台灣電力公司

Application and Study of Virtual Synchronous Generator in Microgrid and International Standards

TPRI Taiwan Power Research Institute

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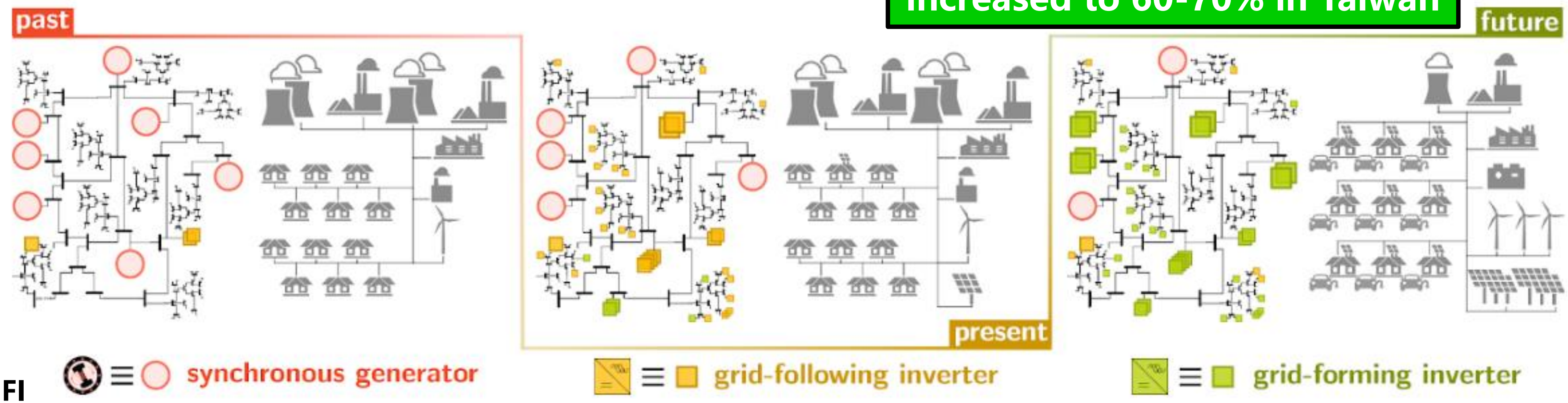
Outline

Introduction

Introduction

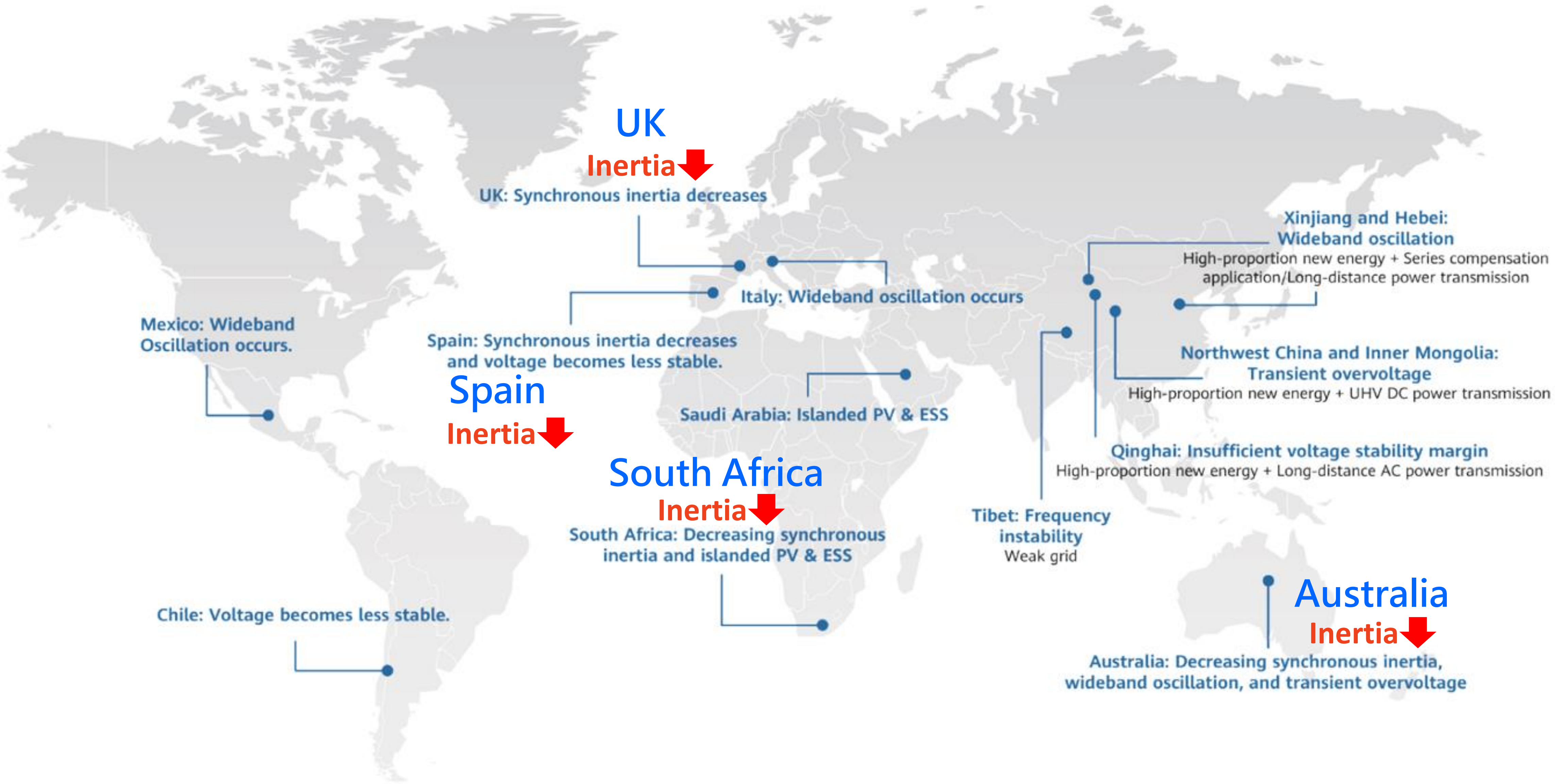
- Due to the increase of distributed generations (DGs), such as PV sources, battery energy storage systems, and wind turbines, the **power-electronics inverters** are required to transfer the energy of DGs to the loads or electrical grids.
- The traditional synchronous generators can contribute mechanical **inertia**, which can prevent the frequency forming changing dramatically as loads increase or decrease. **However, the inverter-based resource (IBR) inverters have no mechanical inertia**.
- According to the NREL research, if the number of the grid following inverters exceeds **30%**, the grid will become unstable.

In 2050，Renewable Energy increased to 60-70% in Taiwan



Ref. : UNIFI

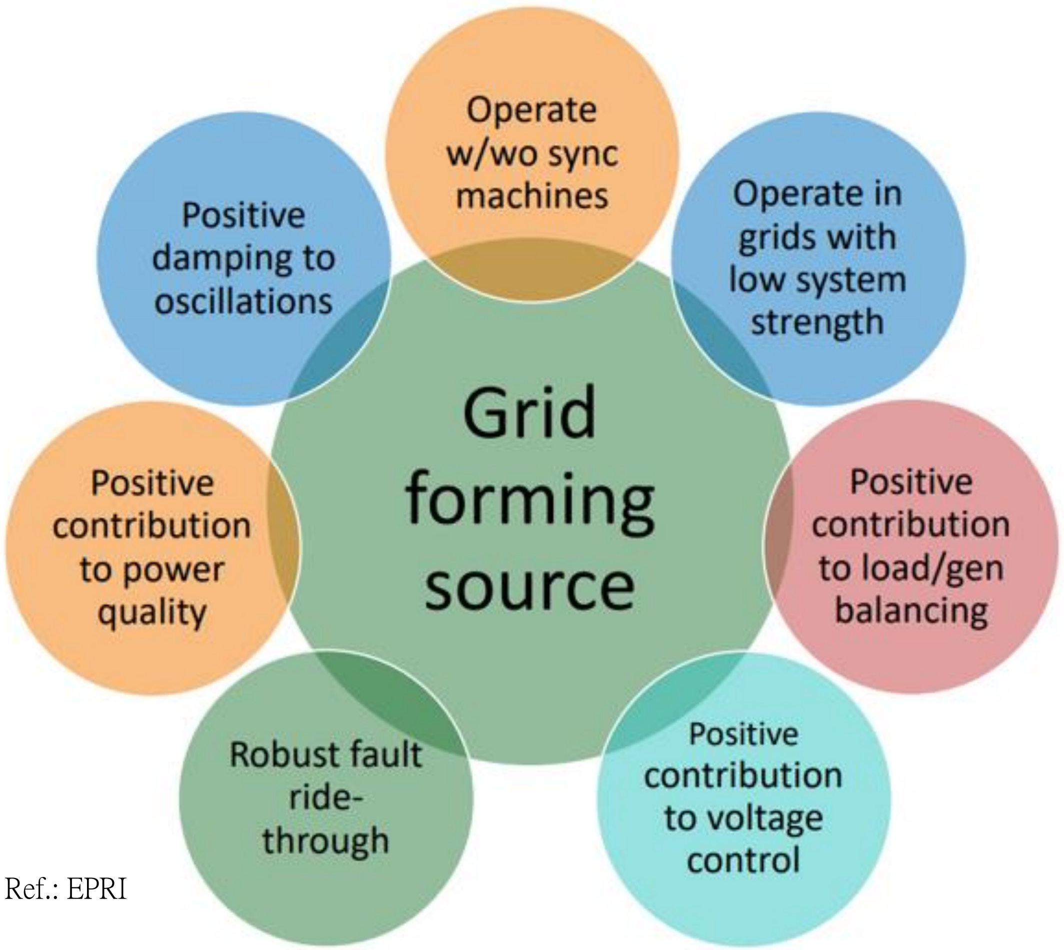
Introduction



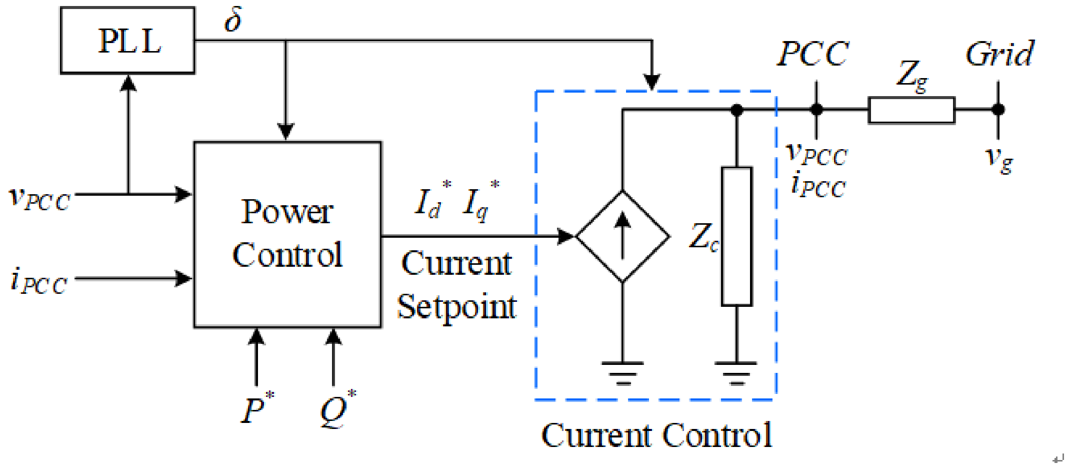
Ref: Fusionsolar Smart PV & ESS Generator White Paper

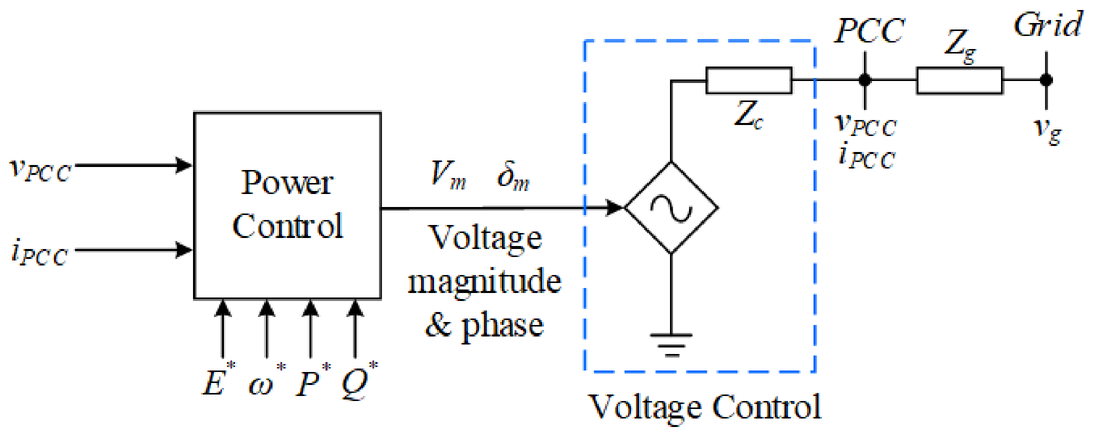
Introduction

- Grid Forming Inverter can be used to improve the power grid stability.



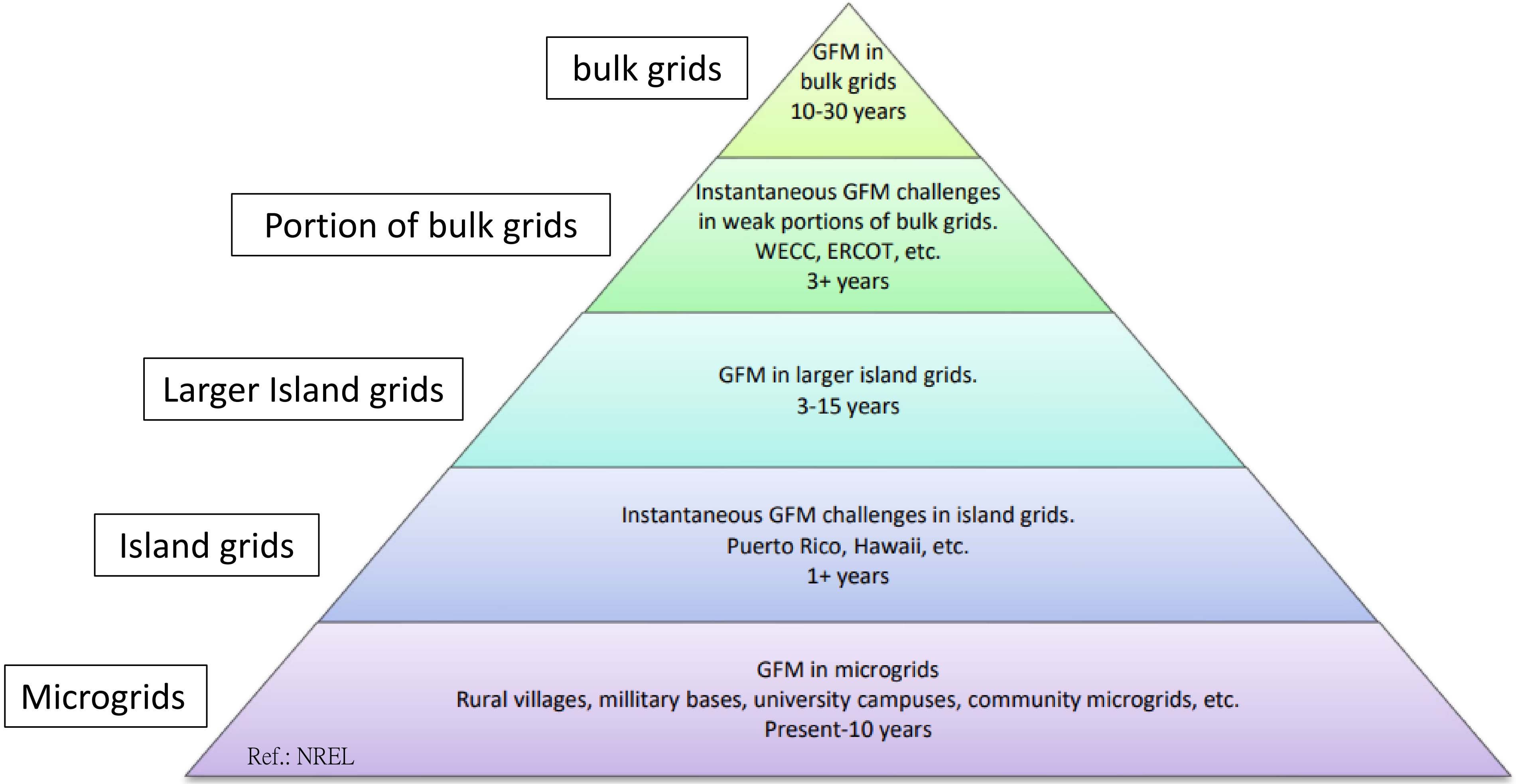
Ref.: EPRI





Introduction

- The following shows GFMI application path.

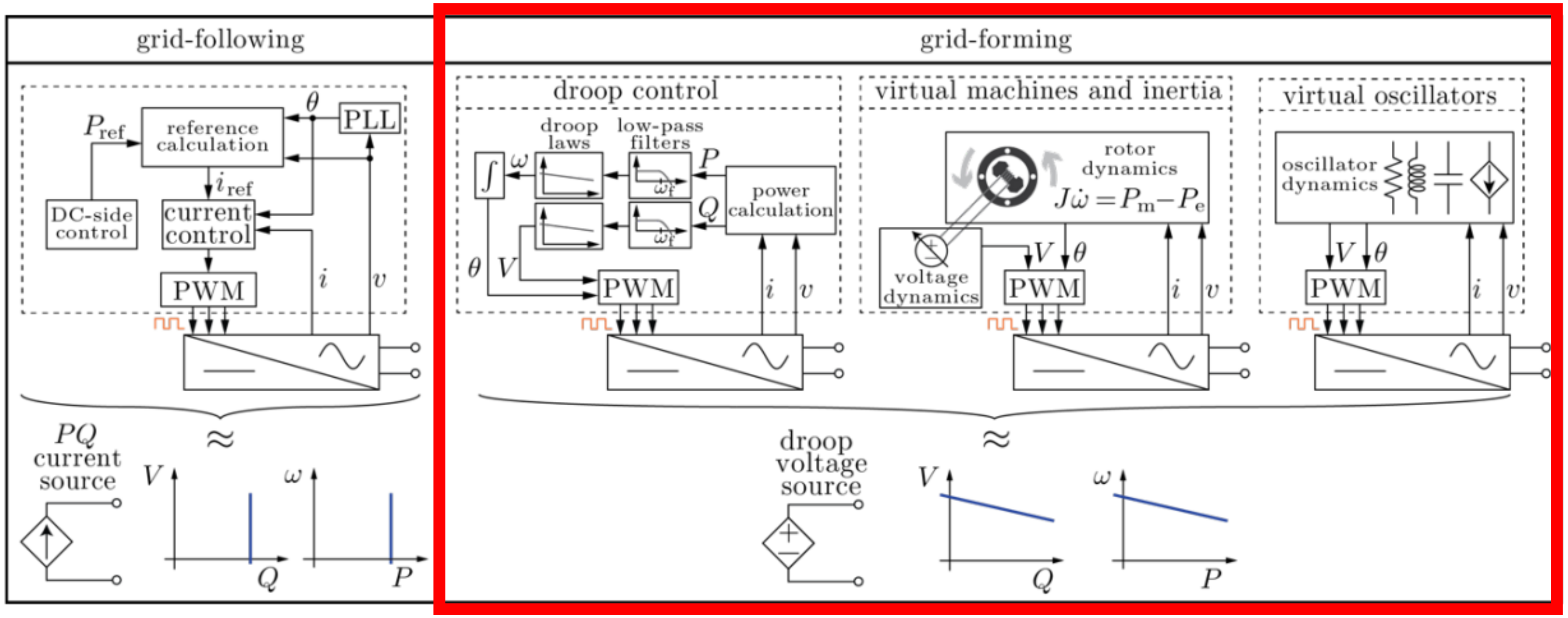


Grid Forming Control

- Inverter Control Method
- Droop Control
- VSG Control
- VOC Control
- Advantages of VSG Control

Inverter Control Method

- **Grid Forming Inverter Control Method: Droop Control, Virtual Synchronous Generator/Machine, Virtual Oscillator, etc.**
- **Since the concept of virtual synchronous generator control method is similar to that of traditional synchronous machine, virtual synchronous machine control method is currently the most commonly used control method for Grid-forming Inverter.**

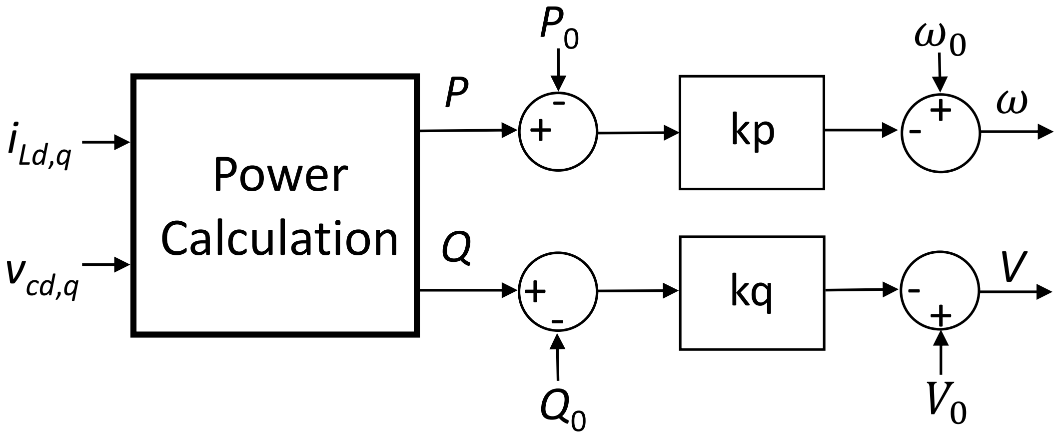


Ref.:

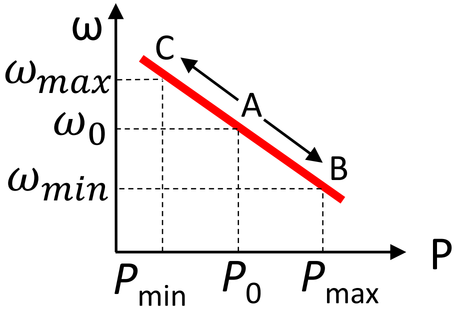
- P2988™/D6.0 Draft Recommended Practice for Use and Functions of Virtual Synchronous Machines.
- Yashen Lin, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, Gab-Su Seo, Brian J. Pierre, and Abraham Ellis, "Research Roadmap on Grid-Forming Inverters," NREL, November 2020.

Droop Control

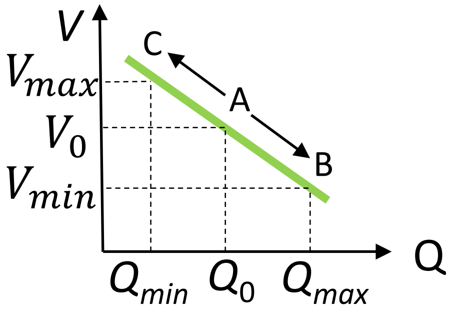
This control method mainly simulates the primary response of a traditional synchronous machine. Its main purpose is to distribute active and reactive power among the inverters. The size of the allocation is based on the actual converter capacity and the setting of the droop parameter. The advantage of this method is that it does not require communication.



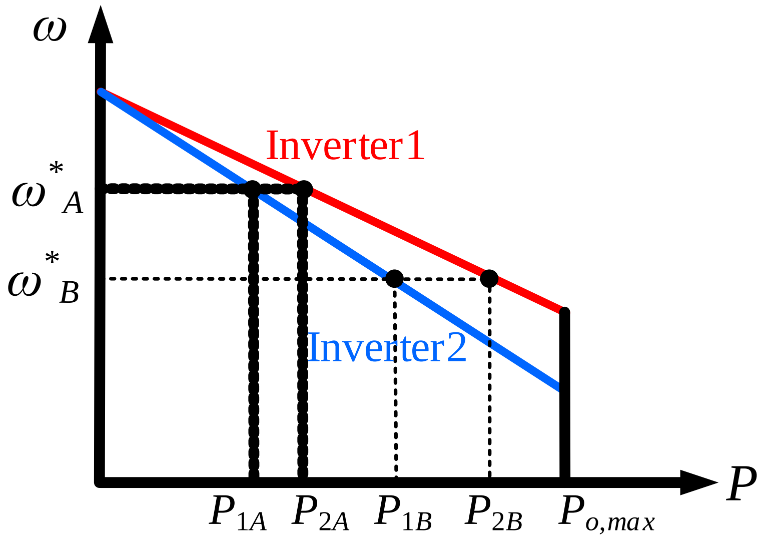
P-ω droop



Q-V droop

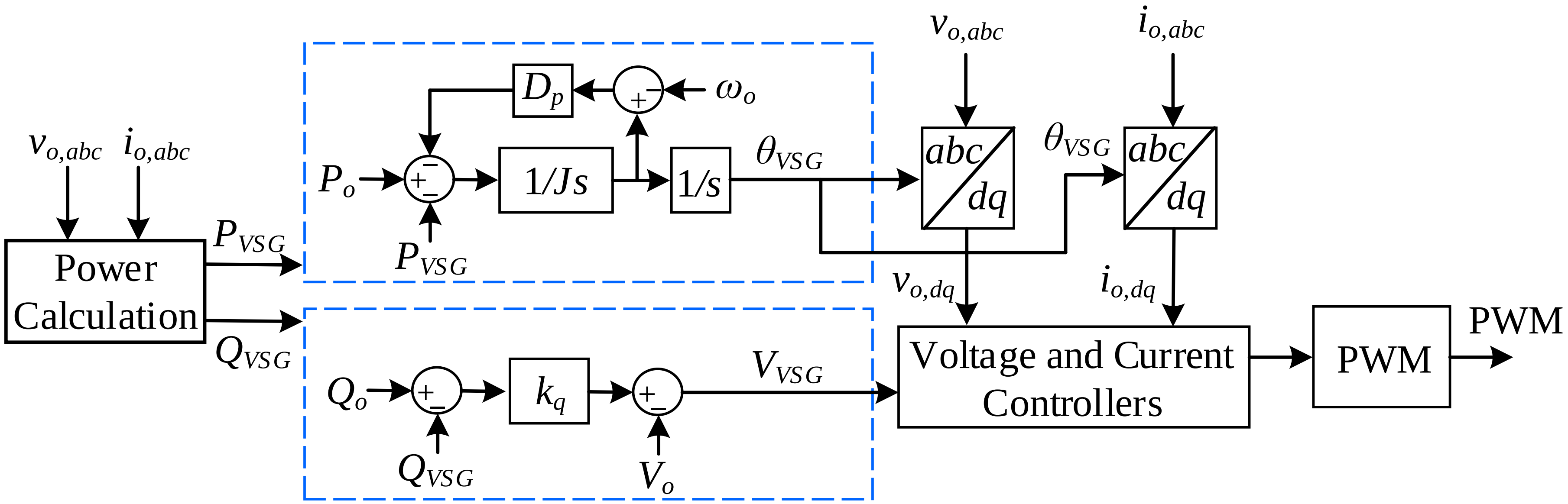


- When two inverters are connected in parallel, the output power will be distributed according to the droop parameters.



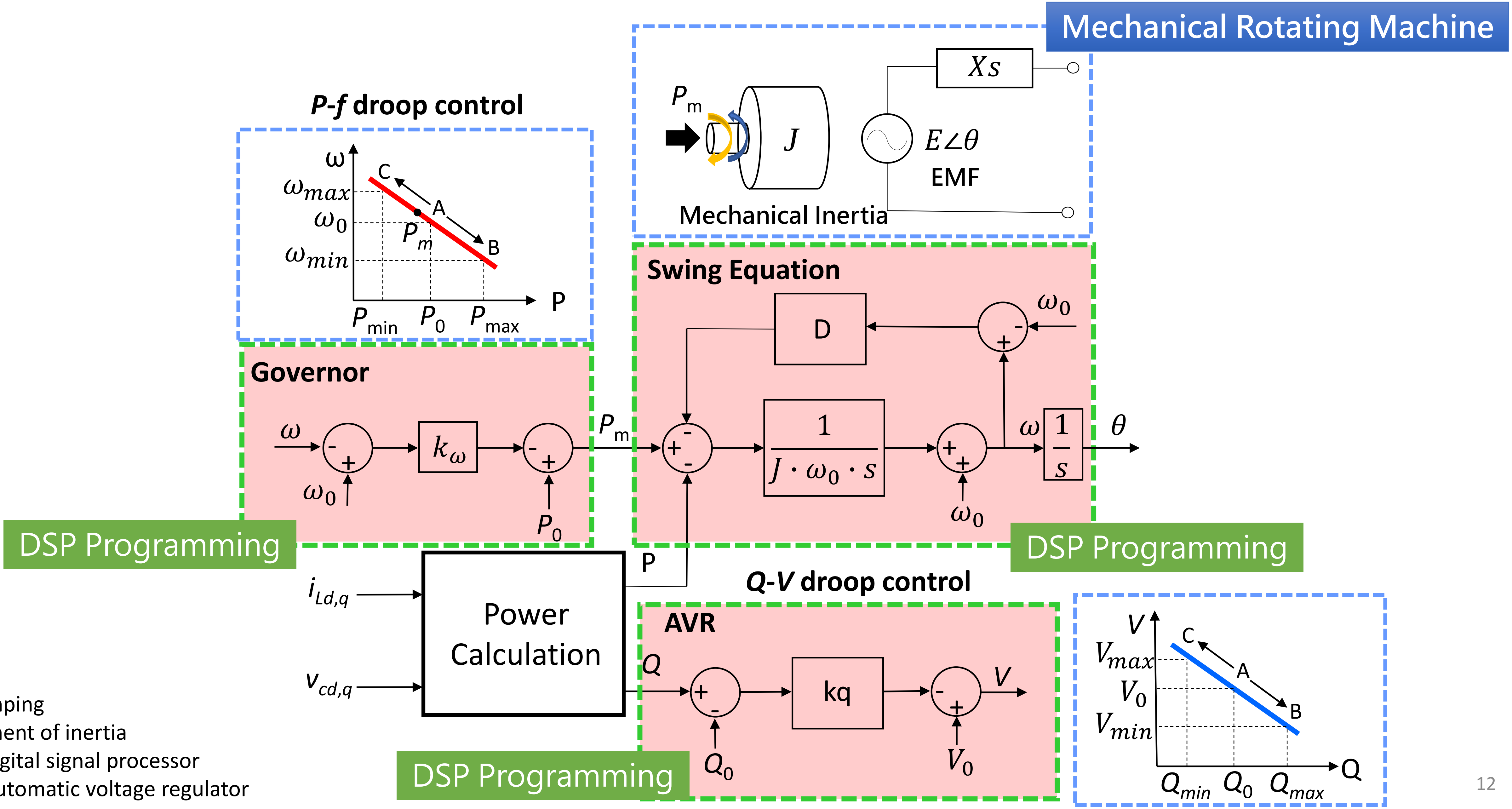
VSG Control

The inverter can be made to have the characteristics of a synchronous generator by changing the control method. A more common way is to use the Swing Equation. The dynamic characteristics of the output frequency and power can be changed by adjusting the virtual inertia J and virtual damping D of the virtual synchronous generator. Since the concept of virtual synchronous generator control method is similar to that of traditional synchronous machine, virtual synchronous generator control method is currently the most commonly used control method for grid forming inverter.



Ref.: "Grid-Forming Technology in Energy Systems Integration," ESIG, March 2022.

VSG Control

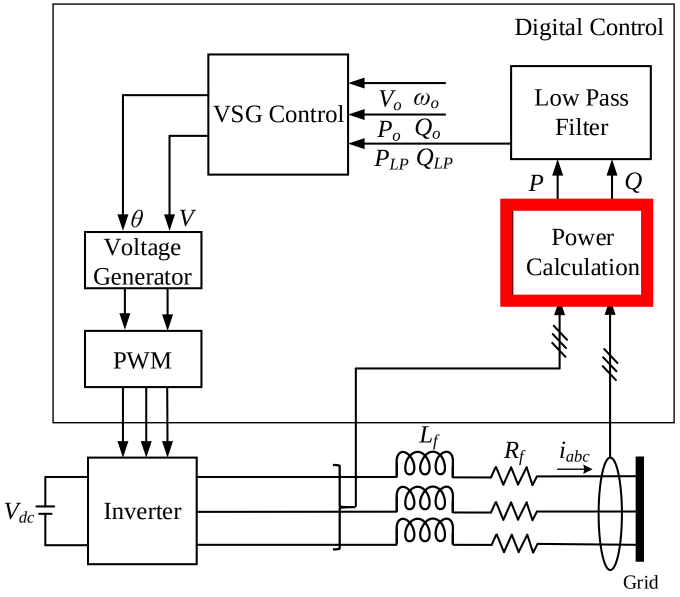


D: Damping
J: Moment of inertia
DSP: digital signal processor
AVR: automatic voltage regulator

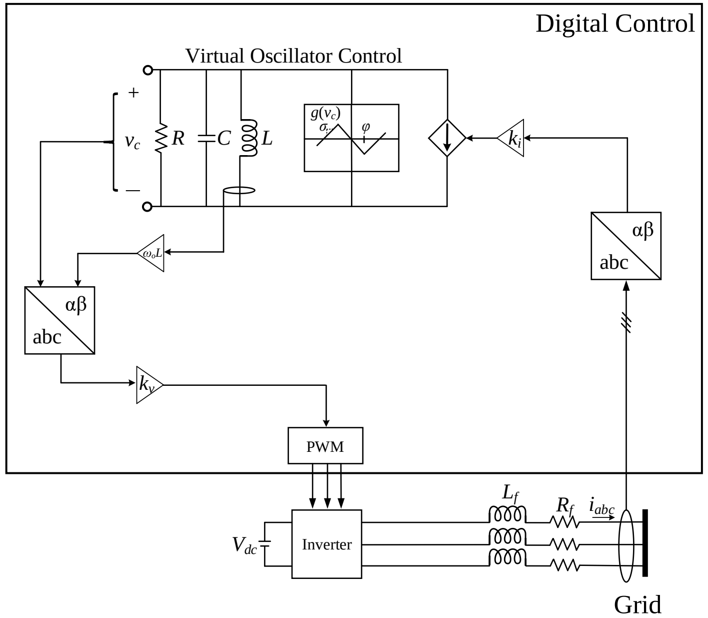
VOC Control

The lower right figure is a basic conceptual architecture diagram of the virtual oscillator control method. Since the virtual oscillator control method only needs to detect the output current of the inverter and does not need to calculate the active power and the reactive power, the virtual oscillator control method can achieve a faster response speed. The LC parallel resonant tank can determine the output frequency of the Inverter. Different from droop control and VSG control, VOC is a time domain controller, which enables the interconnected inverters to quickly achieve synchronization under any initial conditions. VOC is an attractive control mode in power system applications due to its fast synchronization, precise power distribution, simplicity and robustness. In addition, VOC does not require a phase-locked loop (PLL) and reduces the computational burden of an analog synchronizer.

VSG Control



VOC Control



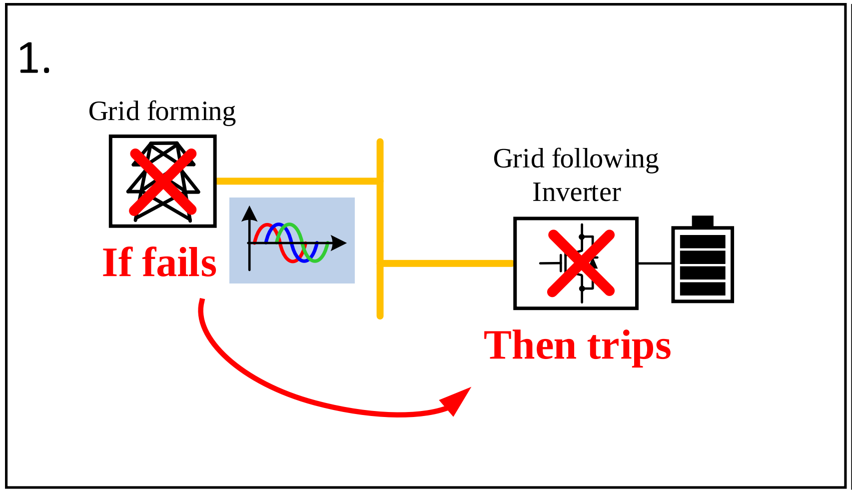
Comparison of Three Control Methods

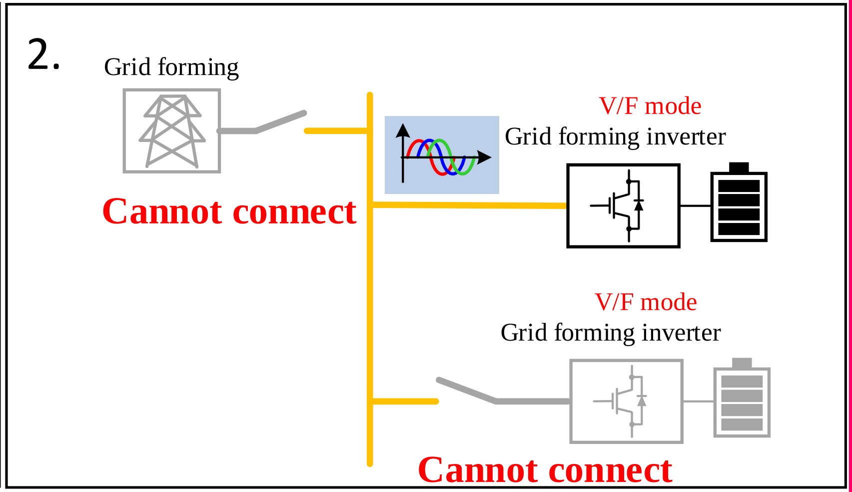
From the table below, we can see that the original droop control does not have the virtual inertia function, but it can slow down the frequency change by adding a low-pass filter. The virtual synchronous generator control method based on the swing equation has the ability to provide virtual inertia and is currently the more commonly used method. The control method based on the virtual oscillator has a good power distribution effect. In addition, the virtual oscillator control method has a faster response speed.

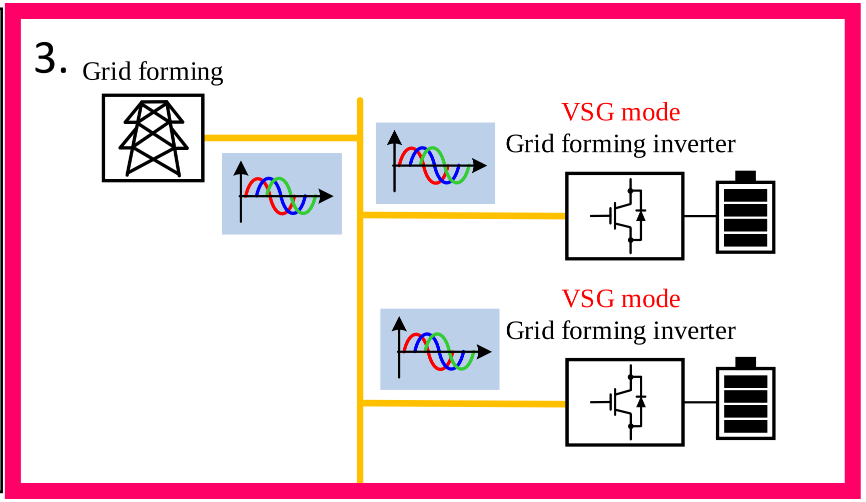
Grid Forming Control Method	Control Method	Inertia Providing	Response Time	Power Sharing	Output Power Oscillation	Power Dispatch Capability
Droop Control	traditional droop control	No	Faster	Average	No	Yes
	with low pass filter	Yes	Slower	Average	No	Yes
Virtual Synchronous Control	swing equation	Yes	Slower	Average	Yes	Yes
Virtual Oscillator Control (Now in Academic Level)	Van der Pol	No	Fast	Good	Yes	No
	Dispatchable	No (but Possible)	Fast	Good	Yes	Yes
	Unifi	No (but Possible)	Fast	Good	Yes	Yes

Advantages of VSG

Inverter Type	1. Grid following inverter	2. Constant Output V/F	3. VSG
Function Description	Inject Power into grid (No Voltage and Frequency Building)	• Grid forming • No droop • No inertia • Cannot connect with other constant output V/F inverter	• Grid forming • droop • inertia • Can connect with other VSG

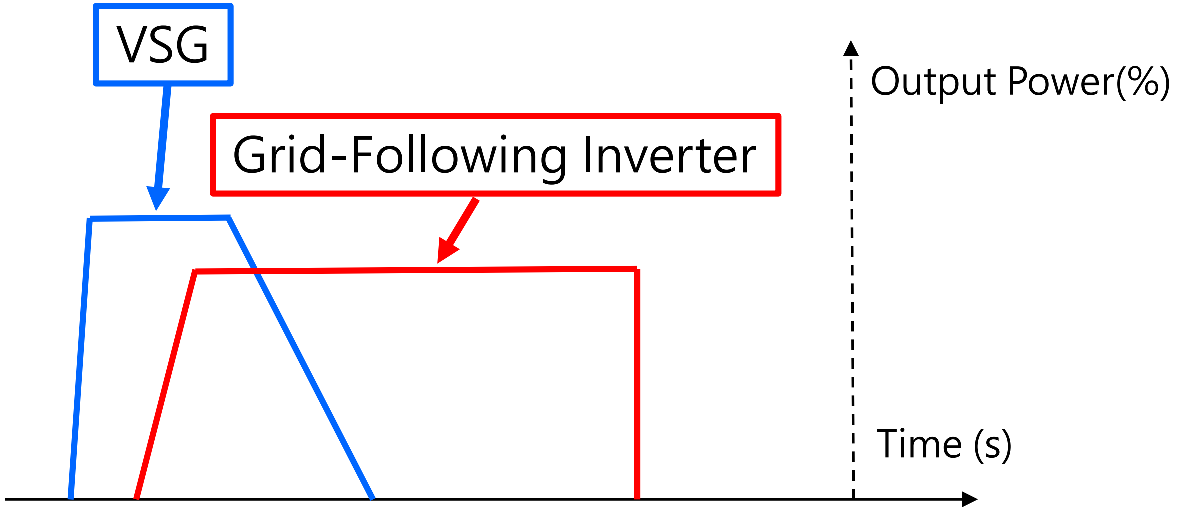




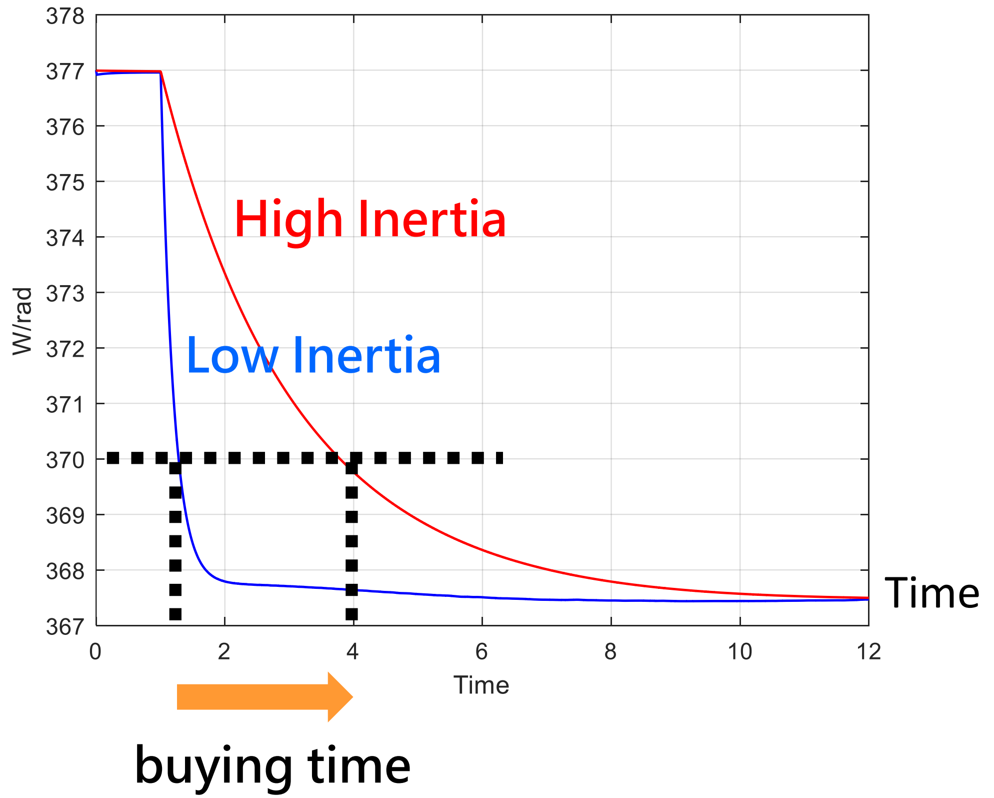


Advantages of VSG

- Grid support function→ Reduce of use of synchronous generator
- Droop function → Automatic load distribution
- Virtual inertia function→ Reduce the RoCoF (buying time for other control mechanisms to react)
- VSG: Faster Response Time
- Grid Following Inverter: Slower Response Time



Response of VSG with different virtual inertia

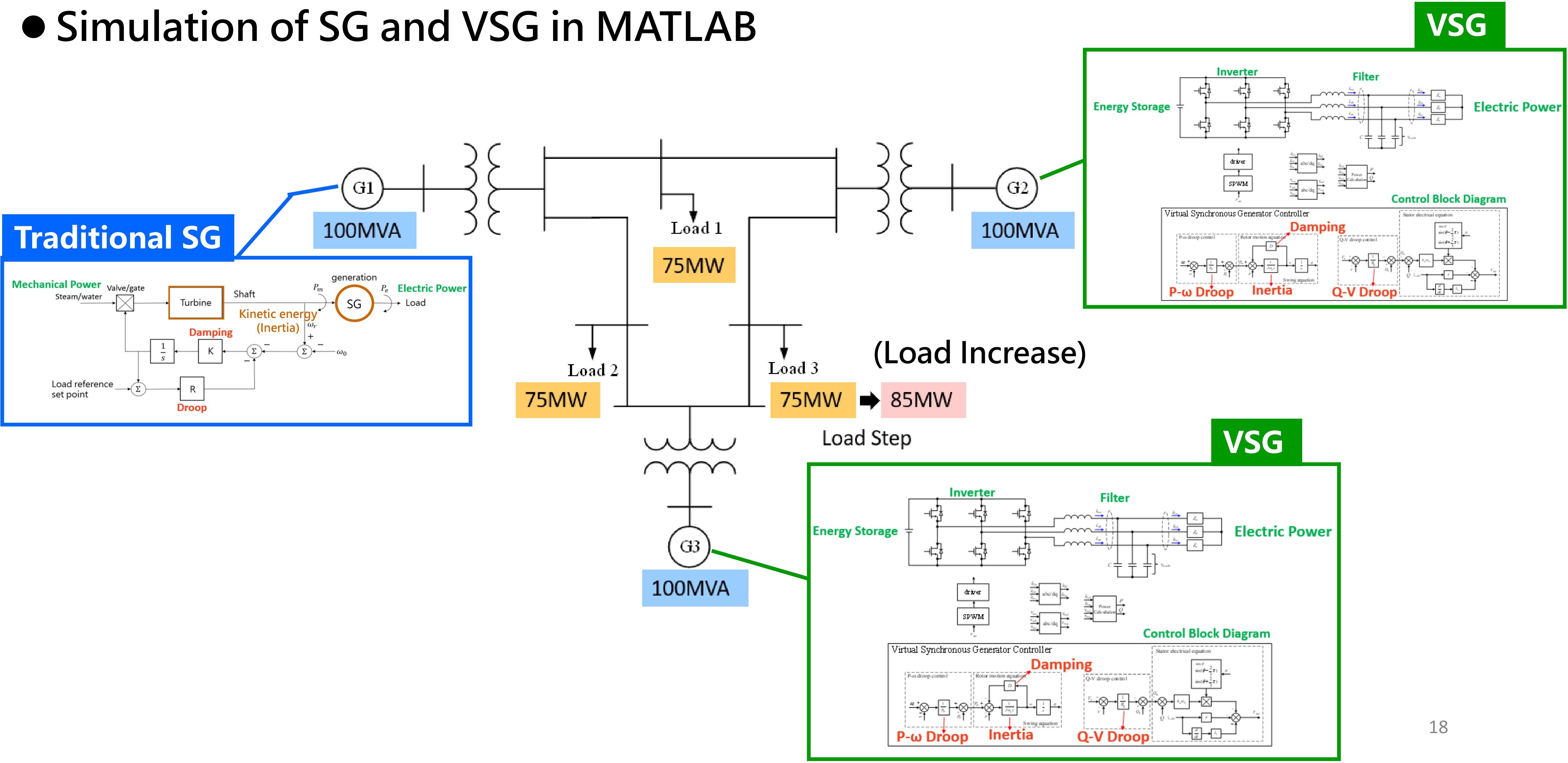


Simulation Verification

- Simulation Verification of VSG
- Simulation Verification of VSG in PV Plant

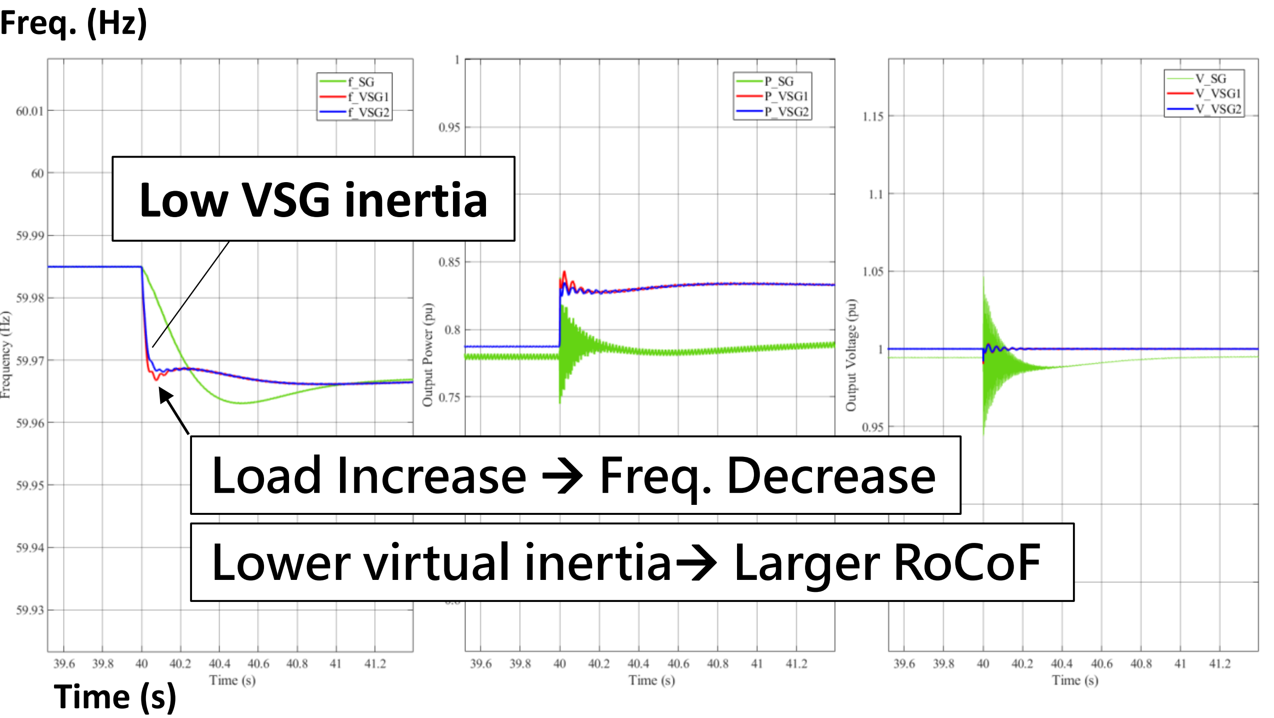
Simulation Verification of VSG

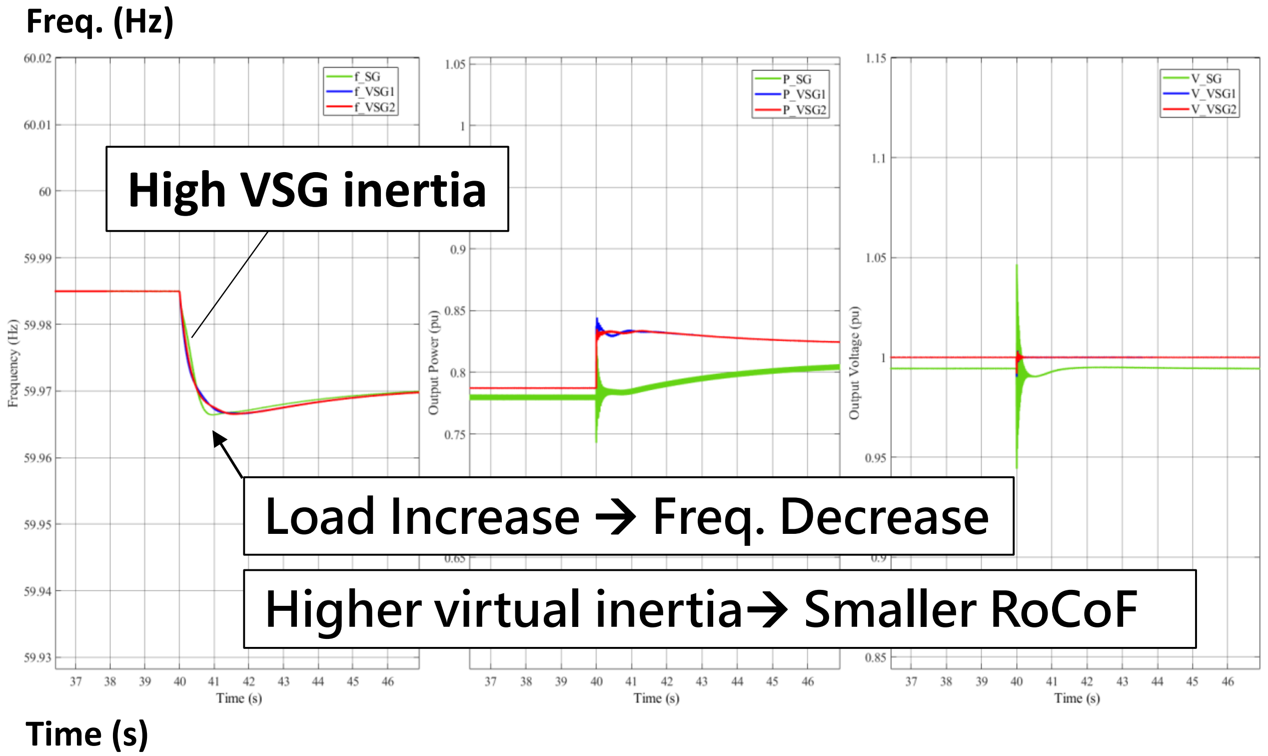
- Simulation of SG and VSG in MATLAB



Simulation Verification of VSG

- Different Virtual Inertia

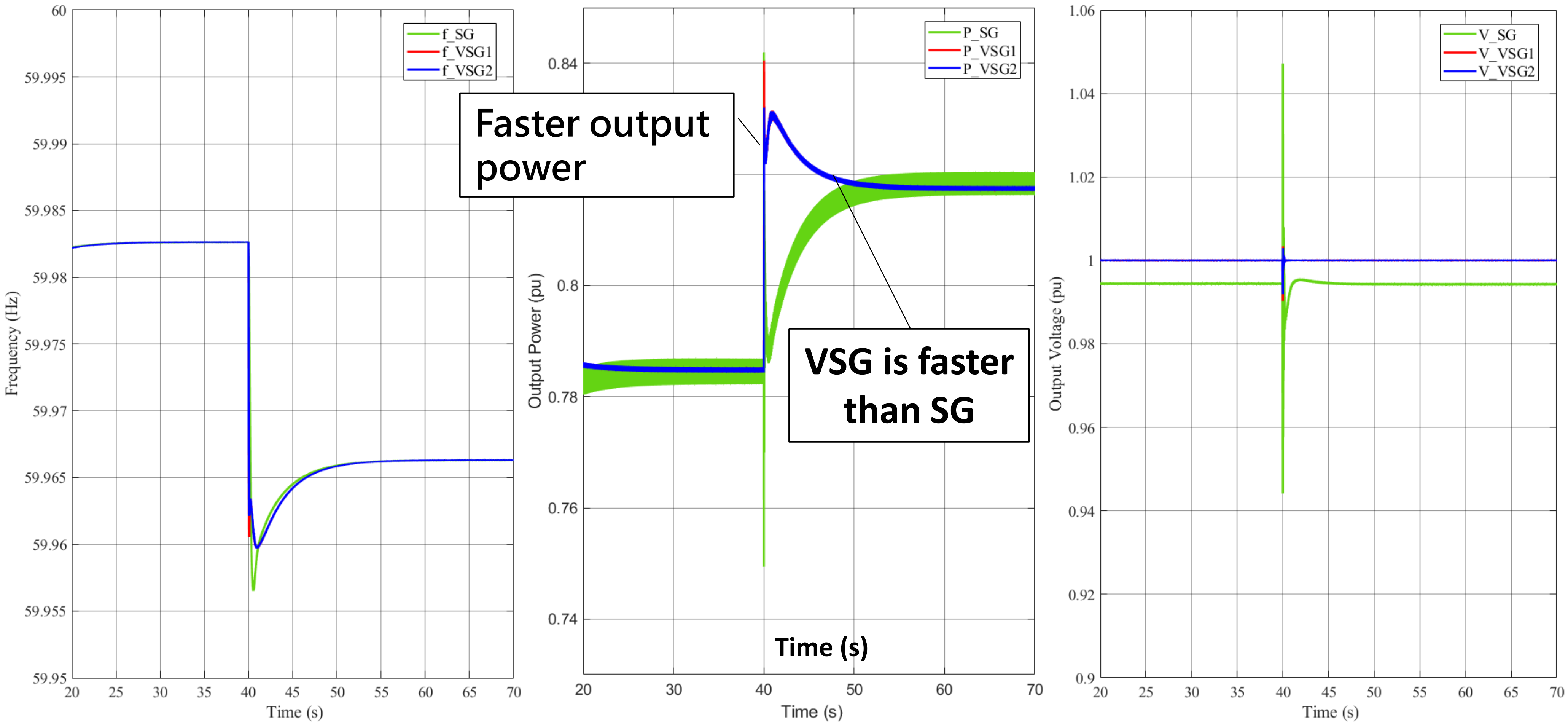




As can be seen from the figure above, by adjusting the inertia constant of the VSG, the rate of change of frequency (RoCoF) can be changed. This can suppress frequency changes when the power system is disturbed, thereby increasing the stability of the power system.

Simulation Verification of VSG

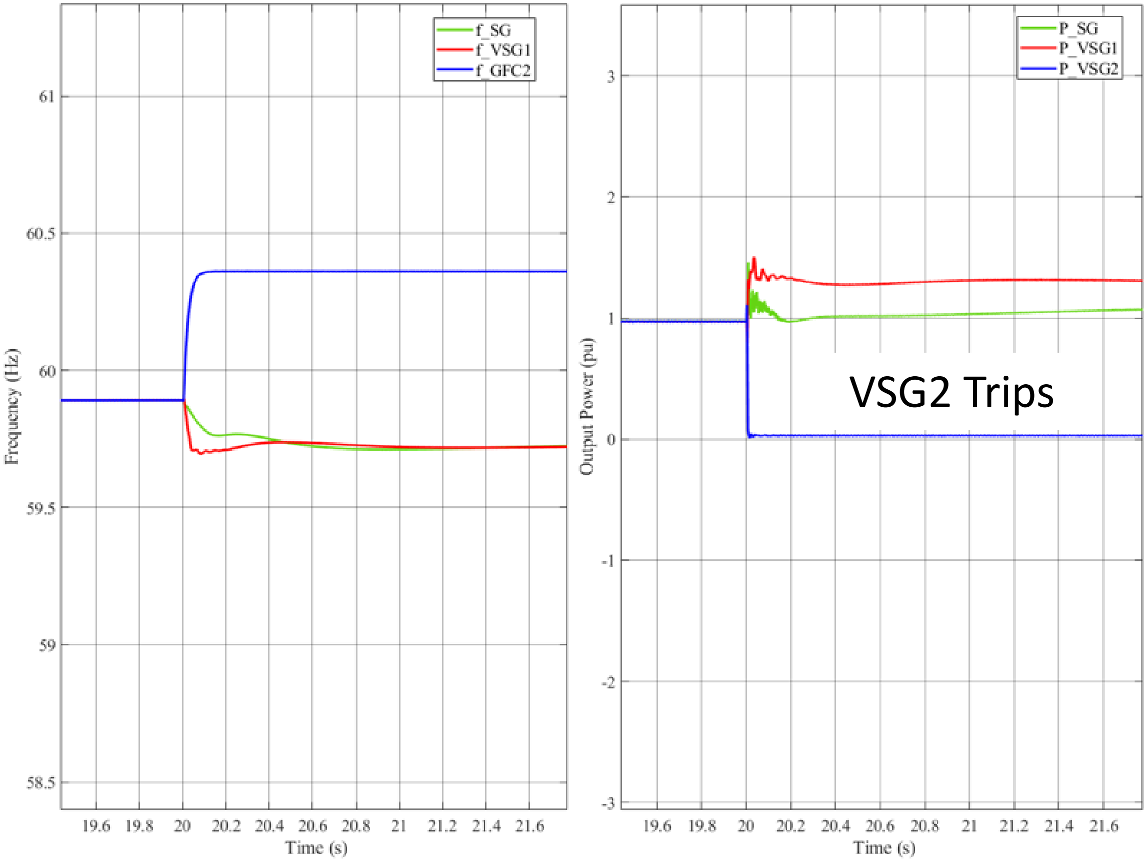
Output Power (pu)



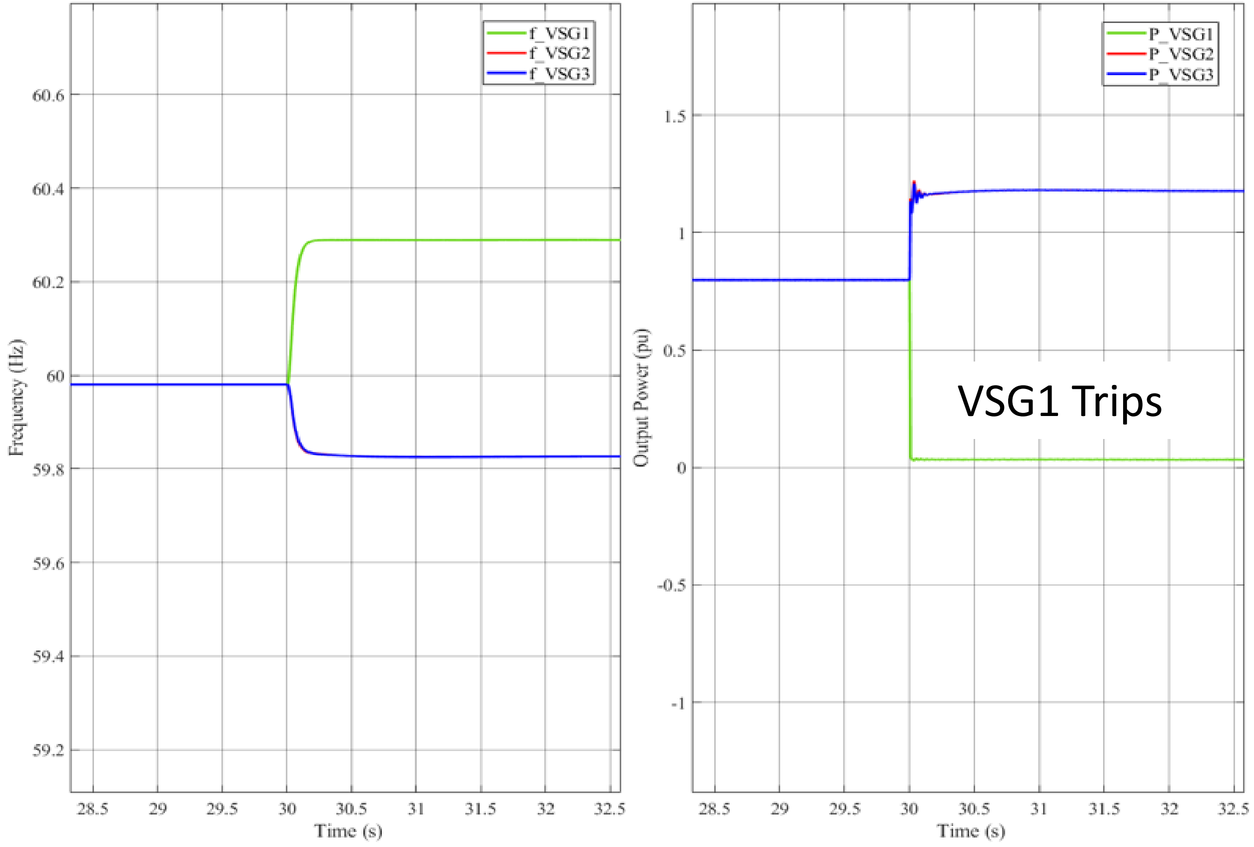
- VSG is power electronically controlled and have a very fast response time.

Simulation Verification of VSG

One SG and Two VSGs



Three VSGs

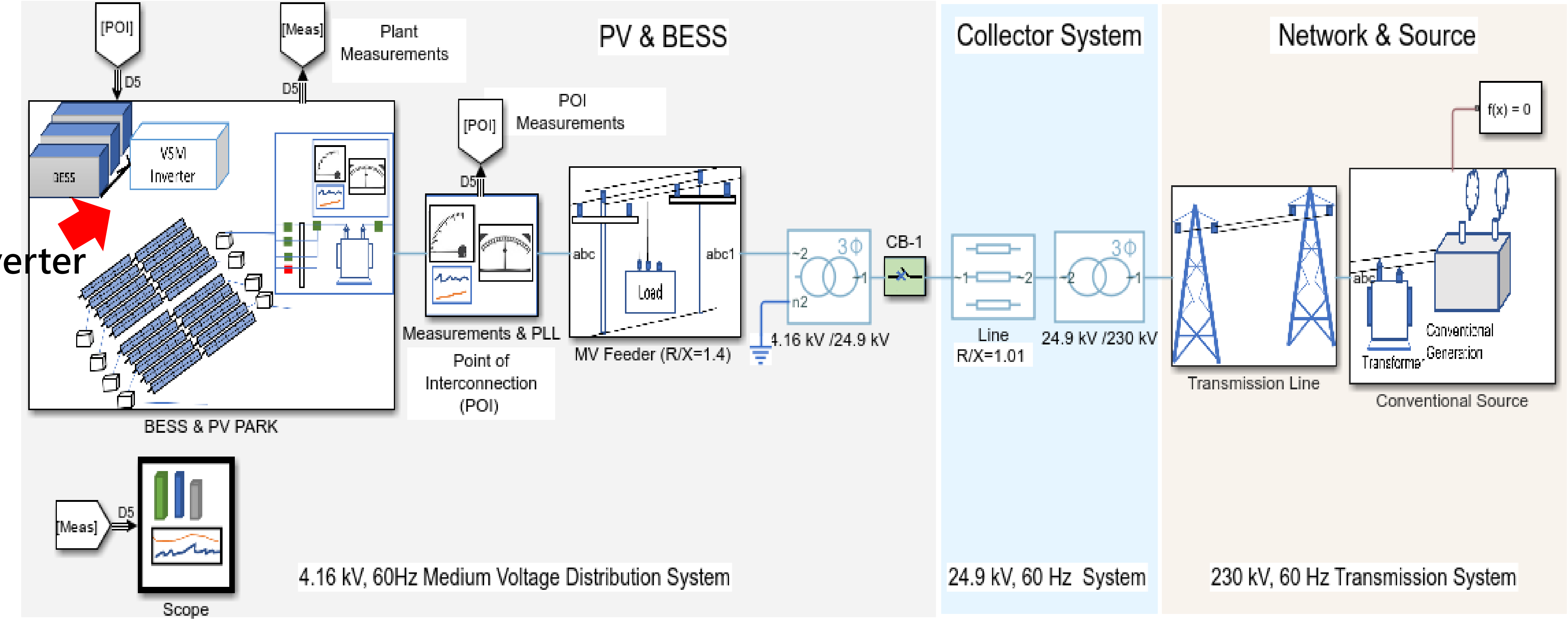


- VSG has the function of supporting the power grid and can replace SG. When a VSG trip occurs, the load is supported by other VSGs or SGs.

Simulation Result-VSG in PV Plant

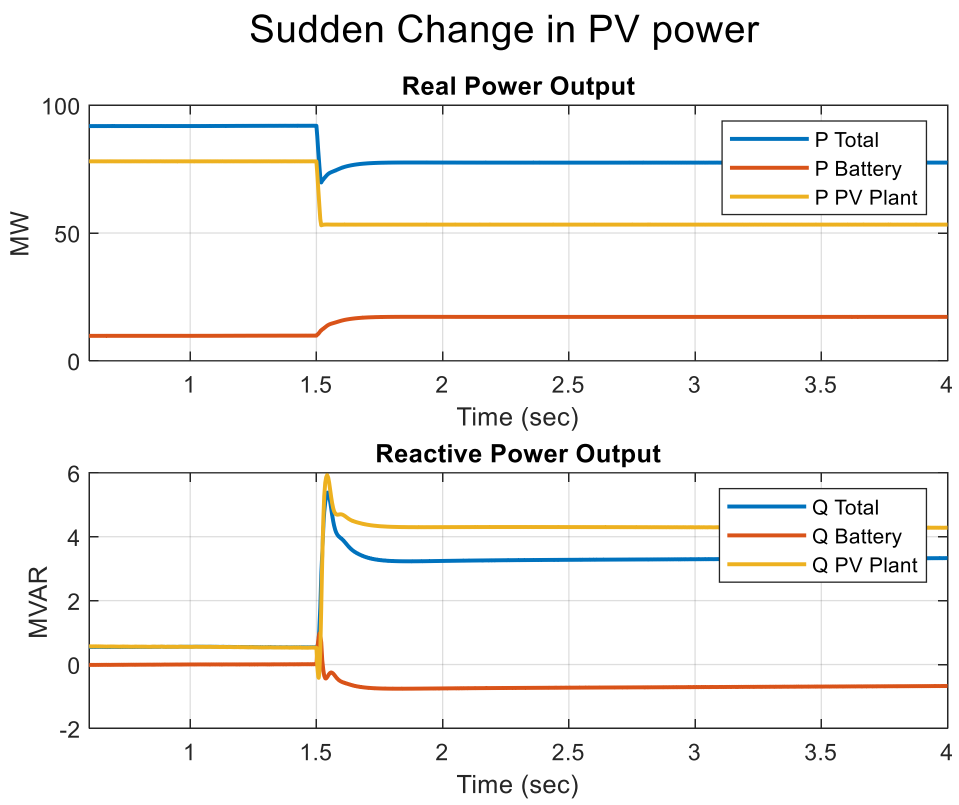
- Analysis of the ability of VSG to stabilize the power grid under high proportion of renewable energy
- Energy storage system uses VSG inverter
- PV uses grid-following inverter

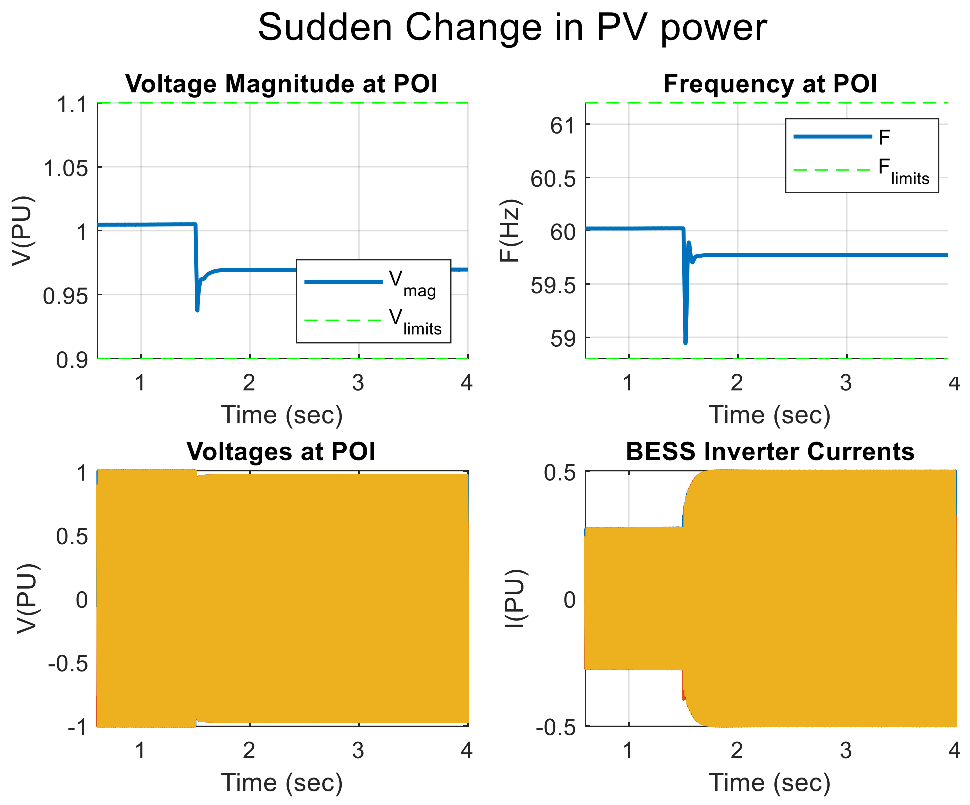
VSG Inverter

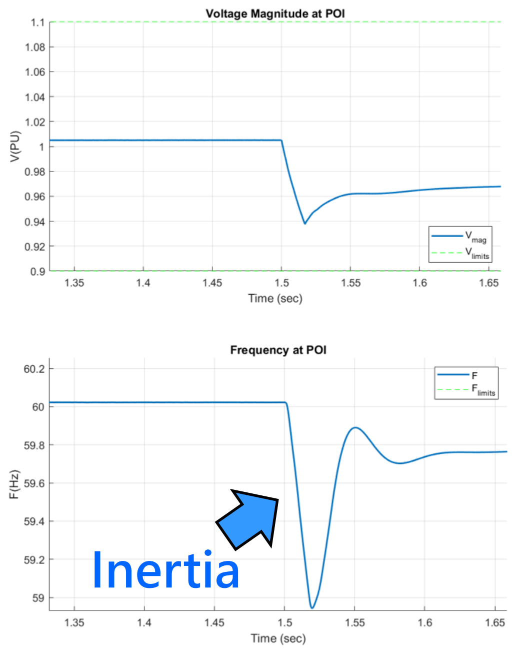


Suddenly decline in PV power (50% reduction)

- When PV power suddenly drops, VSG with BESS provides power to support the grid frequency and voltage.

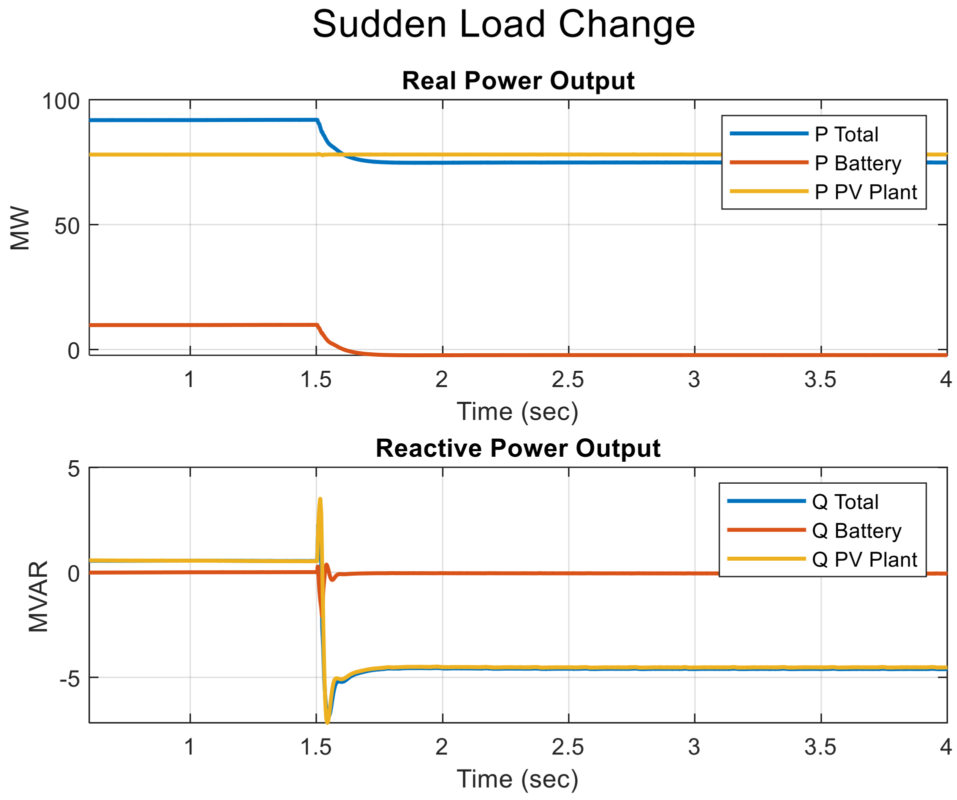


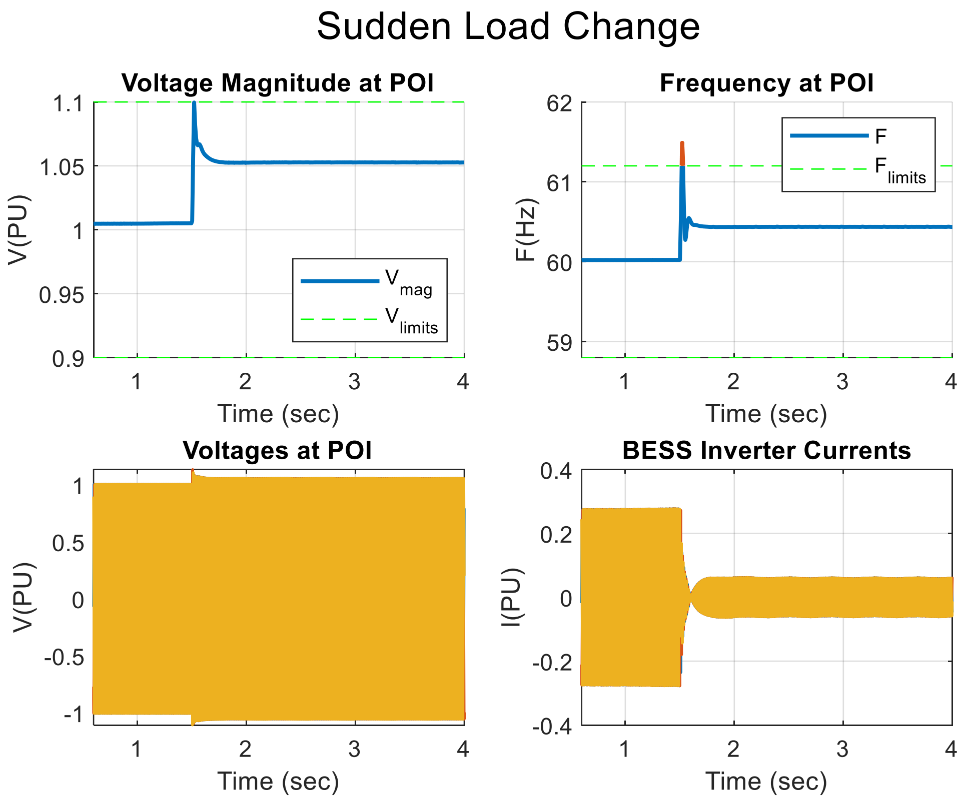




Load Suddenly Decreased by 45%

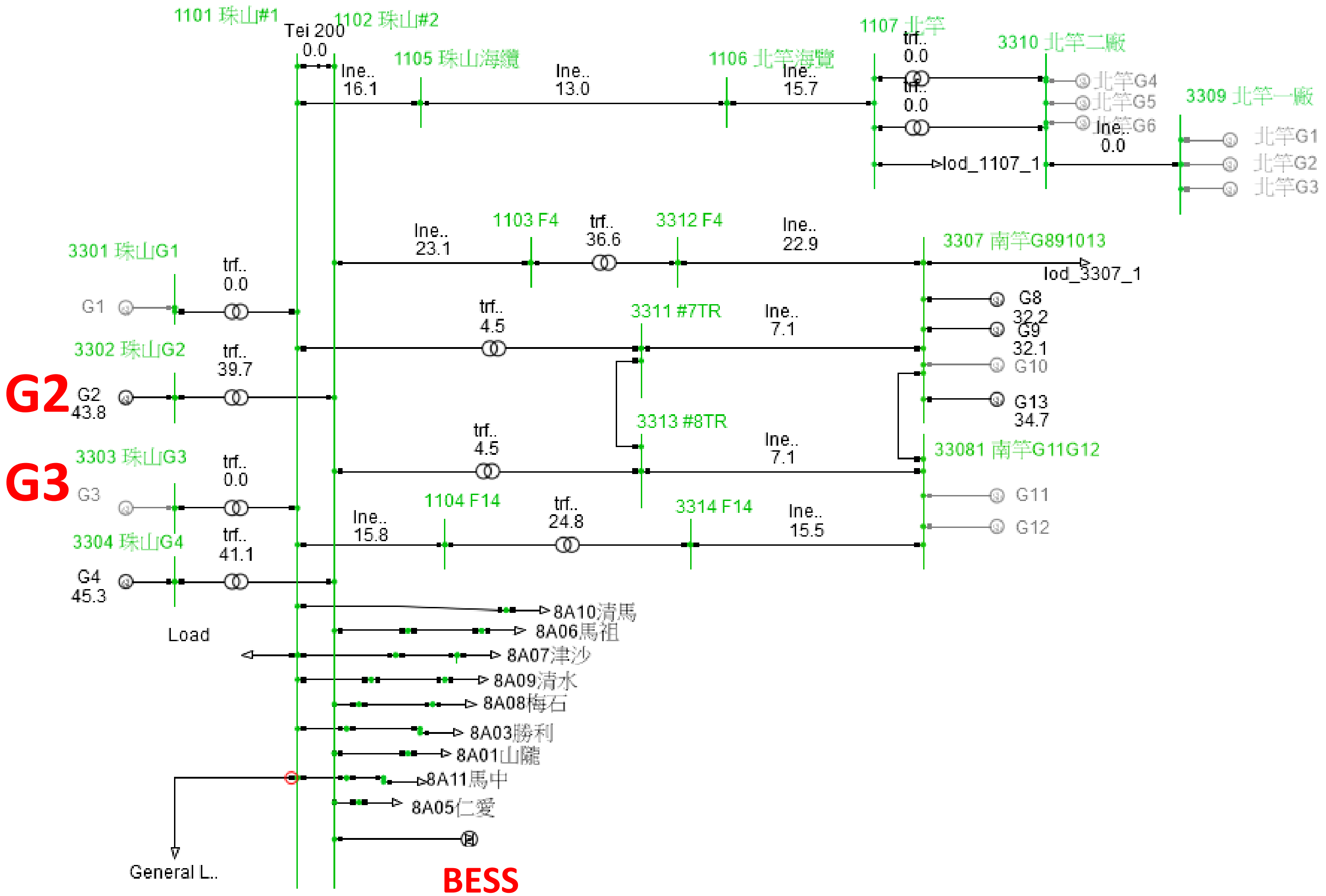
- When the load suddenly decreases, the VSG with BESS aborts power to stabilize the grid frequency and voltage.

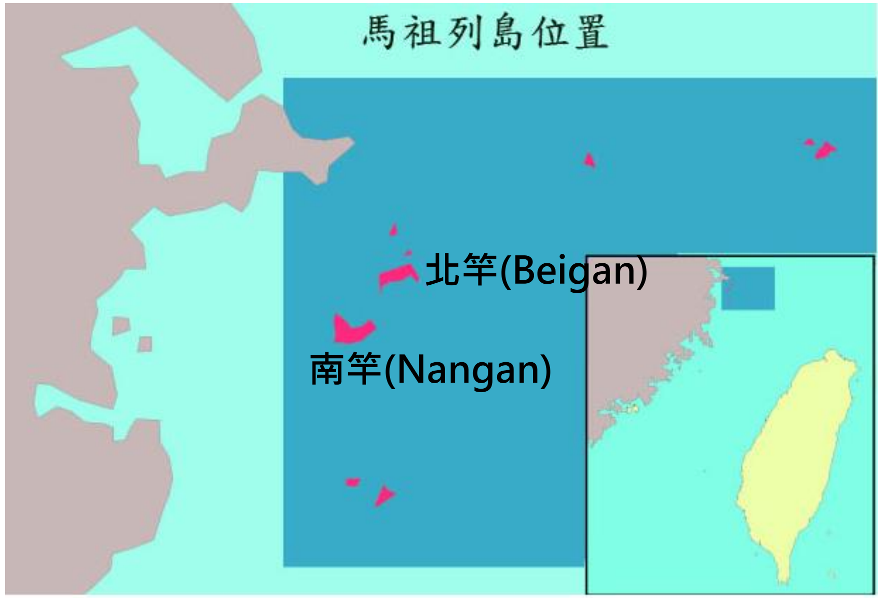




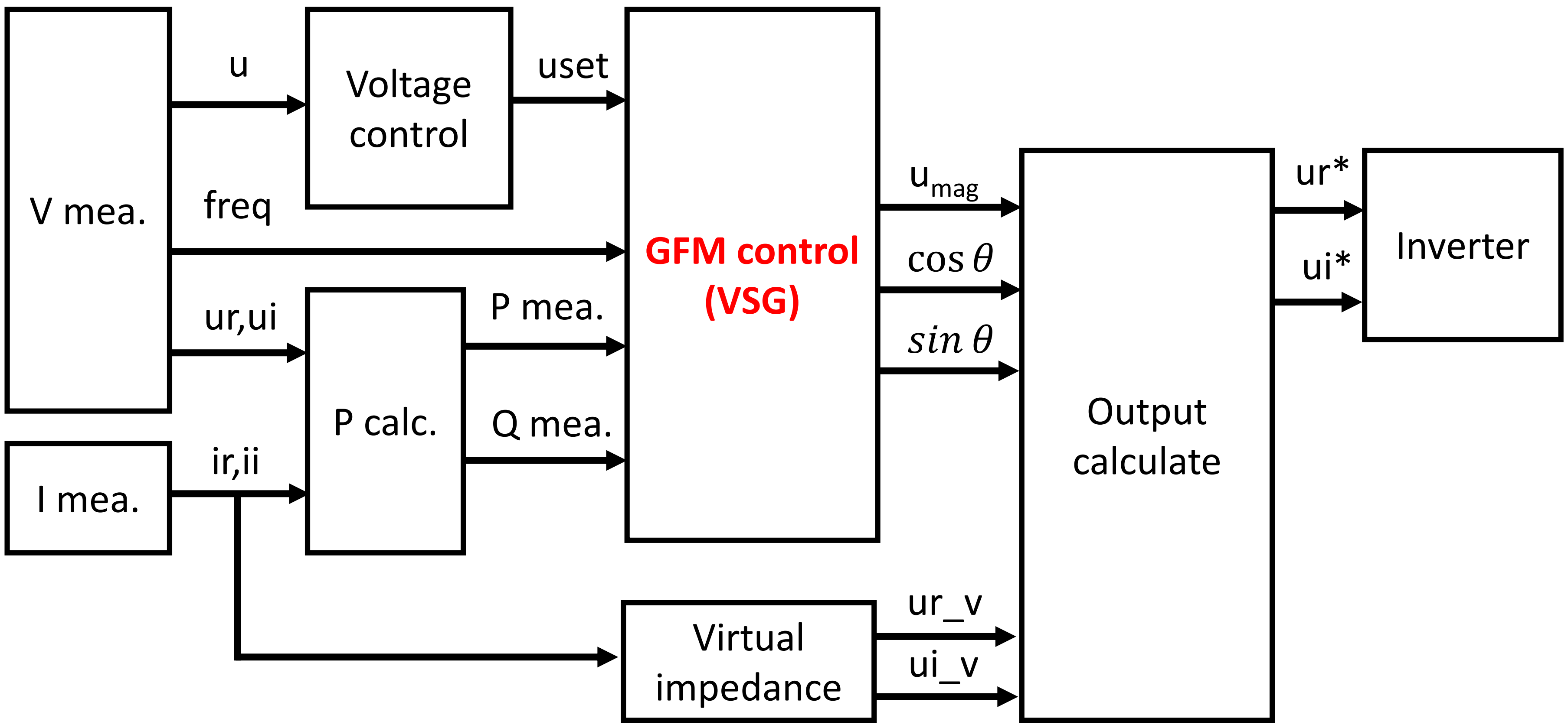
Application of VSG to Mazu (馬祖) Island

- Using PowerFactory software to verify VSG in Mazu power grid



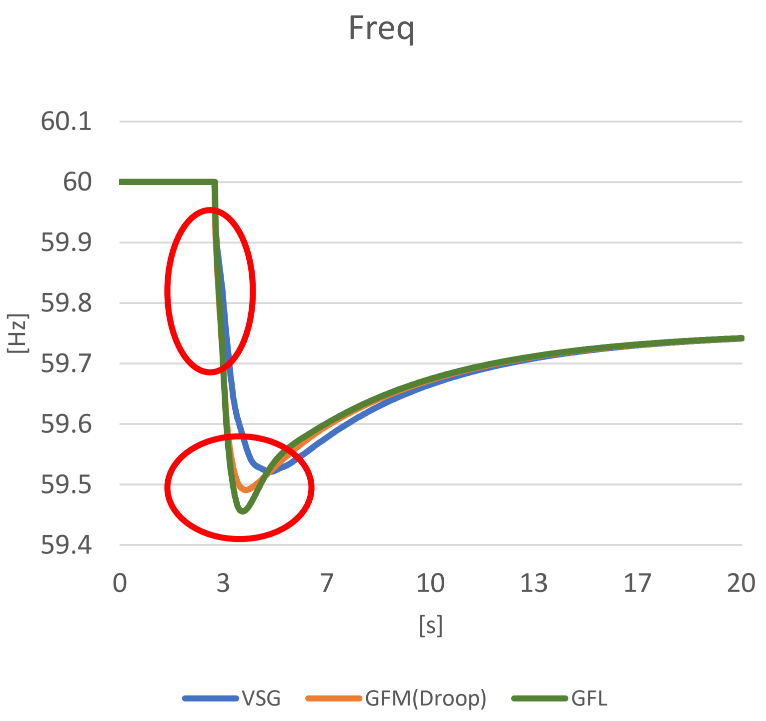


PowerFactory VSG Model

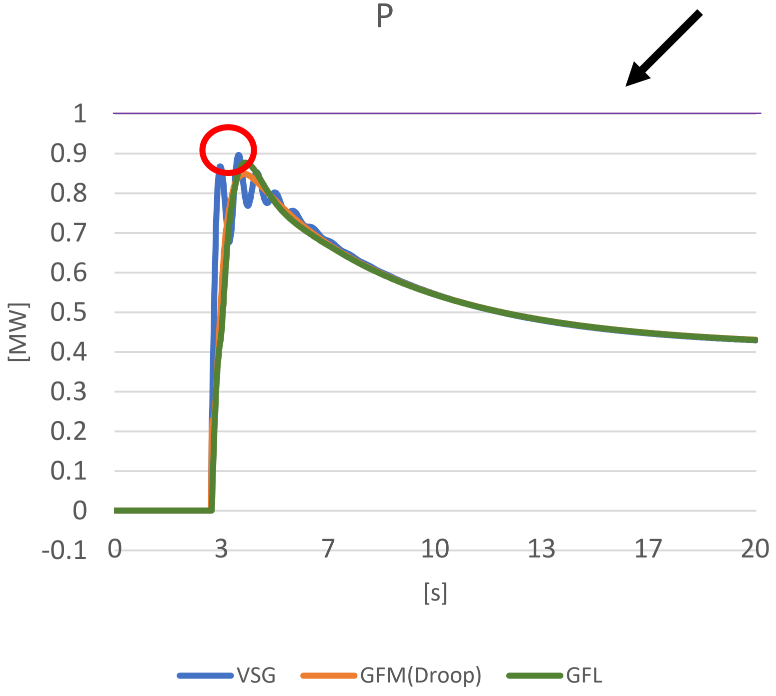


Comparison using Different Control

- 1MW BESS
- Event: N-1 (G2: 1.2MW)



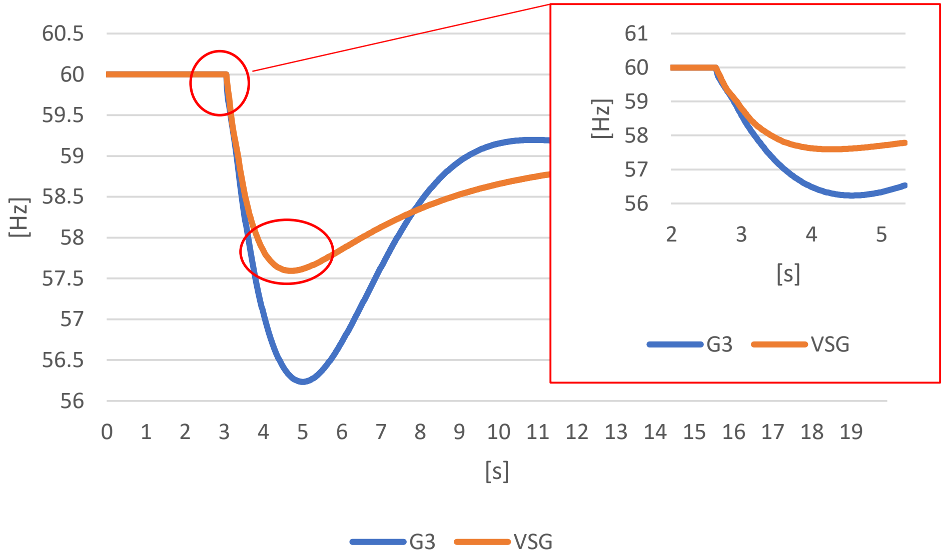
Larger H→ Larger Output Power Overshoot
(The Power Overshoot Cannot Exceed the PCS Output Limit)

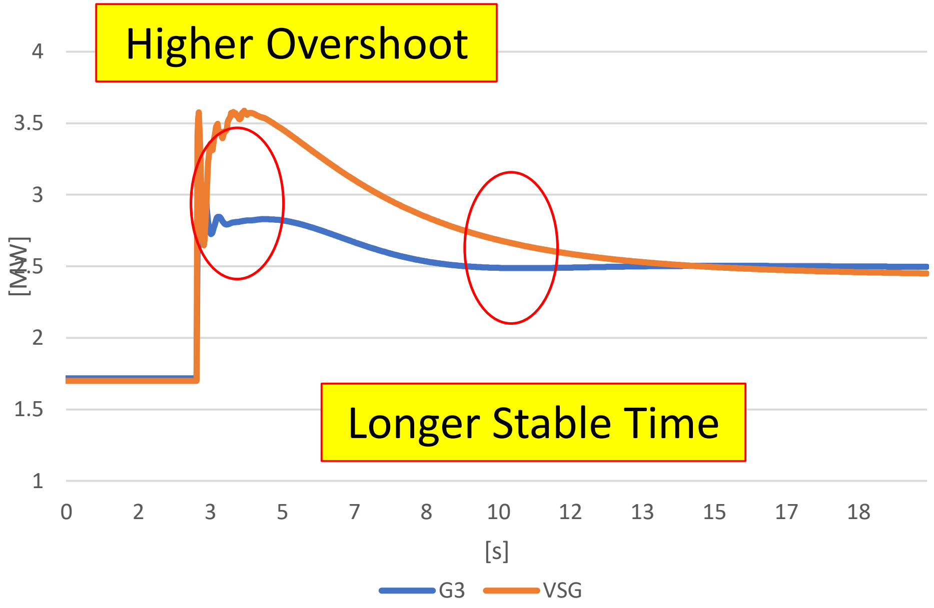


GFM(Droop), GFL: can increase the lowest point
GFM(VSG): can increase the lowest point and decrease RoCoF

Replacing Traditional SG in Frequency Support

	S_{rate}	P_{rate}	H
G3	4.53MVA	1.7MW	1.78s
VSG	4.53MVA	1.7MW	1.78s





- ✓ **Faster Response Time**
- ✓ **Lowest Frequency Improve**

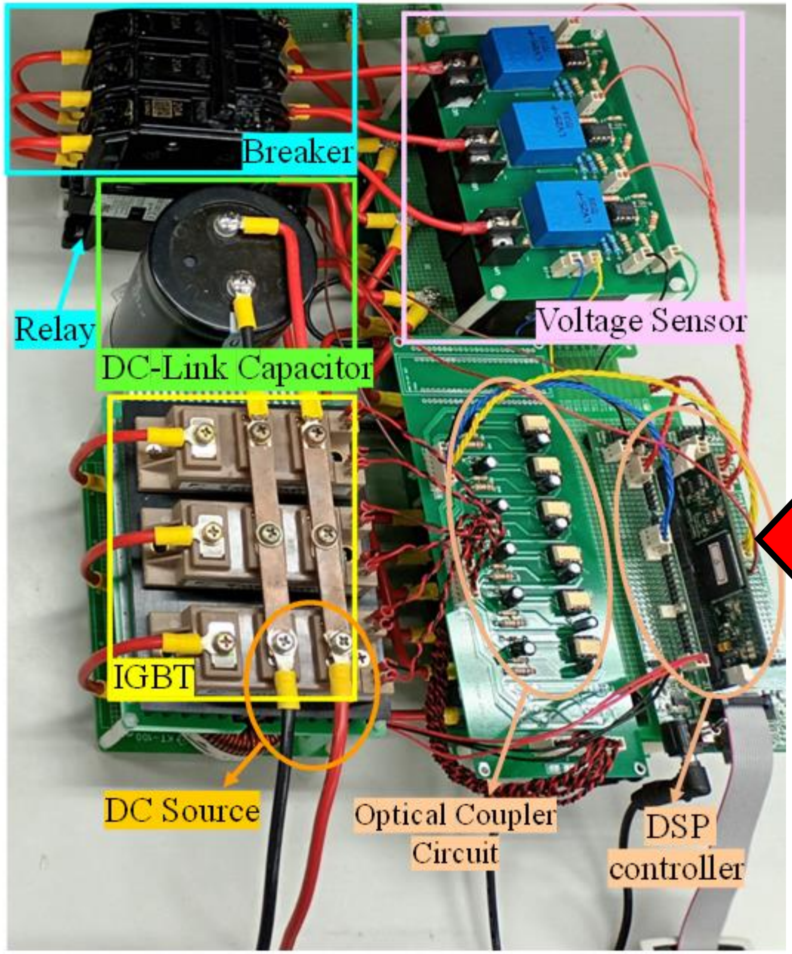
Experimental Verification

- Prototype of Small Scale VSG
- Commercial VSG Test

Prototype of Small Scale VSG

- A prototype is built to verify the performance of VSG

Inverter with VSG control

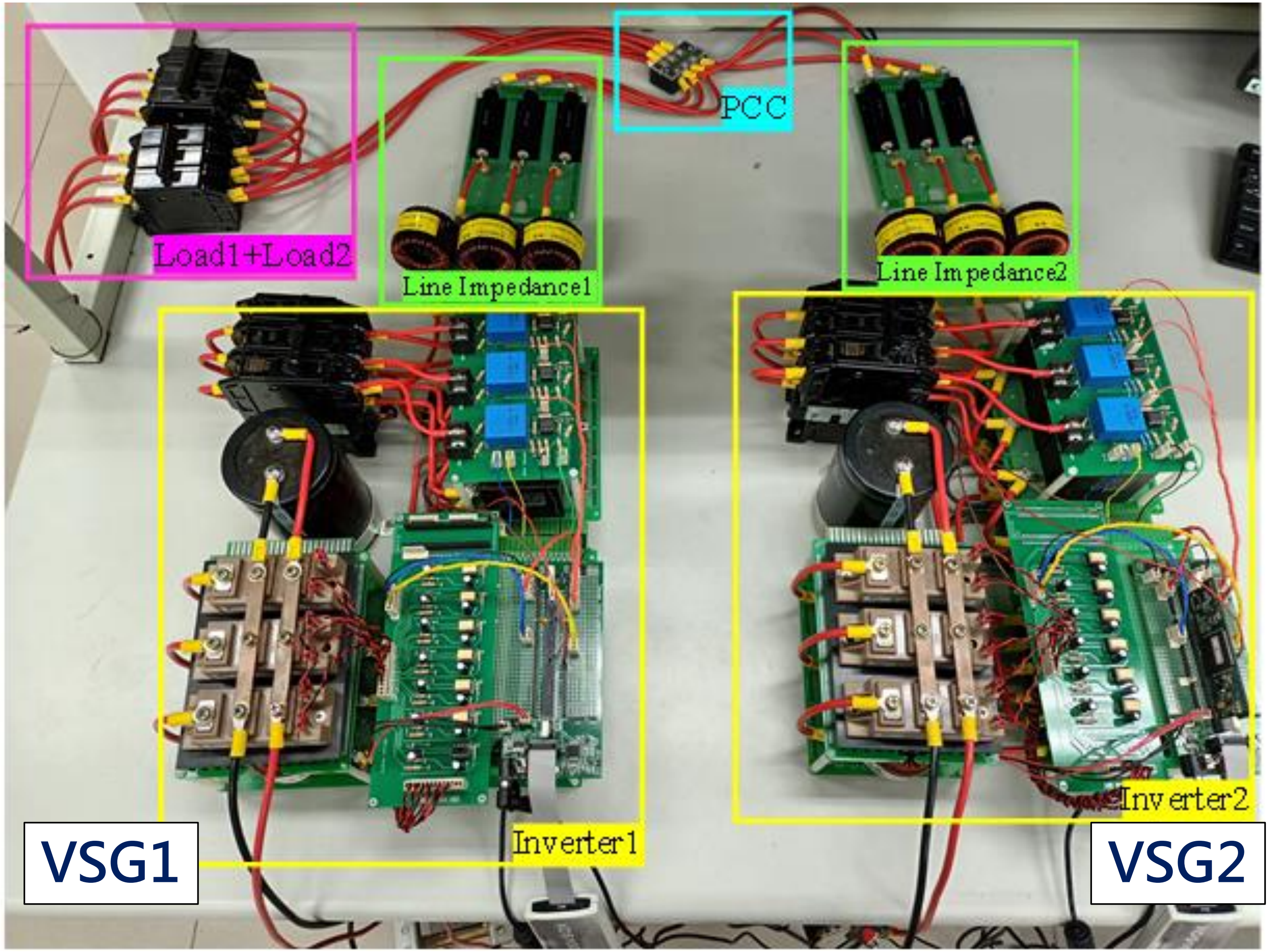


DSP

VSG control algorithm

Parameters	Value
Input DC voltage	450 V
AC line voltage (rms)	220 V
Line frequency	60 Hz
Switching frequency	18 kHz
Filter inductor, $L_{a,b,c}$	2 mH
Filter capacitor, $C_{a,b,c}$	23 µF
DC-link capacitor, C_{dc}	2200 µF
Load	1 kW

Prototype of Two VSG Connection



RoCoF under Different Virtual Inertia

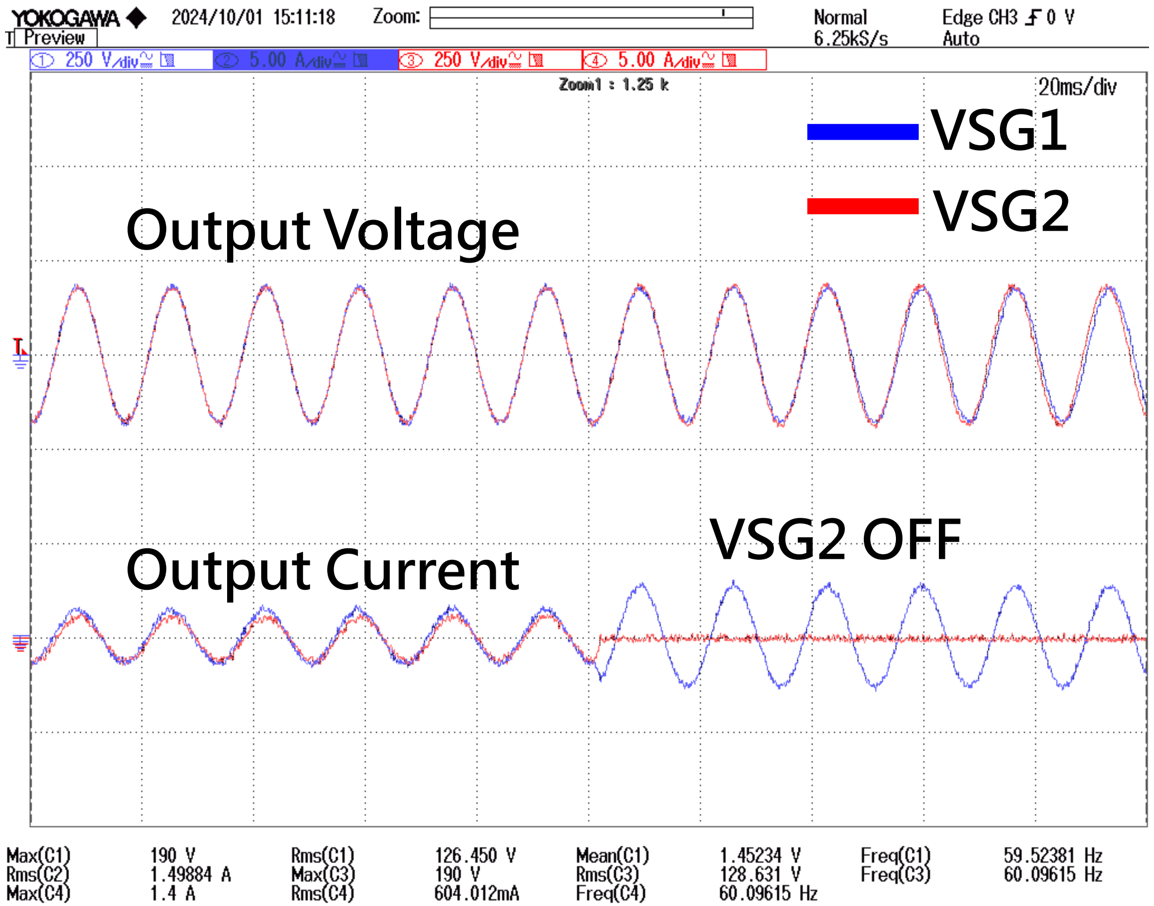
VSG: Pac=0kW→1kW

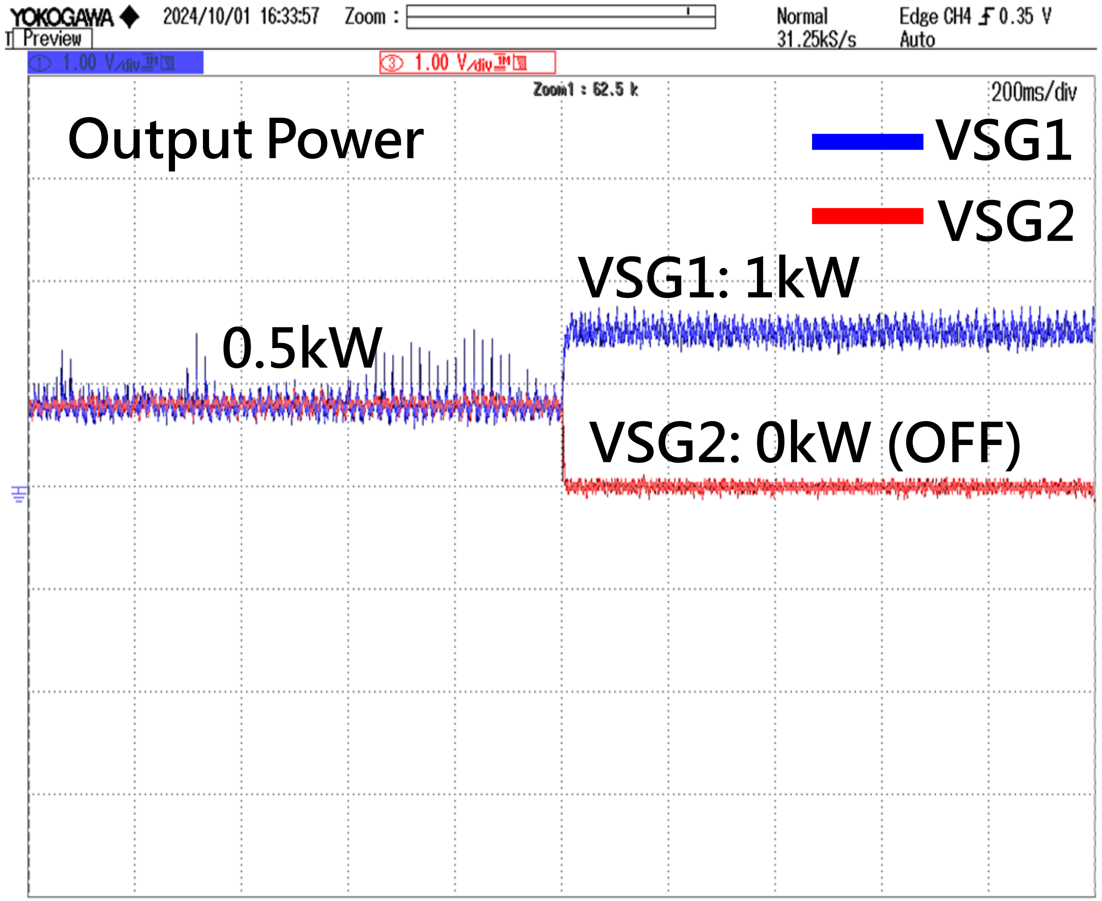
RoCoF under Different Virtual Damping

VSG: Pac=0kW→1kW

One VSG Shut Down

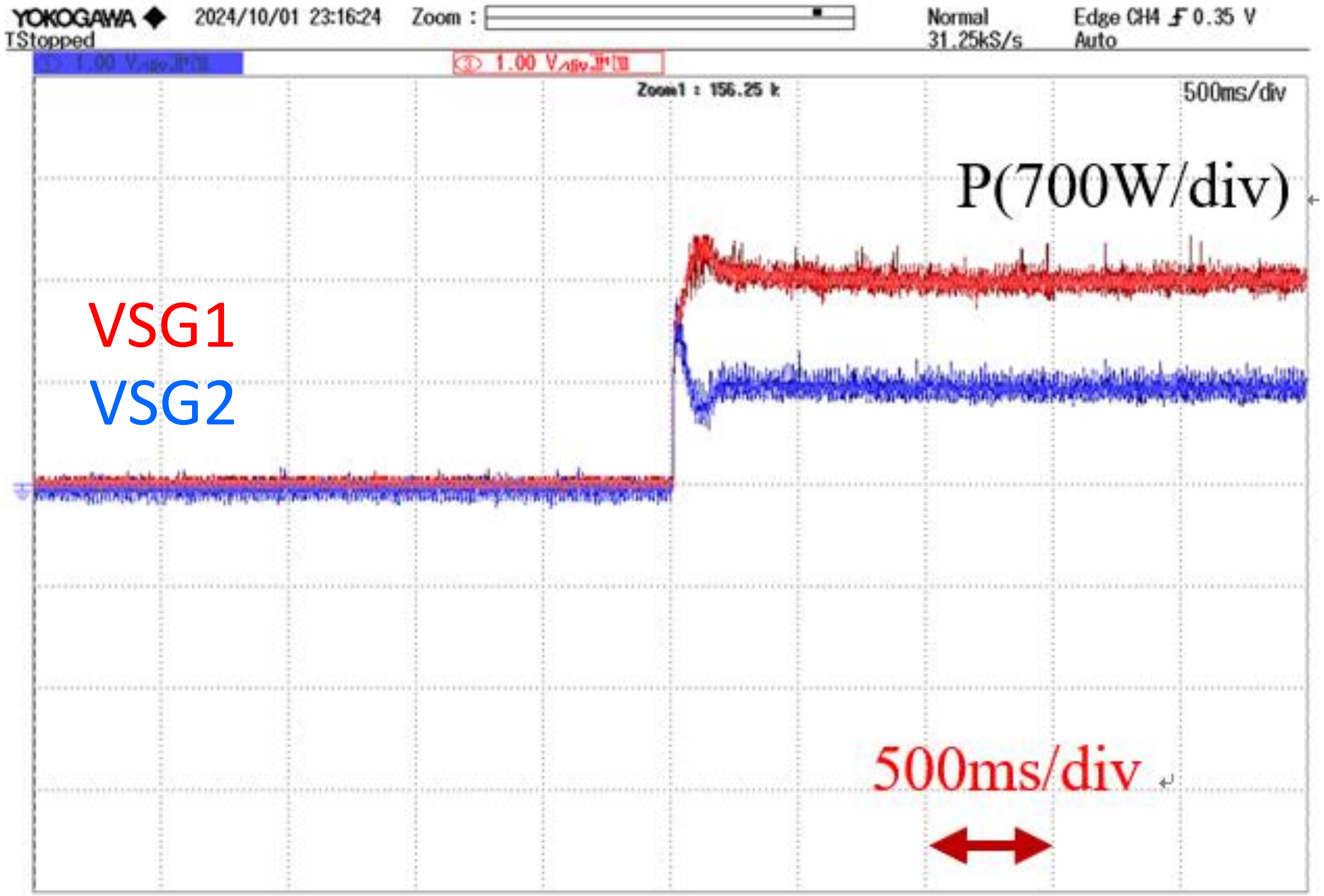
- Two VSGs are ruining. Suddenly, one VSG is shut down.





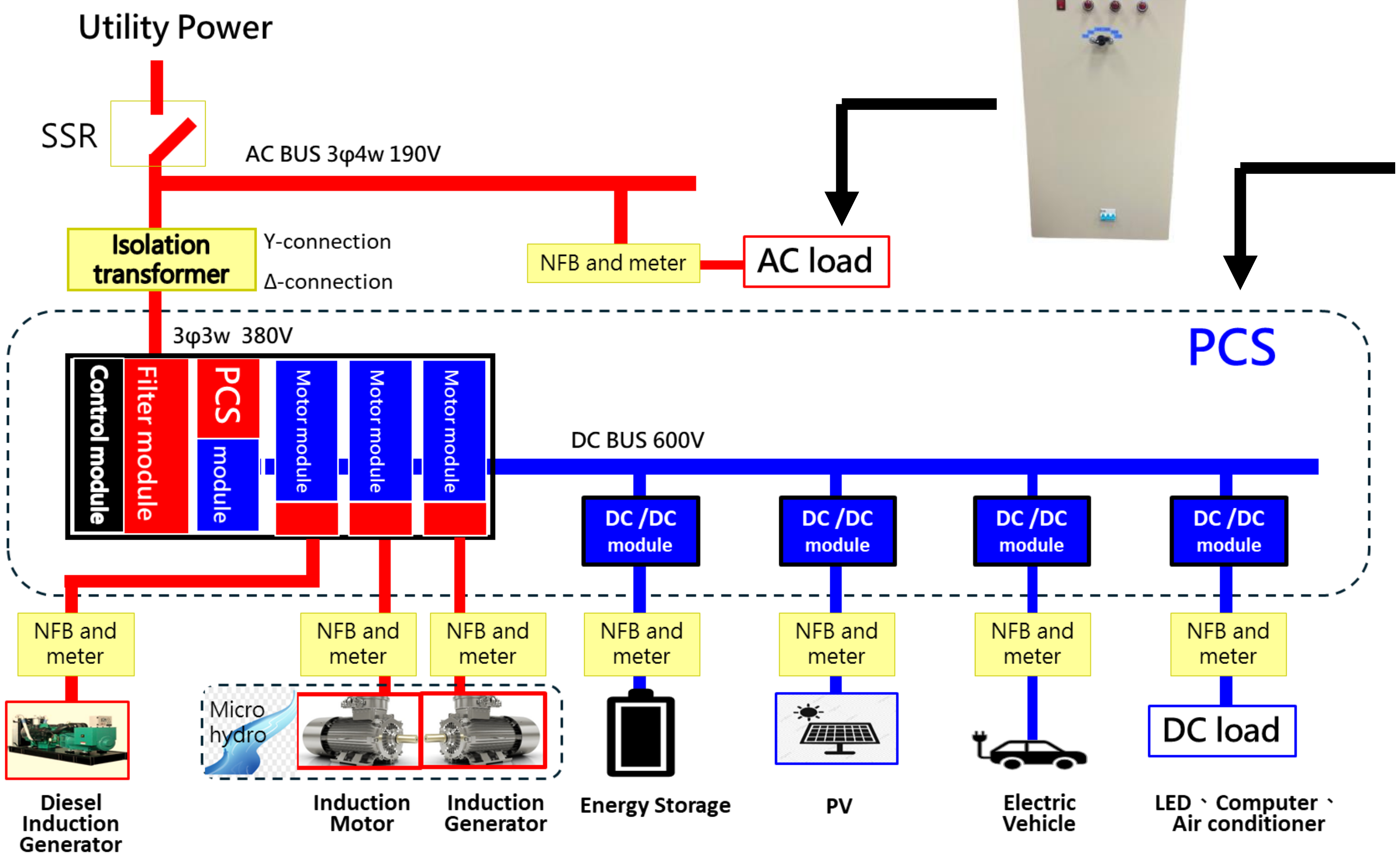
VSGs with Different Droop Coefficients

- Droop Ratio=2:1



Commercial VSG (36kW) Test

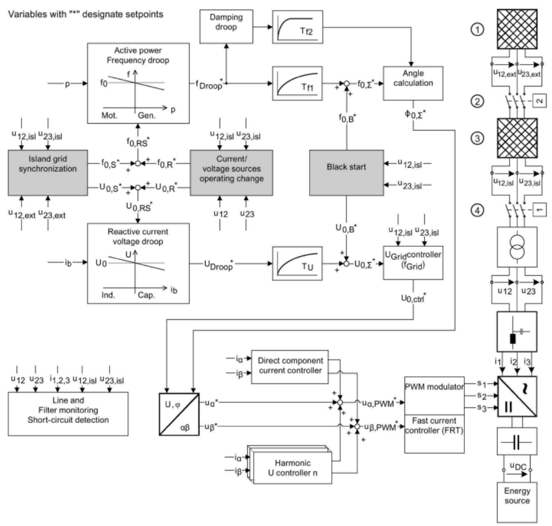
- A 36kW with commercial product is test



Test Item:

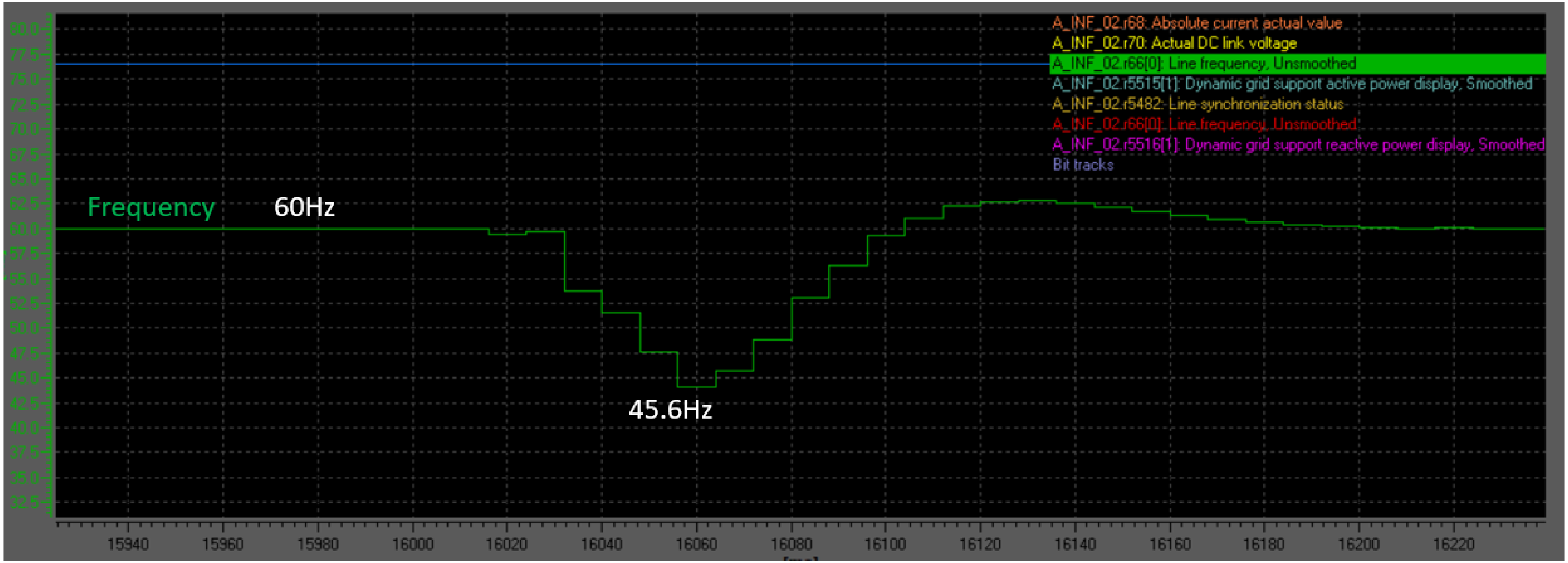
1. Virtual Inertia
2. Seamless Islanding
3. Black Start

Control Block



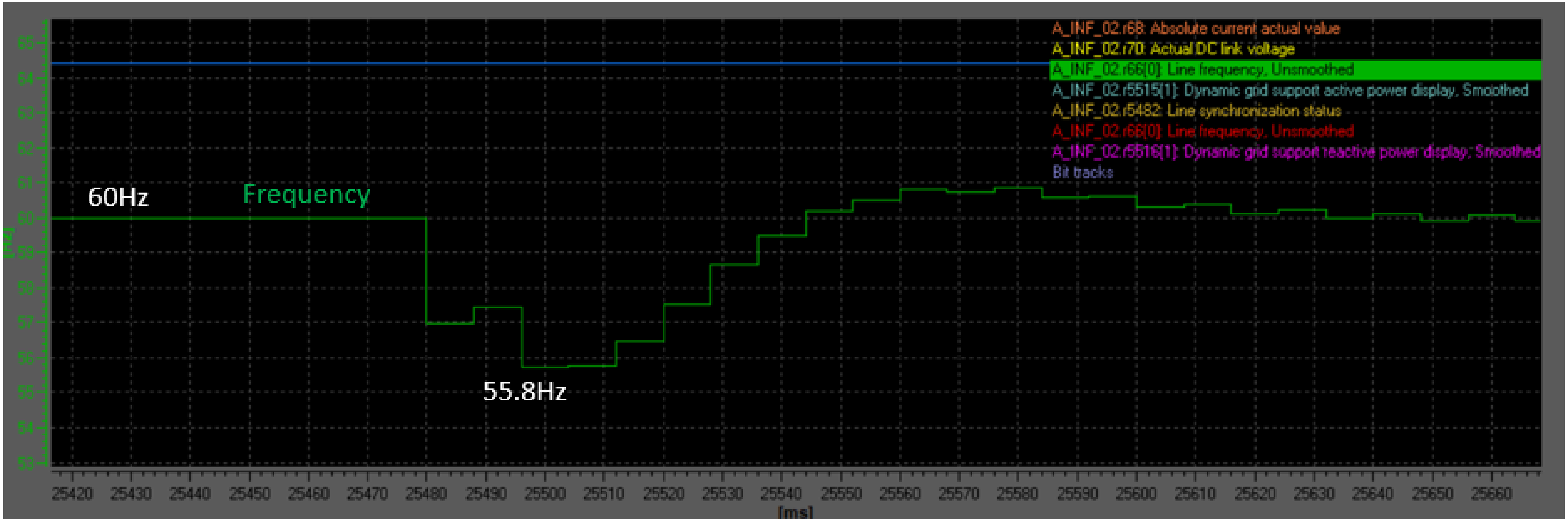
Inertia Test

- Low virtual inertia (Lowest Frequency=45.6Hz)



Inertia Test

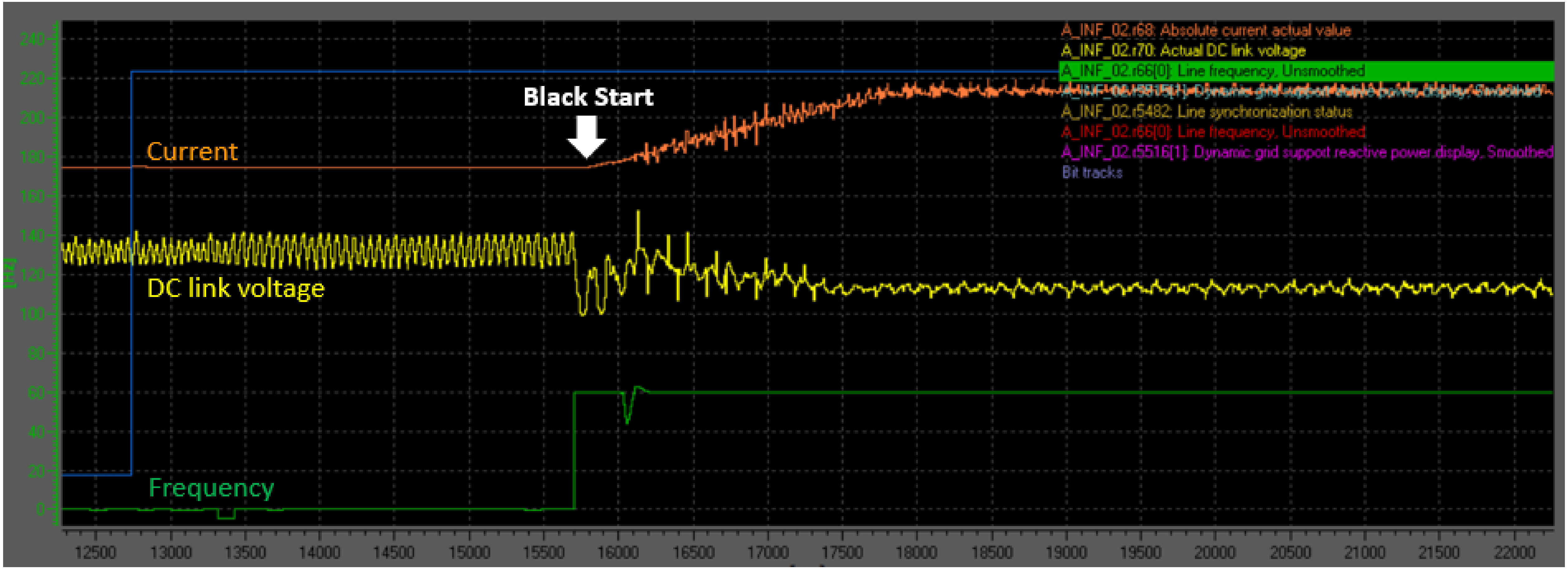
- High virtual inertia (Lowest Frequency=55.8Hz)



By changing the virtual inertia parameter, the lowest frequency can be changed.

Seamless Islanding

Black Start



Black Start
Current
DC link voltage
Frequency
A_INF_02.r68: Absolute current actual value
A_INF_02.r70: Actual DC link voltage
A_INF_02.r66[0]: Line frequency, Unsmoothed
A_INF_02.r5482: Line synchronization status
A_INF_02.r66[0]: Line frequency, Unsmoothed
A_INF_02.r5516[1]: Dynamic grid support reactive power display, Smoothed
Bit tracks
[Hz]
240
220
200
180
160
140
120
100
80
60
40
20
0
12500
13000
13500
14000
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20500
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21500
22000

International Standard/Recommendation

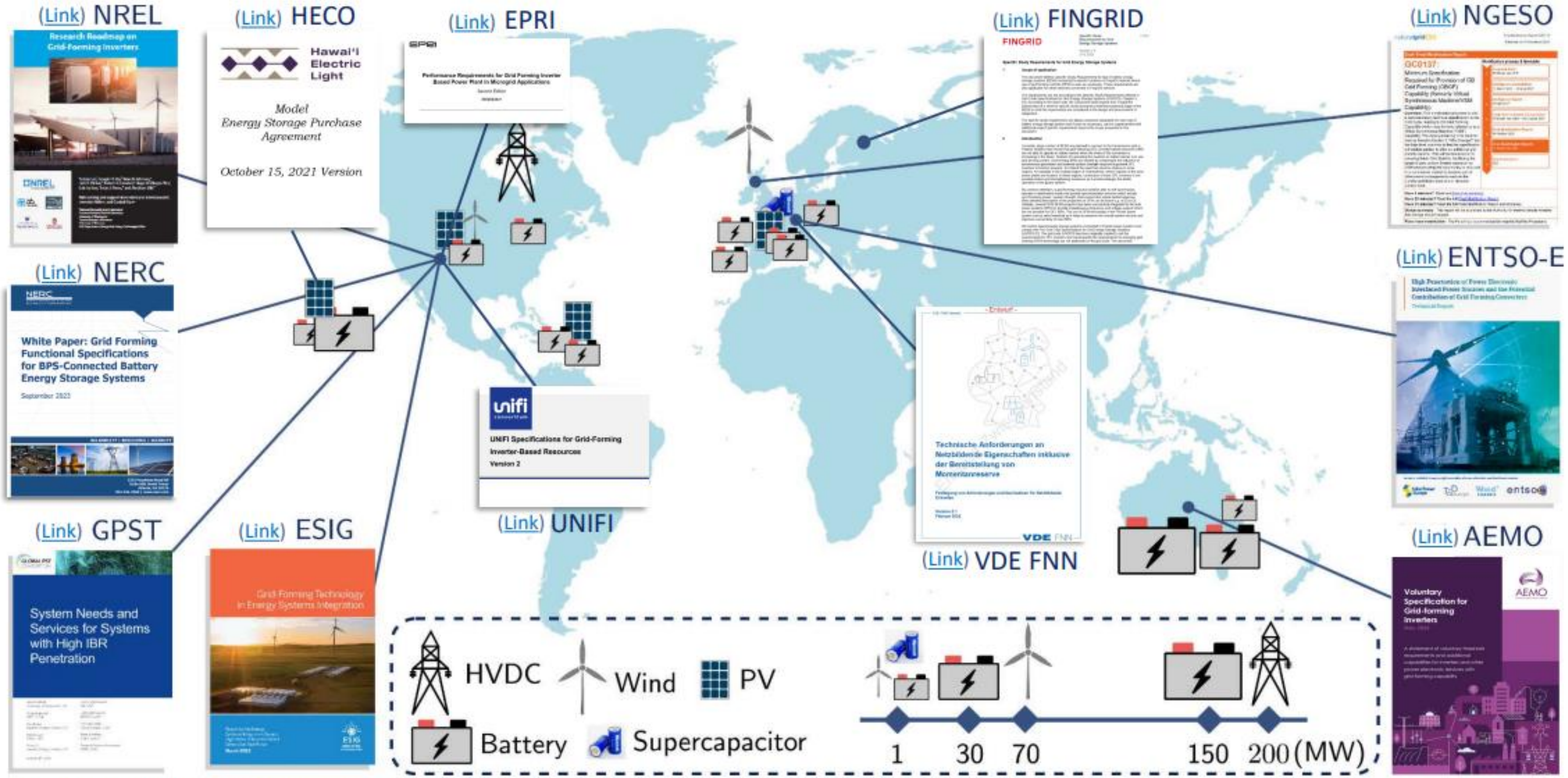
Challenges of lacking performance and conformance test standards for GFM

	GFL	GFM
Performance and functional requirements	IEEE 1547-2018	Presently missing
Conformance Test Procedures	IEEE 1547.1-2020	
Certification	1741 Ed. 3/ 1741SB	

- Due to the lack of GFM standards, utilities need to come up with GFM requirements and verification methods or rely on OEMs
- Inverter OEMs offer customized inverter software and hardware based on specific project needs

Ref.: EPRI

GFM Inverter Requirements Development World-Wide



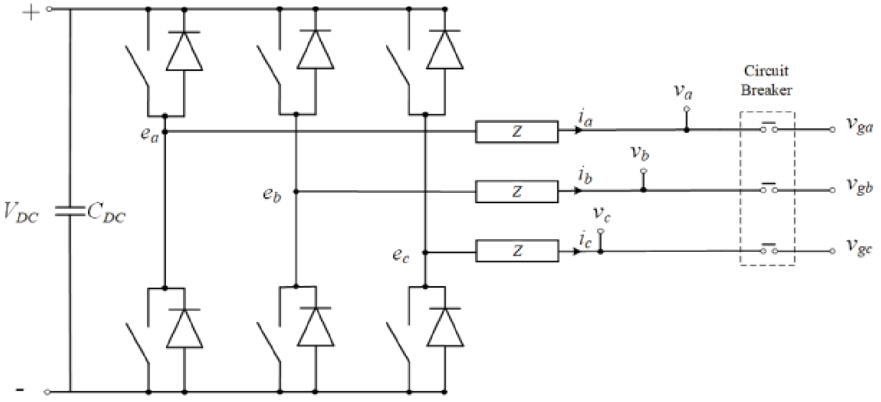
Ref: Tutorial on Grid Forming Inverter Technology, 2023 IEEE PES General Meeting, July 2023 (link); Grid-Forming Specifications and Interconnection Requirements, ESIG (link)

Ref.: EPRI

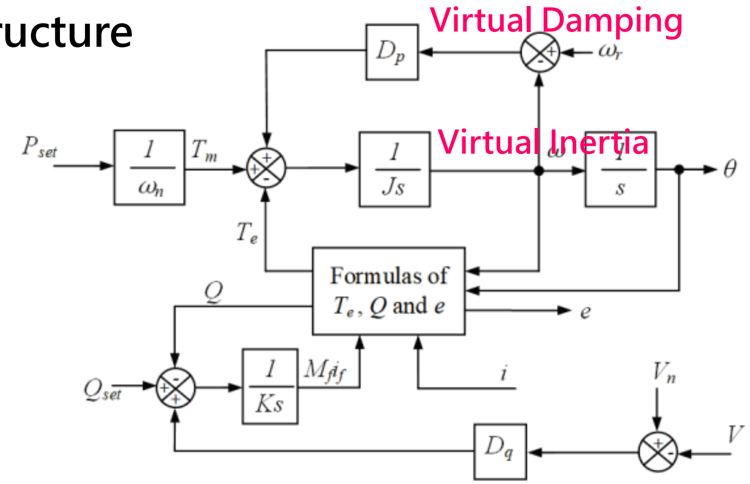
IEEE 2988

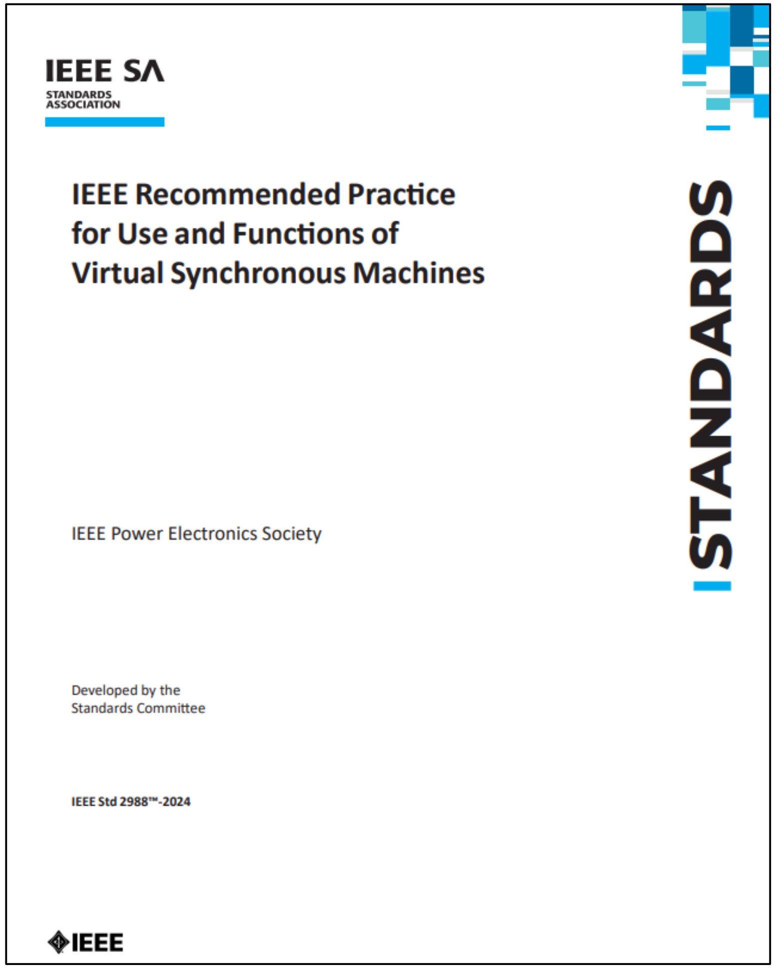
- IEEE 2988 recommends controller implementation for virtual synchronous machines. The controller modeling is based on the swing equation of the traditional synchronous machine.

✓ Hardware Structure



✓ Control Structure




IEEE SA
STANDARDS ASSOCIATION

IEEE Recommended Practice for Use and Functions of Virtual Synchronous Machines

IEEE Power Electronics Society

Developed by the
Standards Committee

IEEE Std 2988™-2024

STANDARDS

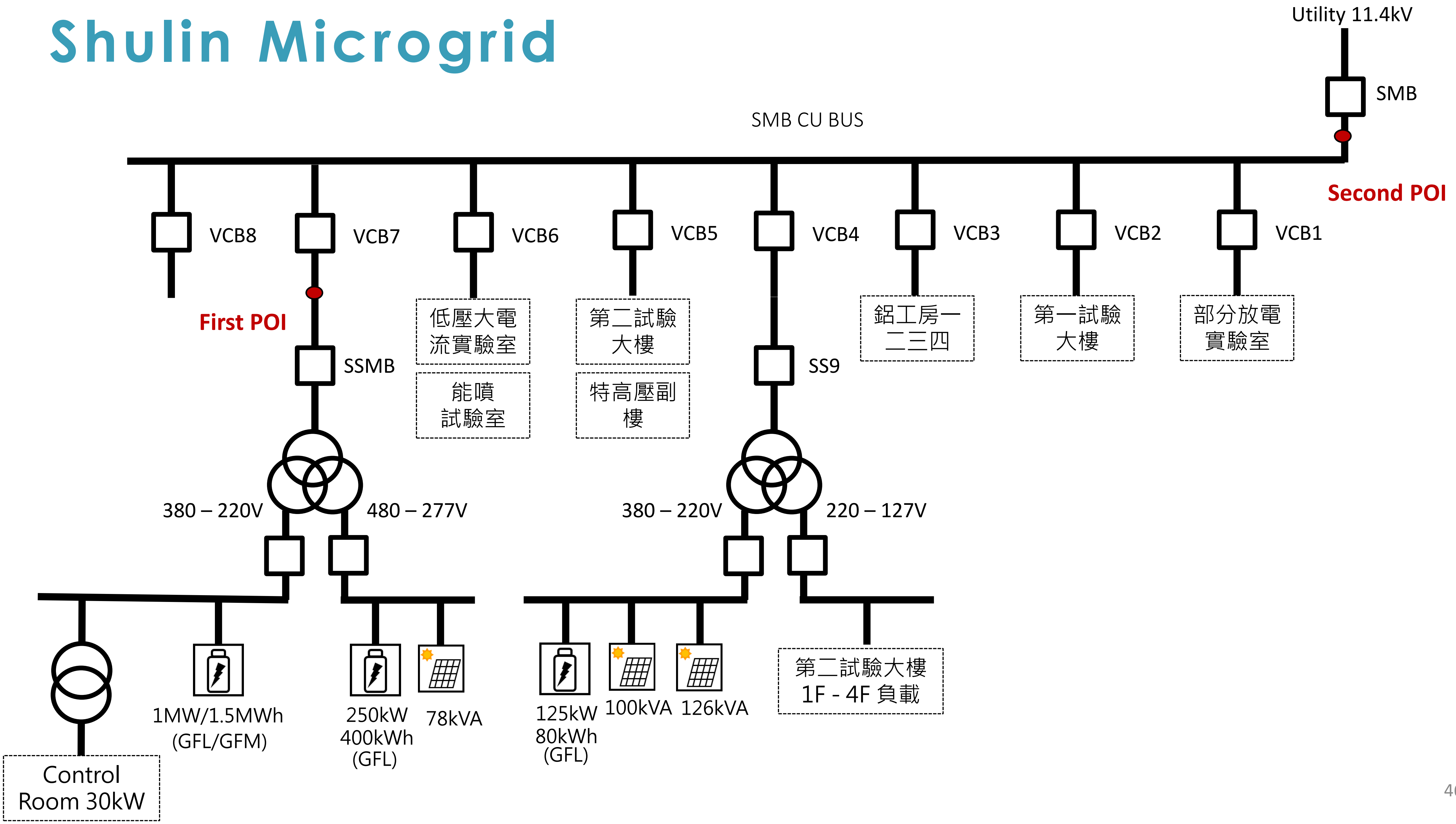
IEEE

Ref.: IEEE 2988

VSG in Shulin Microgrid

- Small Part Shulin Microgrid
- The Whole Shulin Microgrid

Shulin Microgrid



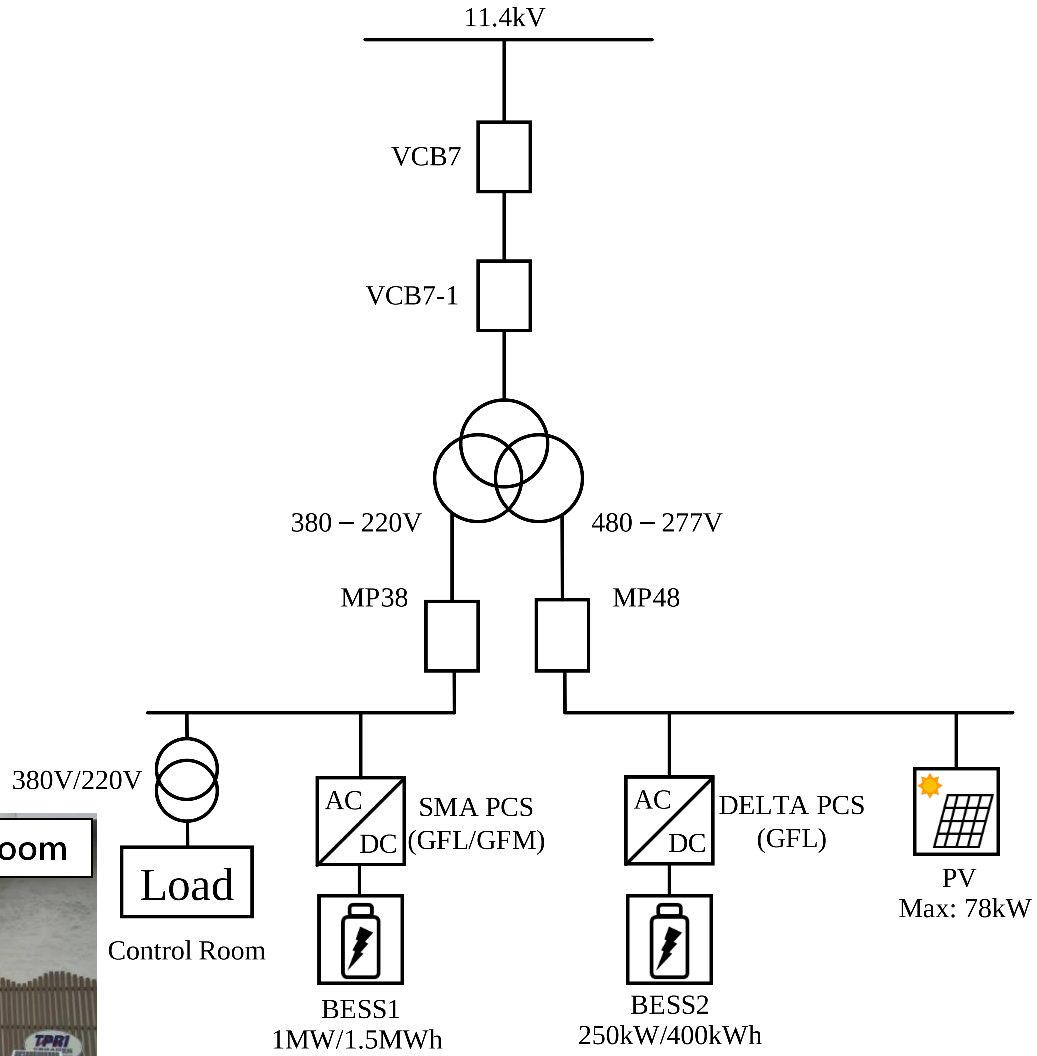
Shulin Microgrid - Testing

40-foot Battery Energy Storage Container

SMA PCS
(grid following & forming)

20-foot Battery Energy Storage Container

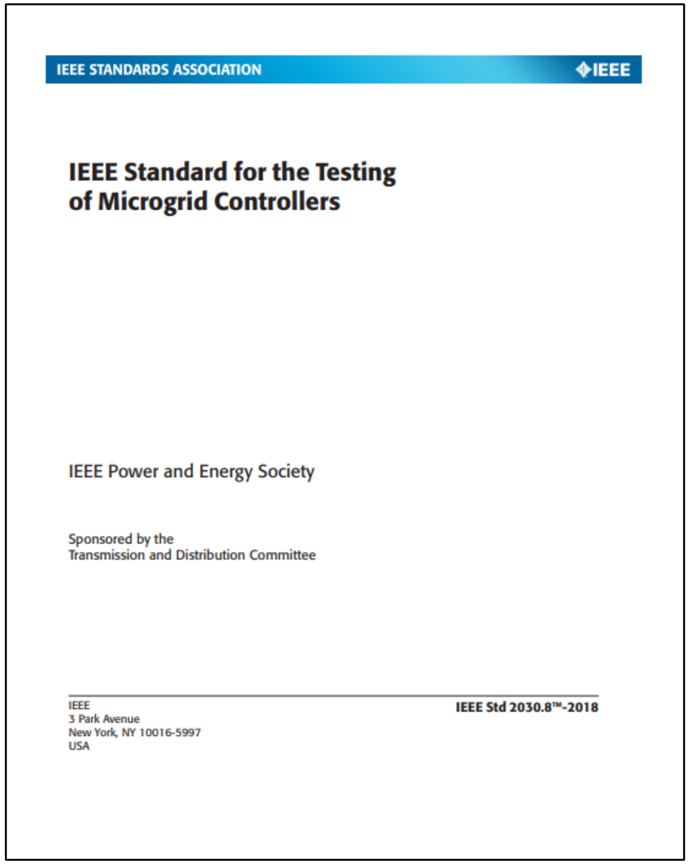
DELTA PCS
(grid following)



Shulin Microgrid-Testing

- There are 4 transition function tests and 2 steady state function tests.
- The testing scenarios are designed according to IEEE Std. 2030.8.

  - IEEE2030.8-2018
    IEEE Standard for the Testing of Microgrid Controllers


IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for the Testing of Microgrid Controllers

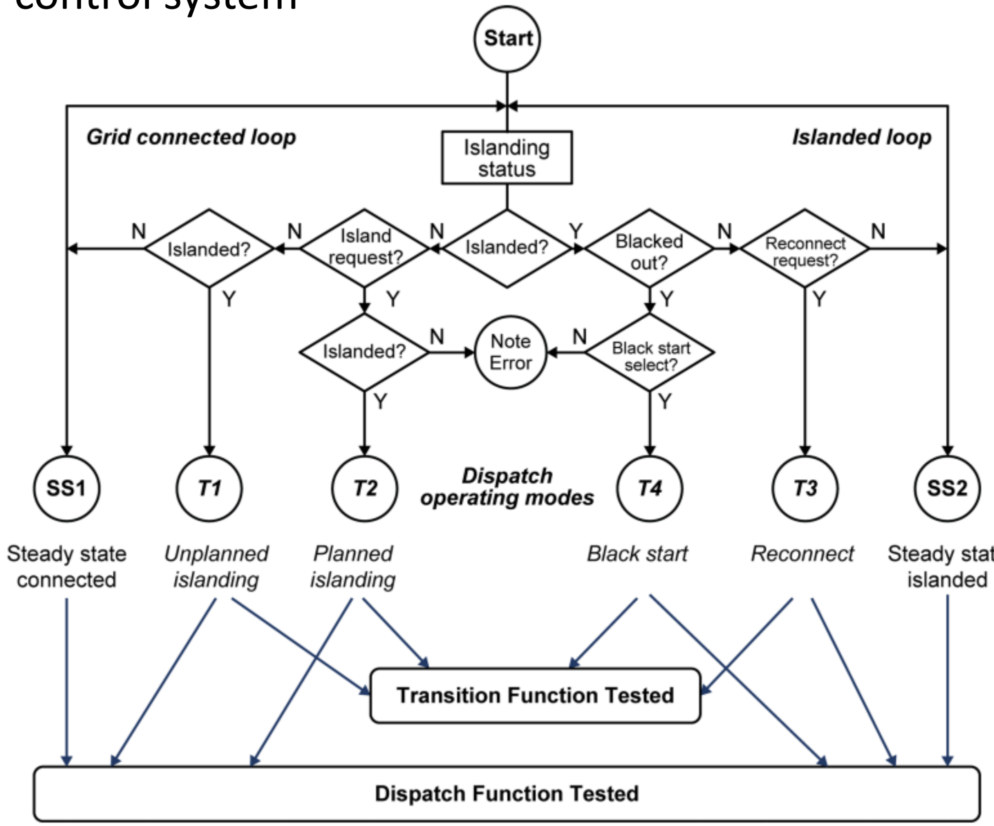
IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 2030.8™-2018

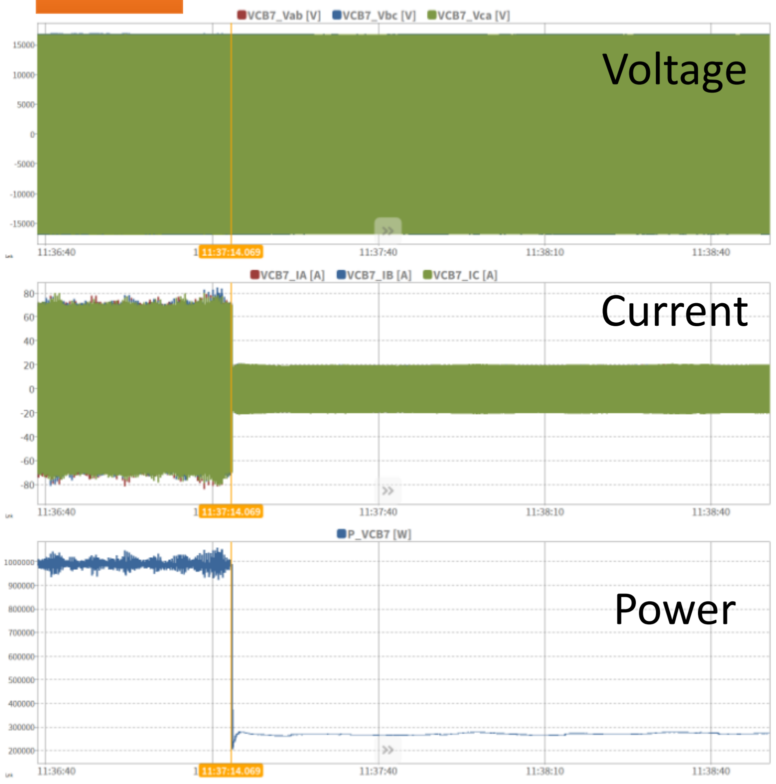
  - Modes of operation and transition logic of the microgrid control system



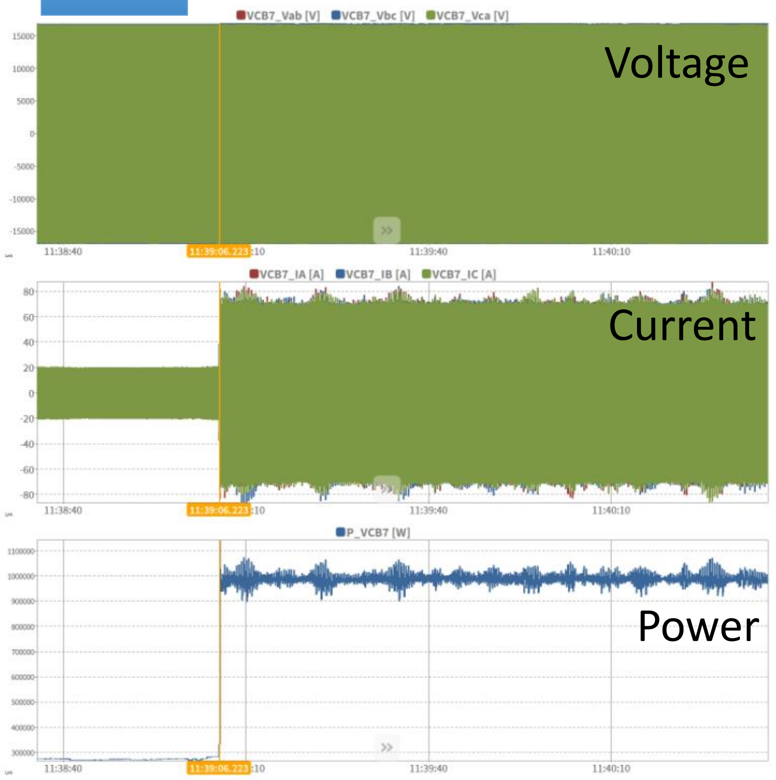
Shulin Microgrid- Steady State Connected (SS1)

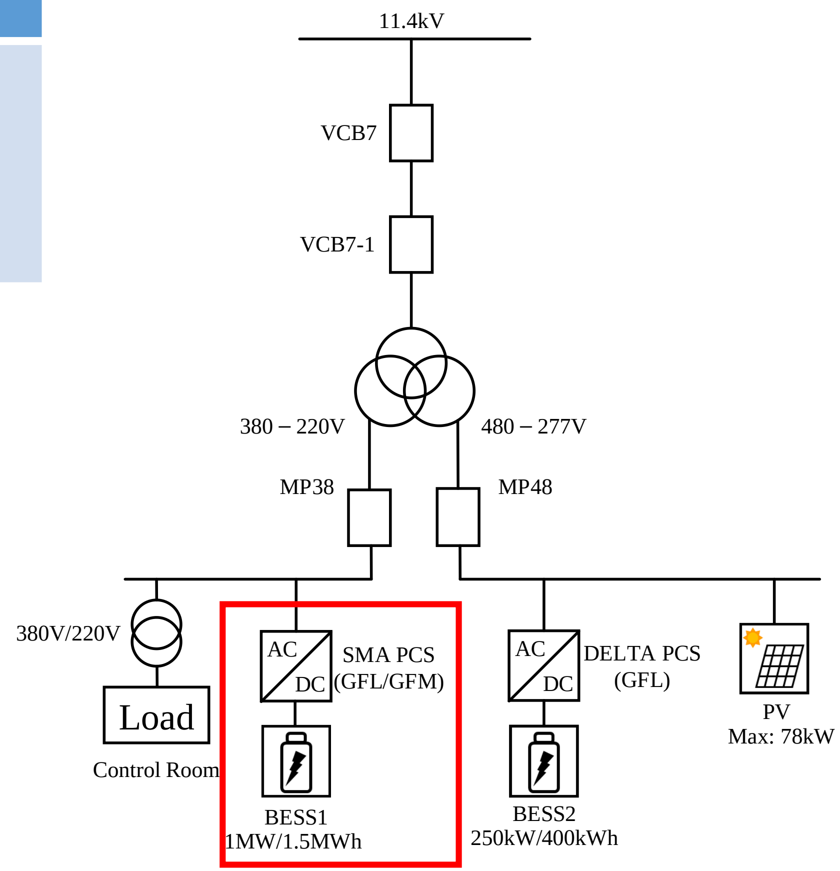
Initial Conditions				Initiating Events
SMA_BESS	Delta_BESS	78kW_PV	30kW Load	(1) BESS Output Step Change (2) PV Inverter Trip (3) Stop/Start Maximum Load (4) Stop/Start Maximum DER (SMA_BESS)
900kW GFL mode Discharge	250kW GFL mode Discharge	ON	ON	

Stop



Start





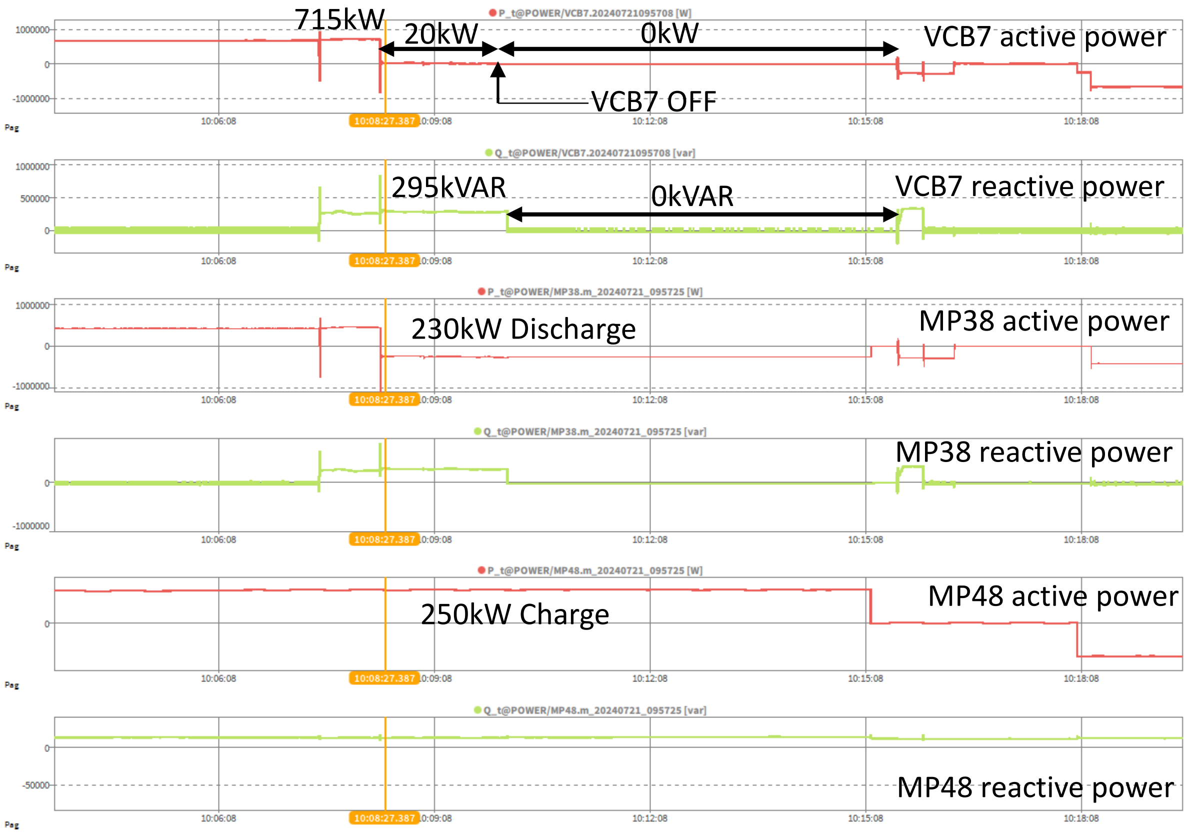
- Stop and Start maximum DER (SMA_BESS): There is not much change in frequency and voltage under grid-connected.

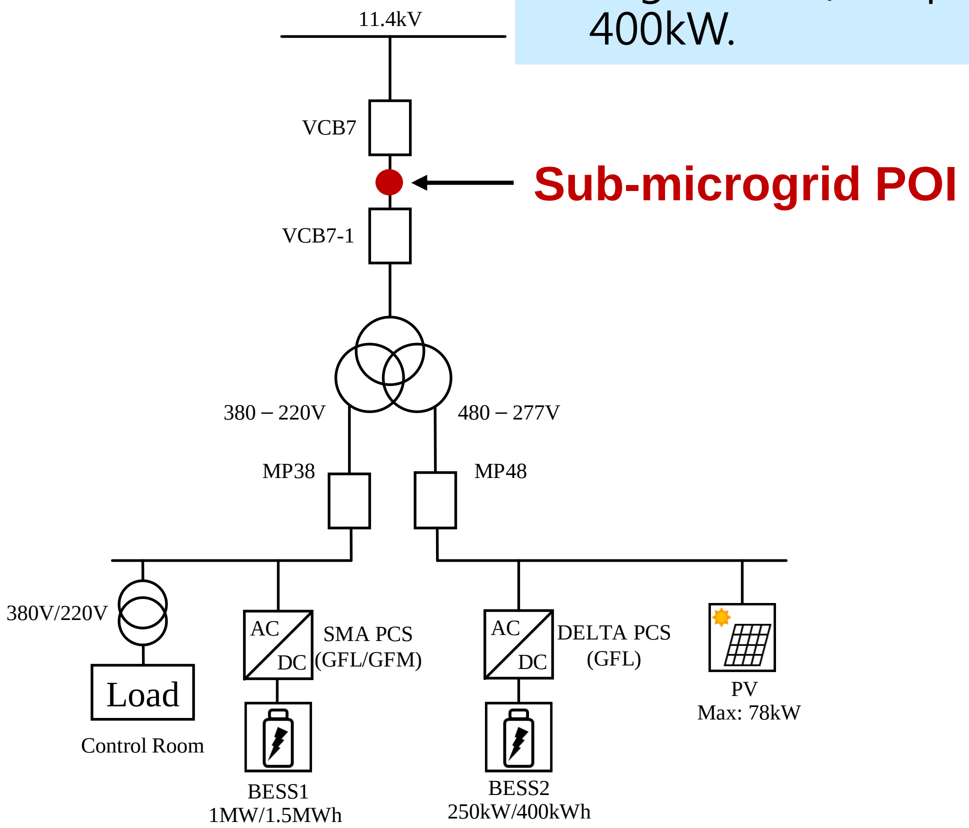
Measured point: VCB7

Shulin Microgrid- Planned Islanding(T2)

	VCB7 Sub Microgrid POI Power	Islanding Transition
1	0kW (actual value will be larger than 0kW)	Success
2	100kW	Success
3	300kW	Success
4	400kW	First time: Fail, Second time: Success
5	800kW	First time: Fail, Second time: Fail

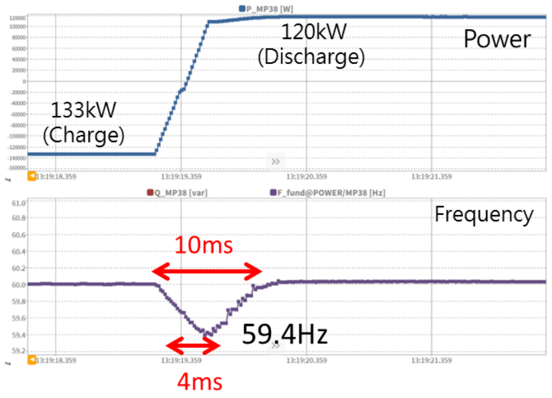
- Planned Islanding: according to IEEE2030.7, the VCB7 Sub Microgrid POI should be set to 0 (if applicable) before changing to islanded mode. We chose different POI active power values and found it will fail if POI active power is larger than (or equal to) 400kW.

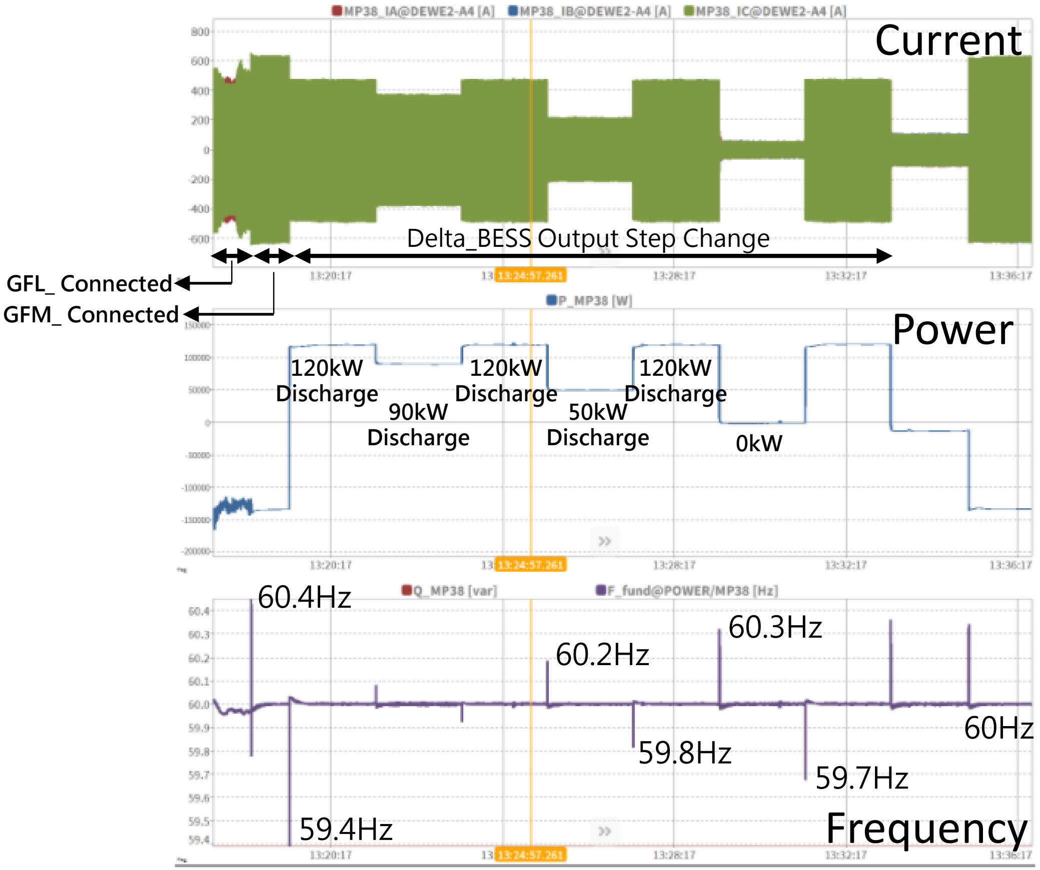


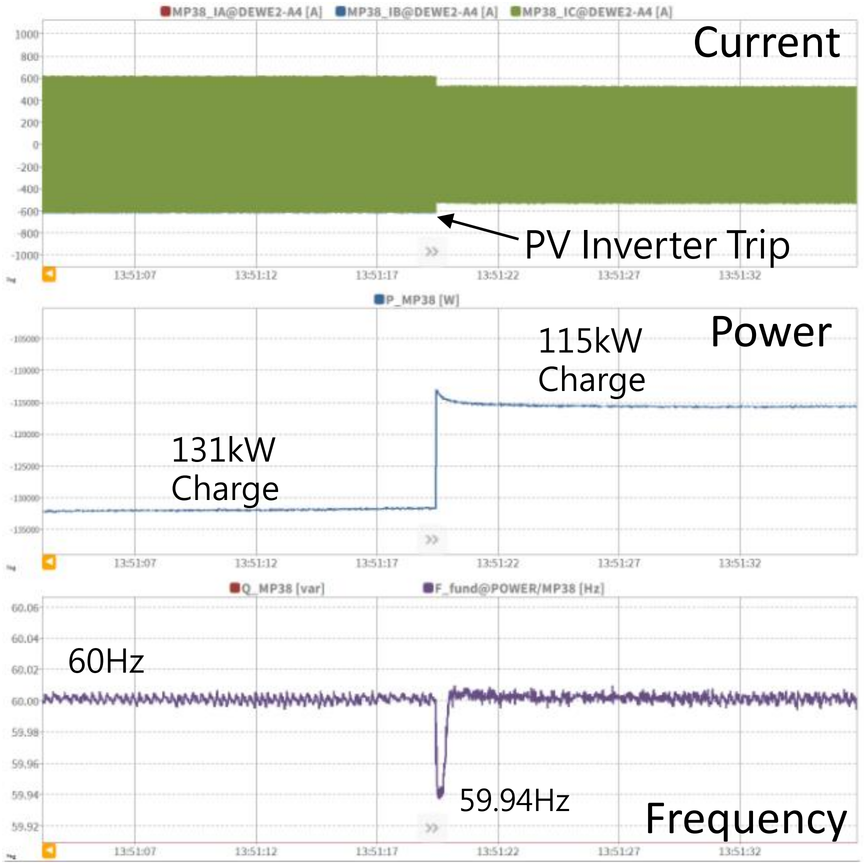


Shulin Microgrid- Steady State Islanded (SS2)

	Initial Conditions				Initiating Events
	SMA_BESS	Delta_BESS	78kW_PV	30kW Load	(1) Delta_BESS Output Step Change (2) PV Inverter Trip (3) Stop/Start Maximum Load
1	GFM mode	250kW GFL mode Discharge	ON	ON	
2	GFM mode	250kW GFL mode Charge	ON	ON	





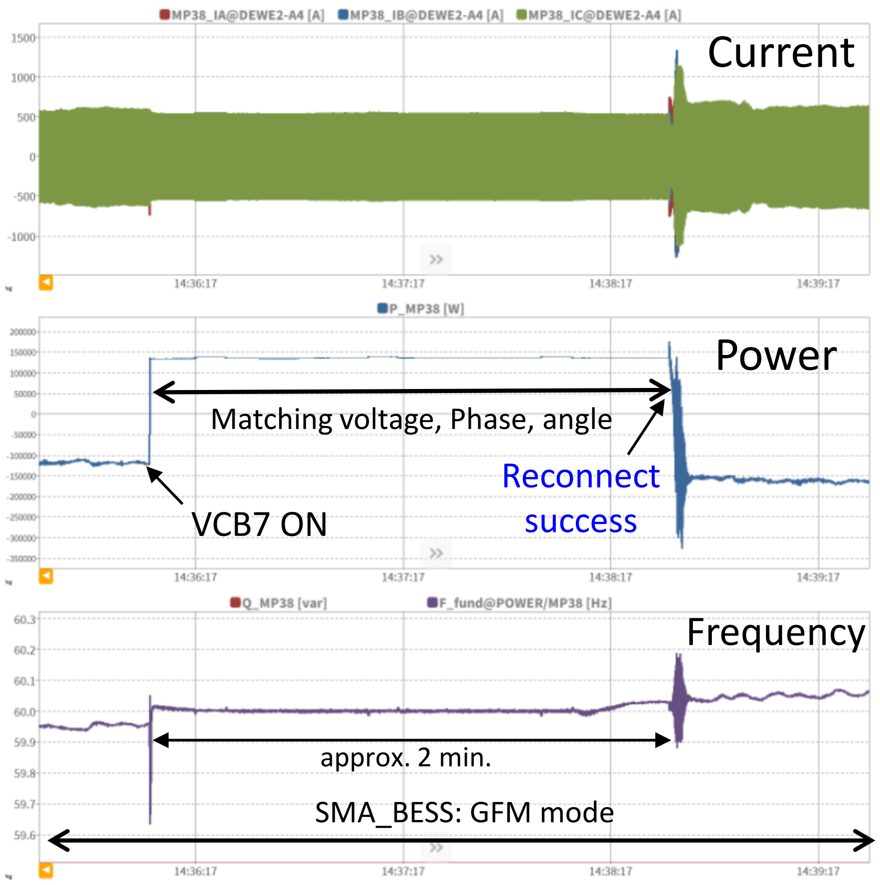


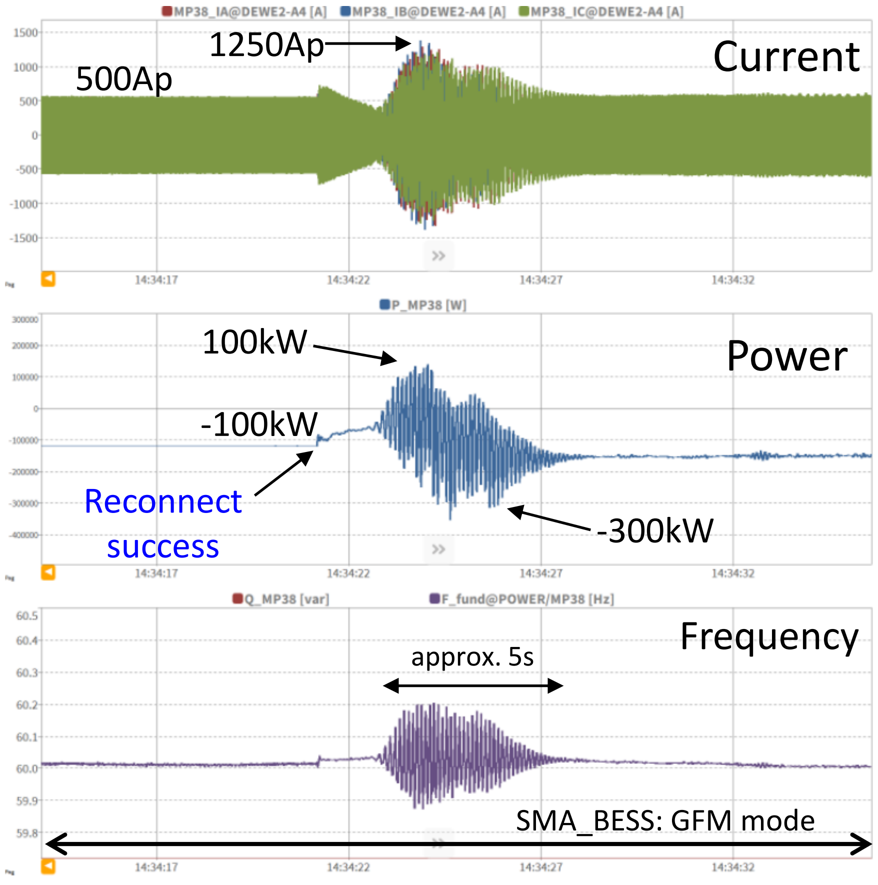
Measured point: MP38

- When a disturbance occurs, the GFM PCS output frequency will change accordingly. The output frequency can return to the steady-state value of 60Hz after a transient change of about 10ms. On the other hand, the SMA PCS has the droop control function.

Shulin Microgrid- Reconnect(T3)

	Initial Conditions				Initiating Events
	SMA_BESS	Delta_BESS	78kW_PV	30kW Load	Reconnect to the main grid
1	GFM mode	250kW GFL mode Discharge	ON	ON	
2	GFM mode	250kW GFL mode Charge	ON	ON	



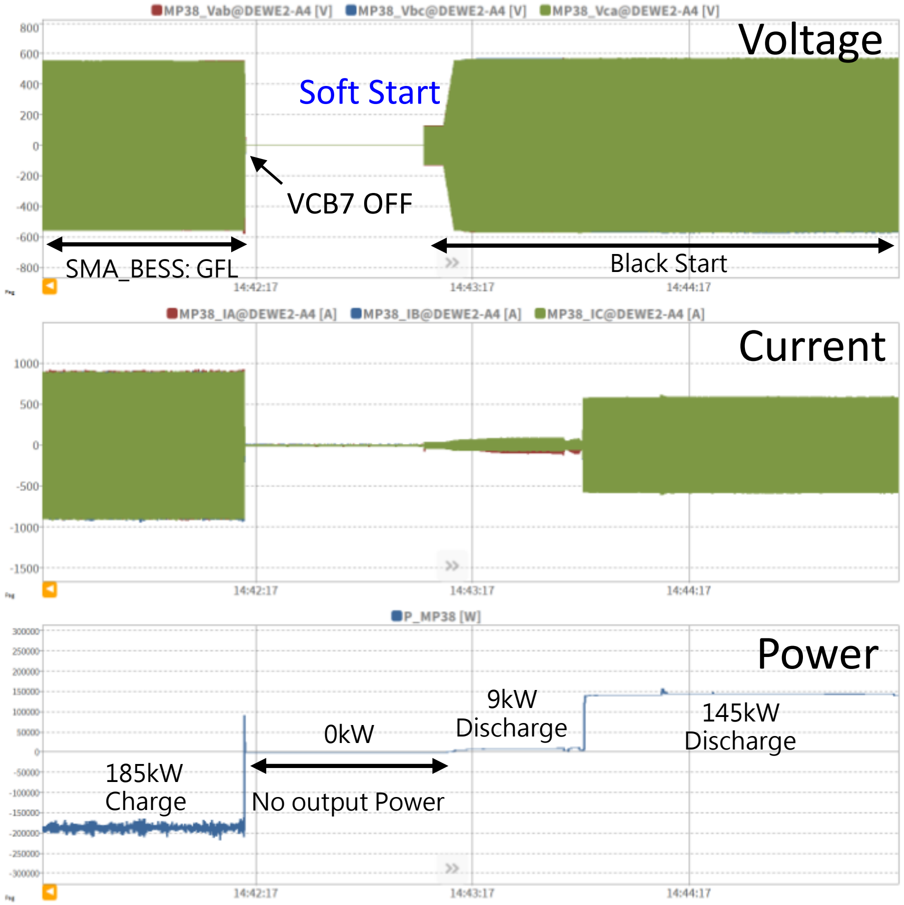


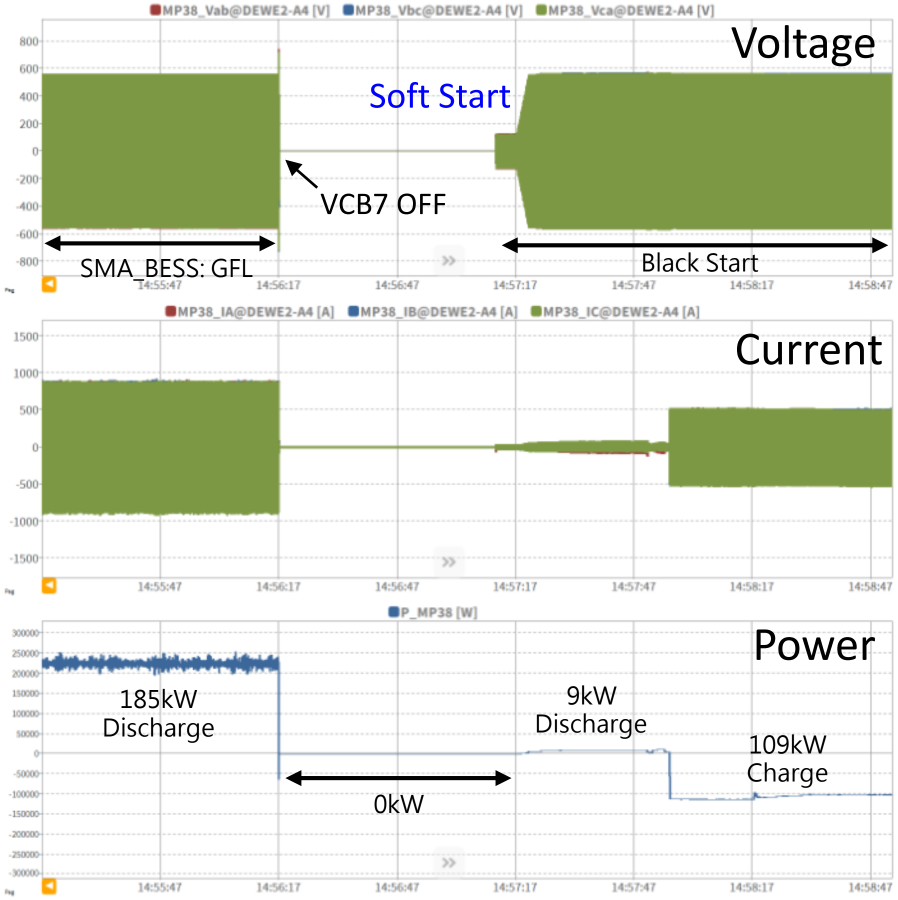
Measured point: MP38

- VCB7 microgrid is reconnected to the grid after about 2 minutes. When reconnecting to the grid, a large inrush current will occur, with the power changing range: +/-200kW and the frequency changing range: 59.9Hz~60.2Hz.

Shulin Microgrid- Unplanned Islanding(T1) and Black Start (T4)

	Initial Conditions				Initiating Events
	SMA_BESS	Delta_BESS	78kW_PV	30kW Load	1. Unplanned Islanding 2. Black Start
1	400kW GFL mode Charge	250kW GFL mode Charge	ON	ON	
2	400kW GFL mode Discharge	250kW GFL mode Discharge	ON	ON	

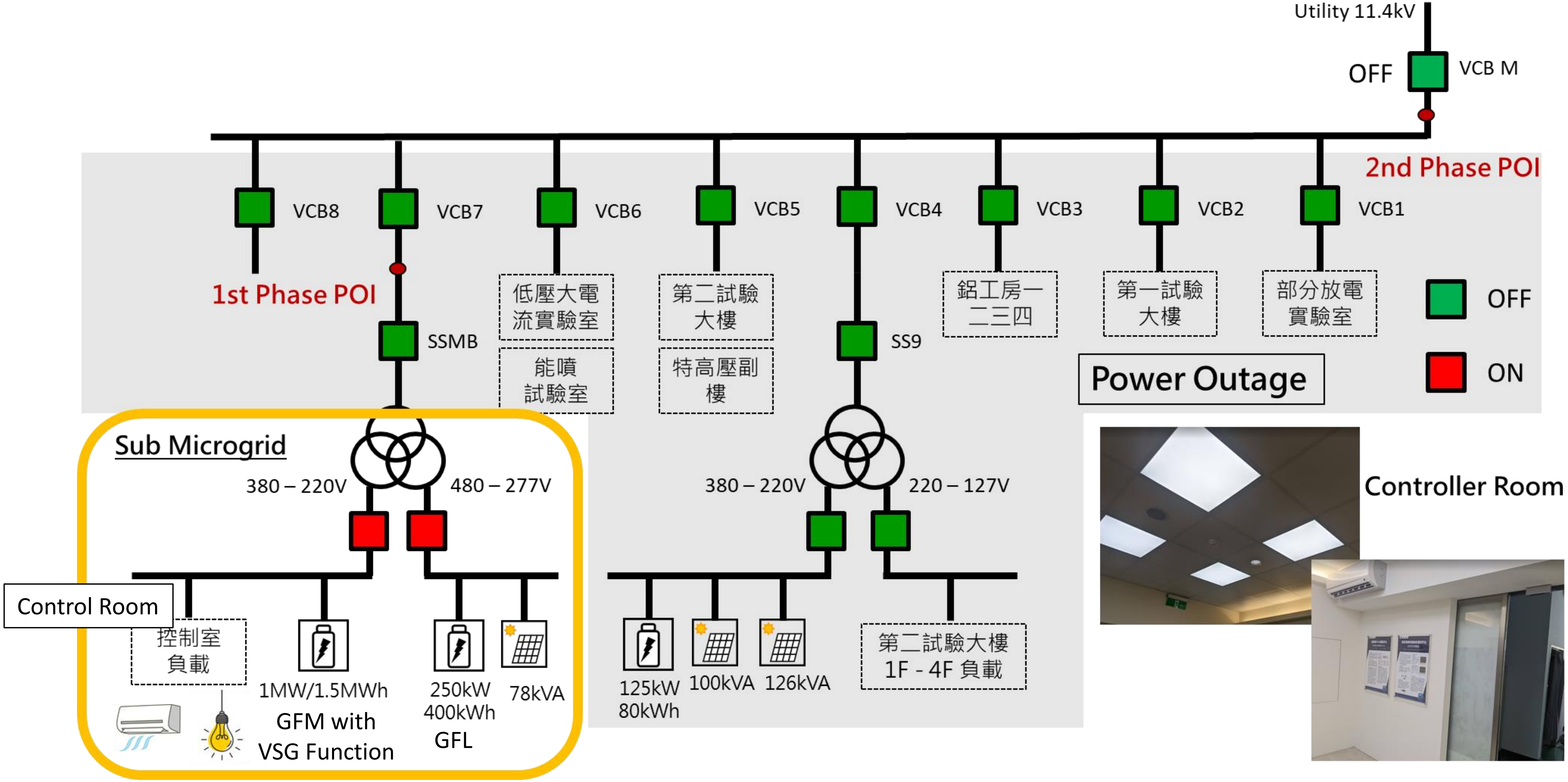




Measured point: MP38

- The figures show the waveforms of unplanned POI turn-off and black start. After turning off VCB7, SMA PCS stops operating and PV inverter is disconnected. After a while, SMA PCS is turned to GFM mode and do the black start.

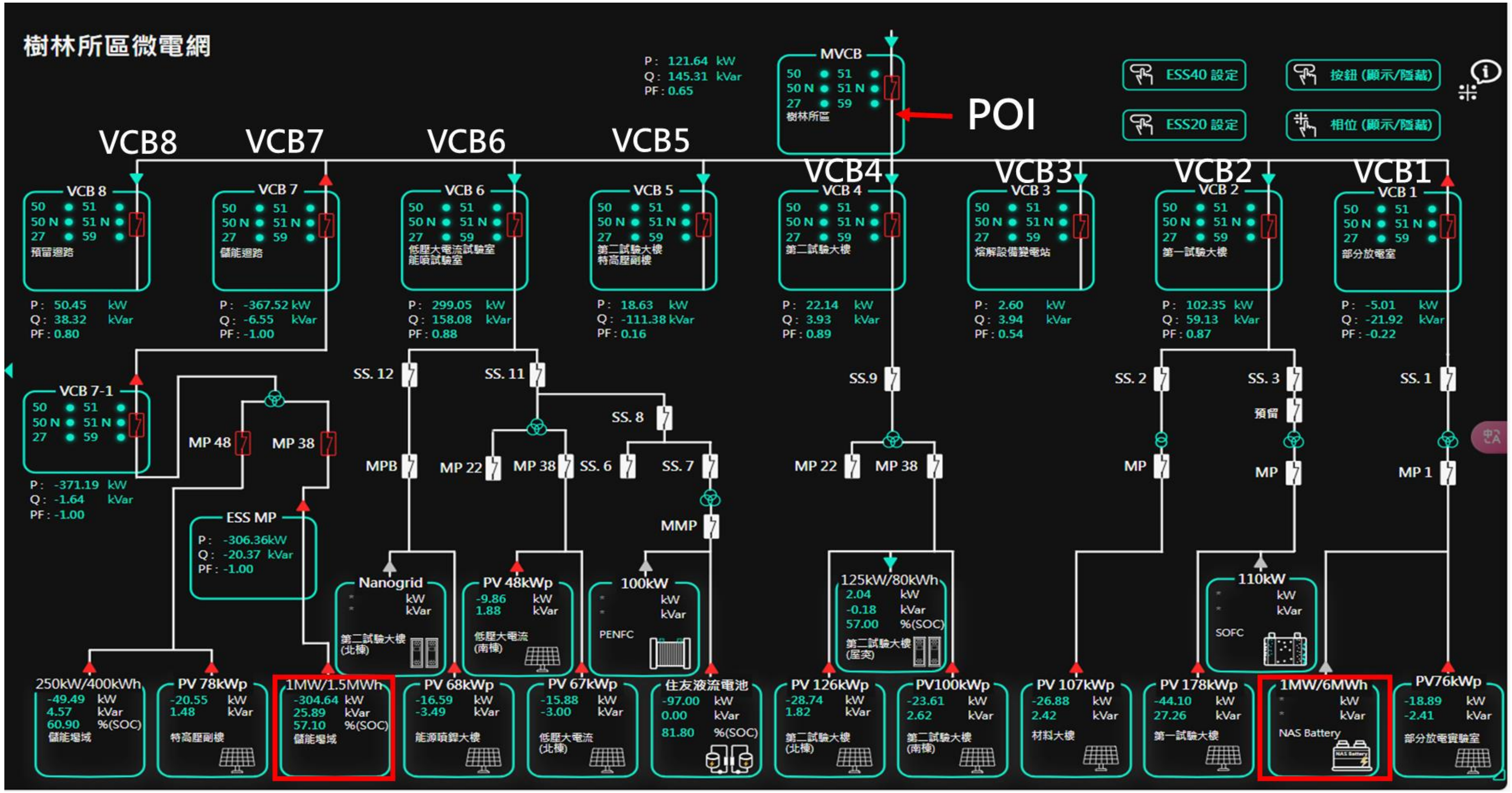
Shulin Microgrid-Islanded Operation



Controller Room

The Whole Campus Shulin Microgrid

- We have finished the tests (4 transition function tests and 2 steady state functions)
- In the future, we will (1) do two VSGs coordinated operation, (2) one VSG trips, (3) one VSG turns on, (4) suddenly large load turns on/off, (5) suddenly PV turns on/off etc.



GFM with VSG Function

GFM with VSG Function

- ✓ Based on Shulin Microgrid, we can verify the functions of VSG and microgrid. Moreover, we can develop the testing procedures and standards.

Conclusion

- As the proportion of Renewable Energy gradually increases, inertia and stability will decrease. If the number of the grid following inverters exceeds 30%, the grid will become unstable.
- The grid forming inverter with VSG function can be used to strengthen the power stability.
- VSG is the key technology towards high renewable energy power system.
- By simulation and experimental tests, including small scale prototype and Shulin microgrid , we verify the benefits of using VSG in power grid.
- Many countries are developing standards of GFM or VSG. Therefore, Standard development of GFM or VSG is also very important for Taipower Company.

Thank You For Your Listening