Flow Method
  - Prepare data
  - Make active power equations
  - Solve voltage angle δ by DC Flow Method
  - Calculate active power flow of transmission lines
- Microgrid/VPP Designer
  - Prepare data
  - Input node and branch data
  - Solve load flow by Newton-Raphson Method

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

for Barbados

JICA Expert Team, Nippon Koei Co., Ltd.

Barbados Assumed Grid

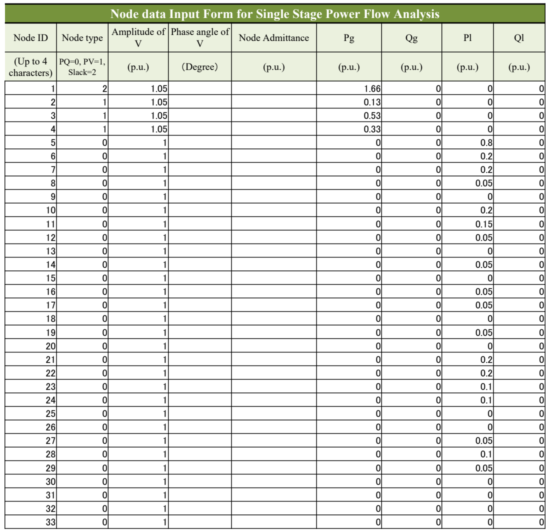


Assumed values and network structure are used in this example.

33 nodes

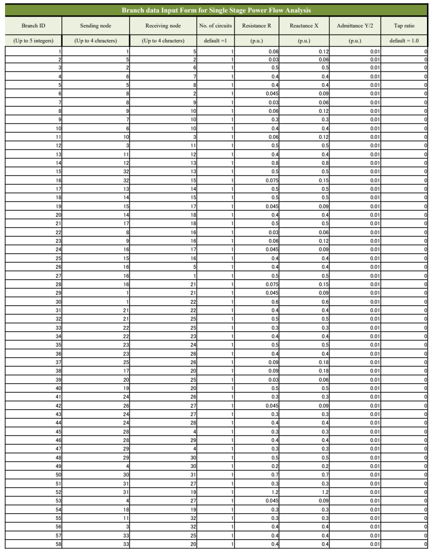
No. 1~4 nodes have turbine generators.

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

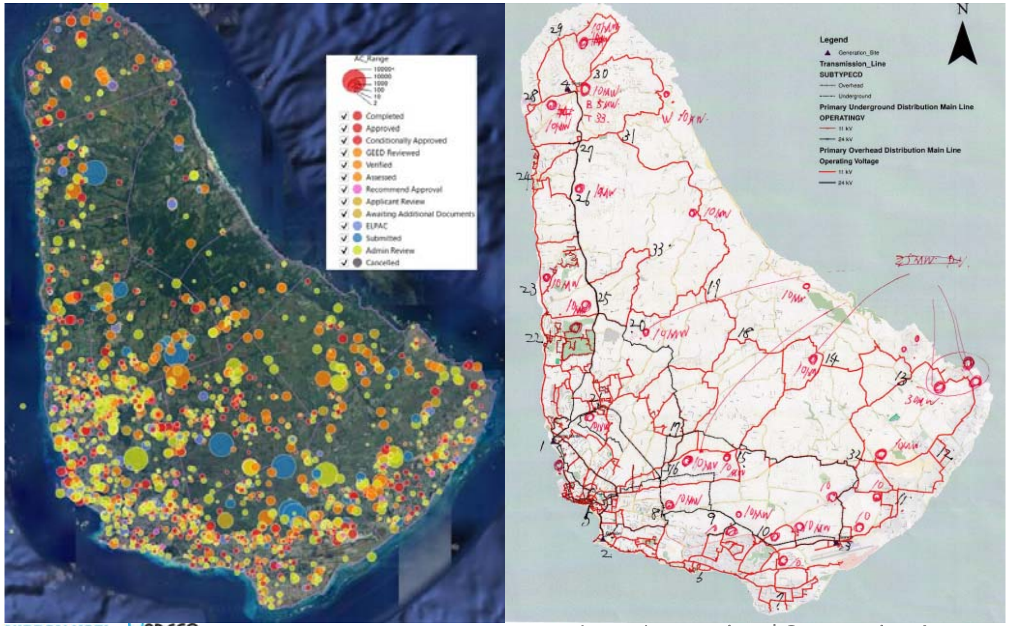
Transmission Line in Barbados

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

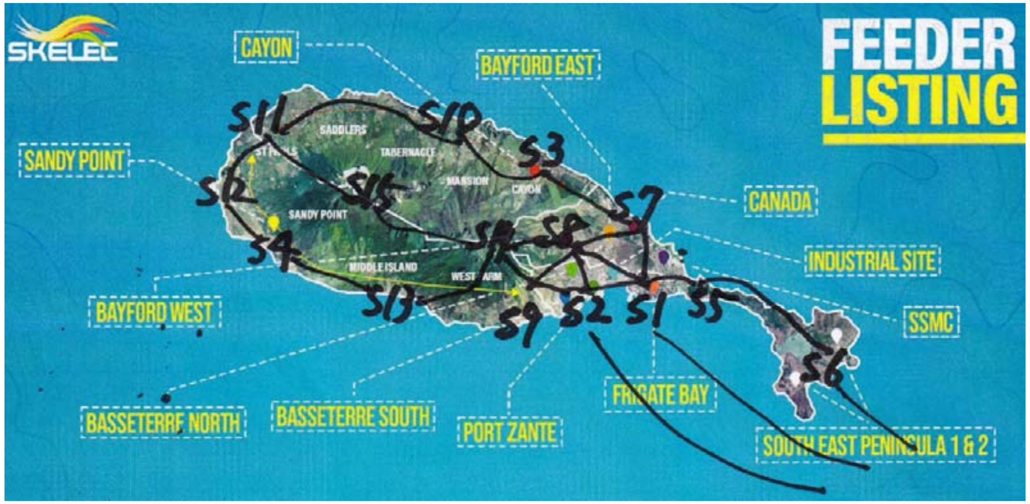
Day 2 (Exercise)

for Saint Kitts and Nevis

JICA Expert Team, Nippon Koei Co., Ltd.

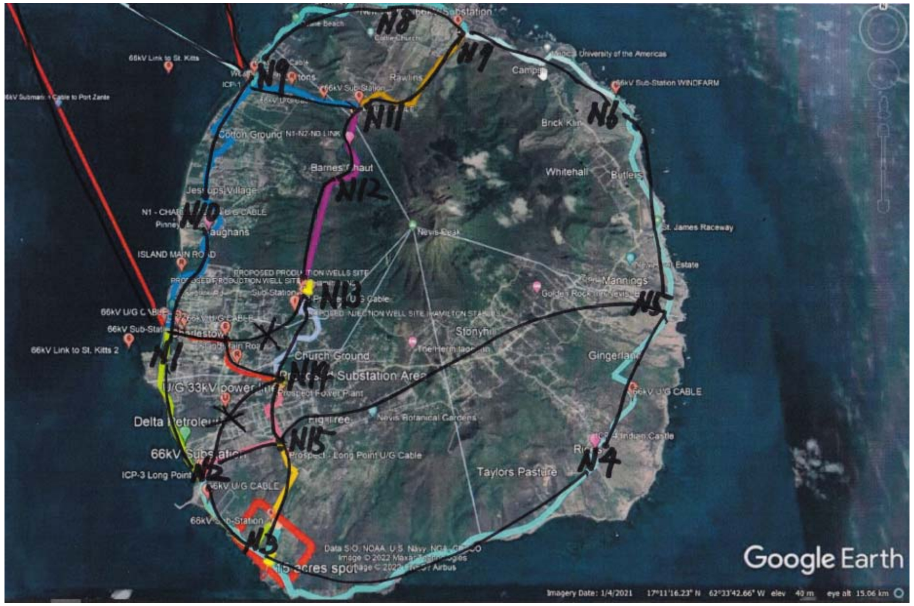
Saint Kitts Assumed Grid

15 nodes



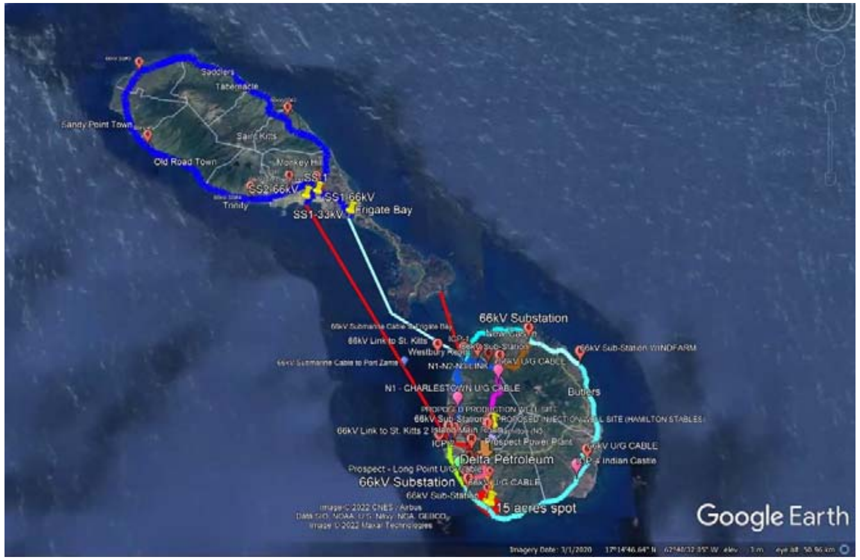
Nevis Assumed Grid

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.

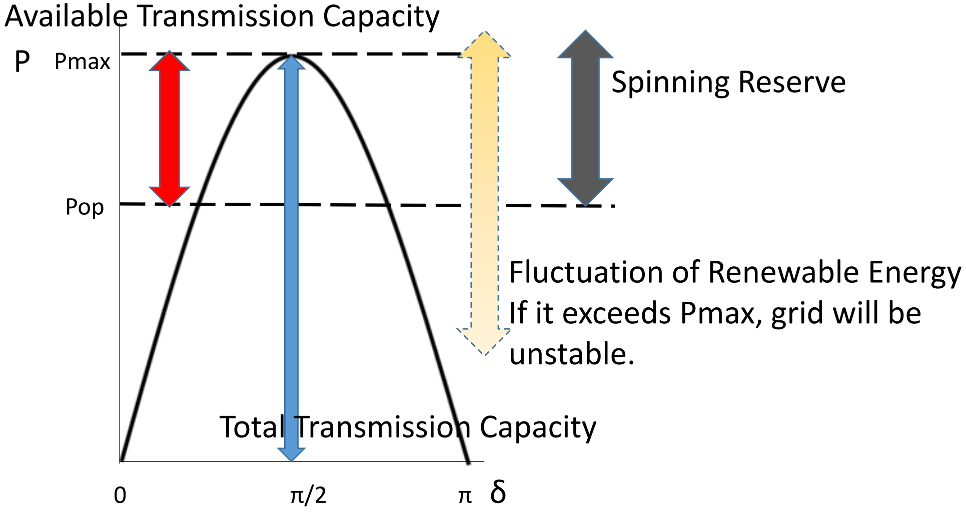
Role of Us: Power System Engineer

- 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



Fluctuation of Renewable Energy
If it exceeds Pmax, grid will be unstable.

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

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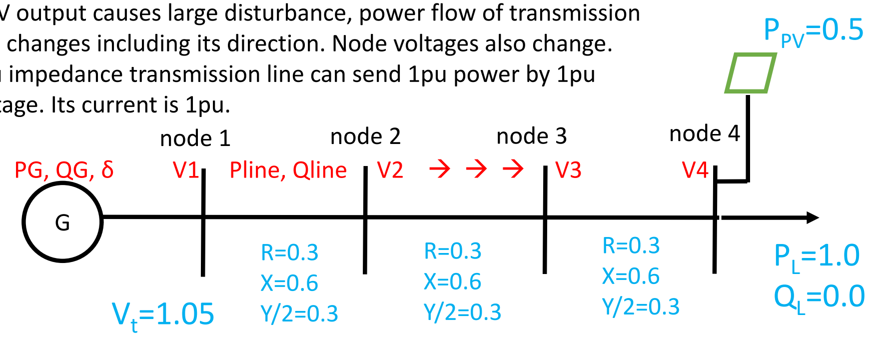
Power System with Installation of PV

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)

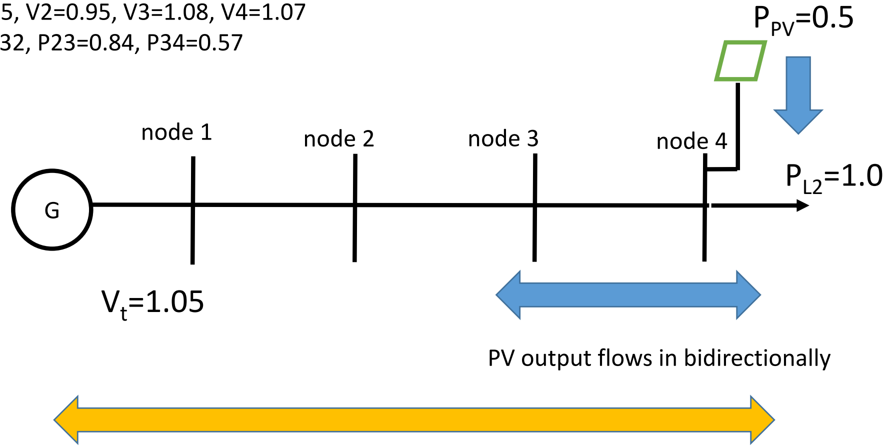
Load Flow Analysis

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
   - 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

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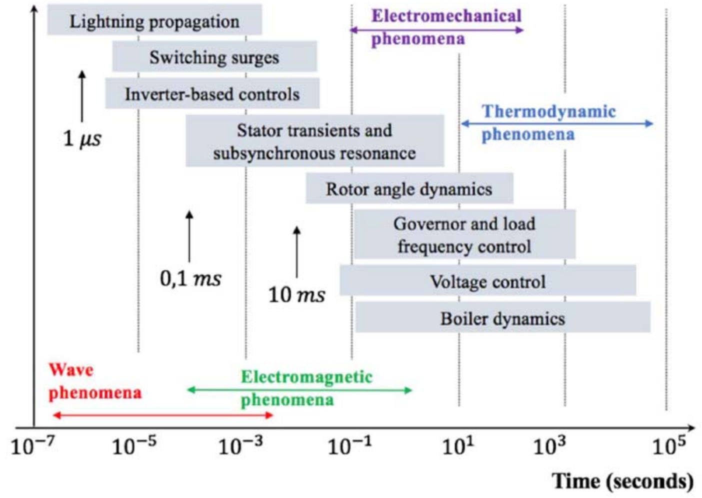
1. Overview of Stability

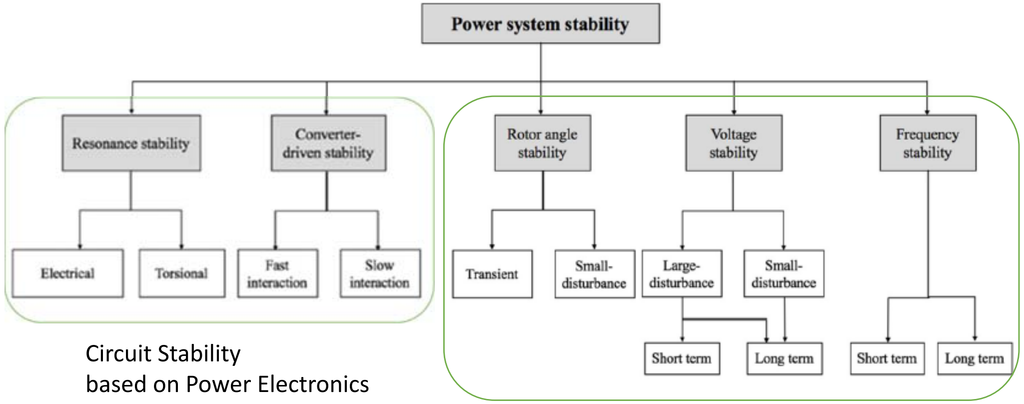
- STABILITY
  - If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.

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



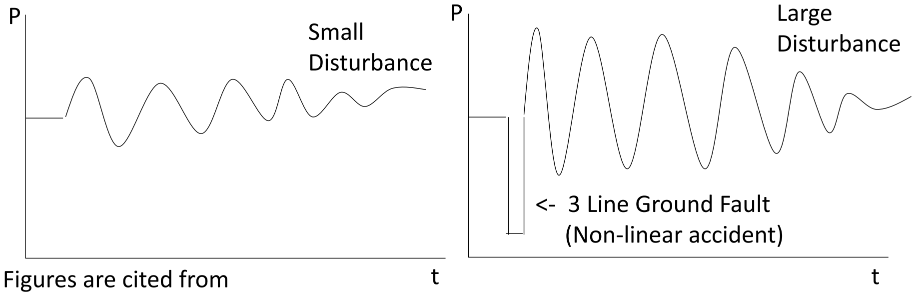
Circuit Stability
based on Power Electronics
Technology

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.

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

$$J\frac{d^2\delta}{dt^2} = T_{\mathrm{m}} - T_{\mathrm{e}}$$

$$\omega J\frac{d^2\delta}{dt^2} = P_{\mathrm{m}} - P_{\mathrm{e}}$$

$$M = \omega J$$

$$M\frac{d^2\delta}{dt^2} = P_{\mathrm{m}} - P_{\mathrm{e}} = P_a$$

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

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

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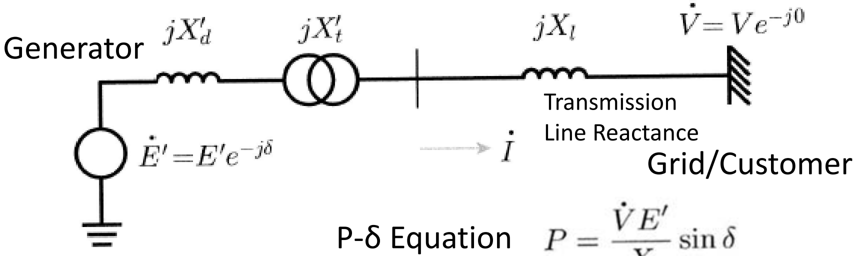
2. Stability Model
- Simplified Grid Model-



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

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

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

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.

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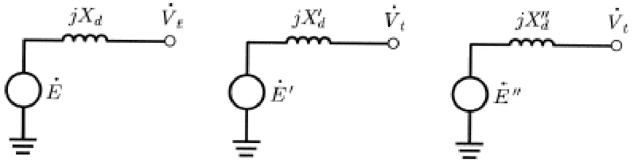
3 Types of Equivalent Circuits of Synchronous Generator

- 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.

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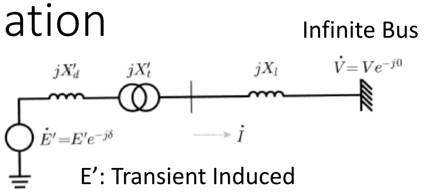
3. Equal Area Criterion

- 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



E’: Transient Induced
Electromotive Force

Power equation

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

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

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

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

Equal Area Criterion for Stability Analysis

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

*P*max=>ATC

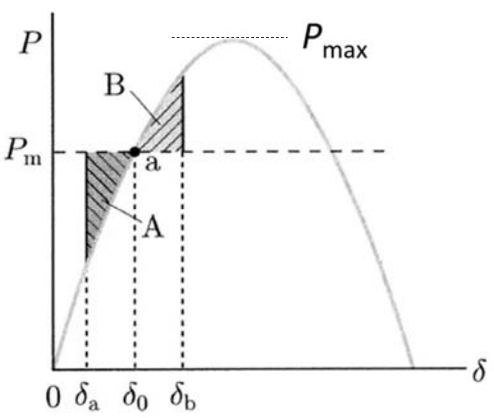
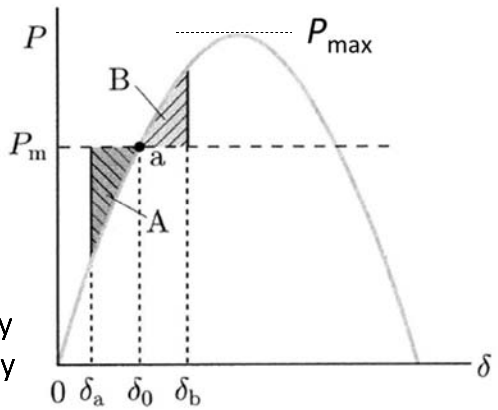


Figure is cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Equal Area Criterion for Stability Analysis

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

*P*max=>ATC



A: Acceleration Energy
B: Deceleration Energy

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

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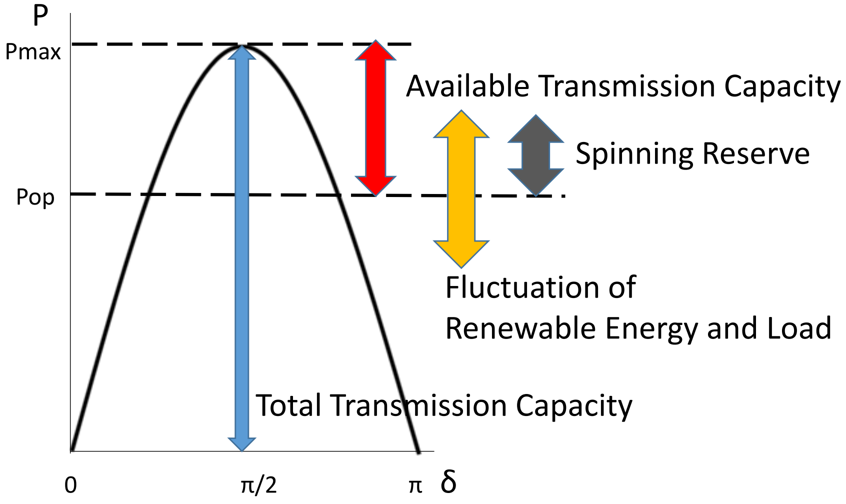
4. Available Transmission Capacity & Spinning Reserve

- 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

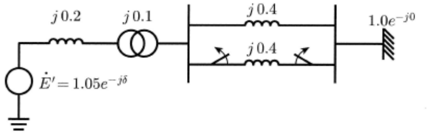
→Energy mix of several resources will be helpful for improving grid stability.

5. Exercise of Equal Area Criterion

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

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

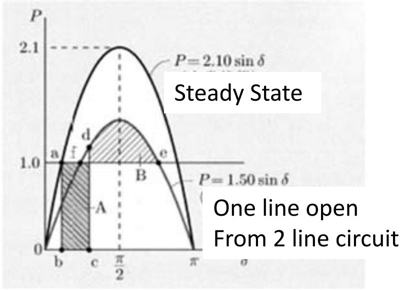
$$X = 0.2 + 0.1 + \frac{0.4}{2} = 0.5$$



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

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

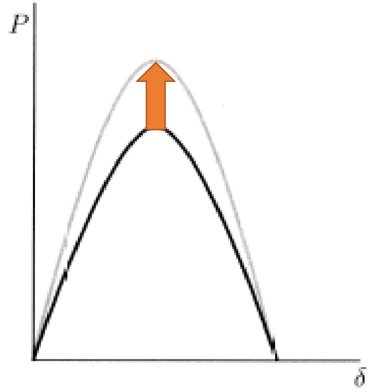
$$P = \frac{1.05}{0.7}\sin\delta = 1.50\sin\delta$$



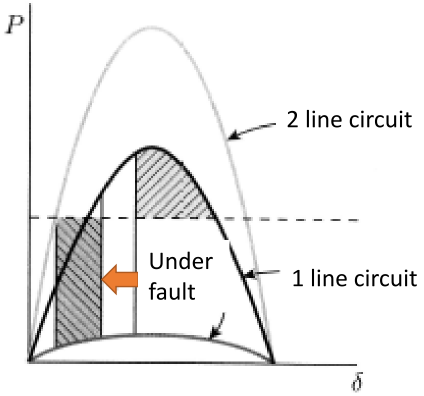
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

(a) Voltage to be High



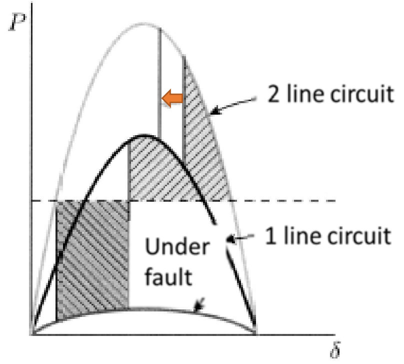
(b) High Speed Circuit Breaker



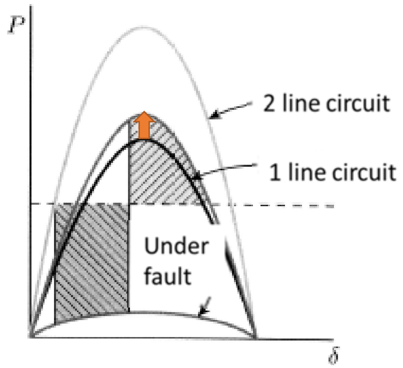
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

(c) High Speed Recloser



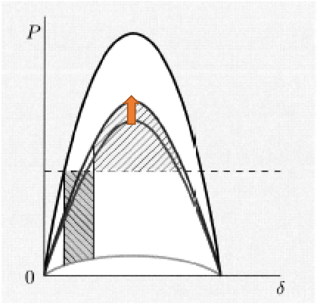
(d) High Speed AVR



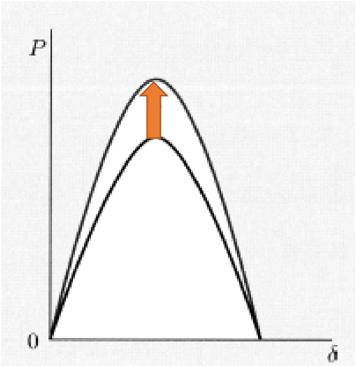
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

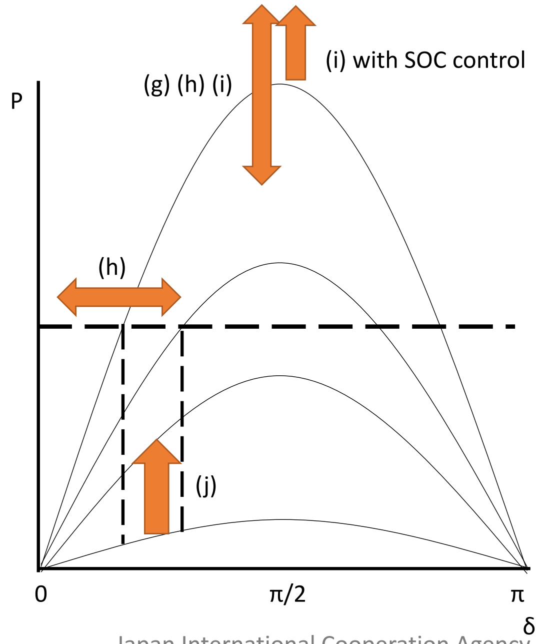
(i) Battery

Change Pmax

(j) SCO

(Synchronous Condenser)

Change P during fault



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

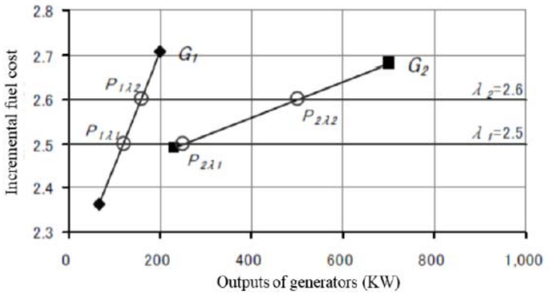
- Load Frequency Control (LFC)

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

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

- Economic Load Dispatching (ELD)
  - Equal λ method

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



Microgrid/VPP Designer

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

<Functions>

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

VPP: Virtual Power Plant

LFC & ELD Model in Microgrid/VPP Designer

- Simple Grid Model

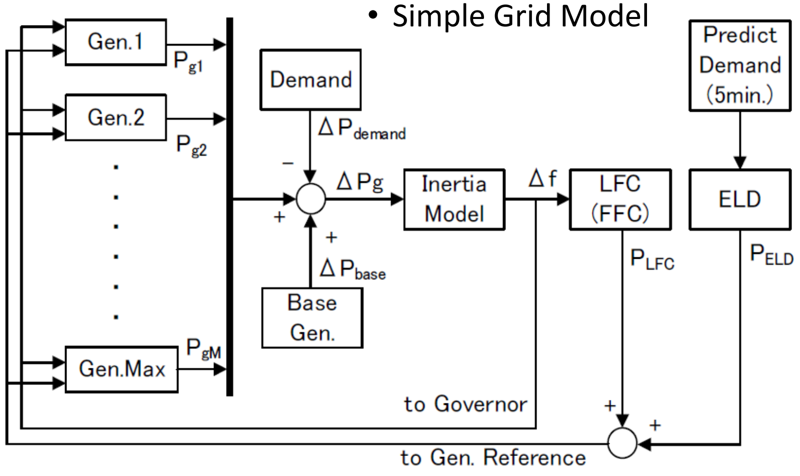


Figure is cited from MicroGrid Designer User and Technical Reference Manual

Inertia Model in Microgrid/VPP Designer

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

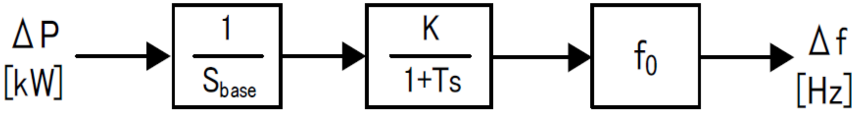


Figure is cited from MicroGrid Designer User and Technical Reference Manual

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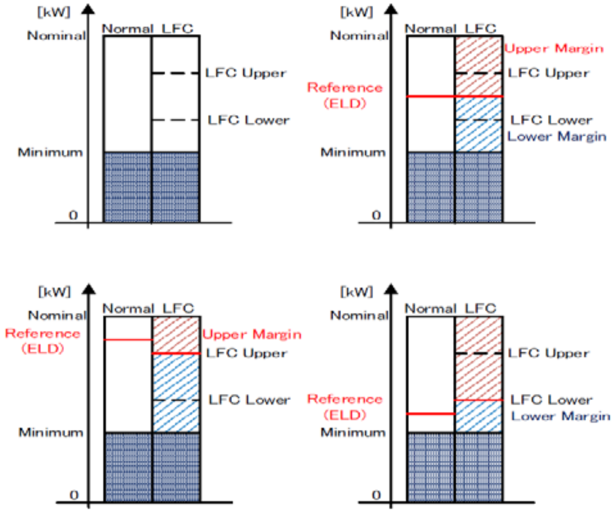
Reference of LFC & ELD

- 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

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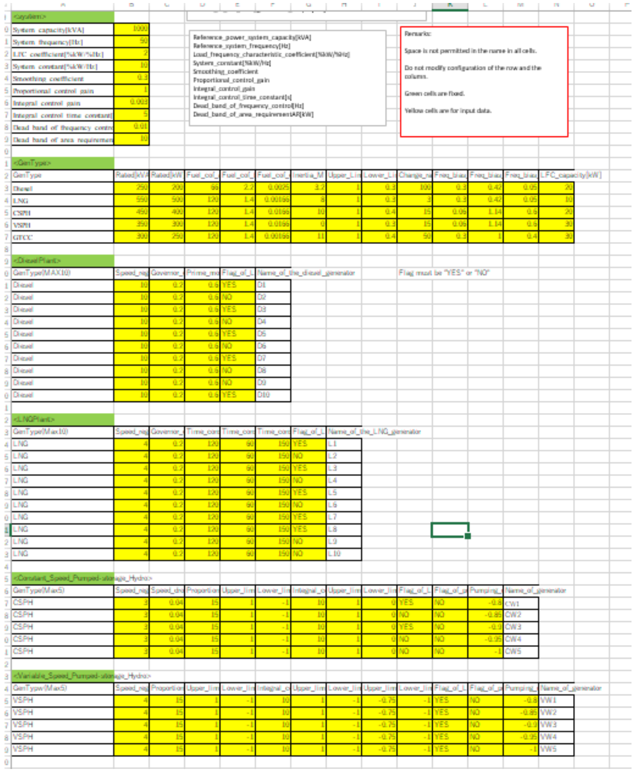
LFC Input Data



<System>

System capacity[kVA]	1000
System frequency[Hz]	50
LFC coefficient[%kW/%Hz]	2
System constant[%kW/Hz]	10
Smoothing coefficient	0.3
Proportional control gain	1
Integral control gain	0.003
Integral control time constant[	5
Dead band of frequency contro	0.01
Dead band of area requiremen	10

Reference_power_system_capacity[kVA]
Reference_system_frequency[Hz]
Load_frequency_characteristic_coefficient[%kW/%Hz]
System_constant[%kW/Hz]
Smoothing_coefficient
Proportional_control_gain
Integral_control_gain
Integral_control_time_constant[s]
Dead_band_of_frequency_control[Hz]
Dead_band_of_area_requirementAR[kW]

Remarks:

Space is not permitted in the name in all cells.

Do not modify configuration of the row and the column.

Green cells are fixed.

Yellow cells are for input data.

<GenType>

GenType	Rated[kVA	Rated[kW	Fuel_col_	Fuel_col_	Fuel_col_	Inertia_M	Upper_Lim	Lower_Li	Change_ra	Freq_bias	Freq_bias	Freq_bias	LFC_capacity[kW]
Diesel	250	200	66	2.2	0.0025	3.2	1	0.3	100	0.3	0.42	0.05	20
LNG	550	500	120	1.4	0.00166	8	1	0.3	3	0.3	0.42	0.05	10
CSPH	450	400	120	1.4	0.0166	10	1	0.4	15	0.06	1.14	0.6	20
VSPH	350	300	120	1.4	0.0166	0	1	0.3	15	0.06	1.14	0.6	30
GTCC	300	250	120	1.4	0.00166	11	1	0.4	50	0.3	1	0.4	30

<DieselPlant>

Flag must be "YES" or "NO"

GenType(MAX10)	Speed_reg	Governor_	Prime_mo	Flag_of_L	Name_of_the_diesel_generator
Diesel	10	0.2	0.6	YES	D1
Diesel	10	0.2	0.6	NO	D2
Diesel	10	0.2	0.6	YES	D3
Diesel	10	0.2	0.6	NO	D4
Diesel	10	0.2	0.6	YES	D5
Diesel	10	0.2	0.6	NO	D6
Diesel	10	0.2	0.6	YES	D7
Diesel	10	0.2	0.6	NO	D8
Diesel	10	0.2	0.6	NO	D9
Diesel	10	0.2	0.6	YES	D10

<LNGPlant>

GenType(Max10)	Speed_reg	Governor_	Time_con	Time_con	Time_con	Flag_of_L	Name_of_the_LNG_generator
LNG	4	0.2	120	60	150	YES	L1
LNG	4	0.2	120	60	150	NO	L2
LNG	4	0.2	120	60	150	YES	L3
LNG	4	0.2	120	60	150	NO	L4
LNG	4	0.2	120	60	150	YES	L5
LNG	4	0.2	120	60	150	NO	L6
LNG	4	0.2	120	60	150	YES	L7
LNG	4	0.2	120	60	150	YES	L8
LNG	4	0.2	120	60	150	NO	L9
LNG	4	0.2	120	60	150	NO	L10

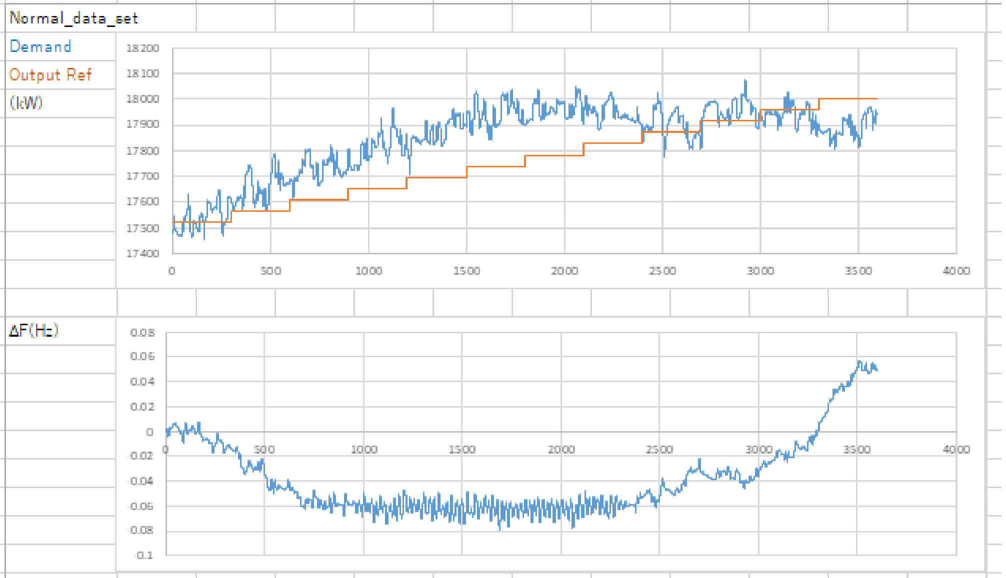
<Constant_Speed_Pumped-storage_Hydro>

GenType(Max5)	Speed_reg	Speed_dro	Proportion	Upper_lim	Lower_lim	Integral_c	Upper_lim	Lower_lim	Flag_of_L	Flag_of_p	Pumping_	Name_of_generator
CSPH	3	0.04	15	1	-1	10	1	0	YES	NO	-0.8	CW1
CSPH	3	0.04	15	1	-1	10	1	0	NO	NO	-0.85	CW2
CSPH	3	0.04	15	1	-1	10	1	0	YES	NO	-0.9	CW3
CSPH	3	0.04	15	1	-1	10	1	0	NO	NO	-0.95	CW4
CSPH	3	0.04	15	1	-1	10	1	0	NO	NO	-1	CW5

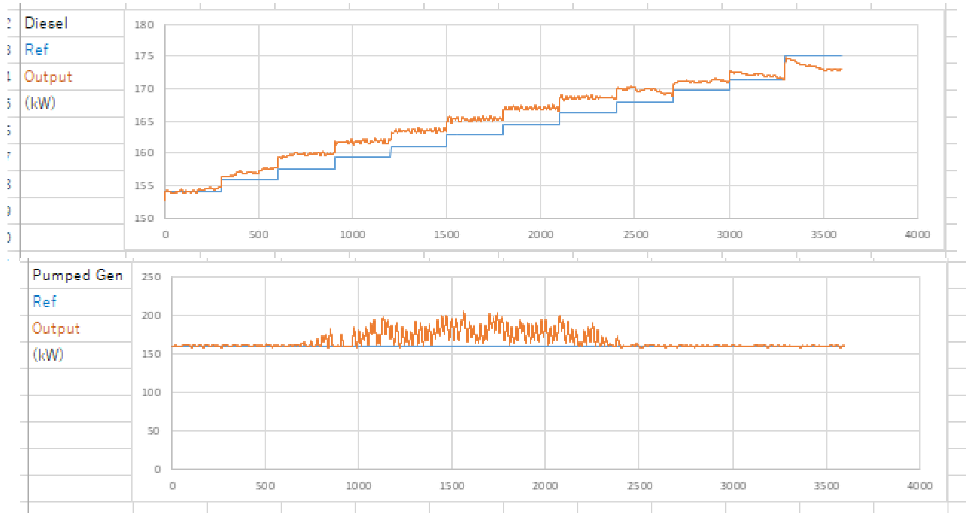
<Variable_Speed_Pumped-storage_Hydro>

GenTypw(Max5)	Speed_reg	Proportion	Upper_lim	Lower_lim	Integral_c	Upper_lim	Lower_lim	Upper_lim	Lower_lim	Flag_of_L	Flag_of_p	Pumping_	Name_of_generator
VSPH	4	15	1	-1	10	1	-1	-0.75	-1	YES	NO	-0.8	VW1
VSPH	4	15	1	-1	10	1	-1	-0.75	-1	YES	NO	-0.85	VW2
VSPH	4	15	1	-1	10	1	-1	-0.75	-1	YES	NO	-0.9	VW3
VSPH	4	15	1	-1	10	1	-1	-0.75	-1	YES	NO	-0.95	VW4
VSPH	4	15	1	-1	10	1	-1	-0.75	-1	YES	NO	-1	VW5

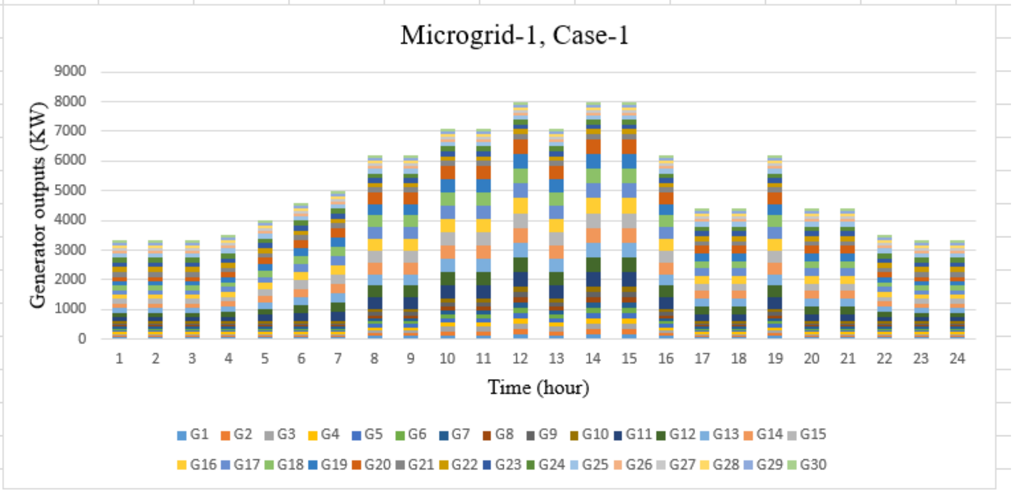
Demand and Frequency -Result of LFC-



Generator Output -Result of LFC-



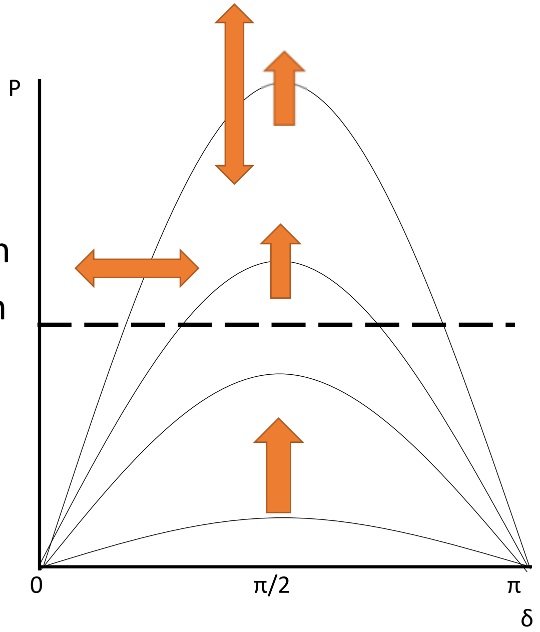
Result of ELD



7. Stability Analysis and Evaluation of Power System

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

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

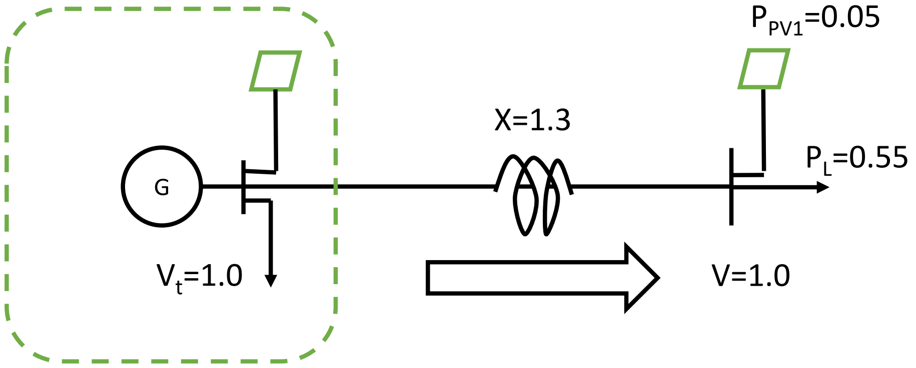


Case Study

- Steps to evaluate stability of Microgrid

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

Power System Model (Example)

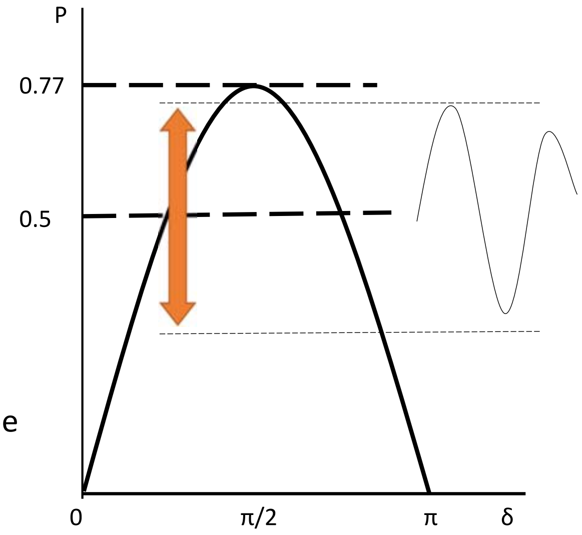


Treat as one generator

DC Flow Method: P=δ/X
0.55-0.55=δ/1.3
δ=0.65rad=37deg

P-δ Curve and Stability Evaluation

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



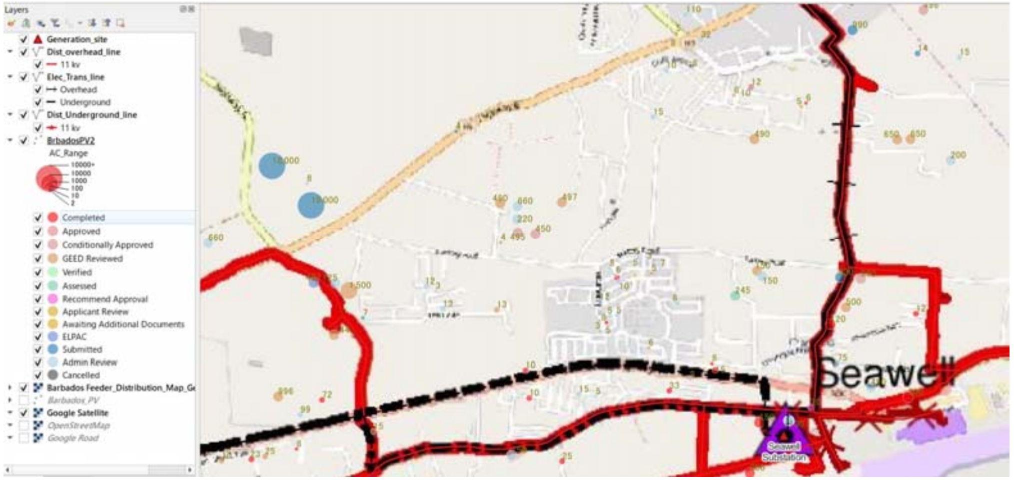
Seminar on Grid Stability with Large RE Day 3 (Exercise)

for Barbados

JICA Expert Team, Nippon Koei Co., Ltd.

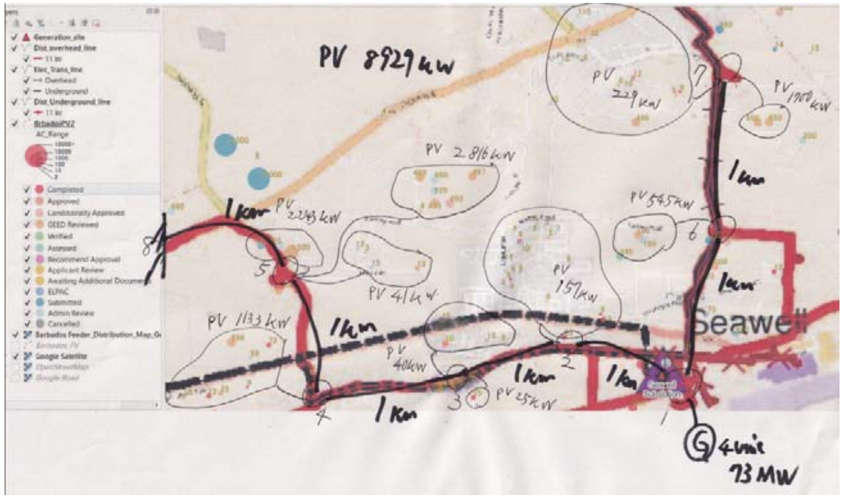
Microgrid (Coverley Villages)

Distribution Line around Coverley Villages

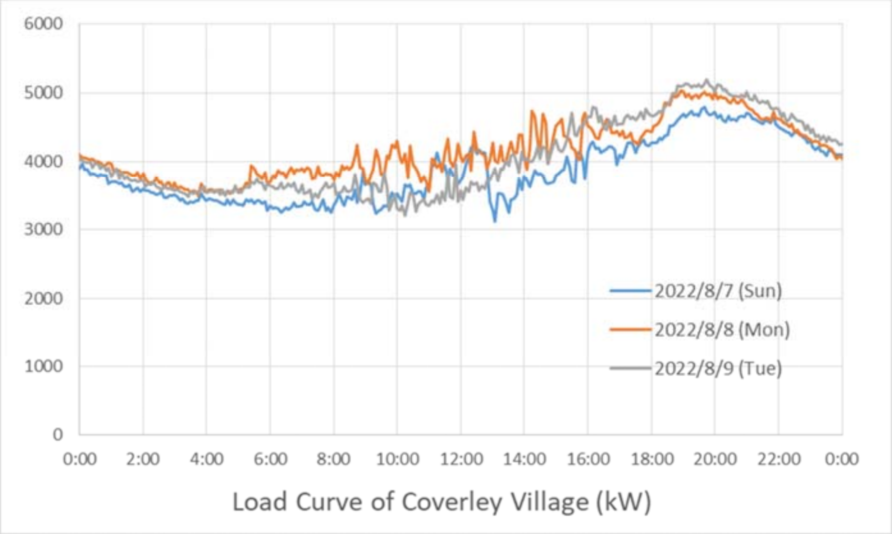


PV allocation and capacity around Coverley Villages

Example of modeling of the grid



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



Parameter of Coverley Villages

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

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

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

Seminar on Grid Stability with Large RE

Appendices

JICA Expert Team, Nippon Koei Co., Ltd.

Exercise 1,2 Answer

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

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

Exercise 3,4 Answer

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

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.

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

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.

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
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	

Technical Cooperation to Promote Energy Efficiency in Caribbean Countries

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

No.	Name	Presen	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.

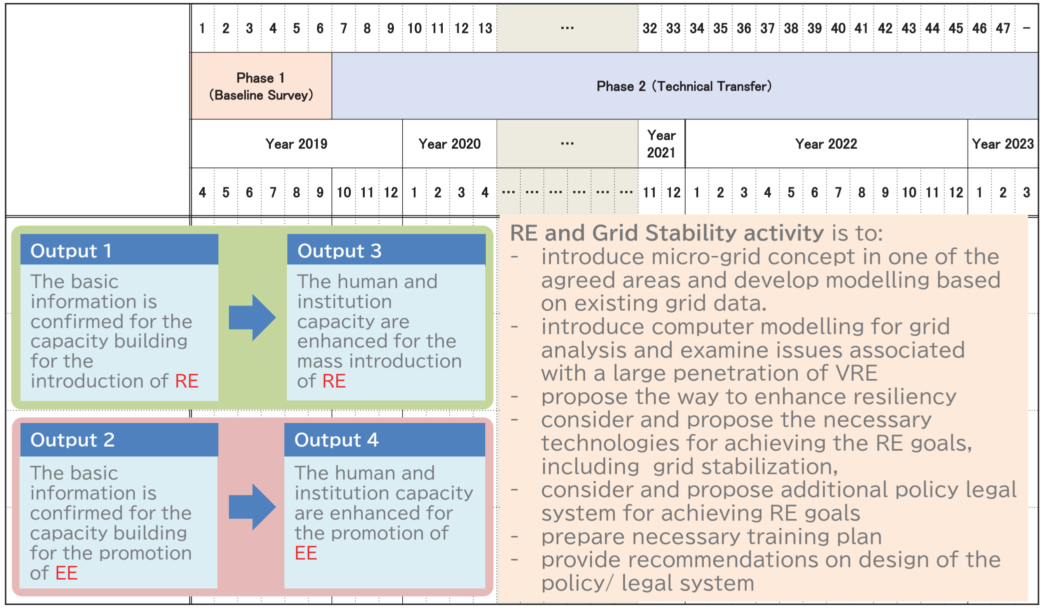
Agenda

- 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



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

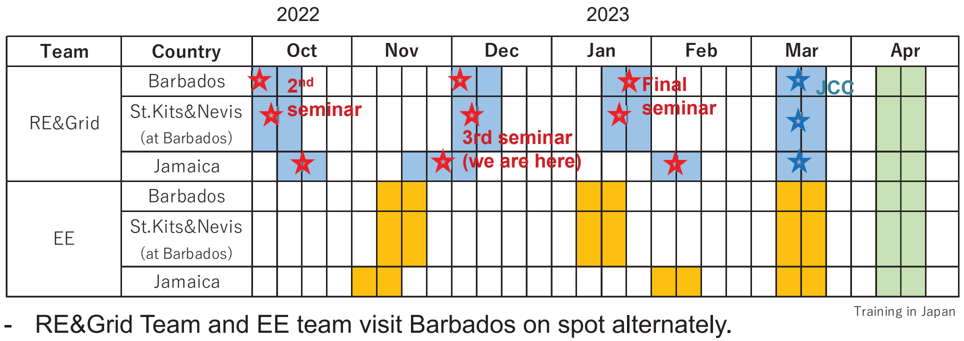
Output 3
The human and institution capacity are enhanced for the mass introduction of RE

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



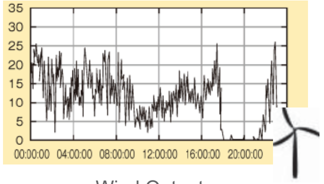
- RE&Grid Team and EE team visit Barbados on spot alternately.
- 1st Seminar on Grid Stability and RE (Introduction, Barbados only) on 27 Jul 2022
- 2nd Seminar on Grid Stability and RE on 3-5 Oct 2022
- **3rd Seminar on Grid Stability and RE on 6-7 Dec 2022**

  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

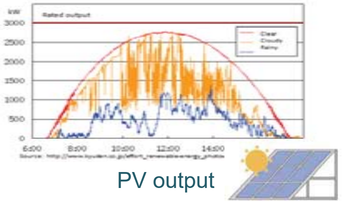
Outline and Agenda for 3rd Seminar on 6 - 7 Dec 2022

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)

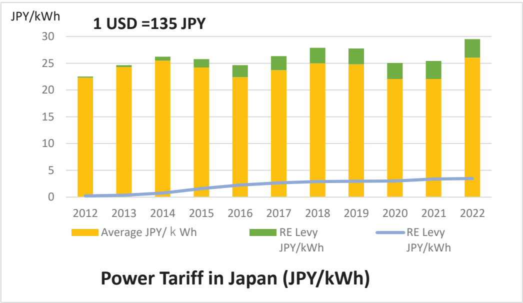
Both (VRE):
- It does not always generate when needed. **Load-supply matching** is an issue
- Time coincidence of VRE, there can be times when there is too much supply. Curtailment of VRE is necessary **→energy storage/control cost need to be considered.**

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

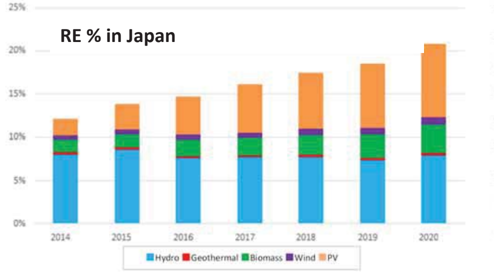
Is the increase in RE penetration so far helping or hurting electricity price?



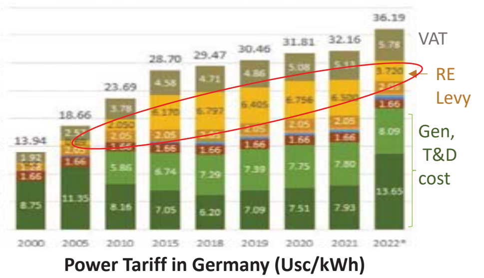
Power Tariff in Japan (JPY/kWh)

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

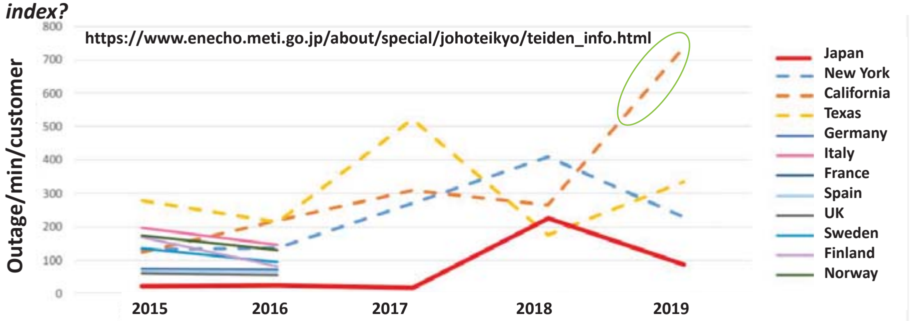


Power Tariff in Germany (Usc/kWh)

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

Outage trend and VRE affect on Outage

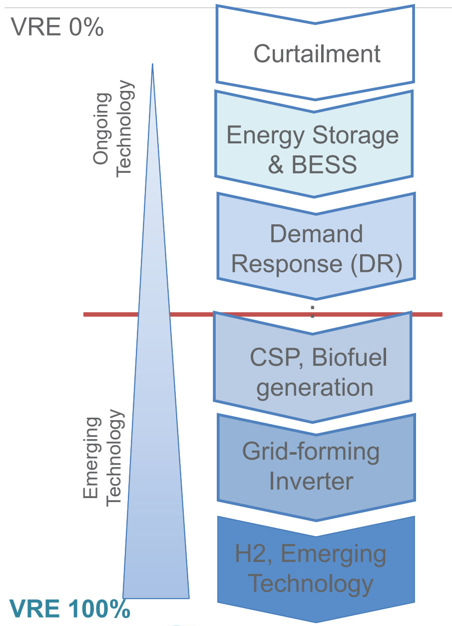
Has the increase in RE penetration begun to affect the momentary interruption(MAIFI) index?



- **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



Curtailment

Energy Storage & BESS

Demand Response (DR)

CSP, Biofuel generation

Grid-forming Inverter

H2, Emerging Technology

Voltage and frequency Stabilization

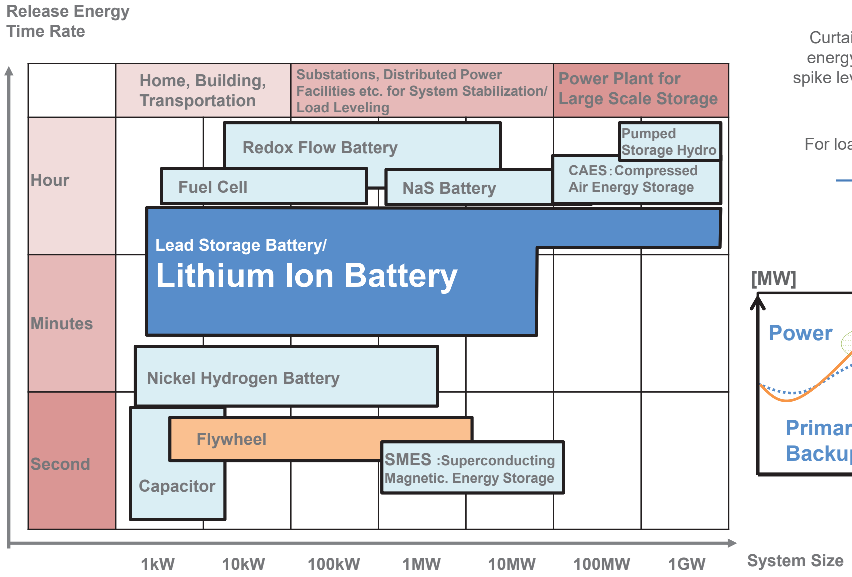
- Curtailment of VRE energy in PCS to make grid stables, smart inverter
- **Governor Free (GF), Economic Load Dispatch (ELD), Load Frequency Control (LFC)**
- **Energy storage: Battery, flywheel**
- **Synchronous condenser, Statcom**
- EV charging time shift
- Demand side management
- Regulatory framework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

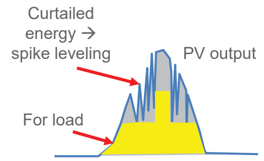
Insufficient Inertia, Synchronizing Force

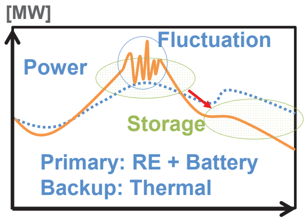
- **Battery-Motor generator set**
- **Biofuel (diesel, jet) for DG**
- CSP (Concentrated Solar Thermal Power)
- Gravitational Power
- **Grid forming Inverter**
- H2 generation from RE by electrolysis
- Seasonal large scale storage

Battery and Energy Storage

Positioning for Energy Storage Technology







Primary: RE + Battery
Backup: Thermal

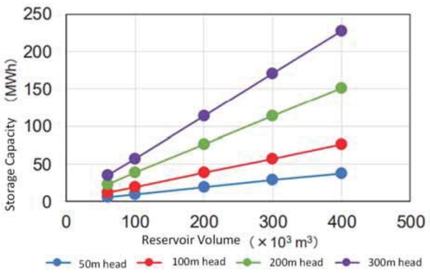
Source: NEDO Renewable Energy Technology White Paper Chapter 9

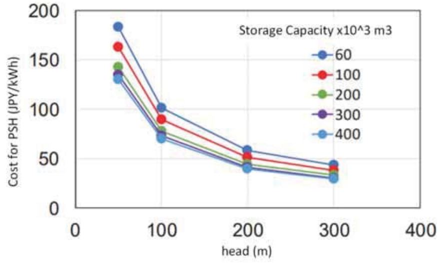
Pumped Storage vs Li-Battery

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

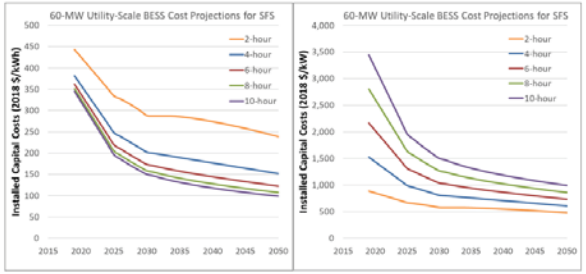
- Challenges: Topology and water. Higher head, lower cost: 700USD/kWh@100m, 350USD/kWh@200m (100,000m3) .
- Long lead time, Environmental Impact Assessment
- Advanta40-50 years life, black start possible
- LiB : 350-450USD/MWh @2022 (for 60MW scale), Cycle: 5000-20,000 @DoD 80-90%

DoD: Depth of Discharge



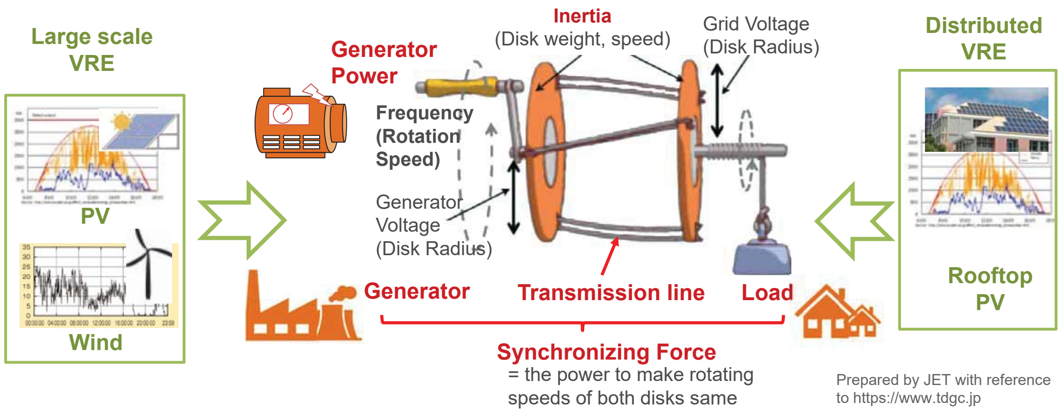


Note: headrace 1500m is assumed for head 200m
Source: Potential Capacity and Cost of Pumped-Storage Power in Japan Strategy for Technology Development Proposal Paper for Policy Making and Governmental Action toward Low Carbon Societies, LCS-FY2018-PP-08, 2019



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

Inertia and Synchronizing Force with RE



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

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

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

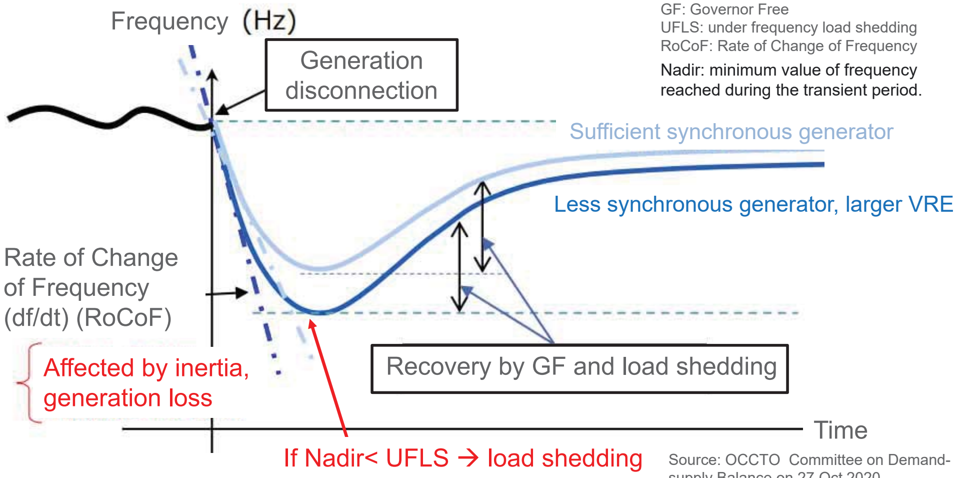
Fluctuation of large scale VRE affects to generator at generation side and load side

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

Inertia and Synchronizing Force with RE

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

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

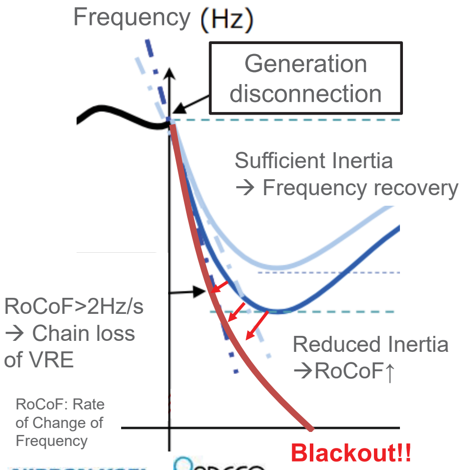


GF: Governor Free
UFLS: under frequency load shedding
RoCoF: Rate of Change of Frequency
Nadir: minimum value of frequency reached during the transient period.

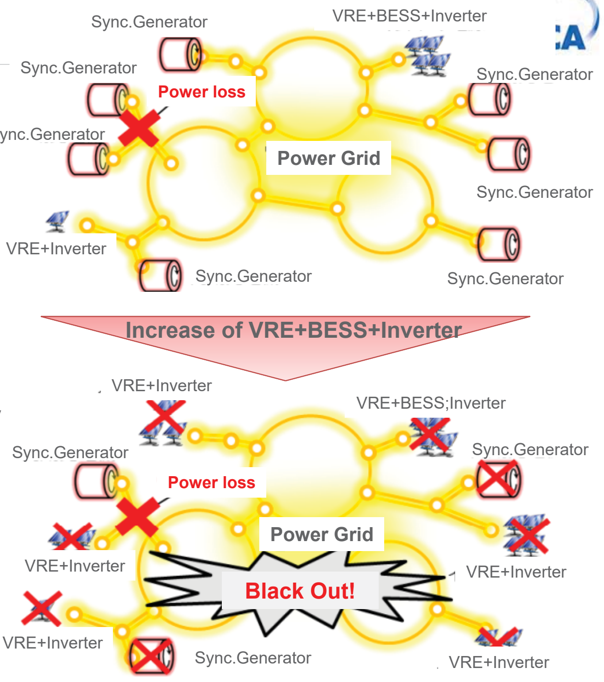
Source: OCCTO Committee on Demand-supply Balance on 27 Oct 2020

Black-out when insufficient Sync. Gen.

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



RoCoF: Rate of Change of Frequency



Source: Transmission and Grid Council, Japan

SCO and STATCOM for Reactive Power

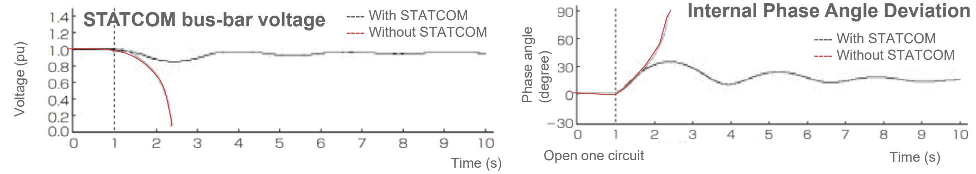
SCO (Synchronous Condenser) :

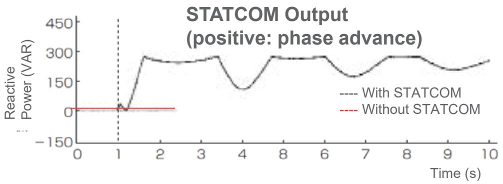
SCO is DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. Though changing field excitation, SCO adjusts reactive power and provides reactive power at the time of voltage drop.

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.

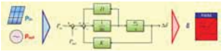




Source: Enhancement of Steady−State Stability and Suppression of Over−Voltage using 450MVA GCT−STATCOM, Mitsubishi Denki Giho, pp.52-55, Vol.87, No.11, 2013.

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

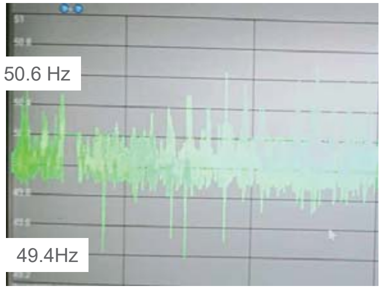
Emerging technology for large RE with Grid stabilization : Generation with Inertia and Synchronous Power

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

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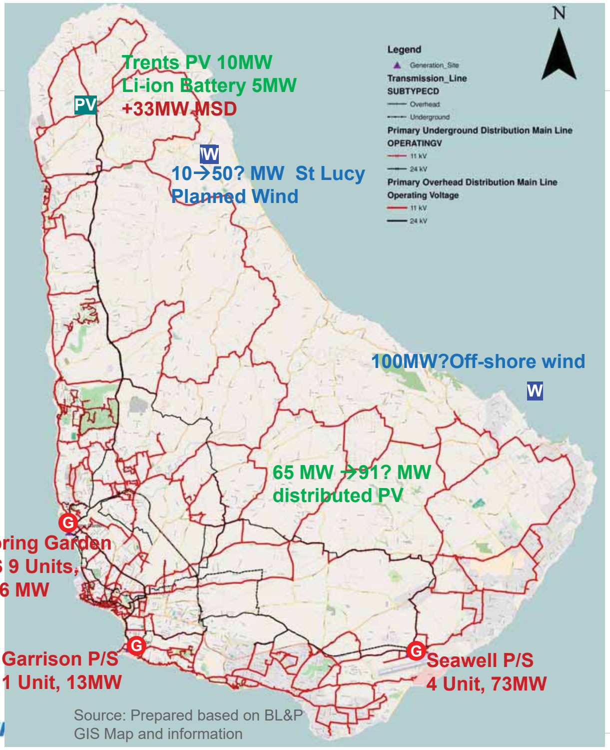
Grid and Generation of Barbados



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

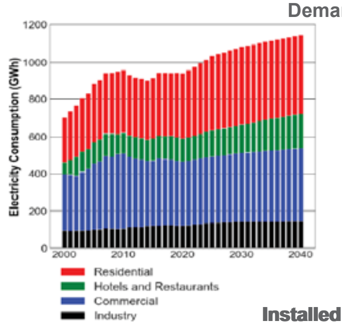
	Location	MW/u	Qy	MW	Remark
Existing					
Total thermal power				**265**	
	Spring Field Total		9	166	LDS, ST, GT
	Garrison	13	1	13	Gas Tubine
	Seawell	13	1	13	Gas Tubine
	Seawell	20	2	40	Gas Tubine
	Trents	8.3	4	33	MSD Engine
Total PV				**75.6**	
	Trents	10	1	10	PV
	Distributed PV		LS	65.6	PV
Total Battery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

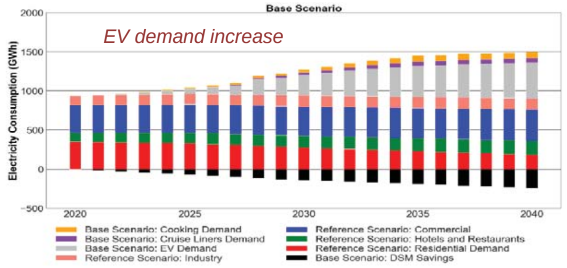
Tentative. Please let us confirm the status and update if any.

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

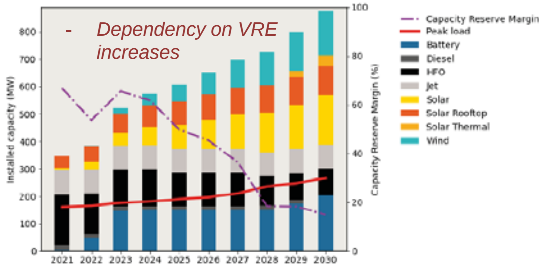
Source: IRRP Draft 2021, MottMacDonald

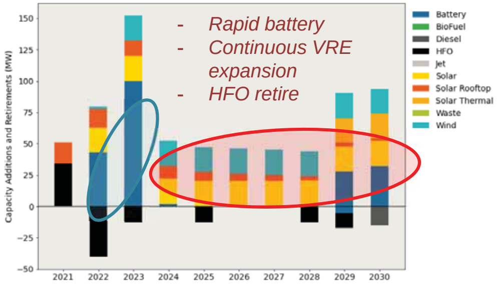
Demand Scenario in IRRP (Base scenario)





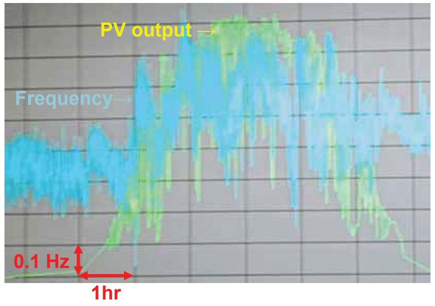
Installed capacity and capacity addition in IRRP (Base Case)

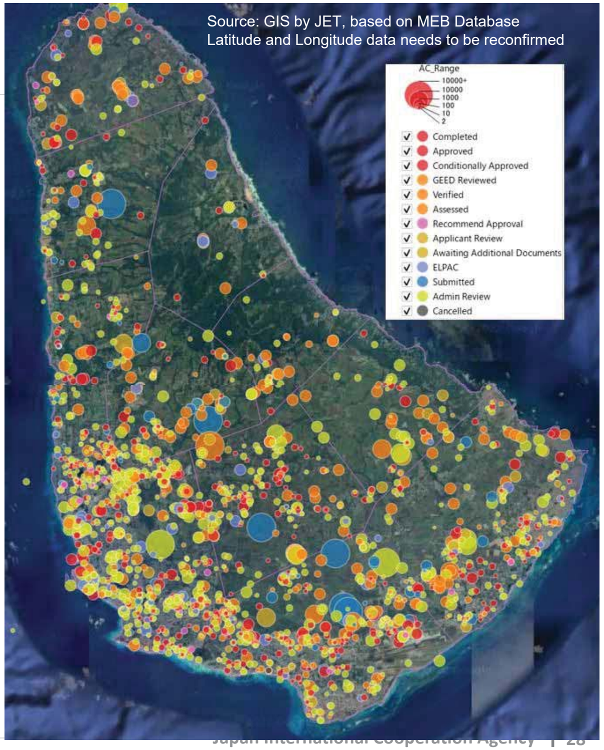




PV and Fluctuation of Frequency in Barbados

- 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

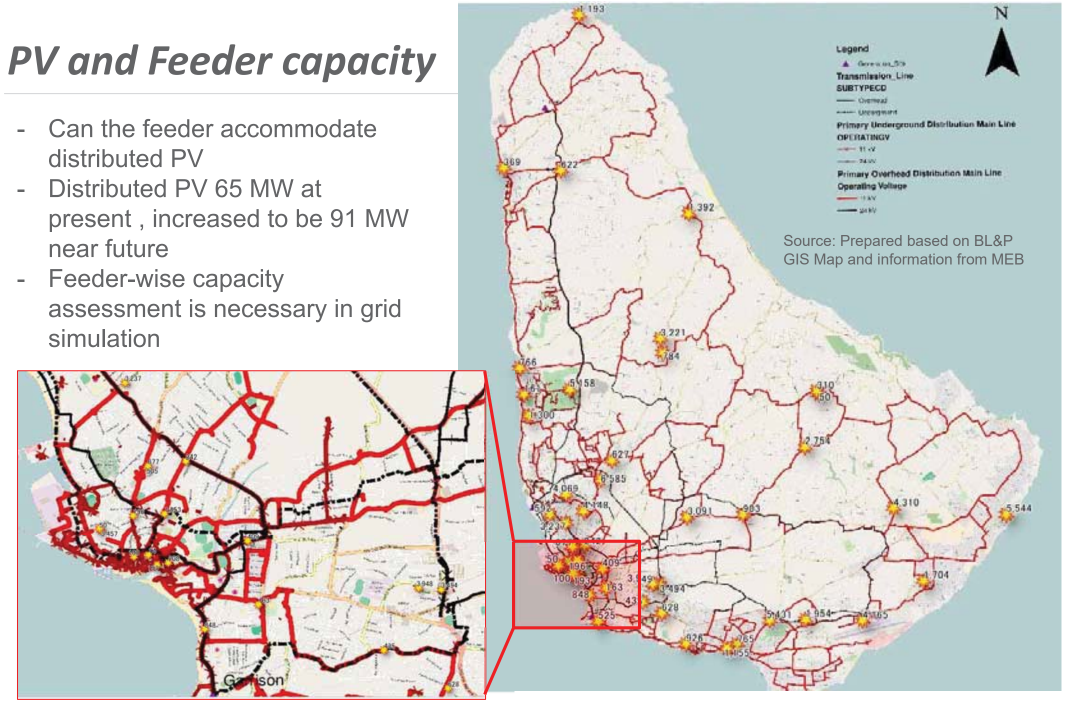




Source: GIS by JET, based on MEB Database
Latitude and Longitude data needs to be reconfirmed

PV and Feeder capacity

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

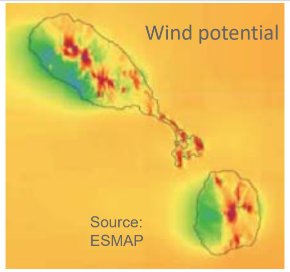


Source: Prepared based on BL&P GIS Map and information from MEB

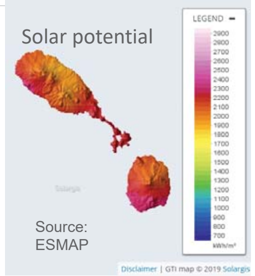
Present Situation and Future Planing of St. Kitts and Nevis

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


Wind potential

Source: ESMAP


Solar potential

Source: ESMAP

Necessary consideration for future RE

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

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

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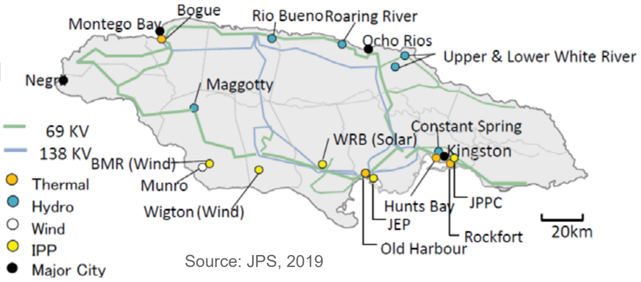
RE Status in Jamaica

Challenges for RE & Grid:

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

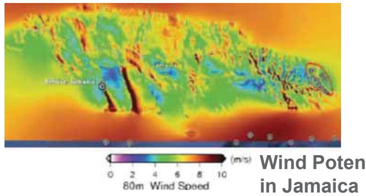


Source: JPS, 2019

VRE Projects in Jamica

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

Source: Prepared by JET with several data sources



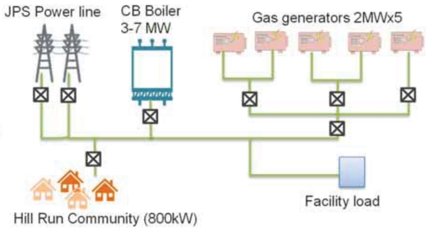
Wind Potential in Jamaica

Source: Sustainable Energy Roadmap 2013

Difficulty due to VRE and Good Practice of Jamaica

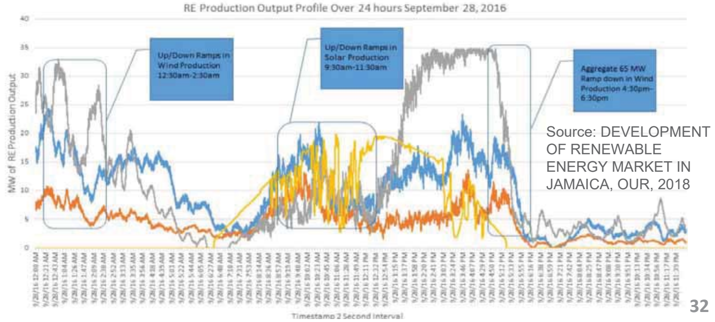
To cope with ＞140MW VRE for 650 MW peak grid in 2016, JPS took following measurement:

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

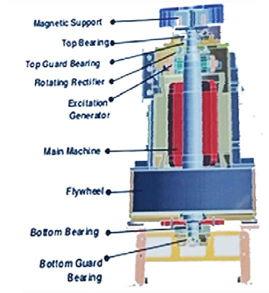
JPS System Control Center

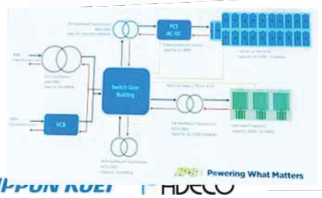


Source: DEVELOPMENT OF RENEWABLE ENERGY MARKET IN JAMAICA, OUR, 2018

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

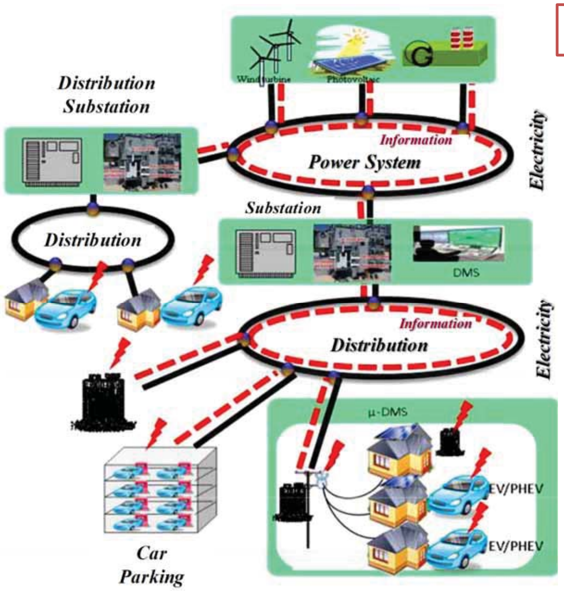
600 kW, Fallen at 25.6m/s wind while 60m/s design
- Additional moment due to Excess of high speed
- Missing control power supply

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

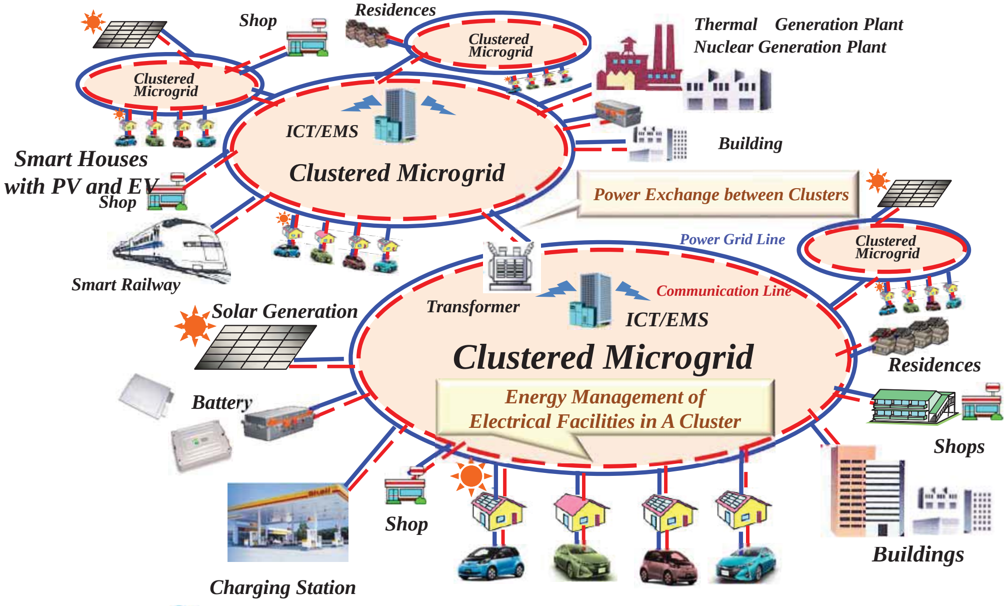


Source: Smart City Development and Recent trend in Electric Power Network, Waseda Univ.

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

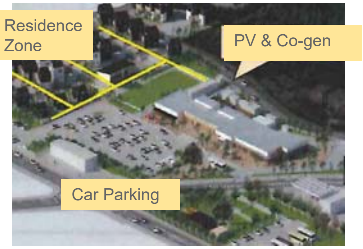
Microgrid for Resilient System
-- Autonomous Micro Grid



Microgrid Planning

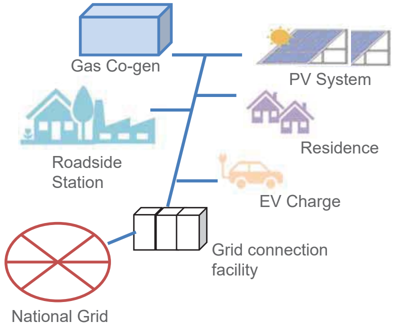
1	**Study for legal requirement of regulators considering affect on transmission line outside of Microgrid**	- Legal requirement for microgrid by the regulatory authority - Method for emergency recovery, switching from microgrid to master grid, Affect on adjacent areas.
2	**Estimation of load and demand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

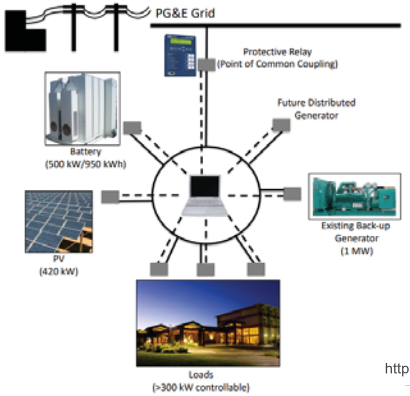
- Gas co-generation (80kWx2), PV system (20kW), Solar heating (37 kW) EV charger,
- Independent power supply for residence zone
- Thermal supply for hot spring by co-gen
- Micrgrid area connected with grid
- Continuous supply during Typhoon (large scale regional power cut approx. 1 week) in Sep 2019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

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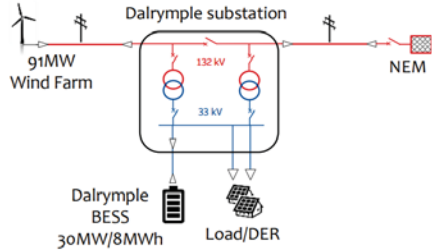
Microgrid Ex.-3: South Australia Yorke Microgrid

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



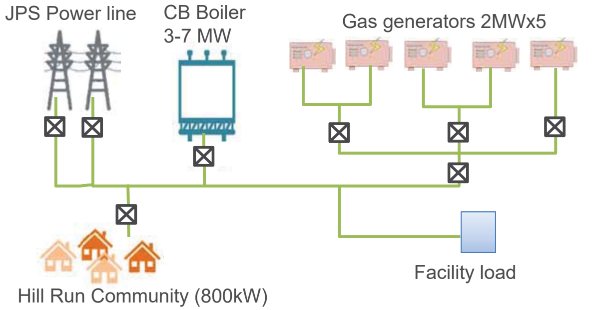
Grid Forming Energy Storage System addresses challenges of grids with high penetration of renewables (A case study), CIGRE, 2020

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

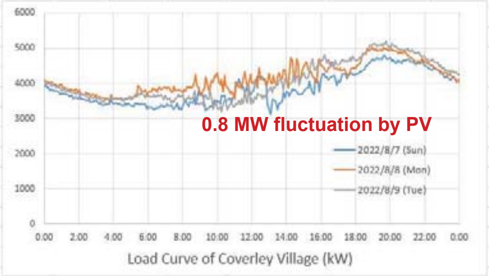
https://www.cvmtv.com/news/major-stories/jps-and-cb-group-collaborates-on-new-power-plant/

- 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



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

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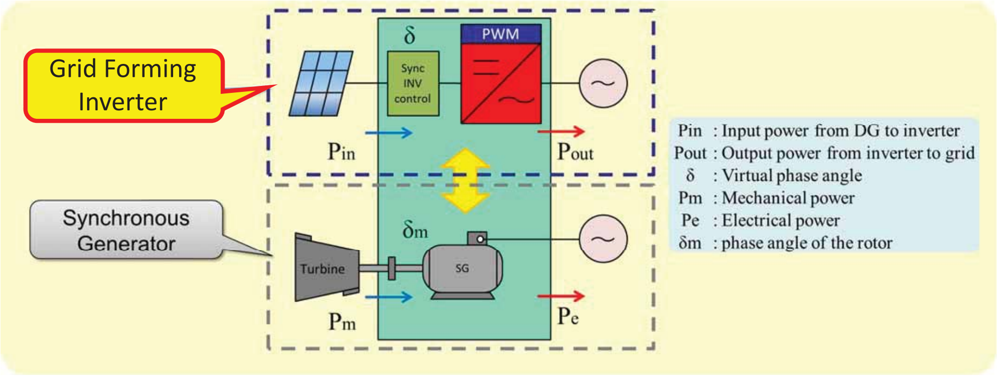
(1) Grid Forming Inverter for VRE



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.

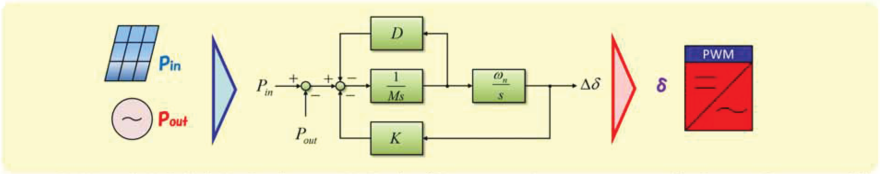
$$\frac{M}{\omega_n}\frac{d^2\delta_m}{dt^2}+\frac{D}{\omega_n}\frac{d\delta_m}{dt}+K\delta_m=P_m-P_e$$

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)

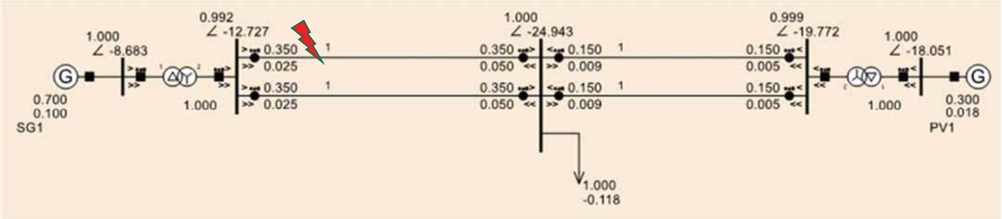
- SCR is the factor to be considered in large RE penetration for grid stability.
- SCR=AC System Capacity/Rated IBR Capacity
  - SCR>3 -------- High SCR, Stable
  - 3>SCR>2 ----- Low SCR
    Small fluctuation continues.
  - 2>SCR -------- Very Low SCR
    Sensitivity of IBR to Grid goes high.
    Grid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

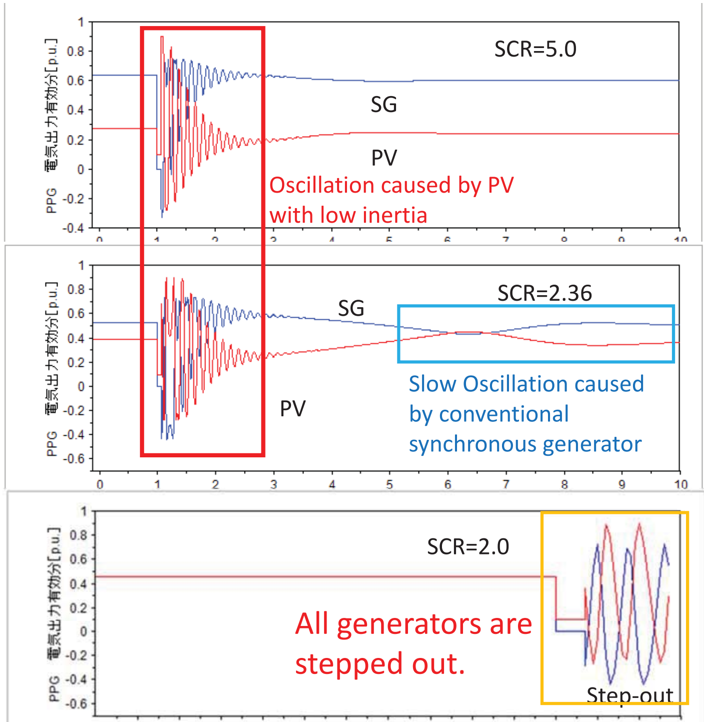


Calculated by CPATFree(CRIEP's Power System Analysis Tools

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.



Oscillation caused by PV with low inertia

Slow Oscillation caused by conventional synchronous generator

All generators are stepped out.

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**

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(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

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

- Available Transmission Capacity from Transient Stability

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

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

---

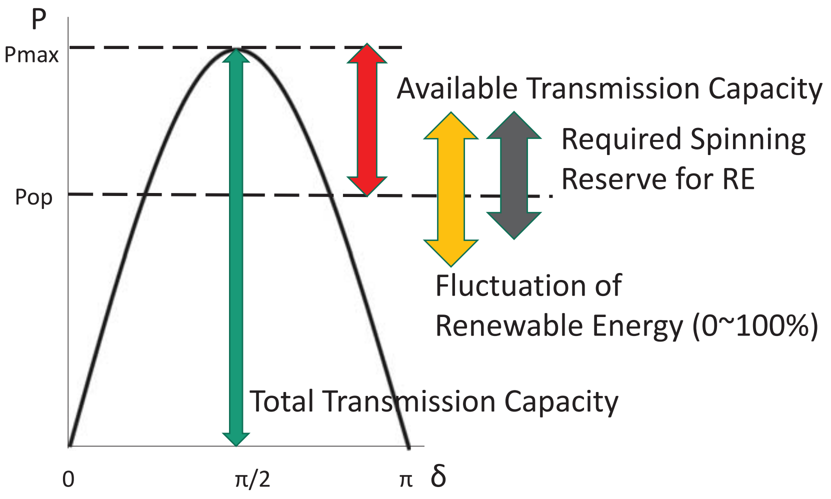
(4) Spinning Reserve

- 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



Available Transmission Capacity

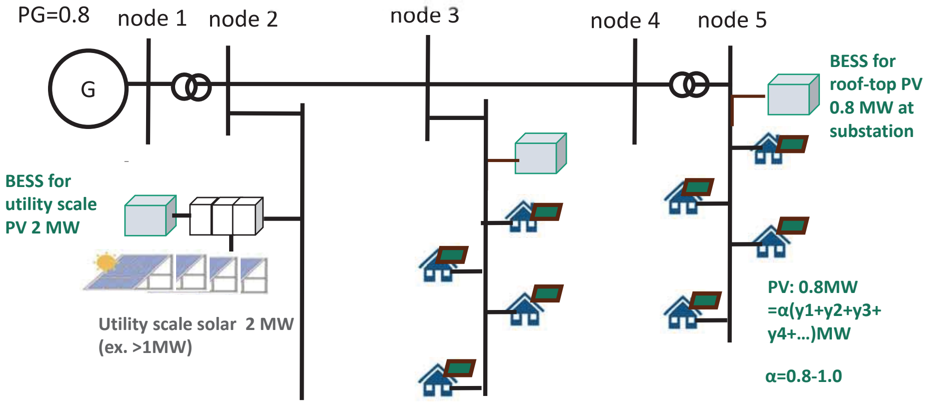
Required Spinning Reserve for RE

Fluctuation of Renewable Energy (0~100%)

Total Transmission Capacity

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.



BESS for utility scale PV 2 MW

Utility scale solar 2 MW (ex. >1MW)

BESS for roof-top PV 0.8 MW at substation

PV: 0.8MW =α(y1+y2+y3+y4+...)MW

α=0.8-1.0

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

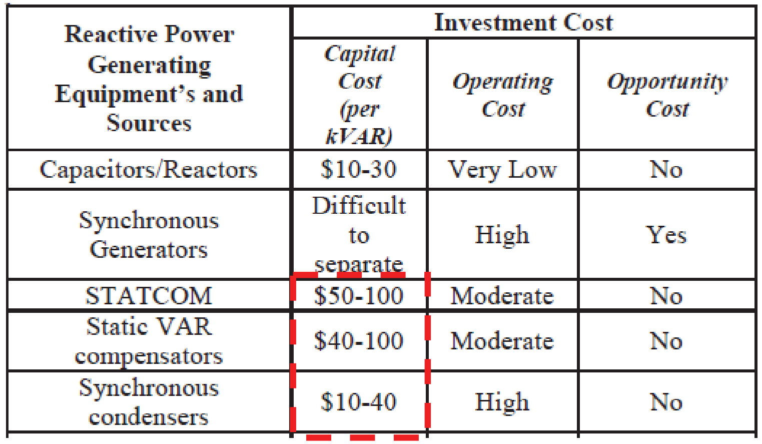
PV : US$ 570,000~720,000/MW

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**

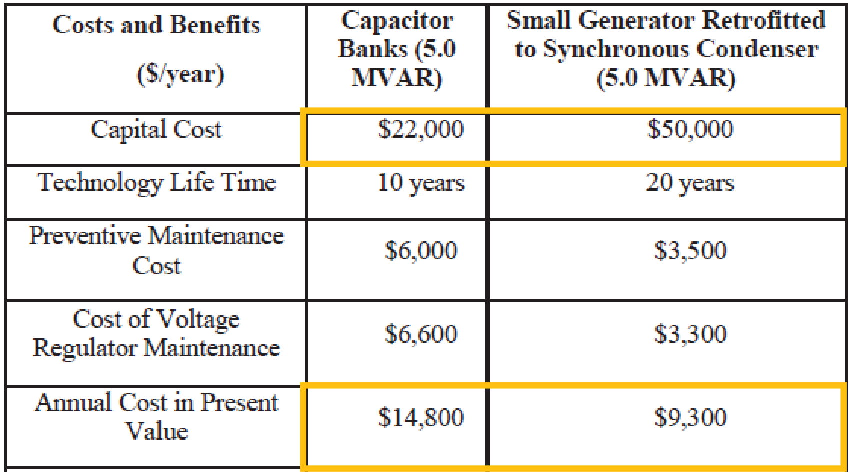
Cost Comparison of Reactive Power Generating Equipment and Sources



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



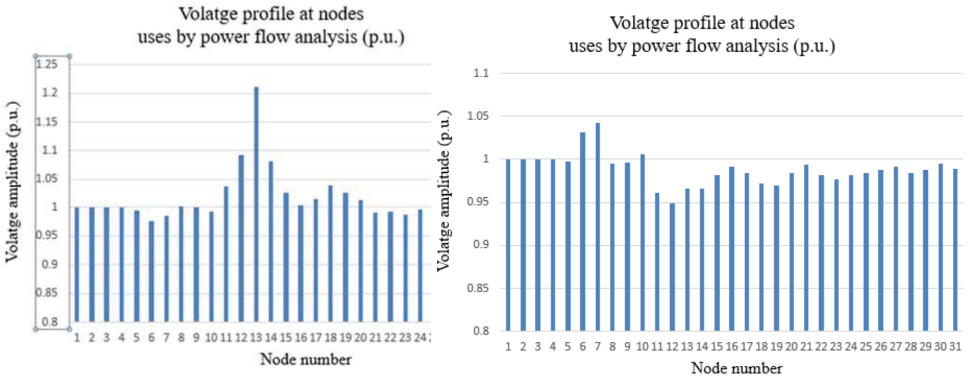
Costs and Benefits ($/year)	Capacitor Banks (5.0 MVAR)	Small Generator Retrofitted to Synchronous Condenser (5.0 MVAR)
Capital Cost	$22,000	$50,000
Technology Life Time	10 years	20 years
Preventive Maintenance Cost	$6,000	$3,500
Cost of Voltage Regulator Maintenance	$6,600	$3,300
Annual Cost in Present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

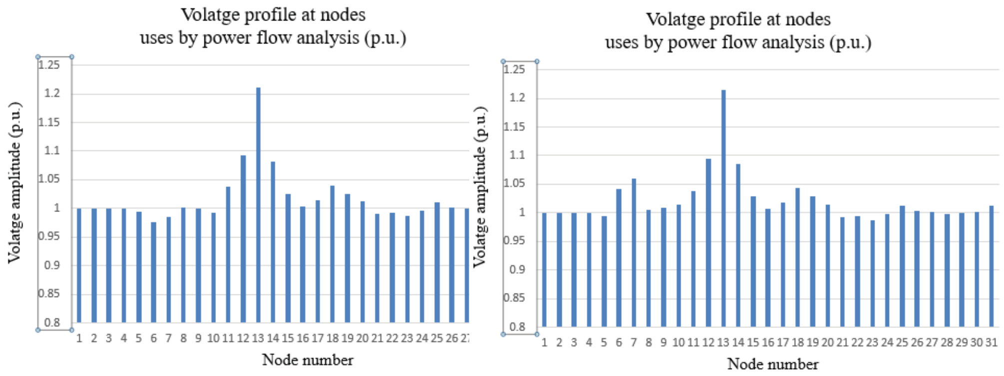
without Battery in end nodes   with Battery in end nodes

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

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

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

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

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

$$\dot{V}_{\mathrm{p}} = \dot{I}_{\mathrm{p}} \dot{Z}_{\mathrm{p}}$$

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

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

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

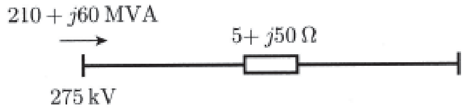
Example of Conversion to Per Unit

(1) Calculate Base Value

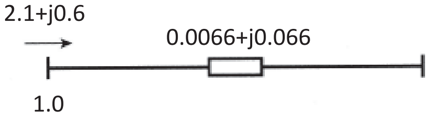
Vbase=275kV

(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:

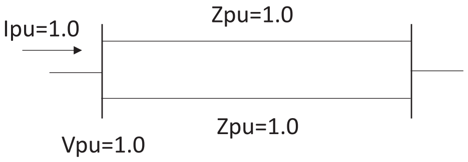
1pu(|Z|=0.93Ω) impedance transmission line can send 1pu(100MVA) power by 1pu(11kV) voltage. Its current is 1pu(9.1kA).

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



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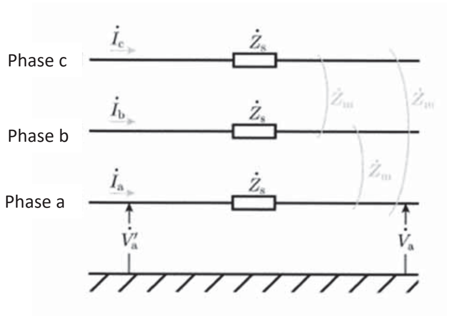
2. Modeling of Power System Equipment

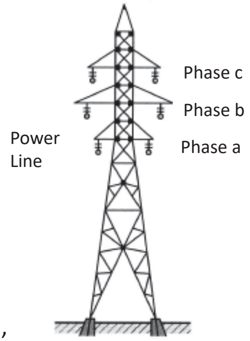
- Make it easy to analyze feature of power system equipment
- Modeling of Components of Power System
  - Transmission Line
  - Synchronous Generator
  - PV(Photovoltaic Generator)
  - WT(Wind Turbine Generator)
  - Load

Transmission Line

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



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

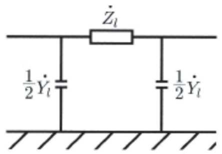


Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

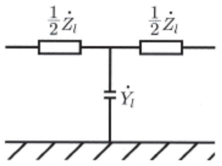
Equivalent Circuit of Transmission Line

Two types of Equivalent Circuit

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



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



- Π (pai) model is easy to handle in analysis, because it is not necessary to add new node at the middle point of transmission line.

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

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

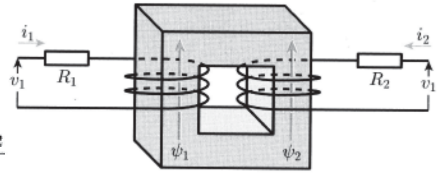
Transformer

- Mathematical equations of transformer

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

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

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



$$\begin{cases} \dot{V}_1 = \dot{I}_1 R_1 + j\omega(L_1 \dot{I}_1 + M_{12}\dot{I}_2) = (R_1 + j\omega L_1)\dot{I}_1 + j\omega M_{12}\dot{I}_2 \\ \dot{V}_2 = \dot{I}_2 R_2 + j\omega(M_{21}\dot{I}_1 + L_2 \dot{I}_2) = j\omega M_{21}\dot{I}_1 + (R_2 + j\omega L_2)\dot{I}_2 \end{cases}$$

Magnetic circuit connects two electrical circuits through a transformer.

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

Equivalent Circuit of Transformer

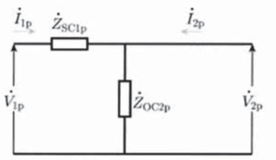
- Relationship of per unit base values

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

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

- Equivalent Circuit and Equation

$$\begin{cases} \dot{V}_{1\mathrm{p}} = \dot{I}_{1\mathrm{p}}\dot{Z}_{\mathrm{SC1p}} + (\dot{I}_{1\mathrm{p}} + \dot{I}_{2\mathrm{p}})\dot{Z}_{\mathrm{OC2p}} \\ \dot{V}_{2\mathrm{p}} = (\dot{I}_{1\mathrm{p}} + \dot{I}_{2\mathrm{p}})\dot{Z}_{\mathrm{OC2p}} \end{cases}$$



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

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

Synchronous Generator (Steady State)

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

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

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

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

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

Load (Consumer)

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

How to make a model of Renewable Energy Generator

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

---

3. Active Power & Frequency

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

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

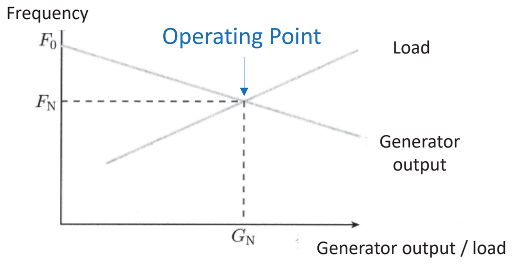


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Frequency Control Scheme

- Frequency Control Scheme is categorized to 4 stages.

(1) Self-control of load

Quick response of Load according to its characteristics.

(2) Turbine Governor control (Governor Free)

Function of synchronous generator

Conventional inverter doesn’t have this.

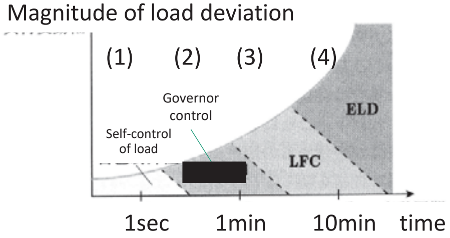
(3) Load Frequency Control

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

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

(4) Economic Load Dispatching

Select most cost effective generator among LFC generators



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

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

Power–Frequency Coefficients

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

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

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

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

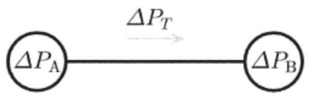
$$K = K_G + K_L \ [\mathrm{MW/Hz}]$$

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

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.

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

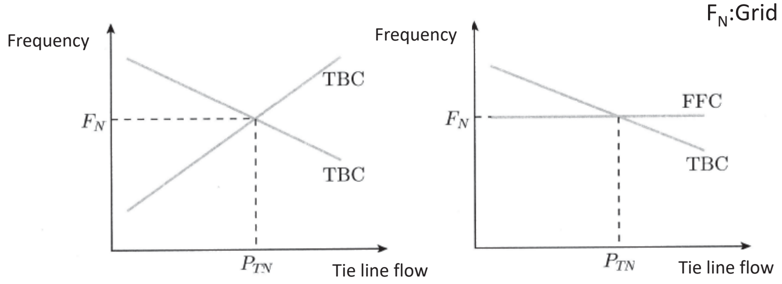
F0: Rated Frequency
F: Frequency of Interconnected Grid
ΔG: Generator Output Change
ΔL: Load Change
ΔP: Chang of Power
ΔF: Change of Frequency
KG: Gain for Generator Output Change
KL: Gain for Load Change
K: Power-Frequency Coefficient

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

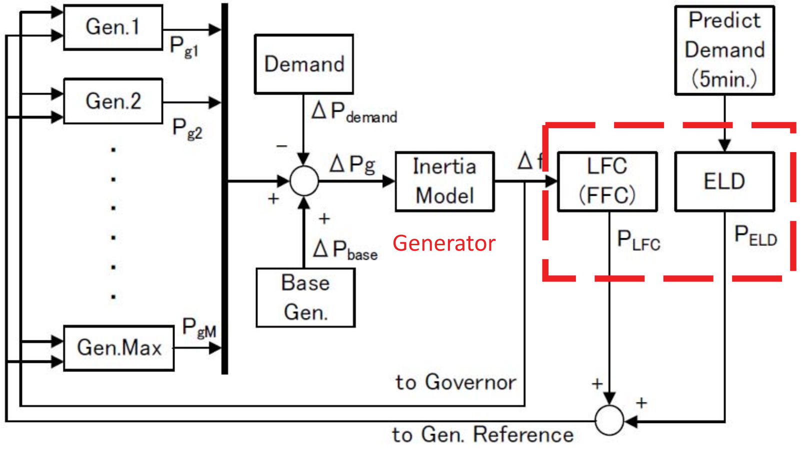


Figure is cited from MicroGrid Designer User and Technical Reference Manual

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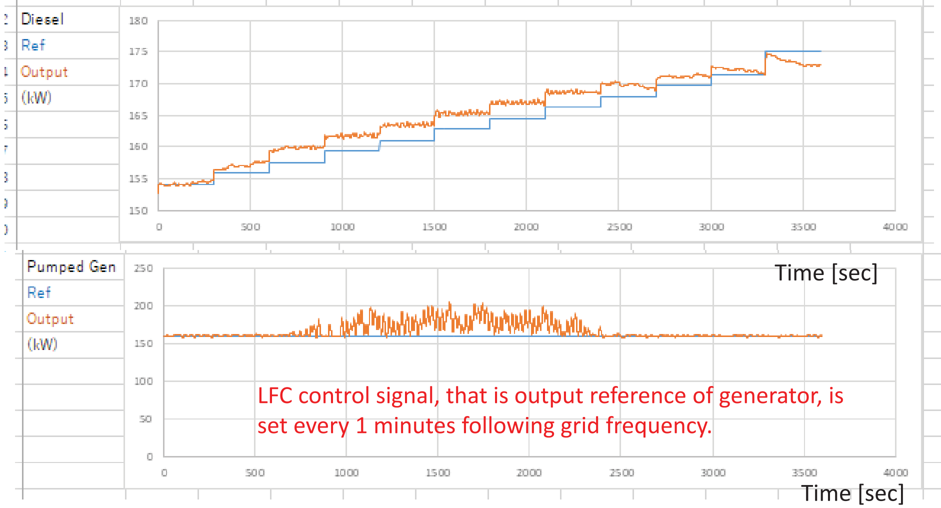
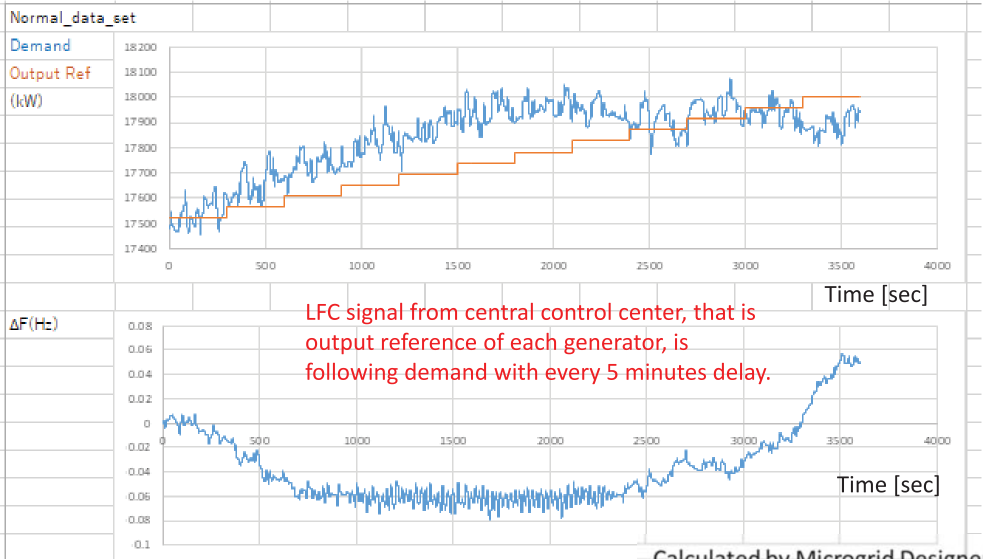
Example of LFC - Generator Output -



LFC control signal, that is output reference of generator, is set every 1 minutes following grid frequency.

Calculated by Microgrid Designer

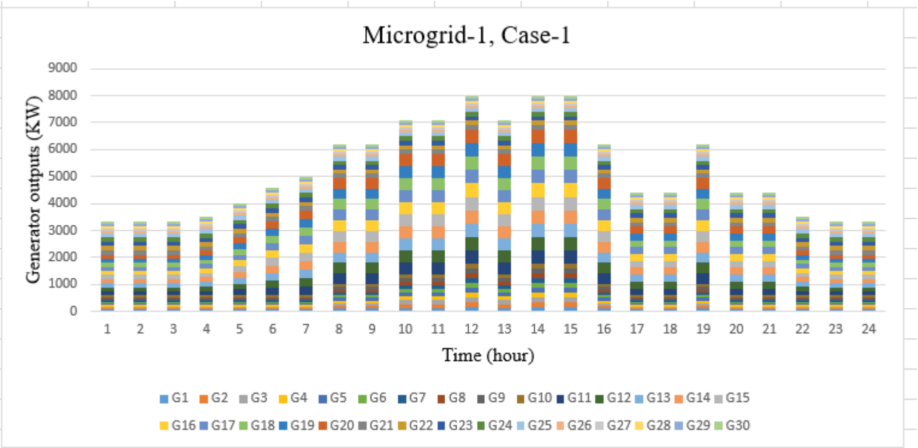
Example of LFC - Demand and Frequency -



LFC signal from central control center, that is output reference of each generator, is following demand with every 5 minutes delay.

Calculated by Microgrid Designer

Example of ELD



Calculated by Microgrid Designer

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4. Reactive Power & Voltage

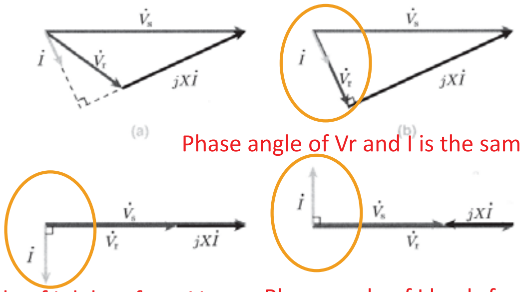
- Most of load consumes reactive power and the voltage of load node will be low.
- Reactive power should be provided or controlled to keep voltage as a set value.
- Providers of reactive power
  - Synchronous generator (SG)
  - Shunt Capacitor (SC)
  - Synchronous Condenser/Capacitor (SCO, RC: Rotary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



Phase angle of Vr and I is the same.

Phase angle of I delays from Vr.

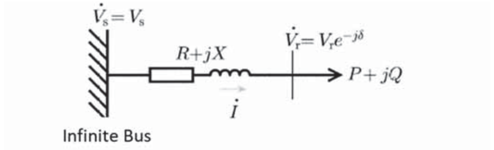
Phase angle of I leads from Vr.

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.

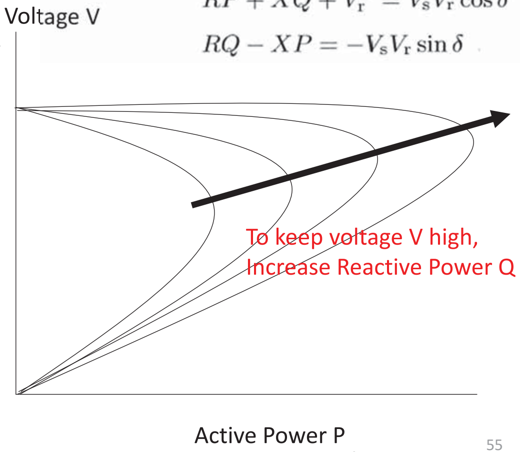
P-V Curve & Q(Reactive Power)

- 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.



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

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



To keep voltage V high,
Increase Reactive Power Q

Lunch Break

Session No. 4
Load Flow Analysis and its Evaluation

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

---

1. Overview of Load Flow Analysis

- Steady state analysis under small disturbance
- System is explained as linear model.
- Voltage, power, angle are constant at a certain time, and kept as the same value under small disturbance at a certain time.

  -> Load Flow Analysis: Algebraic equations

  -> Eigenvalue Analysis: Differential equations

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

Load Flow Analysis

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

Load Flow Analysis

Necessary items to consider Load flow Analysis

Buses are categorized to the following 3 types.

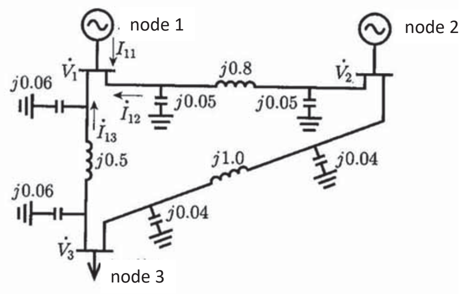
- Slack (Swing) Node
  - Node with largest capacity generator with constant voltage is generally selected.
  - Only the magnitude and phase angle of the voltage are specified.
  - This node supplements the difference between the scheduled loads and generated power that are caused by the losses in the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

Node Admittance Matrix

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

Describe Network Structure

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

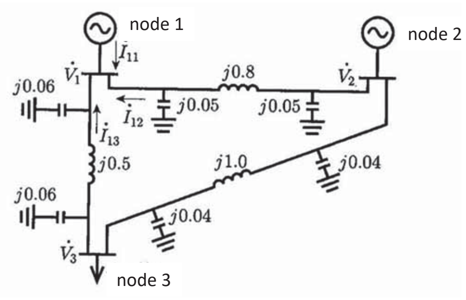


- Calculation example of power flow in 3 nodes network

V1,,,Vn: Node(Bus) Voltage
I1,,,In: Branch(Line) Current
Yij: Admittance between each node

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

Node Admittance Matrix



$$\dot{Y}_{11} = j0.05 + j0.06 + \frac{1}{j0.8} + \frac{1}{j0.5} = -j3.14$$
$$\dot{Y}_{22} = j0.05 + j0.04 + \frac{1}{j0.8} + \frac{1}{j1.0} = -j2.16$$
$$\dot{Y}_{33} = j0.04 + j0.06 + \frac{1}{j1.0} + \frac{1}{j0.5} = -j2.9$$
$$\dot{Y}_{12} = \dot{Y}_{21} = -\frac{1}{j0.8} = j1.25$$
$$\dot{Y}_{13} = \dot{Y}_{31} = -\frac{1}{j0.5} = j2.0$$
$$\dot{Y}_{23} = \dot{Y}_{32} = -\frac{1}{j1.0} = j1.0$$

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

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

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

Power Equation

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

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

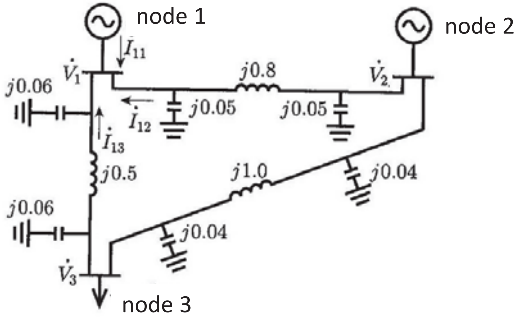
$$P_{ks} = \mathrm{Re}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$
$$Q_{ks} = \mathrm{Im}\left\{ \sum_{m=1}^{N} \dot{Y}_{km}^* (e_m + jf_m)^* (e_k + jf_k) \right\}$$
$$V_{ks}^2 = e_k^2 + f_k^2$$

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

Power Equation (Example of 3 nodes network)

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

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



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

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

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

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

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

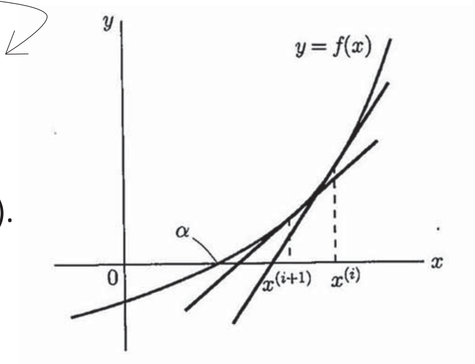


Figure is cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

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

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

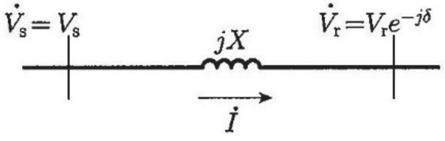
δ : Phase Difference of voltages between both side of a transmission line
X : Transmission line inductance
Pr : Active power that flows in a transmission line

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

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

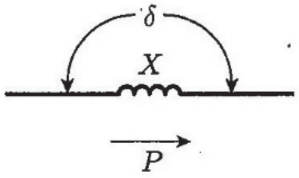


Simplified and Similar to DC circuit solution

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

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

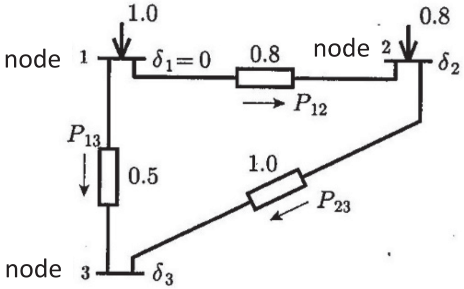
Approximate sinδ by δ



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

$$\delta_2 = 0.104$$

$$\delta_3 = -0.565$$

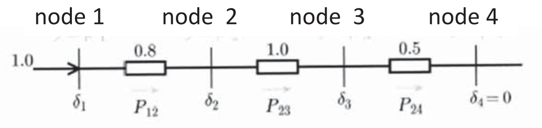
Figure is cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

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

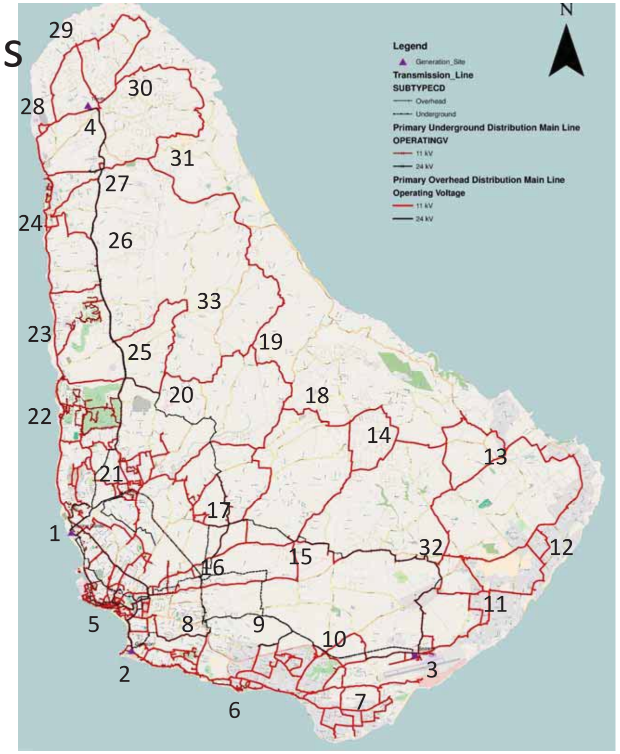
Barbados Grid

33 nodes +24/11kV Substations

=>

50 nodes

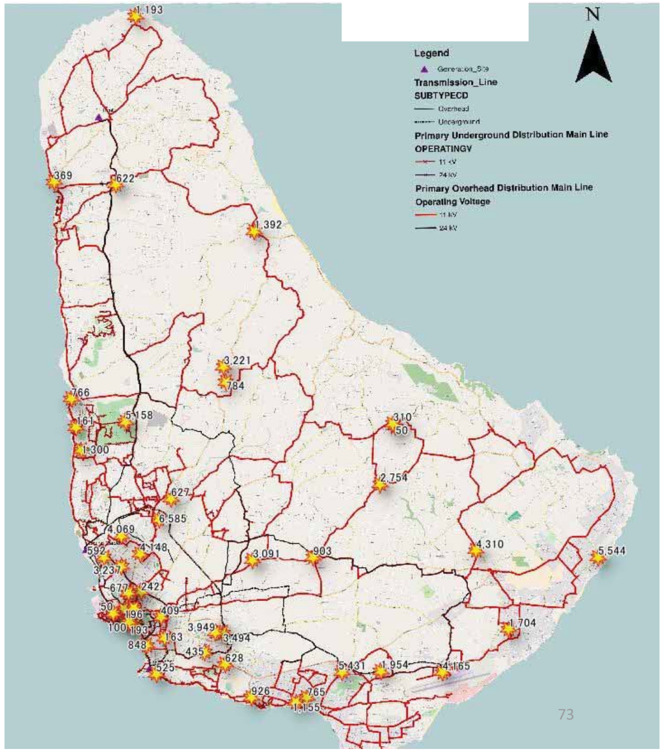
Barbados grid model is based on BL&P GIS map opened to public.



PV location to feeder

Total Capacity of PV in our estimated grid is:

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



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)

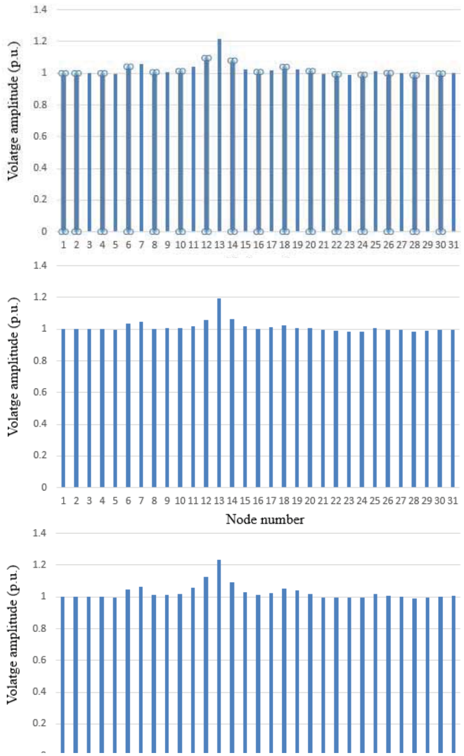
(3) Twice capacity of PV(182MW)

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.



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)

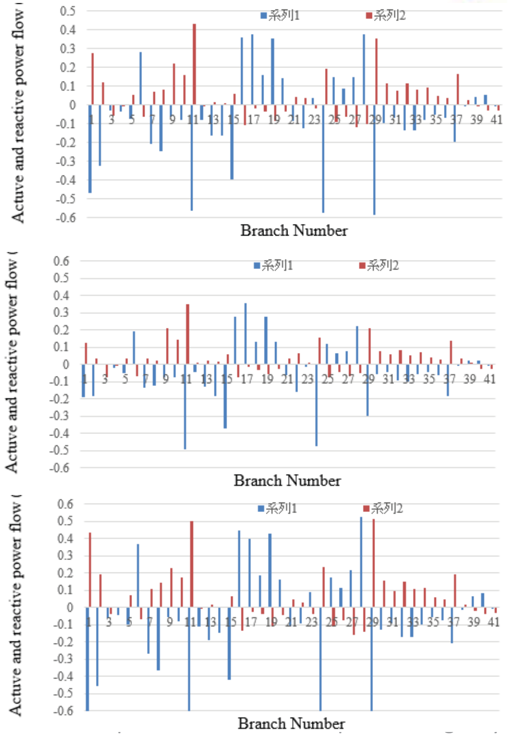
(3) Twice capacity of PV(180MW)

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.



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

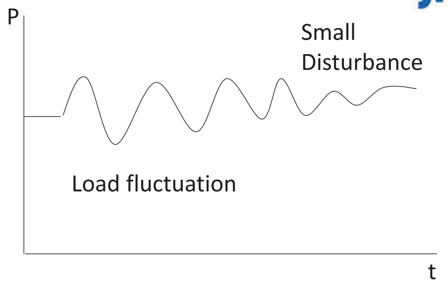
---

1. Overview of Stability

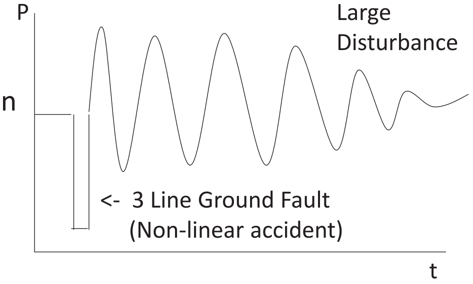
- STABILITY (Definition)
  - If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable.
  - If the system is not stable, it is considered unstable.

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.

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

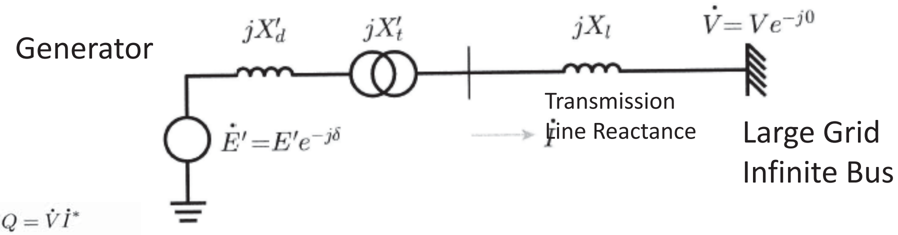
---

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



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

$$X=X_d'+X_t+X_l$$

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

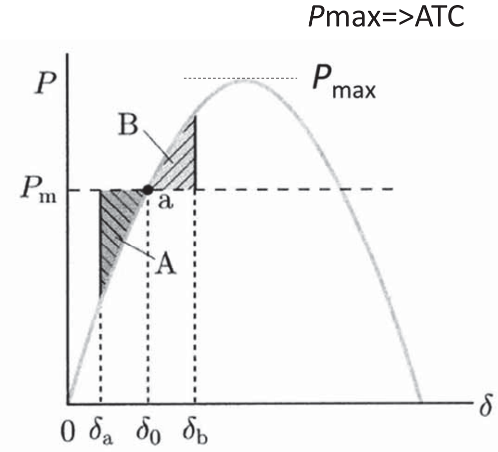


Figure is cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Equal Area Criterion for Stability Analysis

- $P=\frac{V_iV_j}{X}sin\delta$
- $\frac{dP}{d\delta}=\frac{V_iV_j}{X}cos\delta$

● 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

$$P=\frac{V_iV_j}{X}sin\delta$$

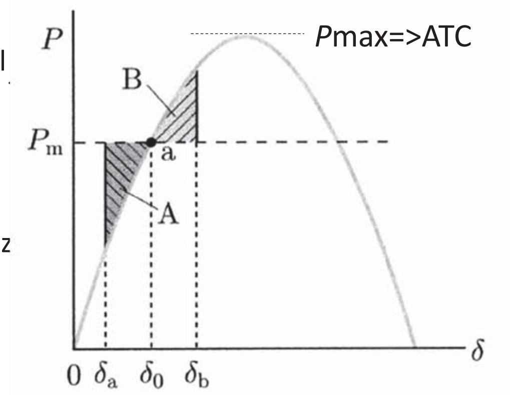


Figure is cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

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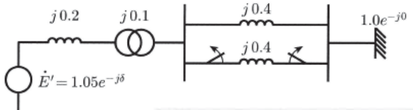
3. Exercise of Equal Area Criterion

- 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.

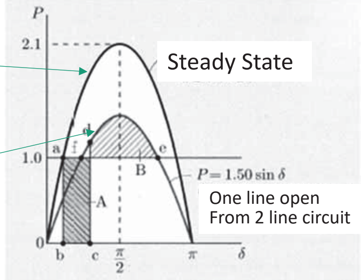
$$V=1.0,\quad E'=1.05$$
$$X=0.2+0.1+\frac{0.4}{2}=0.5$$



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

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

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

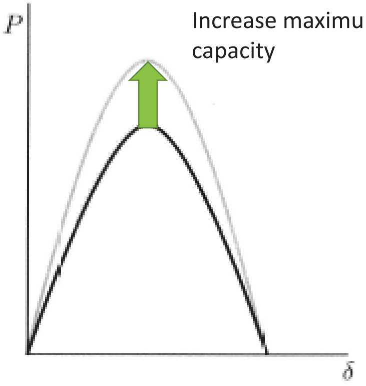


Figures are cited from
M.Kato & H.Taoka, “Fundamental Power System Engineering,” Suurikogaku-sha, 2011.

Solution for stability(1) through Equal Area Criterion

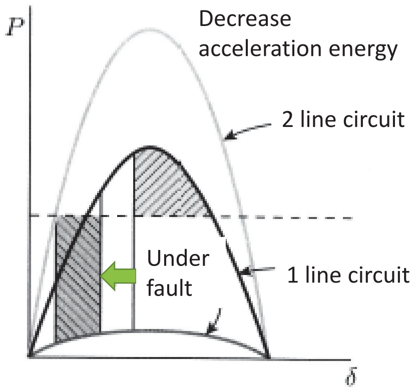
$$P = \frac{V_i V_j}{X} sin\delta$$

(a) To increase Voltage



Increase maximum capacity

(b) High Speed Circuit Breaker



Decrease acceleration energy

2 line circuit

Under fault

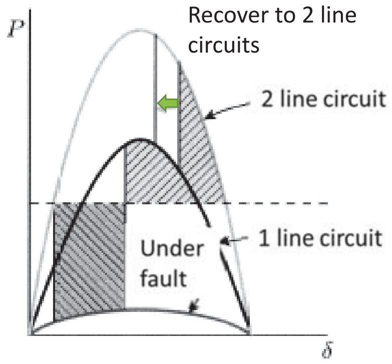
1 line circuit

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



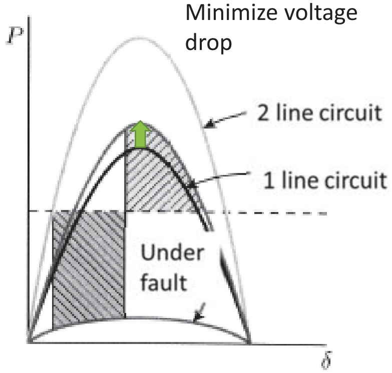
Recover to 2 line circuits

2 line circuit

Under fault

1 line circuit

(d) High Speed AVR



Minimize voltage drop

2 line circuit

1 line circuit

Under fault

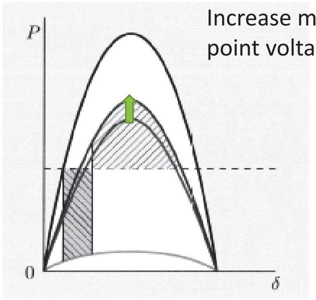
Figures are cited from
M.Kato & H.Taoka, "Fundamental Power System Engineering," Suurikogaku-sha, 2011.

Solution for stability(3) through Equal Area Criterion

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

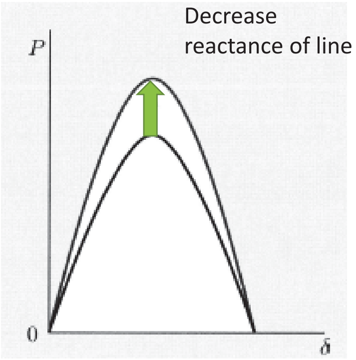
(e) Middle Point

Switch Gear Station



Increase middle point voltage of line

(f) Series Capacitor



Decrease reactance of line

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

Session No. 6
Discussion for future grid and VRE

- Current Grid of Barbados
  - Currently it goes well according to the several measures.
  - Simulation results shows the well controlled grid.
- Assumption of Future Grid (Large amount of RE) in Grid Model and Simulation
  - PVs at east side and west side nodes with/without BESS and Compensators
- Measures
  - BESS , Compensators(SC, SCO, STATCOM)
  - SPS(Special Protection System)

Special Protection System

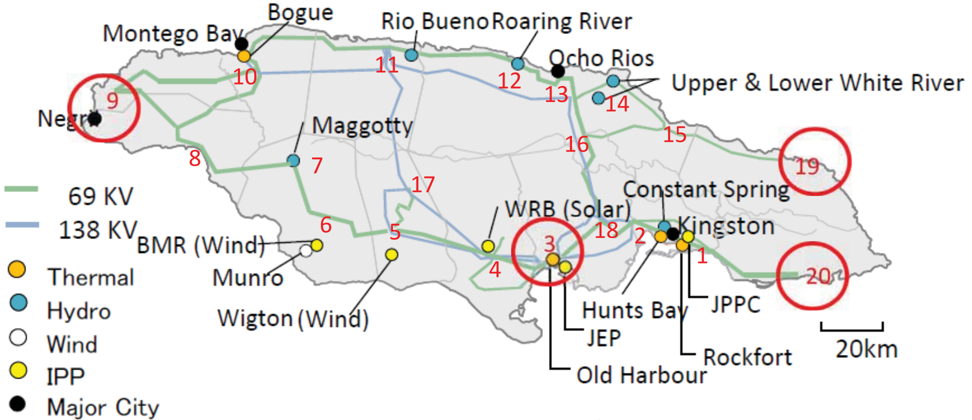
<Definition>

-> Optional functions installed by utility to improve grid protection according to each grid code.

- An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability.
- Such action may include changes in demand, generation (MW and Mvar), or system configuration to maintain system stability, acceptable voltage, or power flows.

Grid of Jamaica

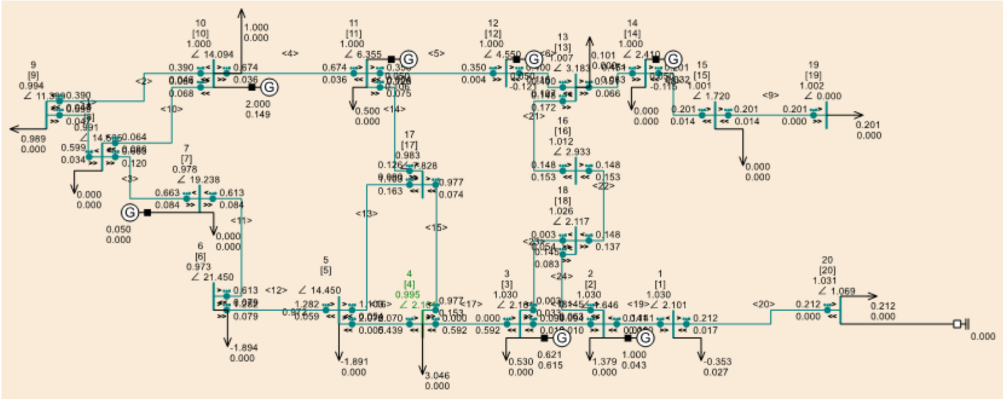
- To Solve Short Term Spinning Reserve Problem -



Red number is node number for power system analysis. Voltages of nodes in red circle became low in the load flow analysis.

* Map is from the presentation document of JPS(Jamaica Power Sector) on May 27, 2019.

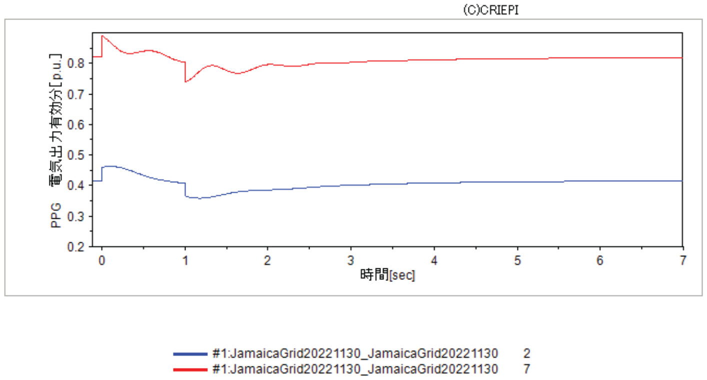
Load Flow Analysis of Jamaica Grid



Calculated by CPATFree(CRIEP's Power System Analysis Tools

Transient Stability Analysis (Case Study)

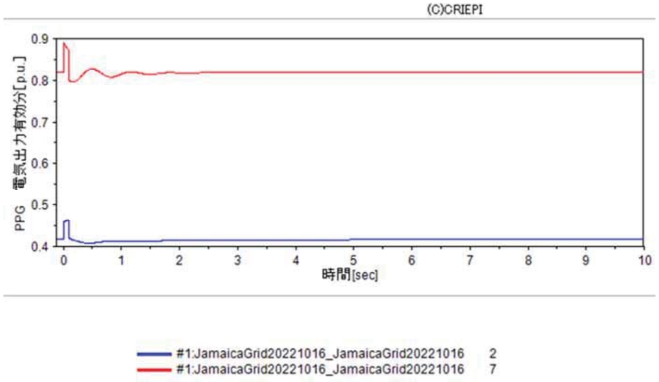
- In case output of PV drops from Max to Zero for 1 second -> Stable



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

Transient Stability Analysis (Case Study)

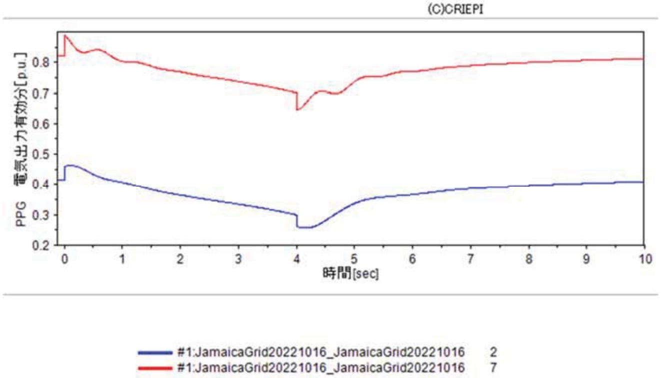
- In case output of PV at node 4 drops from Max to Zero for 1 second -> Stable



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

Transient Stability Analysis (Case Study)

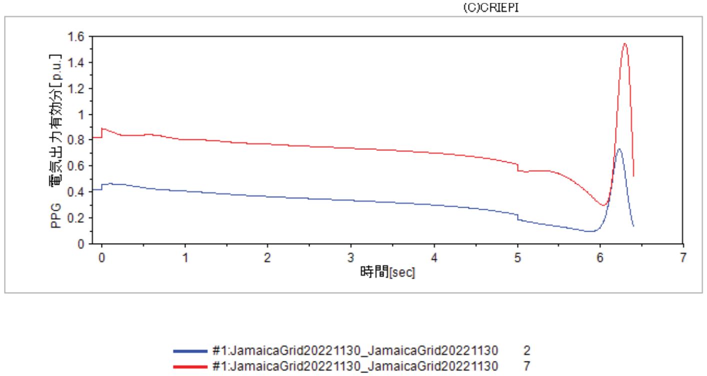
- In case output of PV at node 4 drops from Max to Zero for 4 second -> Stable



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

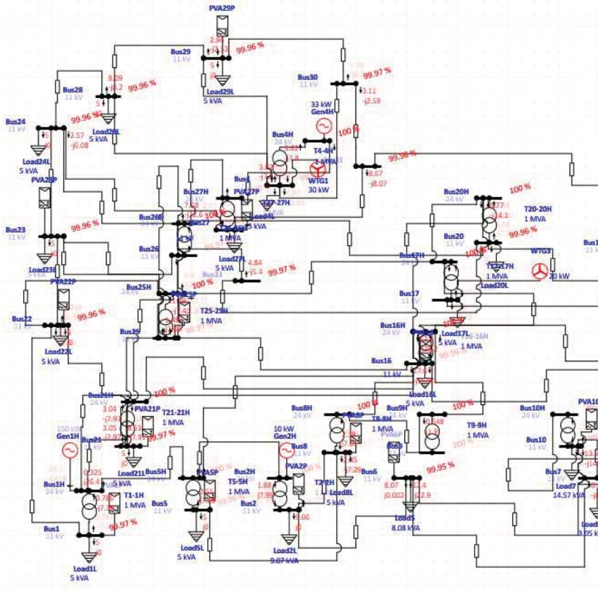
Transient Stability Analysis (Case Study)

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



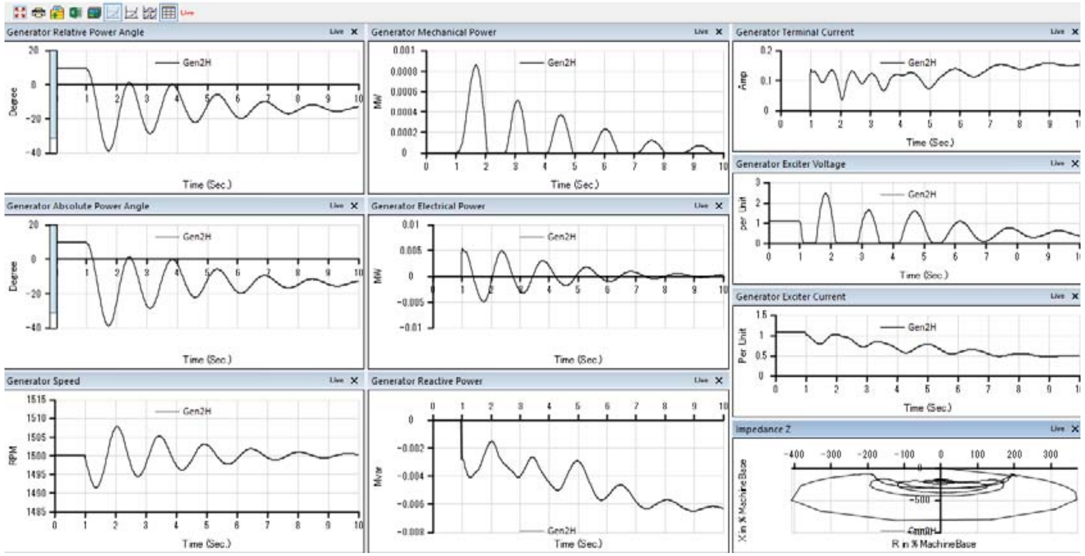
Calculated by CPATFree(CRIEP's Power System Analysis Tools)

Barbados 50 nodes grid map in ETAP

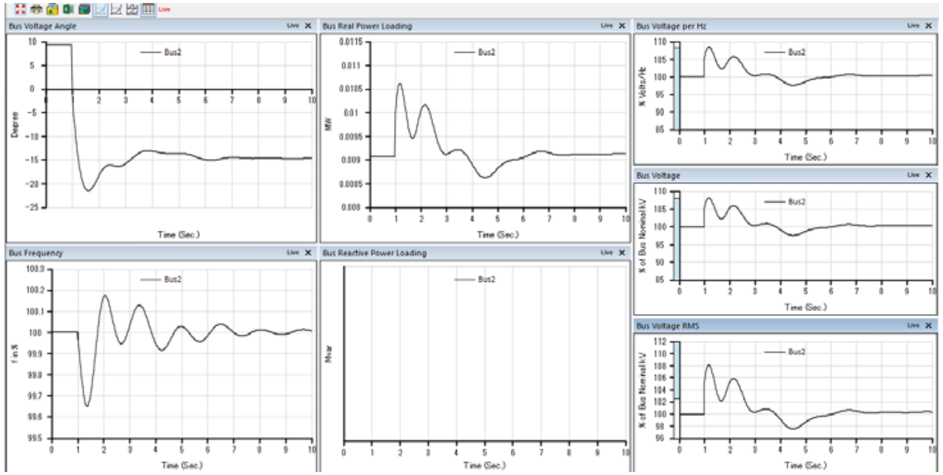


Barbados grid model is based on BL&P GIS map opened to public.

Generator No. 1 Transient after Wind Turbine Trip



Voltage and Power of Bus No. 1 after Wind Turbine Trip



Steps of Stability Analysis and Evaluation

Steps to evaluate stability will be as follows:

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

Per Unit Base calculation method for Transmission Network and Distribution Network

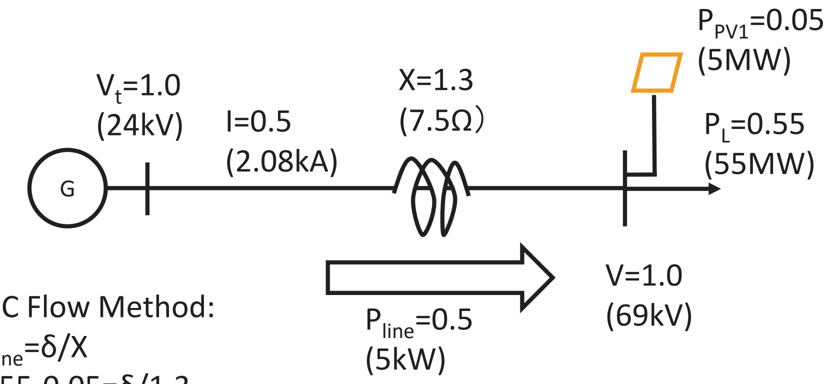
- Transmission Network

Base VA	100MVA
Base Voltage	24kV
Base Current	4.16kA (=100/24)
Base Impedance	5.76Ω (=24*24/100)
Base Admittance	0.174Ω^{-1} (=1/5.76)

- Distribution Network

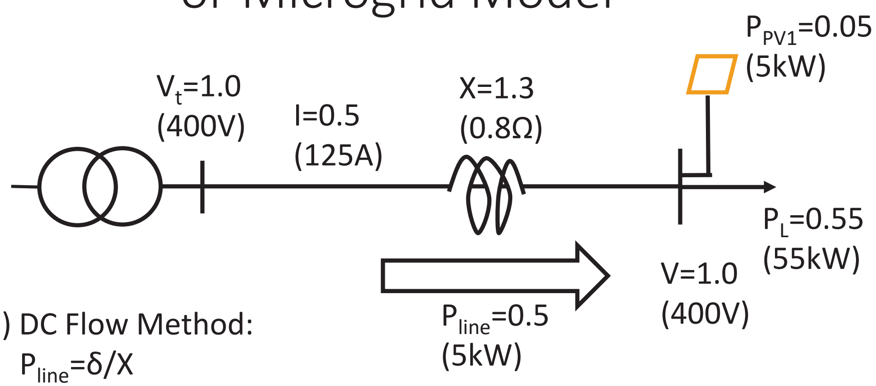
Base VA	100kVA
Base Voltage	400V
Base Current	250A (=100000/400)
Base Impedance	1.6Ω (=400*400/100000)
Base Admittance	0.625Ω^{-1} (=1/1.6)

Transmission Network Model



(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
$I=(P_L-P_{PV1})/V=0.5/1.0=0.5=2.08A$

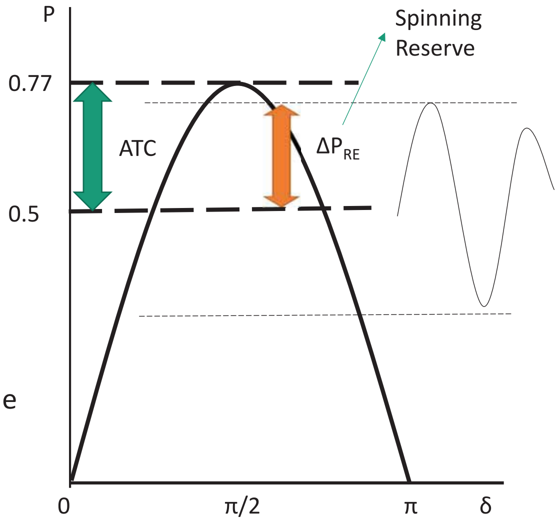
Distribution Network Model or Microgrid Model



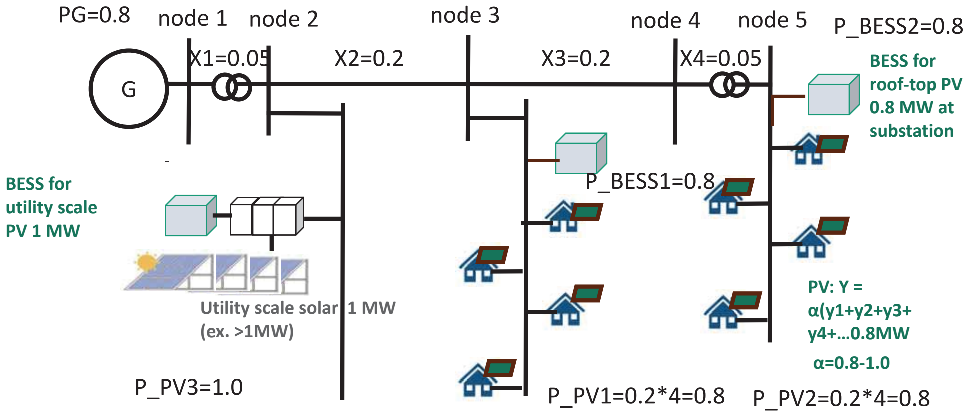
(1) DC Flow Method:
$P_{line}=\delta/X$
$0.55-0.05=\delta/1.3$
δ=0.65rad=37deg
If δ<90deg, these area is stable.
I=(PL-PPV1)/V=0.5/1.0=0.5=125A

P-δ Curve and Stability Evaluation

(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

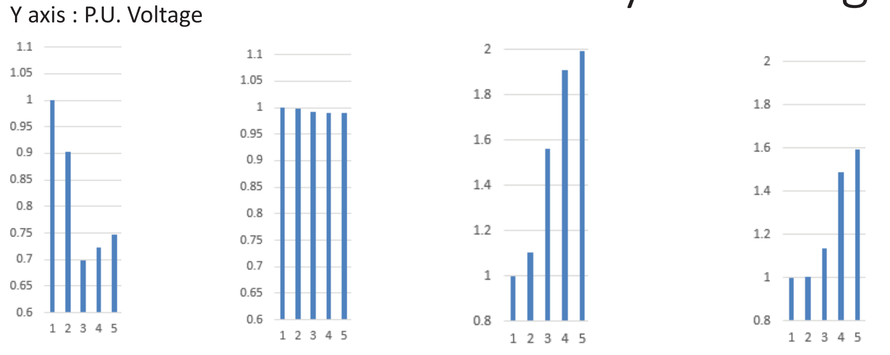


Simple Grid Model for RE



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

Load Flow Analysis of Simple Grid -to see the effect of Battery and Large PV-



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!!

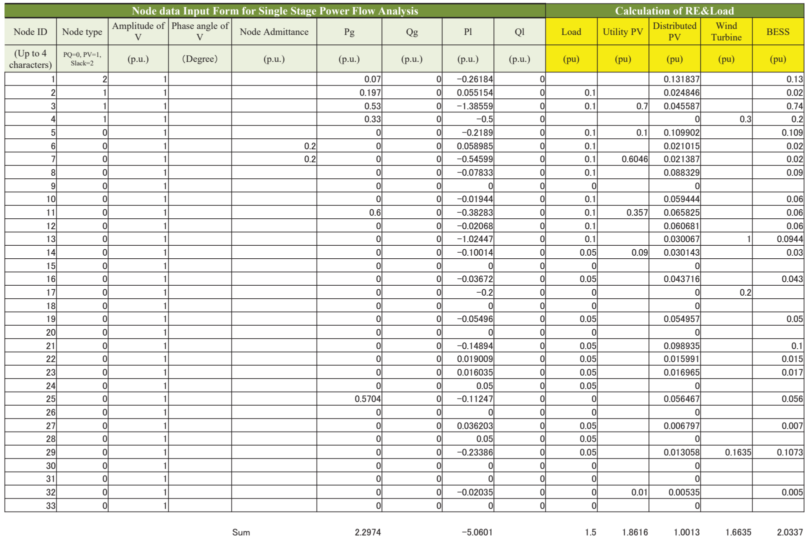
3rd Seminar on Grid Stability and Large RE Day 2

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

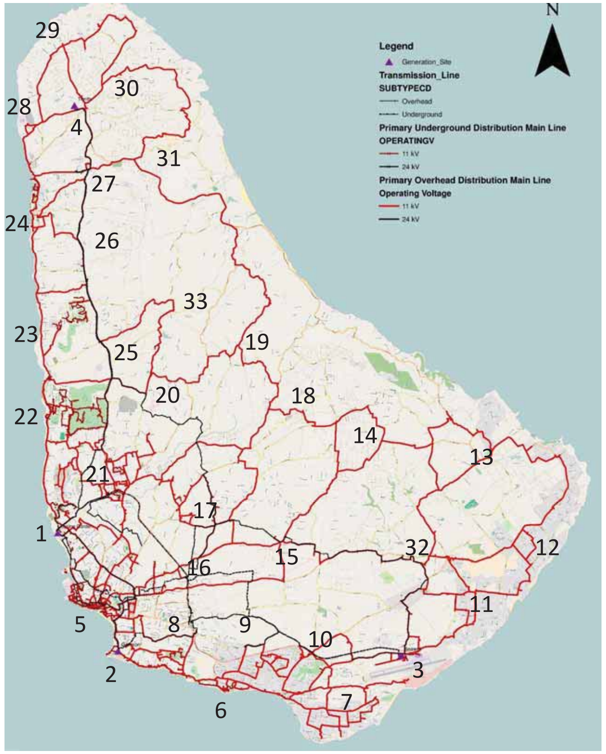


Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load				
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	Utility PV	Distributed PV	Wind Turbine	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)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

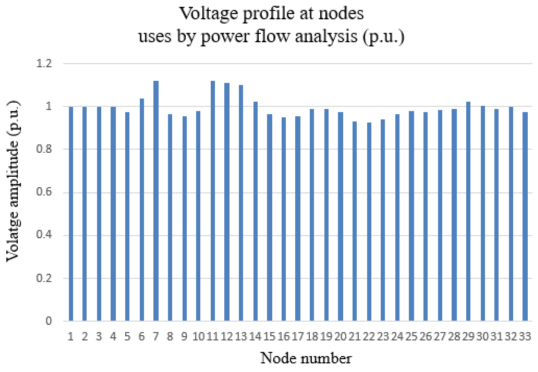
→ Let's input in Microgrid Designer to obtain load flow result

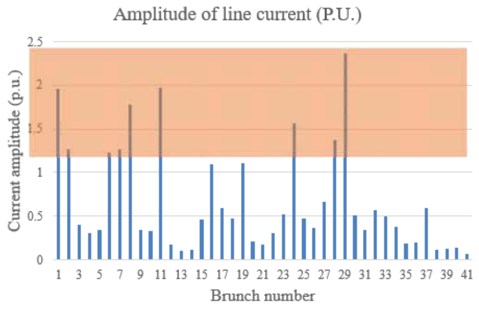
Power Resources	Capacity [MW]	Node
• Thermal Generator	145.4*	1,2,3,4
• WH	3.7*	2
• Distributed Solar	100.13	1~33
• Utility Scale Solar	185.70	3,7,11
• Biofuel	34.04*	25
• Onshore Wind	161.77	29
• Solar CSP	40.00*	11
• Battery	204.64	1~33
• Total	875.38	

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				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.

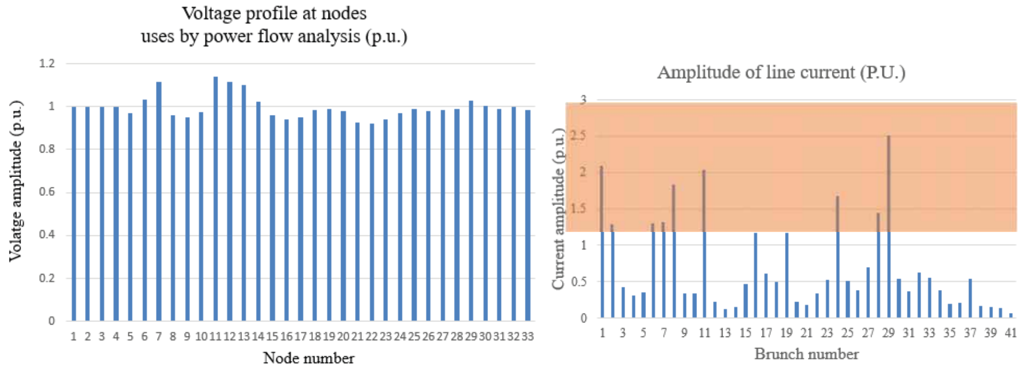
- Generation Capacity planned in 2030 : IRRP Scenario-3

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

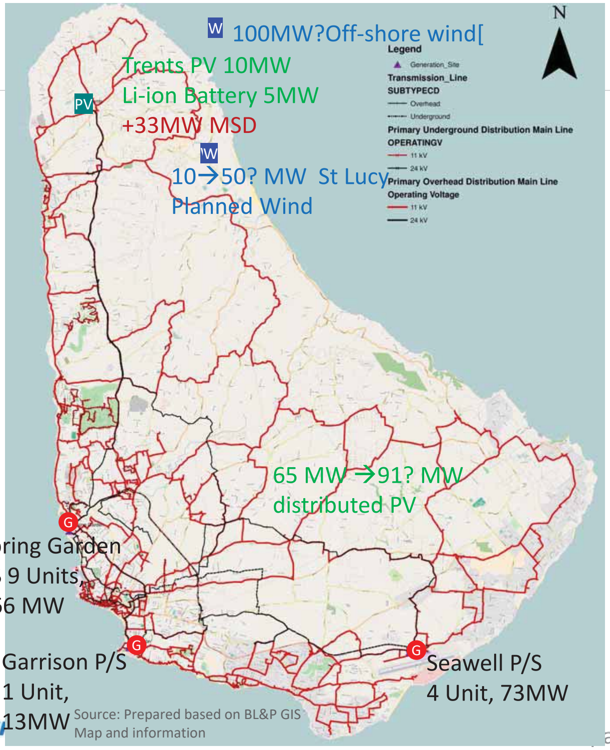
Node data Input Form for Single Stage Power Flow Analysis									Calculation of RE&Load				
Node ID	Node type	Amplitude of V	Phase angle of V	Node Admittance	Pg	Qg	Pl	Ql	Load	Utility PV	Distributed PV	Wind Turbine	BESS
(Up to 4 characters)	PQ=0, PV=1, Slack=2	(p.u.)	(Degree)	(p.u.)	(p.u.)	(p.u.)	(p.u.)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

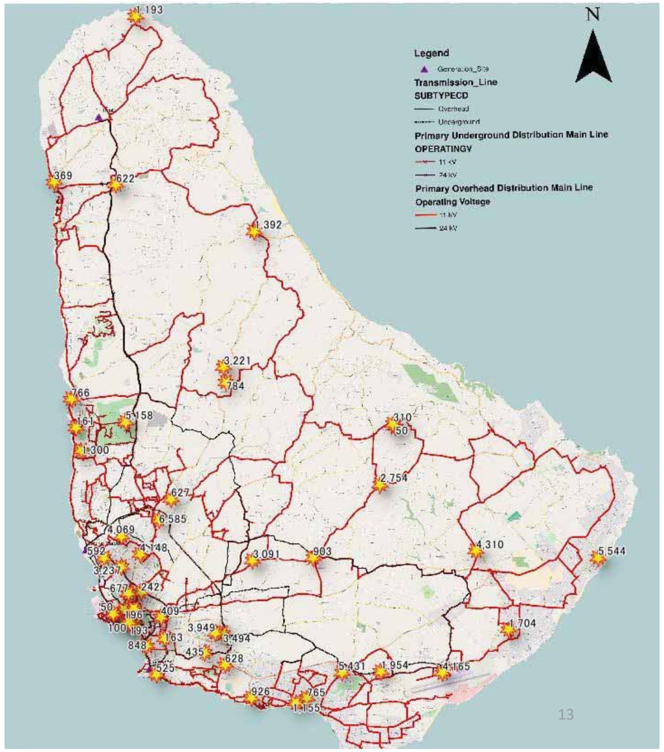
	Location	MW/u	Qy	MW	Remark
Existing					
Total thermal power				265	
	Spring Field Total		9	166	LDS, ST, GT
	Garrison	13	1	13	Gas Tubine
	Seawell	13	1	13	Gas Tubine
	Seawell	20	2	40	Gas Tubine
	Trents	8.3	4	33	MSD Engine
Total PV				75.6	
	Trents	10	1	10	PV
	Distributed PV		LS	65.6	PV
Total Battery	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

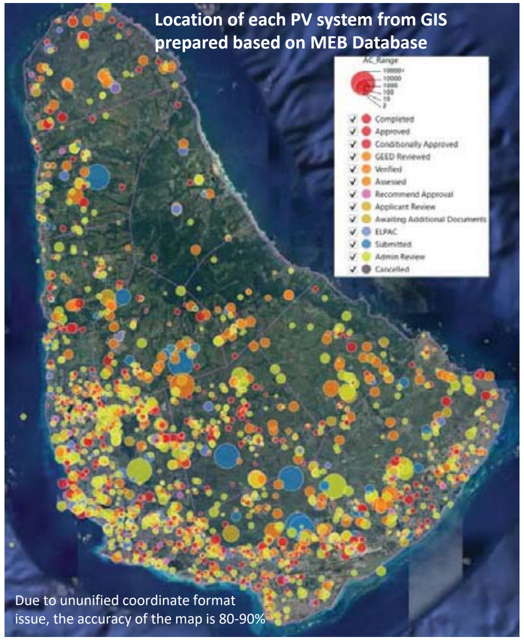
Total Capacity of PV of each feeder :

Installed PV + Licensed to be installed PV = 91MW



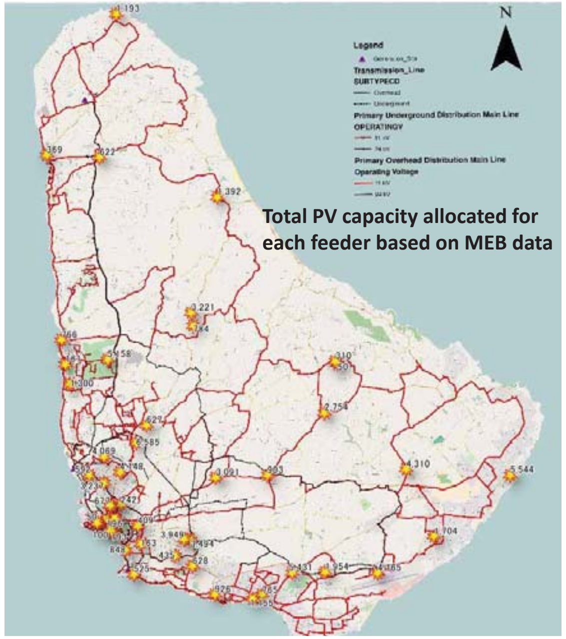
Barbados PV Location

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



Location of each PV system from GIS prepared based on MEB Database

Due to ununified coordinate format issue, the accuracy of the map is 80-90%



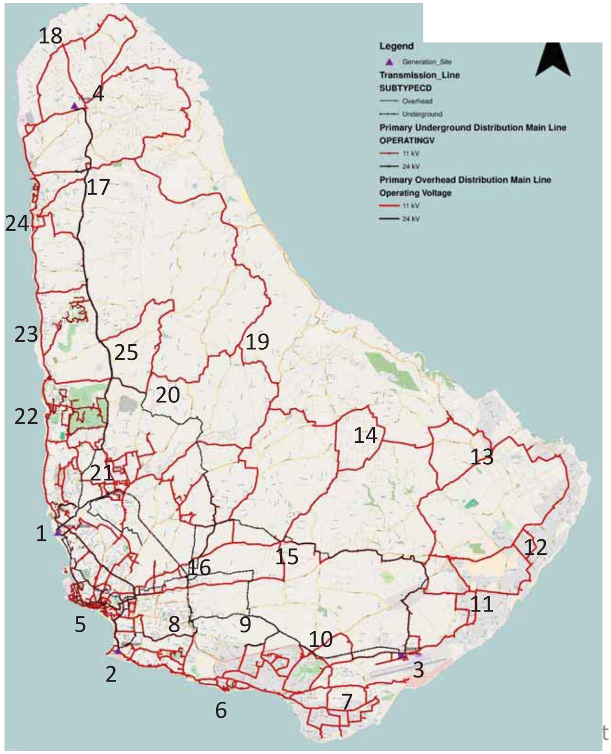
Total PV capacity allocated for each feeder based on MEB data

---

Barbados Grid

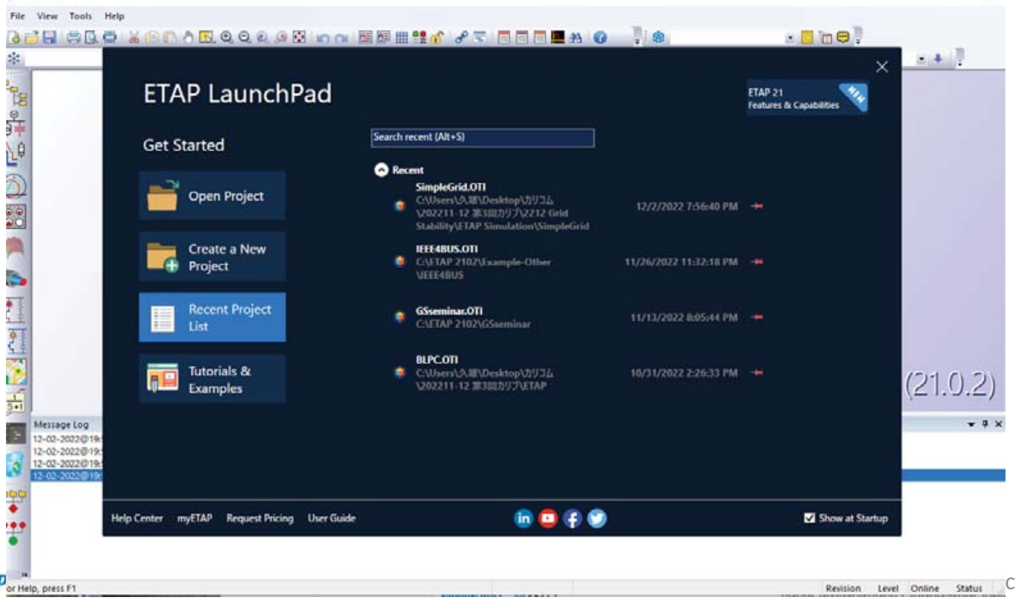
25 nodes

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.



SimpleGrid.OTI
C:\Users\久雄\Desktop\カリコム\202211-12 第3回カリブ\2212 Grid Stability\ETAP Simulation\SimpleGrid
12/2/2022 7:56:40 PM

IEEE4BUS.OTI
C:\ETAP 2102\Example-Other\IEEE4BUS
11/26/2022 11:32:18 PM

GSseminar.OTI
C:\ETAP 2102\GSseminar
11/13/2022 8:05:44 PM

BLPC.OTI
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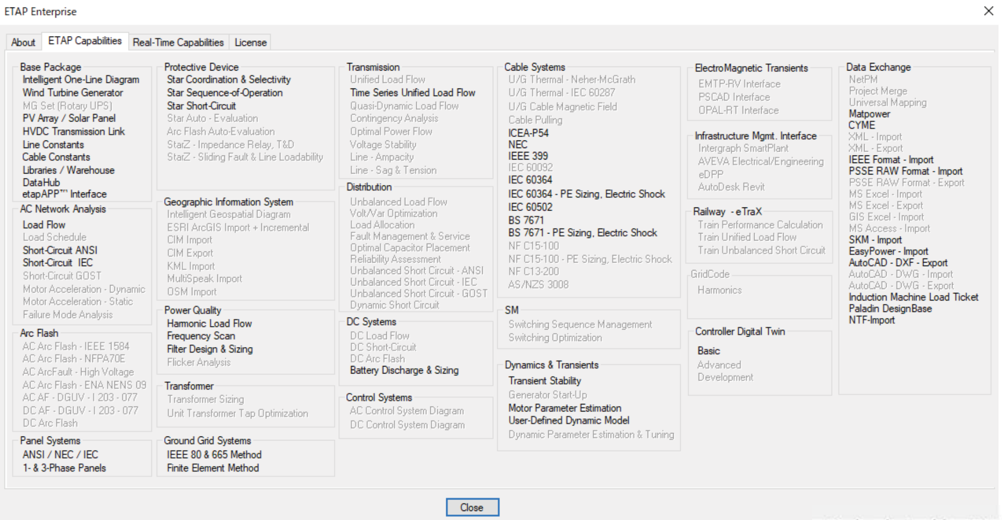
10/31/2022 2:26:33 PM

12-02-2022@19
12-02-2022@19
12-02-2022@19
12-02-2022@19

Functions of ETAP



Base Package
- Intelligent One-Line Diagram
- Wind Turbine Generator
- MG Set (Rotary UPS)
- PV Array / Solar Panel
- HVDC Transmission Link
- Line Constants
- Cable Constants
- Libraries / Warehouse
- DataHub
- etapAPP™ Interface

AC Network Analysis
- Load Flow
- Load Schedule
- Short-Circuit ANSI
- Short-Circuit IEC
- Short-Circuit GOST
- Motor Acceleration - Dynamic
- Motor Acceleration - Static
- Failure Mode Analysis

Arc Flash
- AC Arc Flash - IEEE 1584
- AC Arc Flash - NFPA70E
- AC ArcFault - High Voltage
- AC Arc Flash - ENA NENS 09
- AC AF - DGUV - I 203 - 077
- DC AF - DGUV - I 203 - 077
- DC Arc Flash

Panel Systems
- ANSI / NEC / IEC
- 1- & 3-Phase Panels

Protective Device
- Star Coordination & Selectivity
- Star Sequence-of-Operation
- Star Short-Circuit
- Star Auto - Evaluation
- Arc Flash Auto-Evaluation
- StarZ - Impedance Relay, T&D
- StarZ - Sliding Fault & Line Loadability

Geographic Information System
- Intelligent Geospatial Diagram
- ESRI ArcGIS Import + Incremental
- CIM Import
- CIM Export
- KML Import
- MultiSpeak Import
- OSM Import

Power Quality
- Harmonic Load Flow
- Frequency Scan
- Filter Design & Sizing
- Flicker Analysis

Transformer
- Transformer Sizing
- Unit Transformer Tap Optimization

Ground Grid Systems
- IEEE 80 & 665 Method
- Finite Element Method

Transmission
- Unified Load Flow
- Time Series Unified Load Flow
- Quasi-Dynamic Load Flow
- Contingency Analysis
- Optimal Power Flow
- Voltage Stability
- Line - Ampacity
- Line - Sag & Tension

Distribution
- Unbalanced Load Flow
- Volt/Var Optimization
- Load Allocation
- Fault Management & Service
- Optimal Capacitor Placement
- Reliability Assessment
- Unbalanced Short Circuit - ANSI
- Unbalanced Short Circuit - IEC
- Unbalanced Short Circuit - GOST
- Dynamic Short Circuit

DC Systems
- DC Load Flow
- DC Short-Circuit
- DC Arc Flash
- Battery Discharge & Sizing

Control Systems
- AC Control System Diagram
- DC Control System Diagram

Cable Systems
- U/G Thermal - Neher-McGrath
- U/G Thermal - IEC 60287
- U/G Cable Magnetic Field
- Cable Pulling
- ICEA-P54
- NEC
- IEEE 399
- IEC 60092
- IEC 60364
- IEC 60364 - PE Sizing, Electric Shock
- IEC 60502
- BS 7671
- BS 7671 - PE Sizing, Electric Shock
- NF C15-100
- NF C15-100 - PE Sizing, Electric Shock
- NF C13-200
- AS/NZS 3008

SM
- Switching Sequence Management
- Switching Optimization

Dynamics & Transients
- Transient Stability
- Generator Start-Up
- Motor Parameter Estimation
- User-Defined Dynamic Model
- Dynamic Parameter Estimation & Tuning

ElectroMagnetic Transients
- EMTP-RV Interface
- PSCAD Interface
- OPAL-RT Interface

Infrastructure Mgmt. Interface
- Intergraph SmartPlant
- AVEVA Electrical/Engineering
- eDPP
- AutoDesk Revit

Railway - eTraX
- Train Performance Calculation
- Train Unified Load Flow
- Train Unbalanced Short Circuit

GridCode
- Harmonics

Controller Digital Twin
- Basic
- Advanced
- Development

Data Exchange
- NetPM
- Project Merge
- Universal Mapping
- Matpower
- CYME
- XML - Import
- XML - Export
- IEEE Format - Import
- PSSE RAW Format - Import
- PSSE RAW Format - Export
- MS Excel - Import
- MS Excel - Export
- GIS Excel - Import
- MS Access - Import
- SKM - Import
- EasyPower - Import
- AutoCAD - DXF - Export
- AutoCAD - DWG - Import
- AutoCAD - DWG - Export
- Induction Machine Load Ticket
- Paladin DesignBase
- NTF-Import

Calculated by ETAP

Menu of ETAP

Transient Stability Analysis

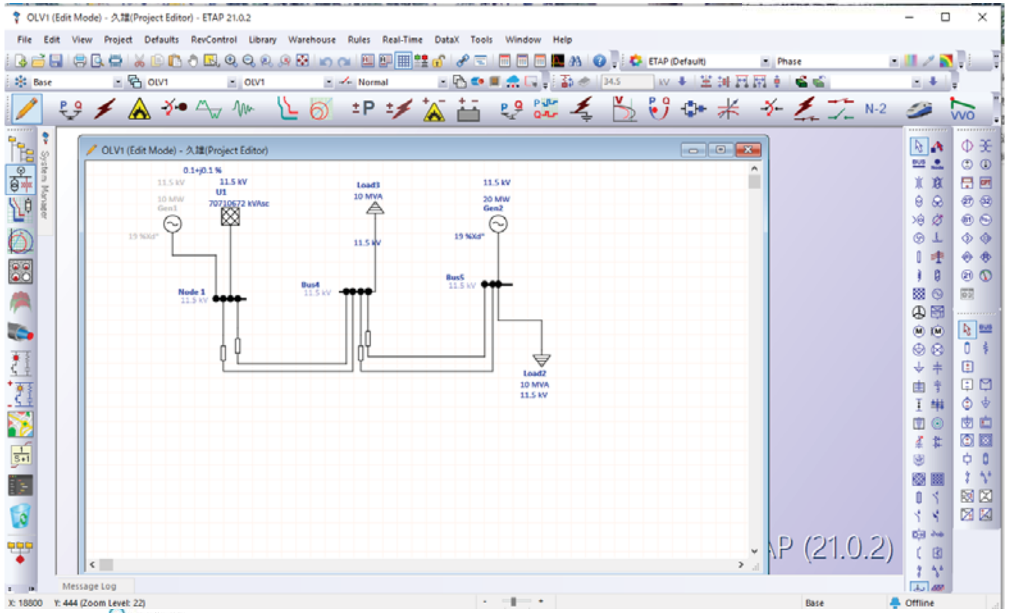
Load Flow Analysis

Modeling Power System

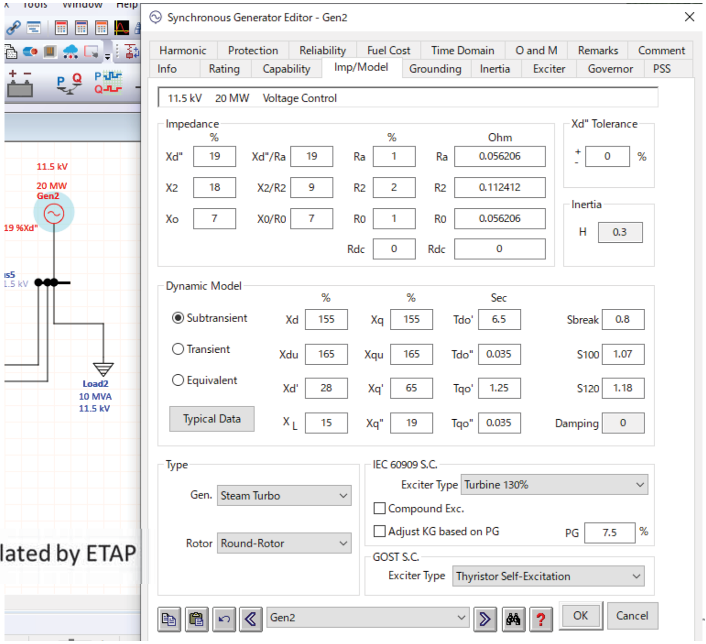
Calculated by ETAP

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



11.5 kV 20 MW Voltage Control

Impedance

	%				%		Ohm
Xd"	19	Xd"/Ra	19	Ra	1	Ra	0.056206
X2	18	X2/R2	9	R2	2	R2	0.112412
Xo	7	X0/R0	7	R0	1	R0	0.056206
				Rdc	0	Rdc	0

Xd" Tolerance ± 0 %

Inertia H 0.3

Dynamic Model

● Subtransient
○ Transient
○ Equivalent

	%		%		Sec		
Xd	155	Xq	155	Tdo'	6.5	Sbreak	0.8
Xdu	165	Xqu	165	Tdo"	0.035	S100	1.07
Xd'	28	Xq'	65	Tqo'	1.25	S120	1.18
X_L	15	Xq"	19	Tqo"	0.035	Damping	0

Type

Gen. Steam Turbo

Rotor Round-Rotor

IEC 60909 S.C.

Exciter Type Turbine 130%

☐ Compound Exc.

☐ Adjust KG based on PG PG 7.5 %

GOST S.C.

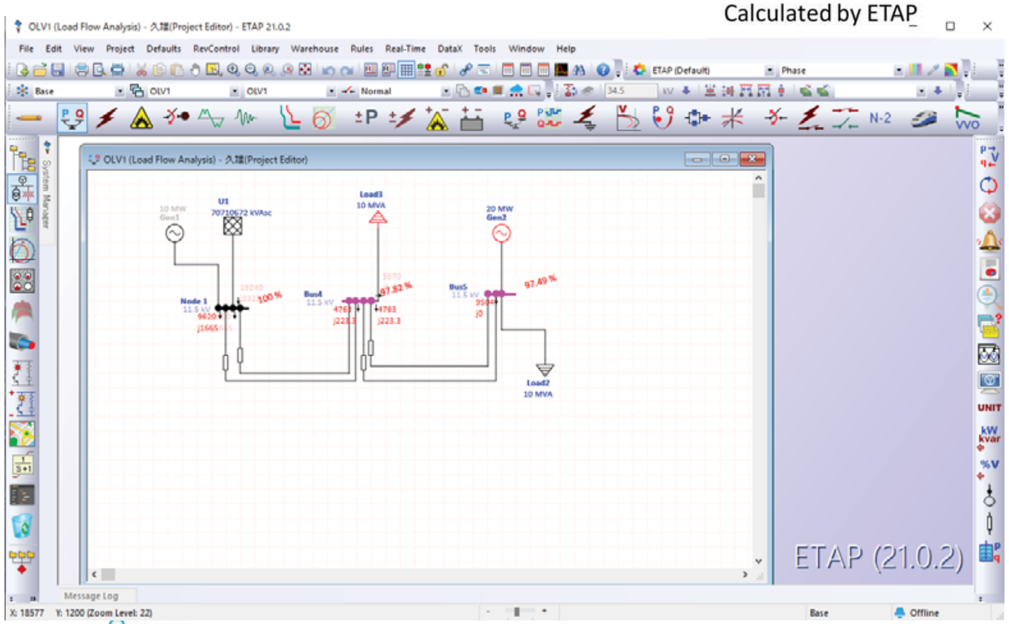
Exciter Type Thyristor Self-Excitation

Gen2

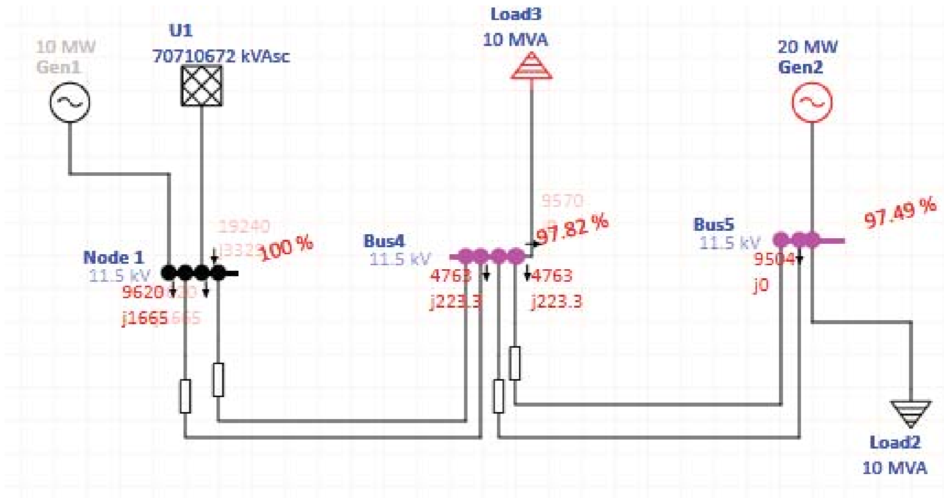
Calculated by ETAP

Example of Load Flow Analysis: Result in ETAP

Calculated by ETAP



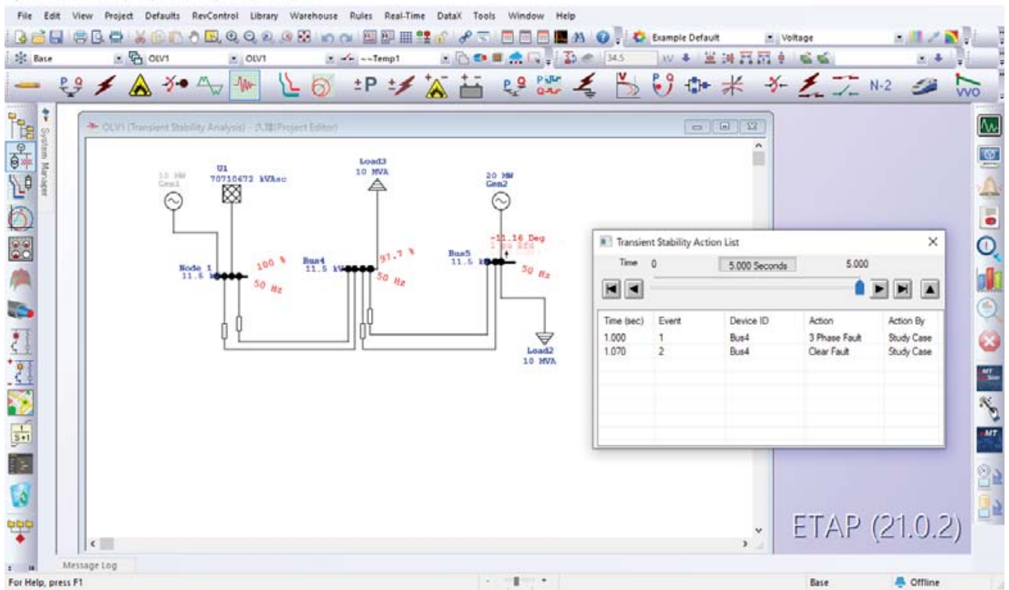
Example of Load Flow Analysis: Result in ETAP



Calculated by ETAP

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

Calculated by ETAP



Transient Stability Action List

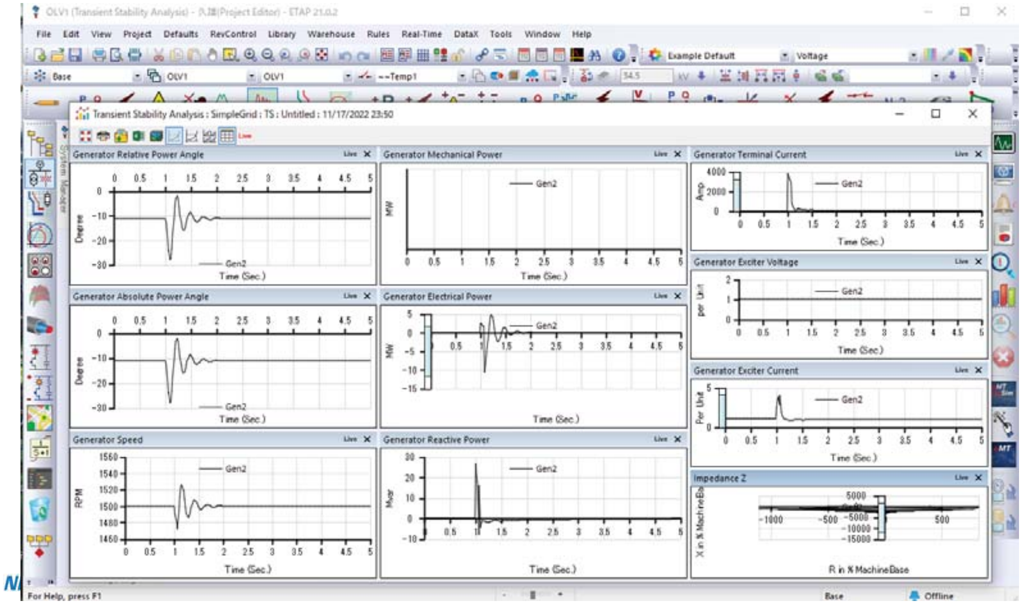
Time 0 | 5.000 Seconds | 5.000

Time (sec)	Event	Device ID	Action	Action By
1.000	1	Bus4	3 Phase Fault	Study Case
1.070	2	Bus4	Clear Fault	Study Case

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

Calculated by ETAP

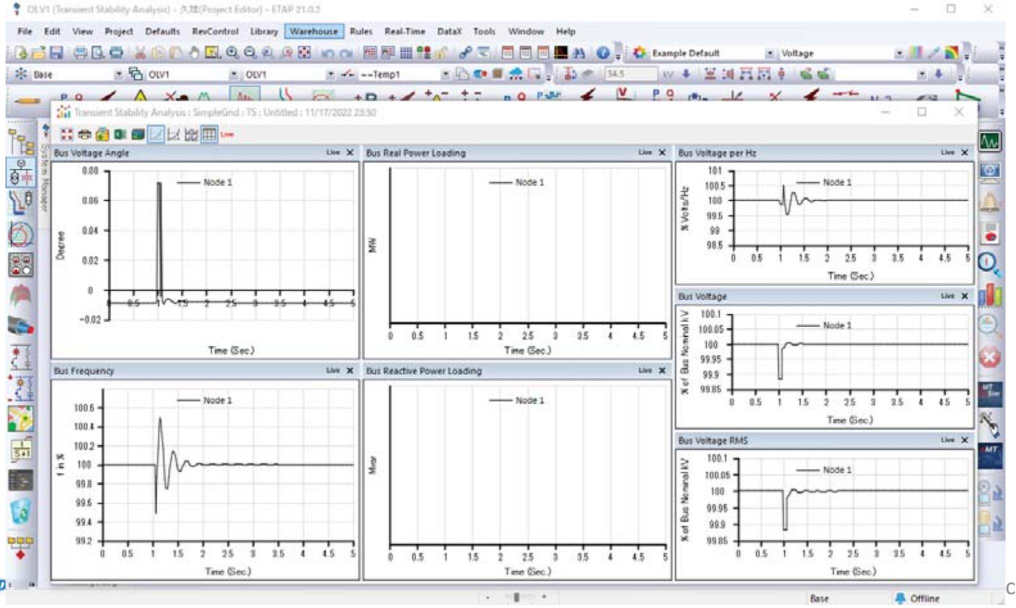
The transient analysis result shows that the system comes back to steady state after the trip



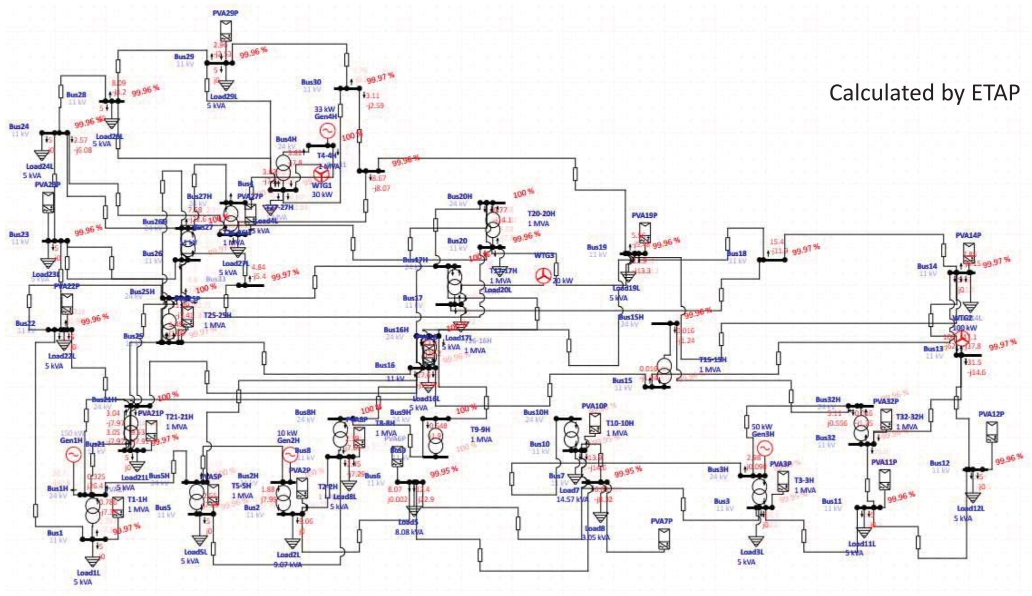
Example of ETAP with the Simple Model Result of Transient Stability Analysis(2)

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

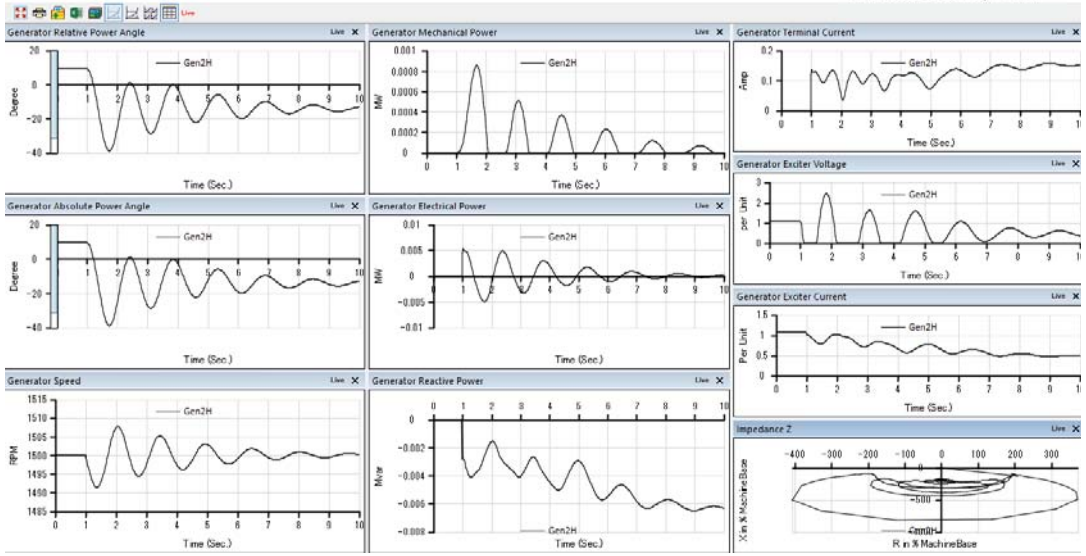


Calculated by ETAP

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

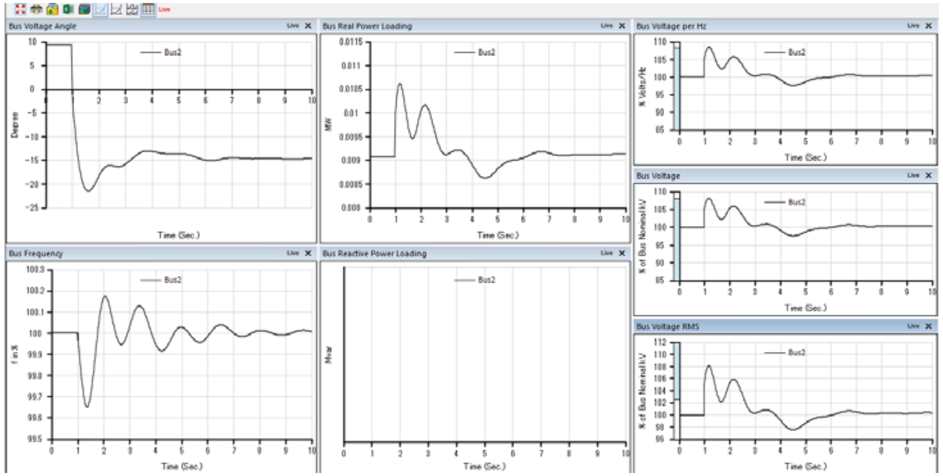
The transient analysis result shows that the system comes back to steady state after the trip

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

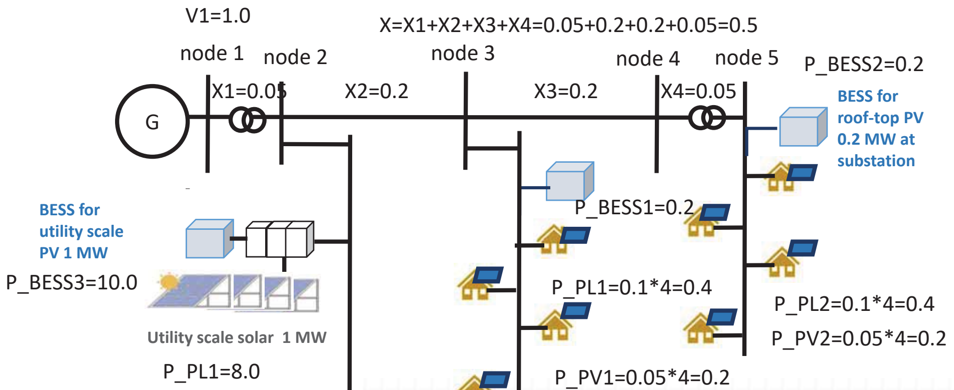
The transient analysis result shows that the system comes back to steady state after the trip



Calculated by ETAP

Simple Grid Model for RE and Battery

Lets prepare a simple model with ETAP and practice!



V1=1.0

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

node 1 node 2 node 3 node 4 node 5

P_BESS2=0.2

G

X1=0.05 X2=0.2 X3=0.2 X4=0.05

BESS for roof-top PV 0.2 MW at substation

P_BESS1=0.2

BESS for utility scale PV 1 MW

P_BESS3=10.0

P_PL1=0.1*4=0.4

P_PL2=0.1*4=0.4

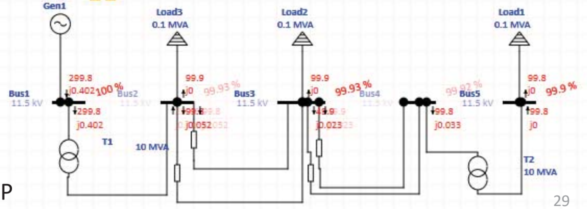
P_PV2=0.05*4=0.2

Utility scale solar 1 MW

P_PL1=8.0

P_PV1=0.05*4=0.2

P_PV3=10.0



Calculated by ETAP

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