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EnergyVille 2023 Symposium on Microgrids

KERI

Distributed Power System Research Center

Grid-Forming Inverter-based Distributed Control for Microgrids

Ph.D. Hyeongjun Yoo
Senior Researcher
Distributed Power System Research Center,
Smart Grid Research Division, KERI

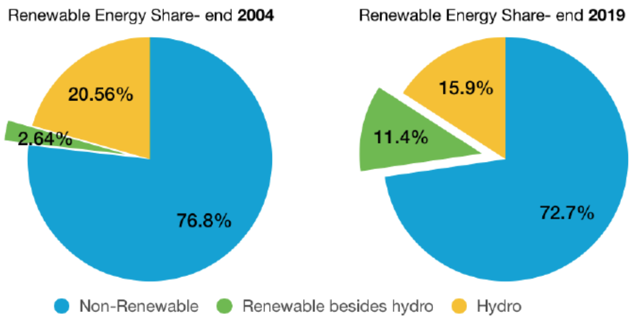
Outline

- Introduction
- GFM Inverter Control Strategy
- Distributed Control Strategy
- Experimental Results
- Conclusion

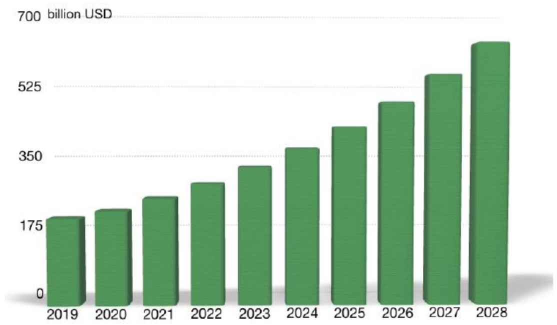
Introduction

*IBR: Inverter-Based Resources

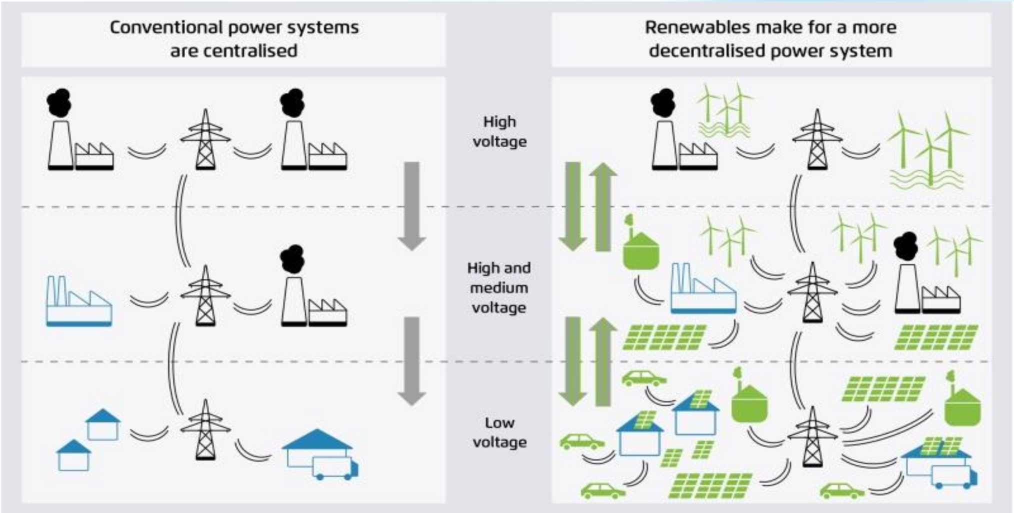
Power Grid Transformation

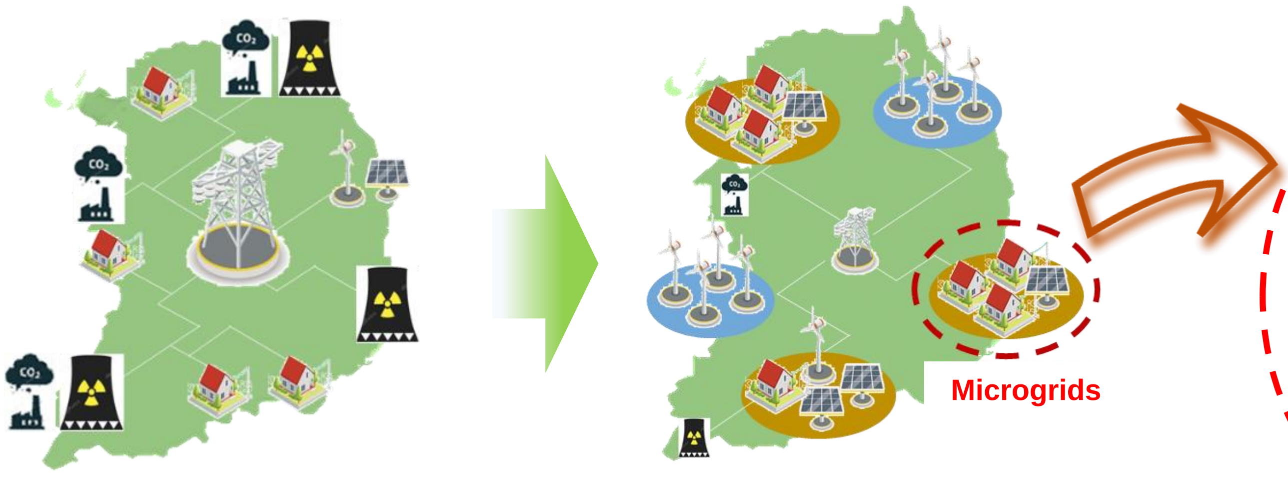


<Renewable energy share of global electricity production in 2004 vs 2019>



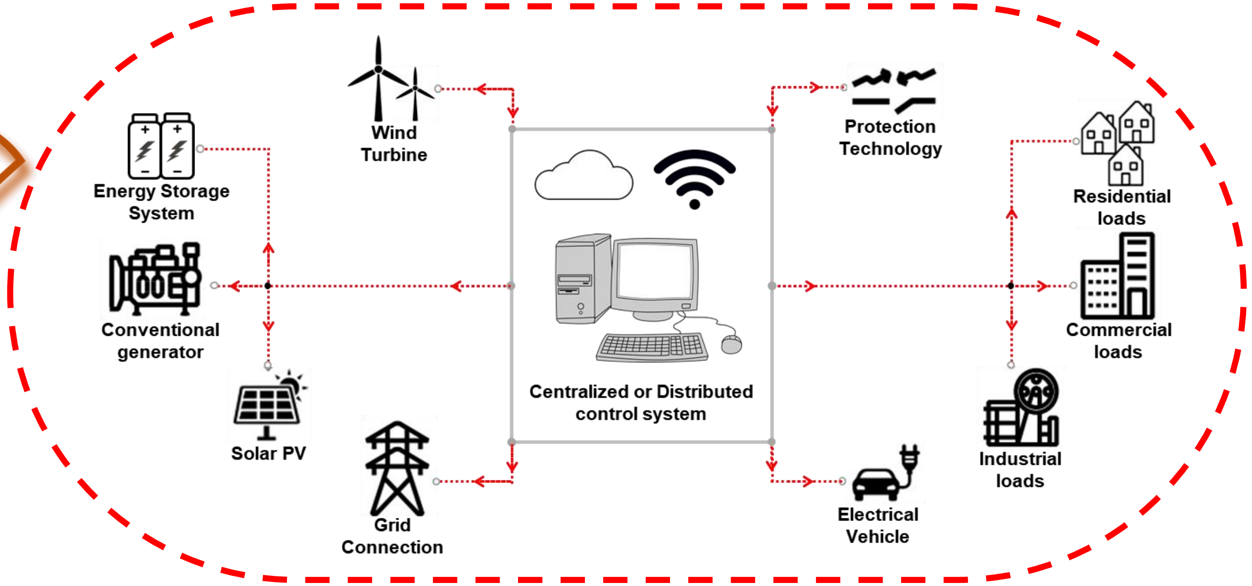
<Projected global DER market growth>





Present

Future



[Ref.] Grid Forming Inverter_EPRI Tutorial, 2022.

Challenges due to Increased IBRs (1)

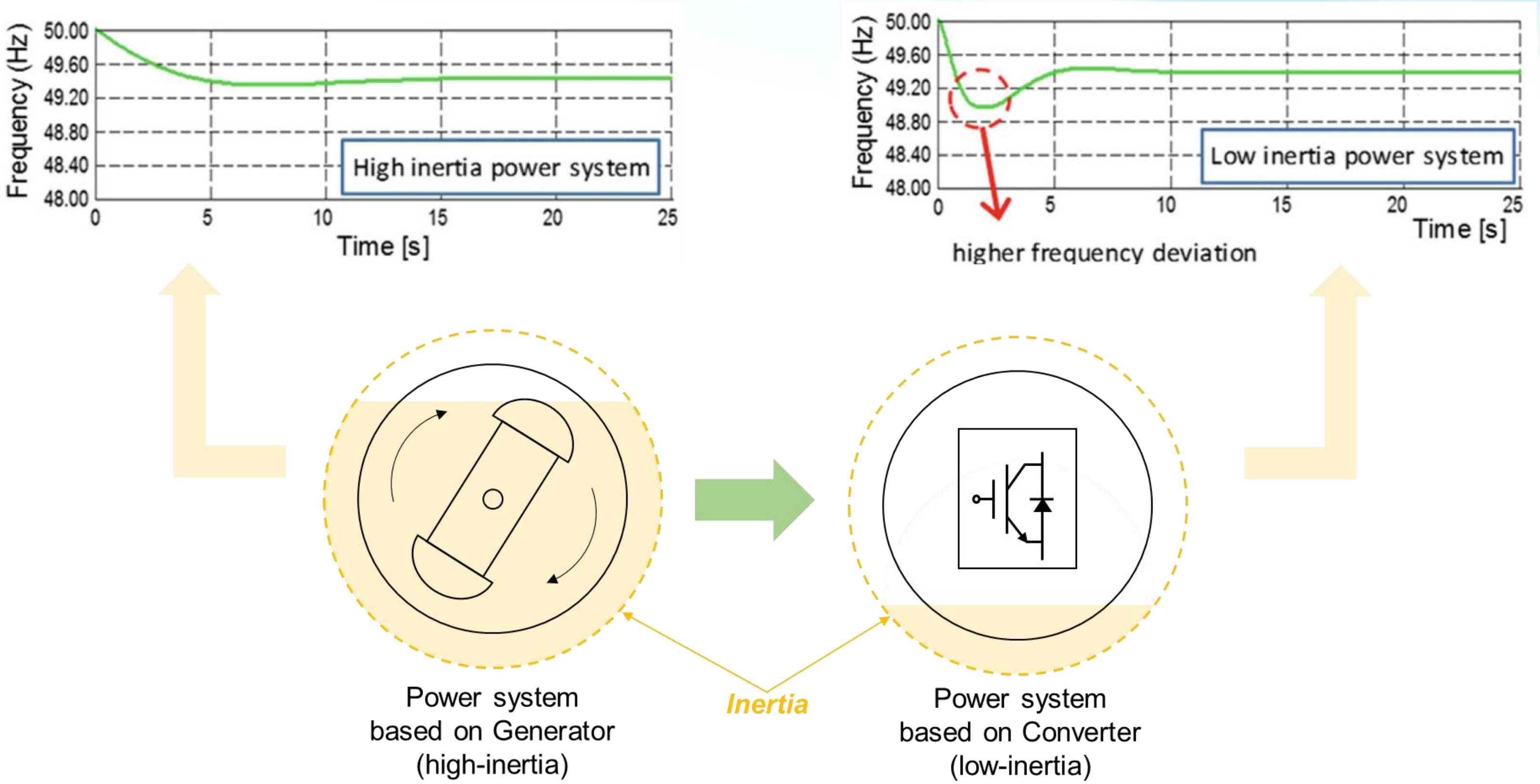
Frequency Stability Issues

Reduction in system inertia (Replacement of SG with IBR)

Reduced time to respond to frequency changes

Increased UFLS activation

Increased possibility of blackouts due to protective relay activation



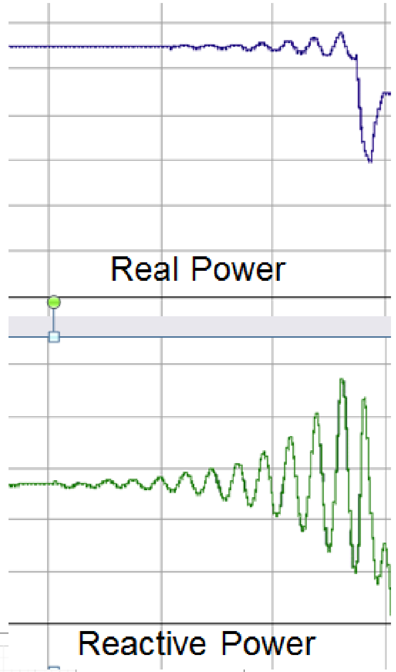
- ✓ In Ireland, Texas, and South Australia, where IBR penetration is high, frequency stability problems occur during certain times of the day.
- ✓ Small island power systems such as New Zealand and Hawaii already face low inertia-related challenges.

Challenges due to Increased IBRs (2)

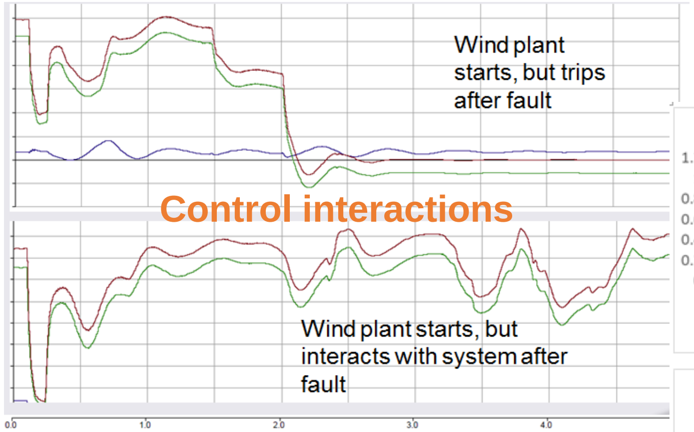
Stability Issues in Weak Grids

- ❖ Failure to ride through disturbances
- ❖ Converter control interactions
- ❖ Converter control instability
- ❖ Cycling between converter control modes
- ❖ Steady-state voltage collapse and power transfer

Control instability

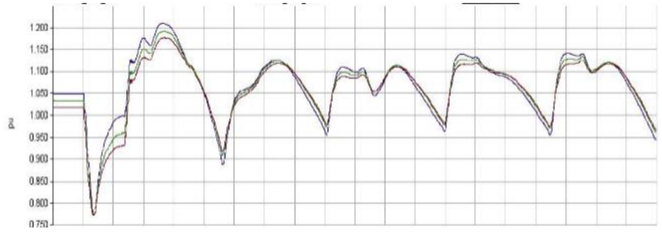


Failure to ride through

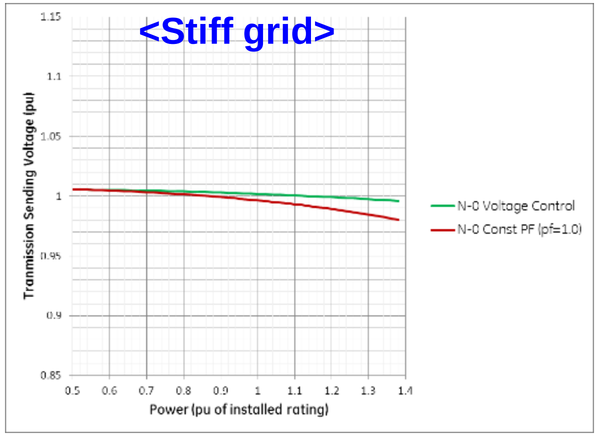


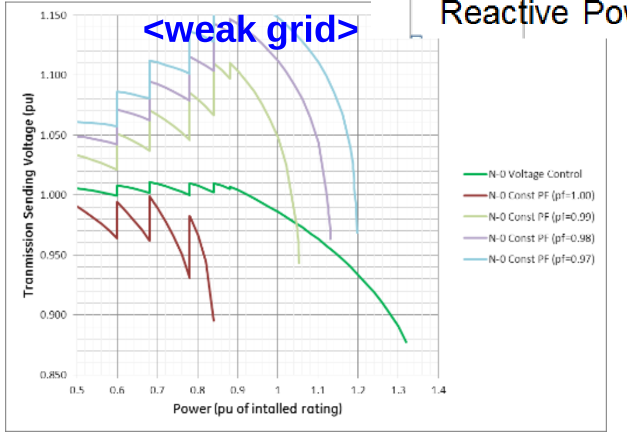
Unstable recovery due to network transfer limits

Voltage instability due to cycling



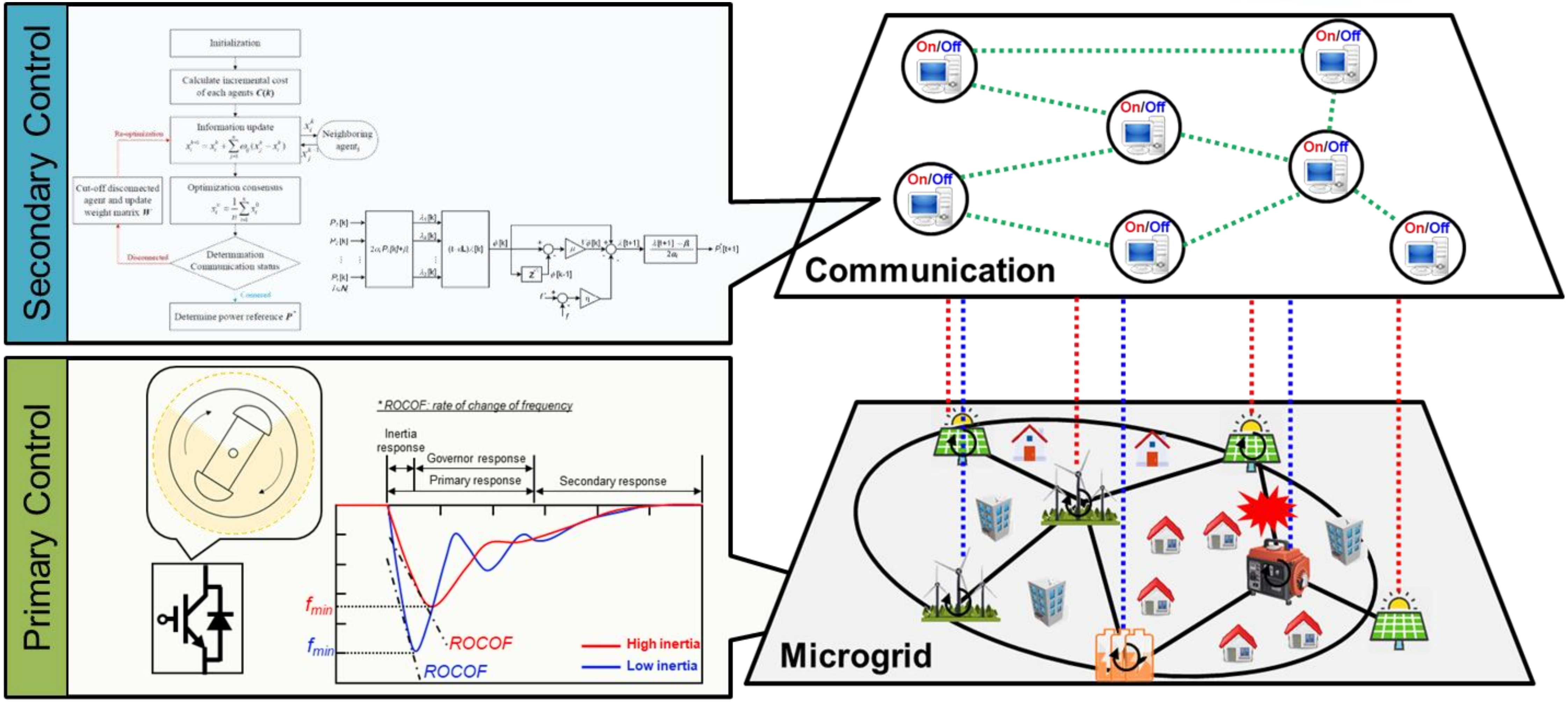
Quasi-steady state voltage collapse





Research Objective

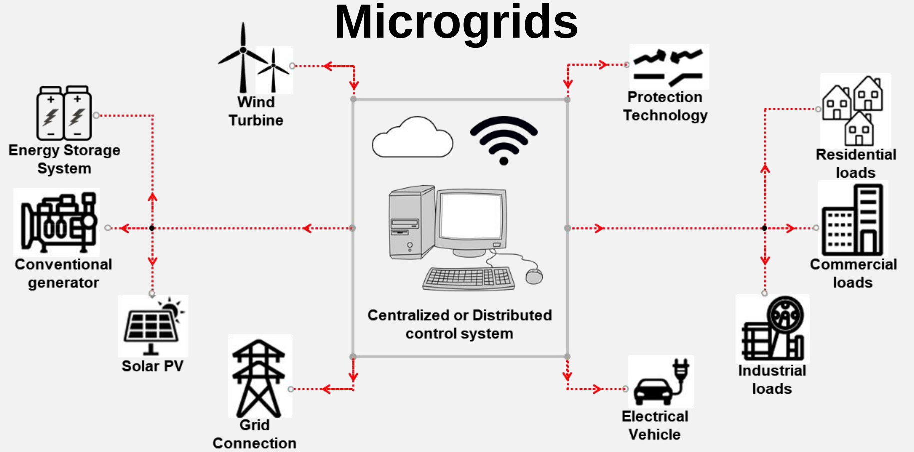
- GFM-based virtual inertia control technology – improving frequency stability
- Distributed operation – Operation system without Central EMS



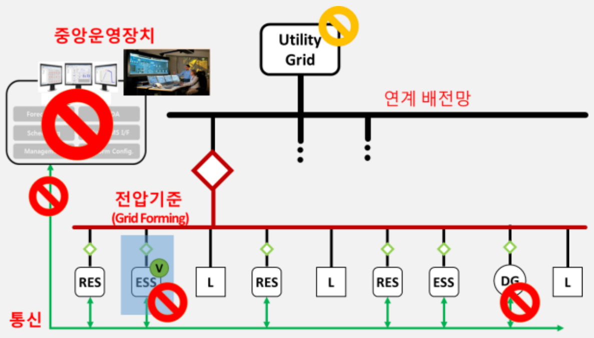
Overview

Development of GFM-based inverter and distributed operation technology for IBR to improve stability and resiliency

Microgrids

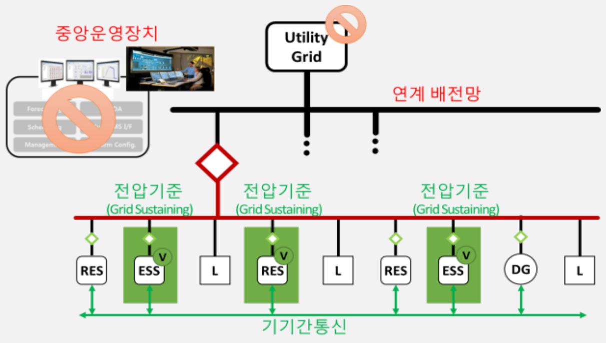


Conventional Microgrids



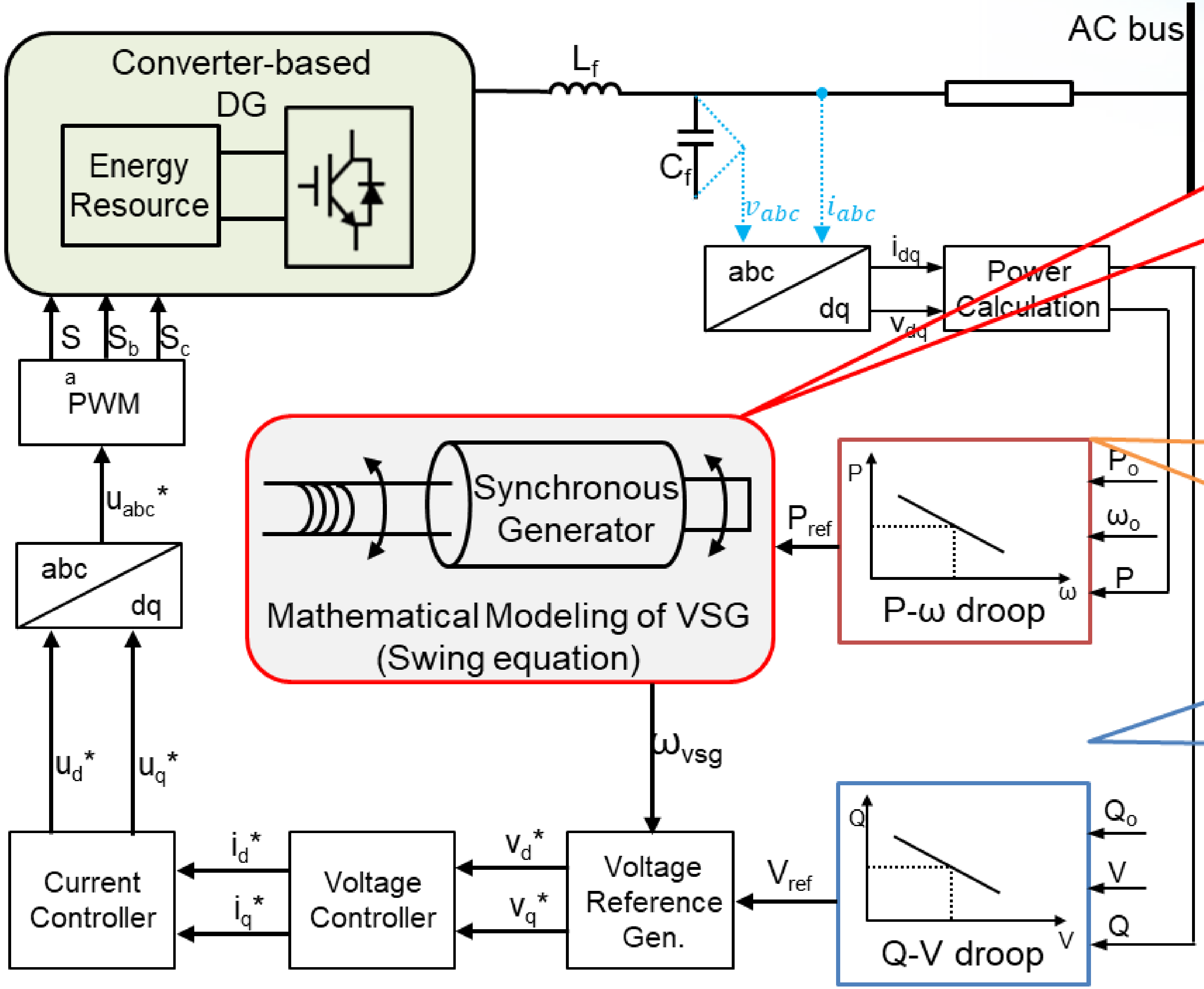
- Centralized EMS
- Single grid-forming source(e.g. diesel, CVCF ESS)
- Grid-following inverter-based resources
- Requires complex infrastructure and communication
- It has a single point of failure, as a malfunction in the central controller can disrupt the entire system

Advanced Microgrid(Proposed technology)



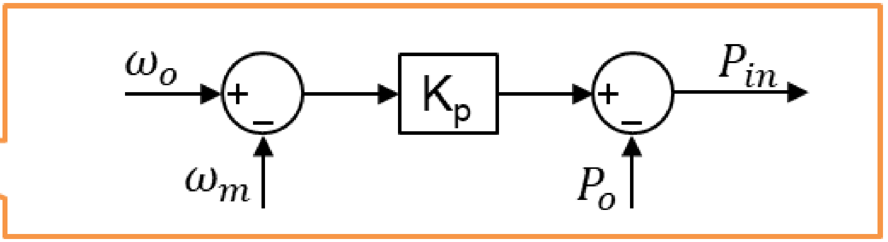
- Distributed Operation without Centralized EMS
- Multiple grid-forming inverter-based resources
- More flexibility and scalability
- More reliable as there is no single point of failure
- Lower initial setup and operational costs

GFM-based VSG for ESS

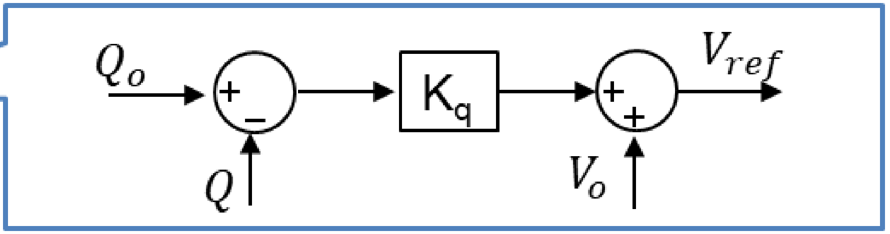


$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g)$$

ω_m: virtual rotor angular frequency
ω_g: output voltage angular frequency
J: virtual inertia
D: damping factor

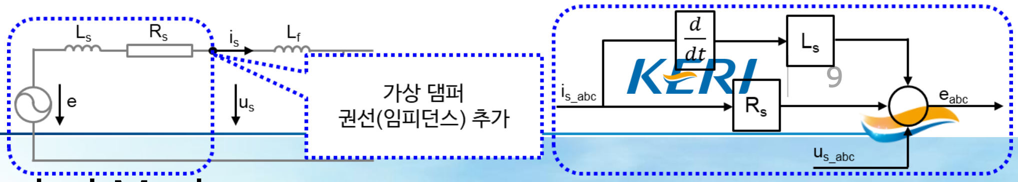


ω_o: nominal angular frequency
P_o: set value of active power
K_p: droop coef.



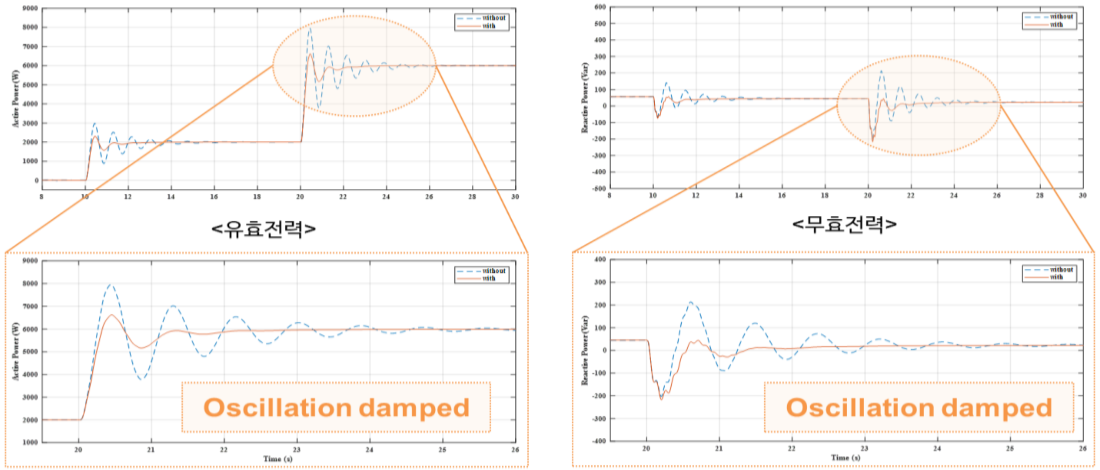
Q_o: set value of reactive power
K_q: damping factor
V_o: nominal voltage

Test of GFM-based VSG(H/W)



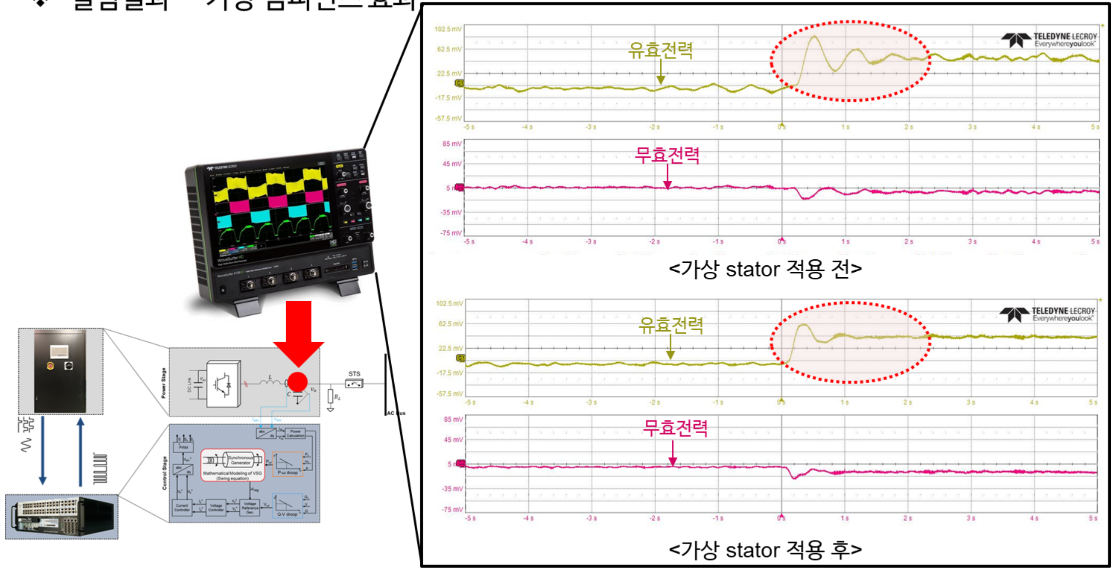
❖ Grid-connected Mode

▪ PQ control



<유효전력> <무효전력>

❖ 실험결과 – 가상 임피던스 효과

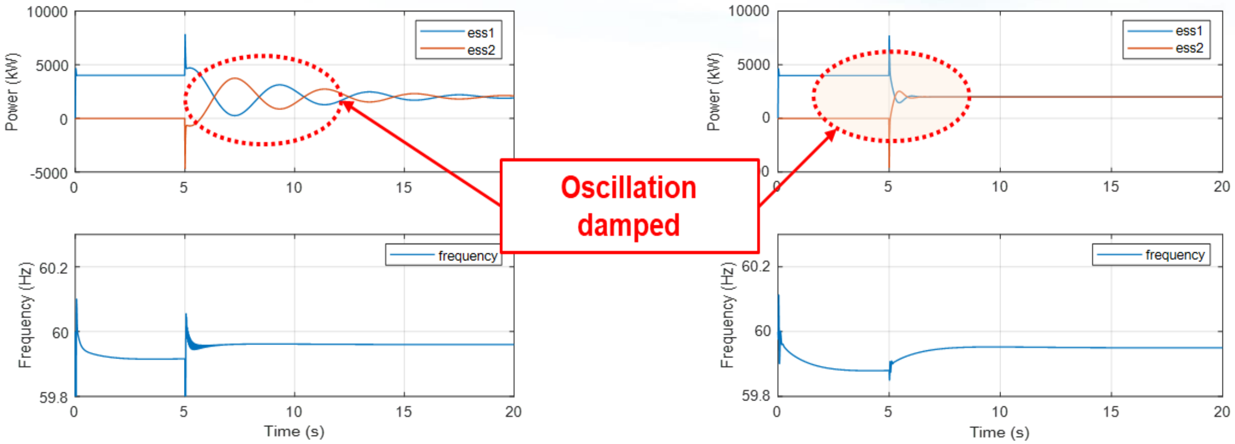


<가상 stator 적용 전>

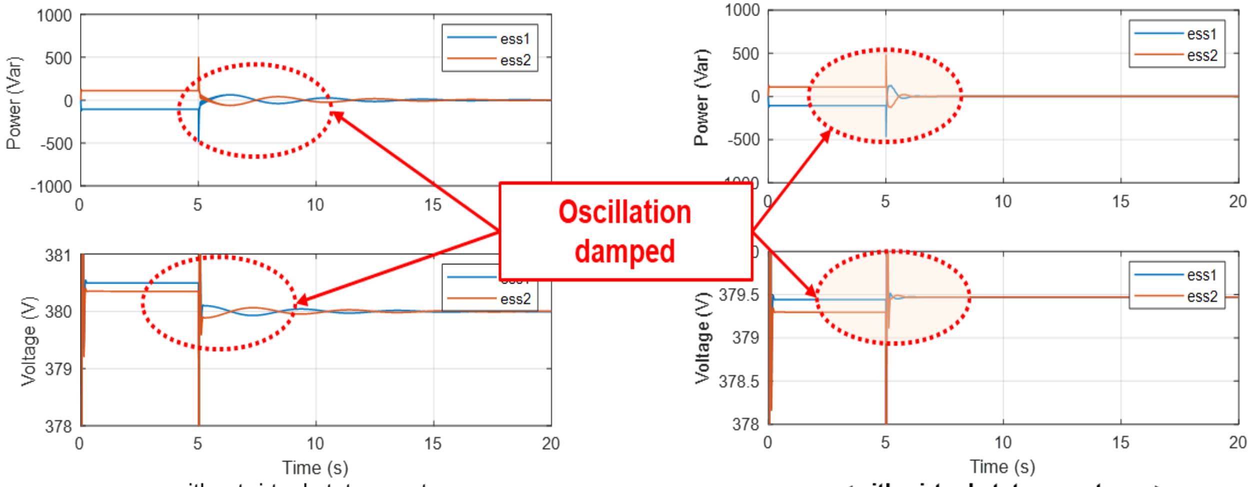
<가상 stator 적용 후>

❖ Islanded Mode

▪ Voltage & Frequency control



<without virtual stator reactance> **<with virtual stator reactance>**

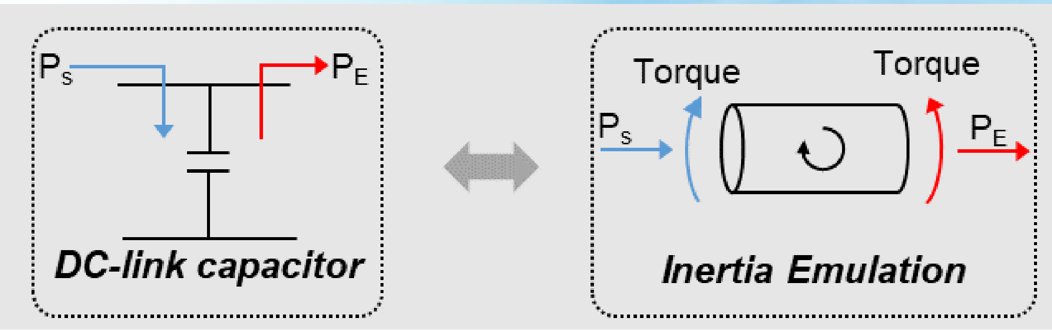


<without virtual stator reactance> **<with virtual stator reactance>**

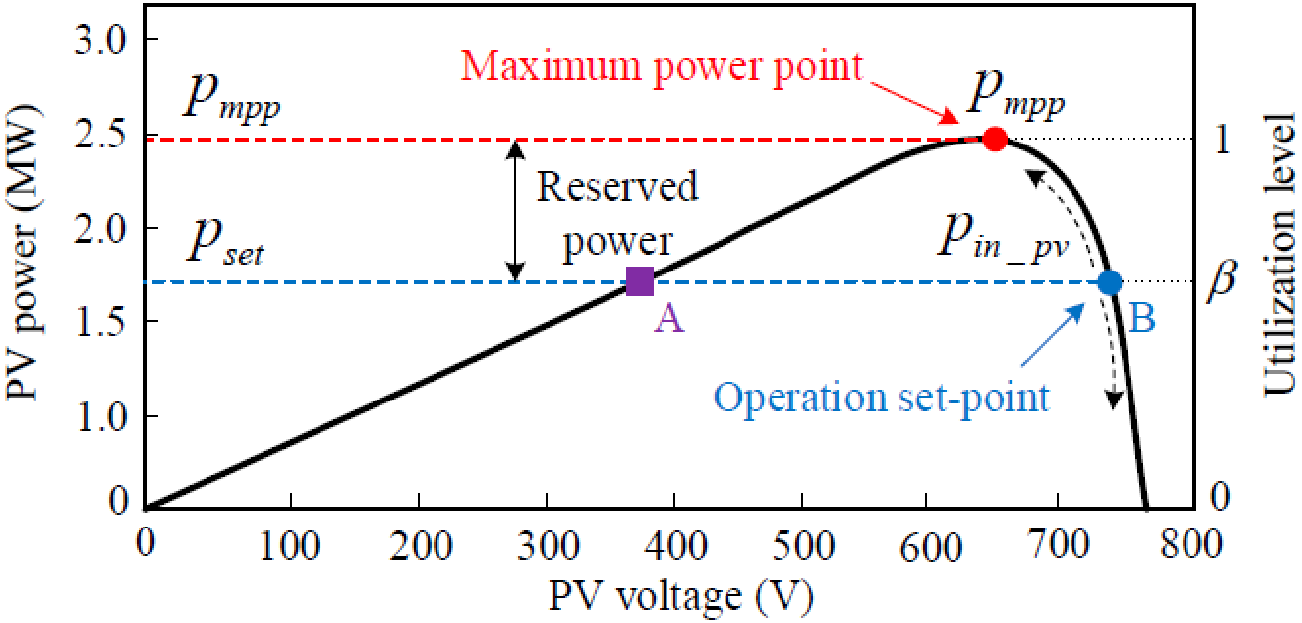
GFM Control Strategy for PV-Inverter

❖ Classification of control strategy for PV-inverter

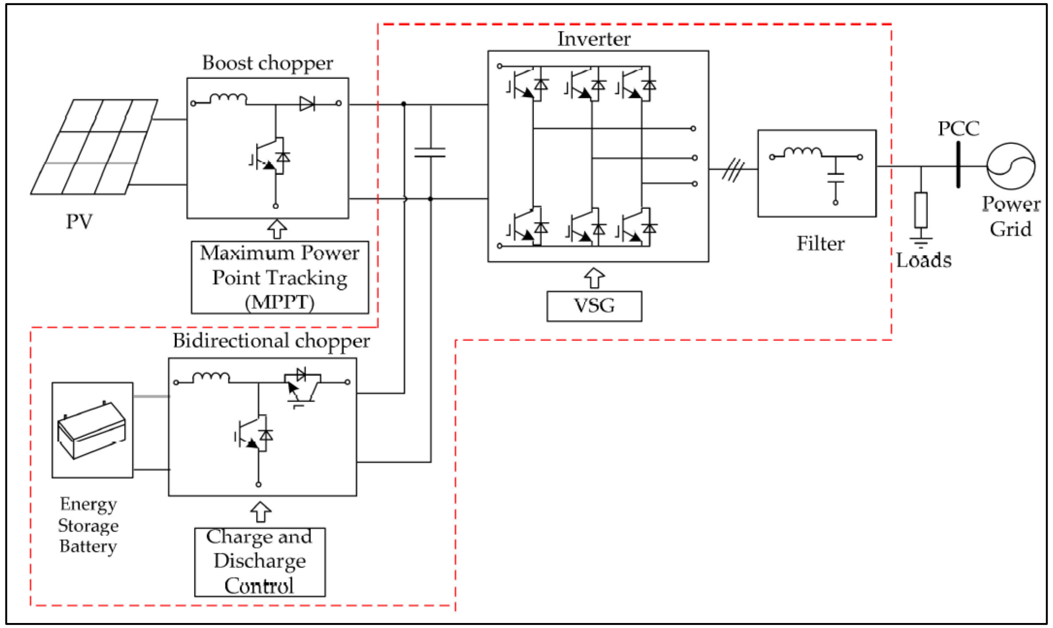
- DC link capacitor
- Energy storage system
- MPPT curve



<Virtual inertia using cap.>



<Virtual inertia using MPP characteristic>

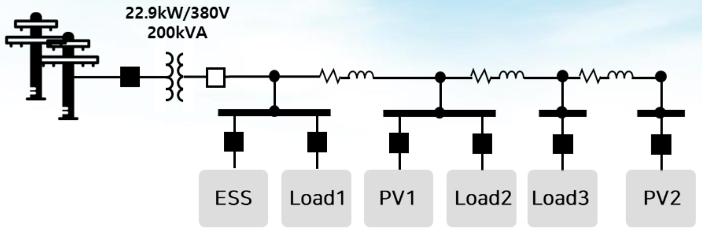


<Virtual inertia using additional ESS>

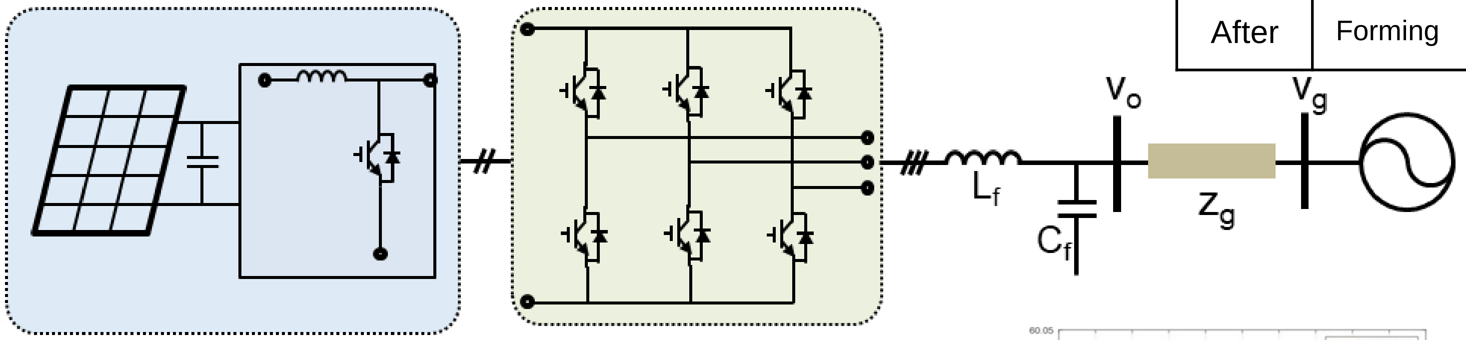
GFM-based PV-VSG

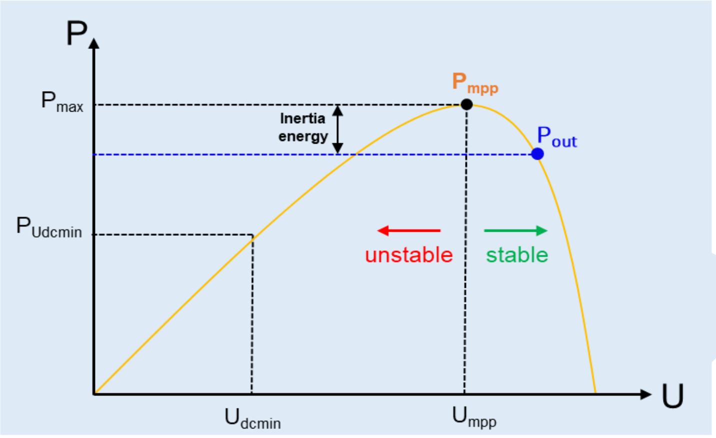
Virtual Inertia Technology for PV system

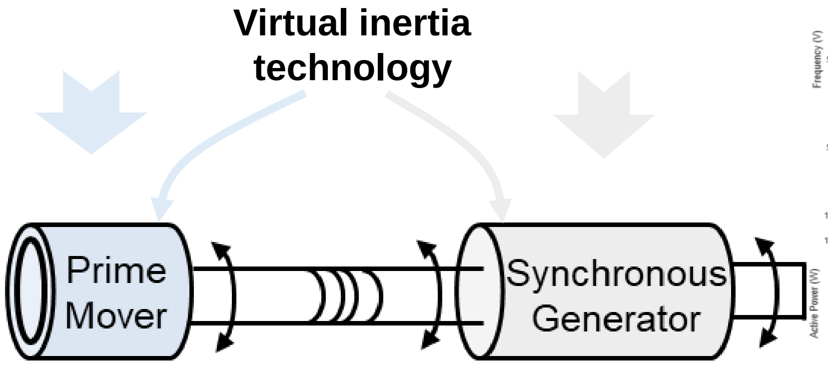
- PV system – DC/DC converter + AC/DC converter
    - DC/DC converter: Prime mover
    - AC/DC converter: Synchronous generator

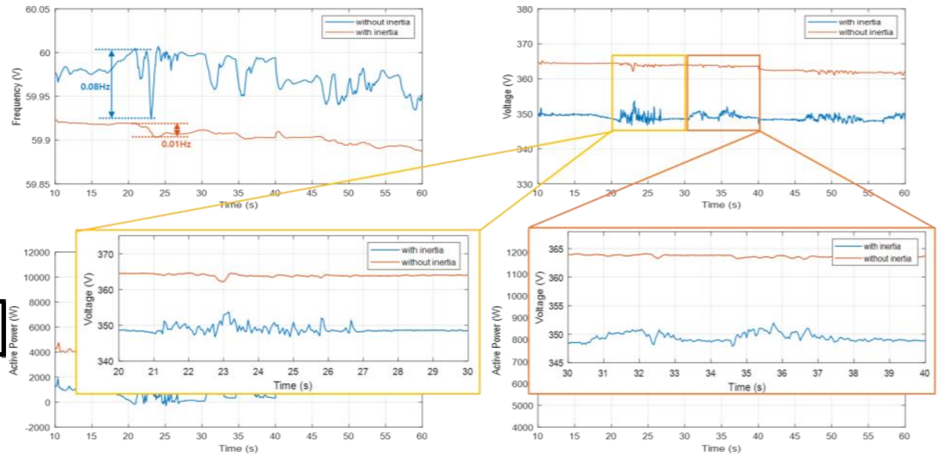


Before	Forming	MPPT	MPPT
After	Forming	Forming	Forming





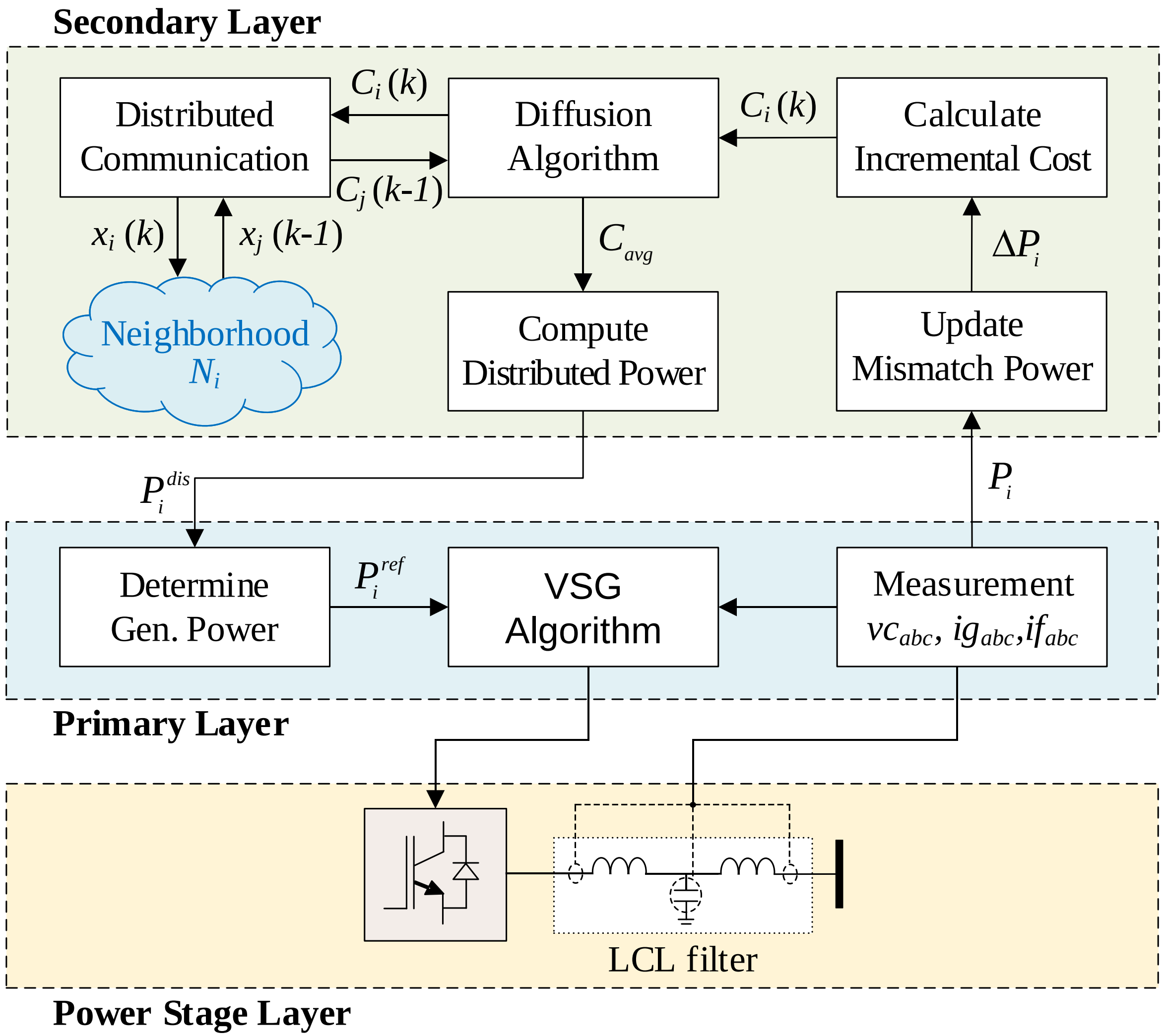


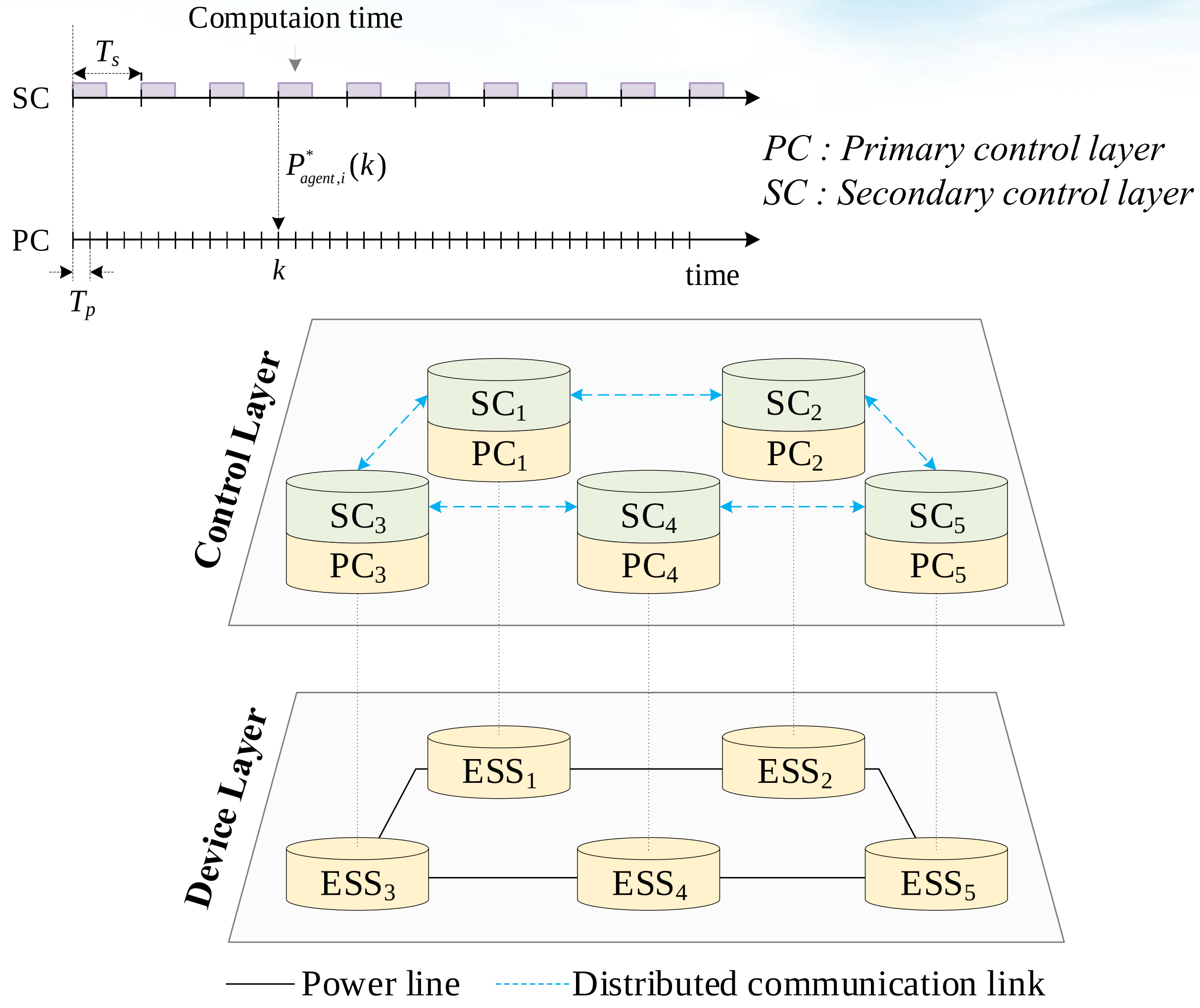


<concept of virtual inertia for pv system>

Structure of Distributed Operation Algorithm

Hierarchical Control for MG





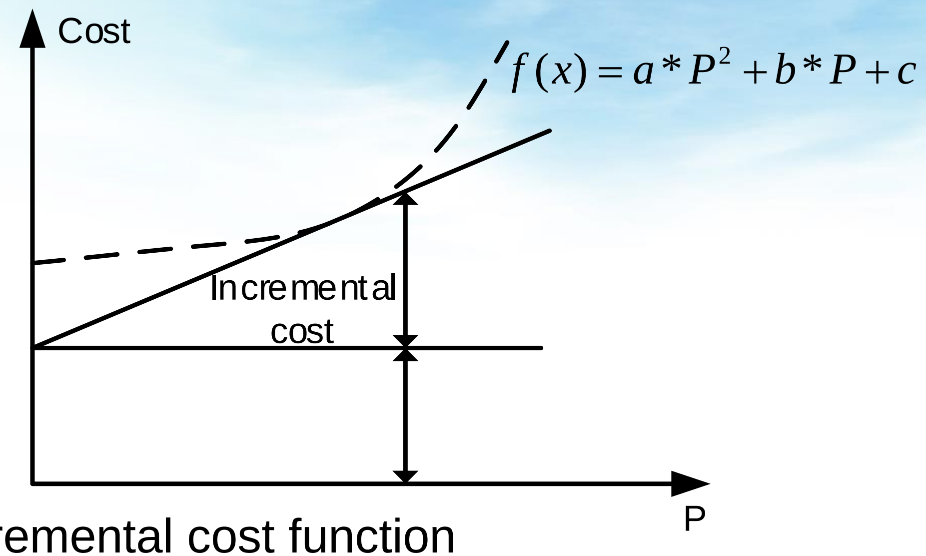
<Distributed control layer>

Distributed Operation Algorithm

❖ Distributed control algorithm based on diffusion algorithm

- Cost function

$$C_e(P_e^{ESS}) = \alpha_e^{ESS}(P_e^{ESS} + 3P_{e,\max}^{ESS} \cdot (DOD))^2 + \beta_e^{ESS}(P_e^{ESS} + 3P_{e,\max}^{ESS} \cdot (DOD)) + \gamma_e^{ESS}$$

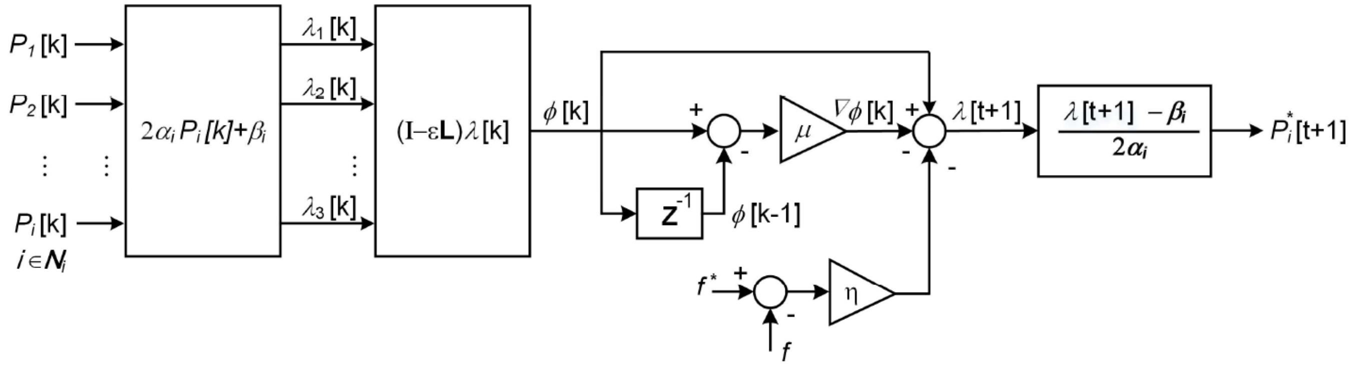


- Diffusion algorithm considering frequency restoration

$$\begin{cases} \Phi[k] = (I - \varepsilon L)\lambda[k] \\ \lambda[k+1] = \Phi[k] - \mu\nabla\Phi_v[k] - \eta(f^* - f) \end{cases}$$

- Incremental cost function

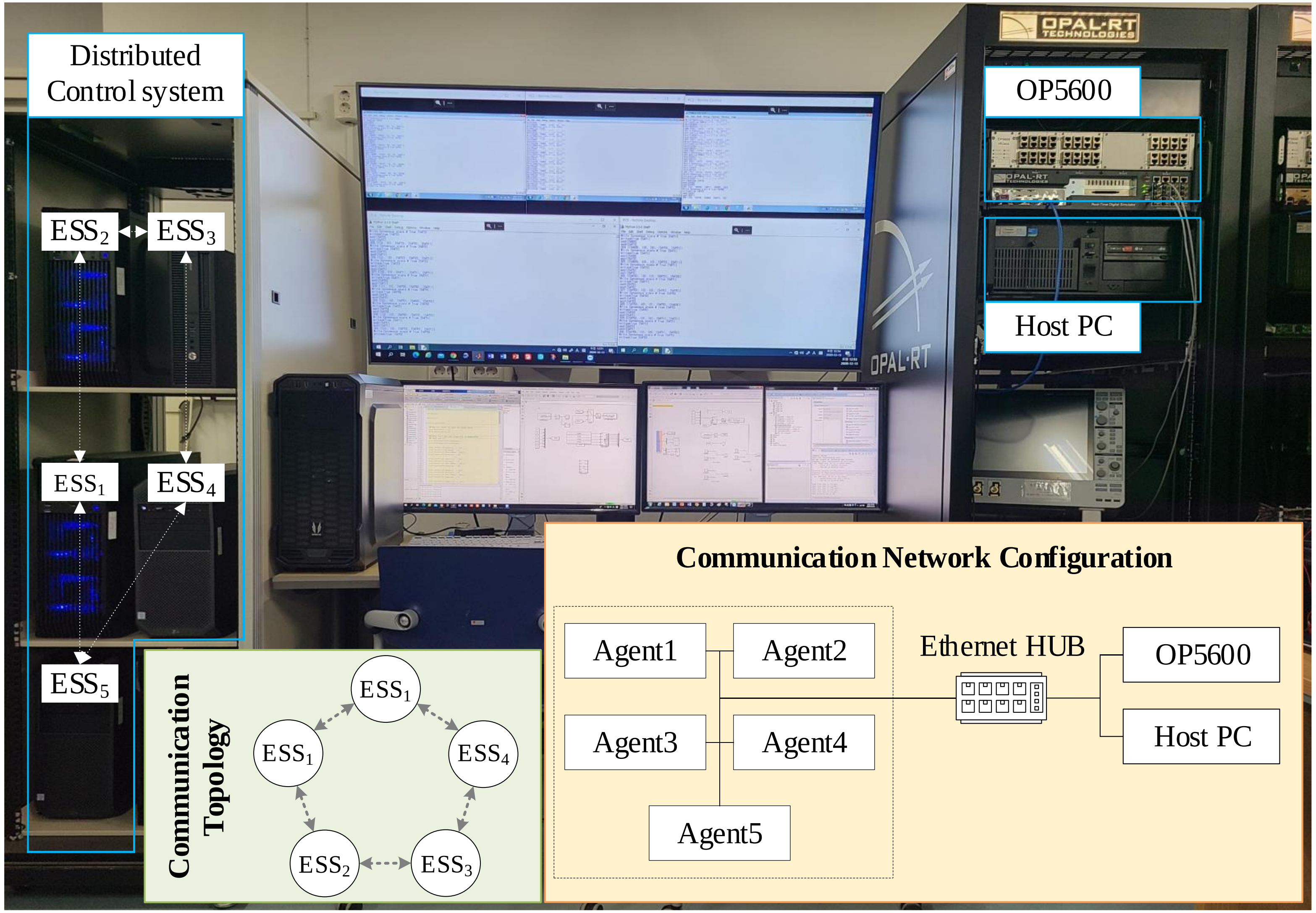
$$\frac{\partial C_e(P_e^{ESS})}{\partial P_e^{ESS}} = 2\alpha_e^{ESS}(P_e^{ESS} + 3P_{e,\max}^{ESS} \cdot (DOD)) + \beta_e^{ESS}$$



- P_e : *Electrical Power*
- $P_{e,max}$: *Max. Power*
- α, β, γ: *battery coeficient*
- DOD : Depth of discharge

HIL-based Test Environment

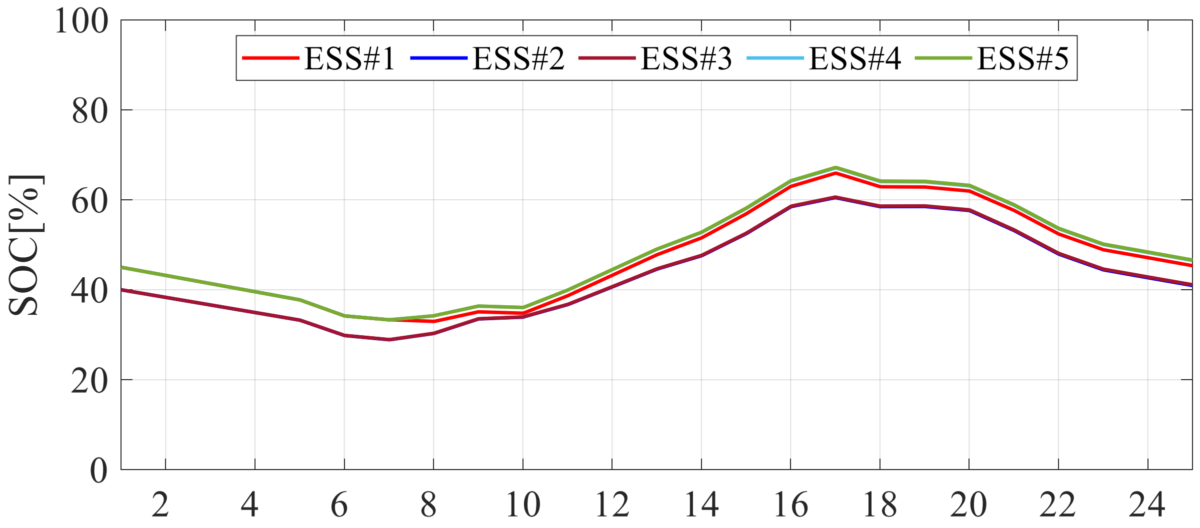
❖ Distributed control technology for microgrids



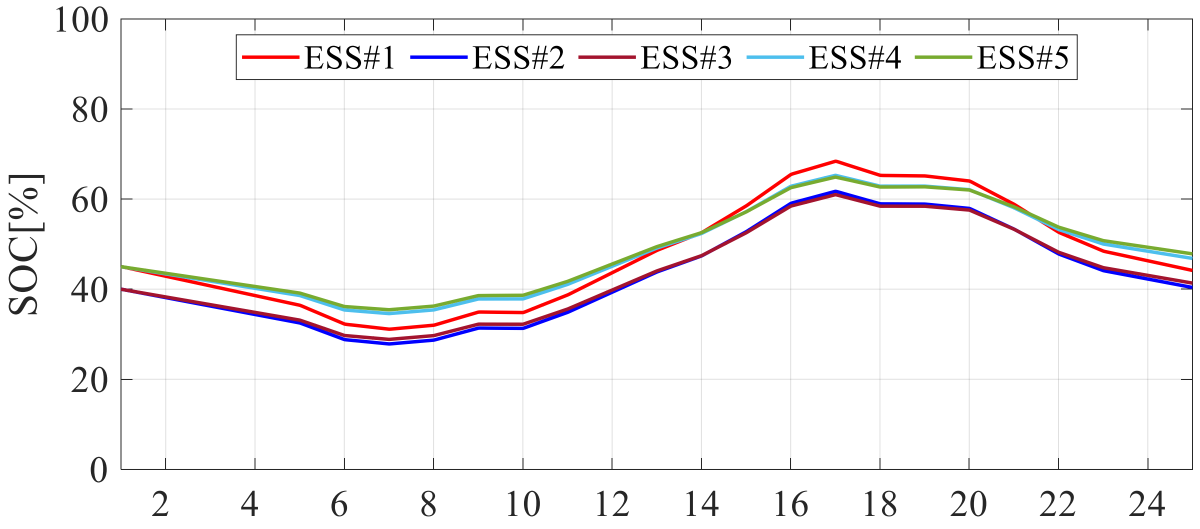
Agent	A_i ($/KW2H)	β_i ($/kWh)	γ_i ($/kWh)
ESS_1	0.001562	3.95	213
ESS_2	0.00174	3.99	234
ESS_3	0.00186	4.02	246
ESS_4	0.00196	4.05	270
ESS_5	0.00208	4.09	283

Symbol	PARAMETER	Value
T_s	Sampling time	50 μs
T_{com}	Communication time	0.1 s
T_{EMS}	EMS command time	30 s
k_{sp},k_{si}	PI gains of secondary controller	0.01,6

Centralized vs distributed control



(a) Centralized



(b) Distributed

<ESS SOC>

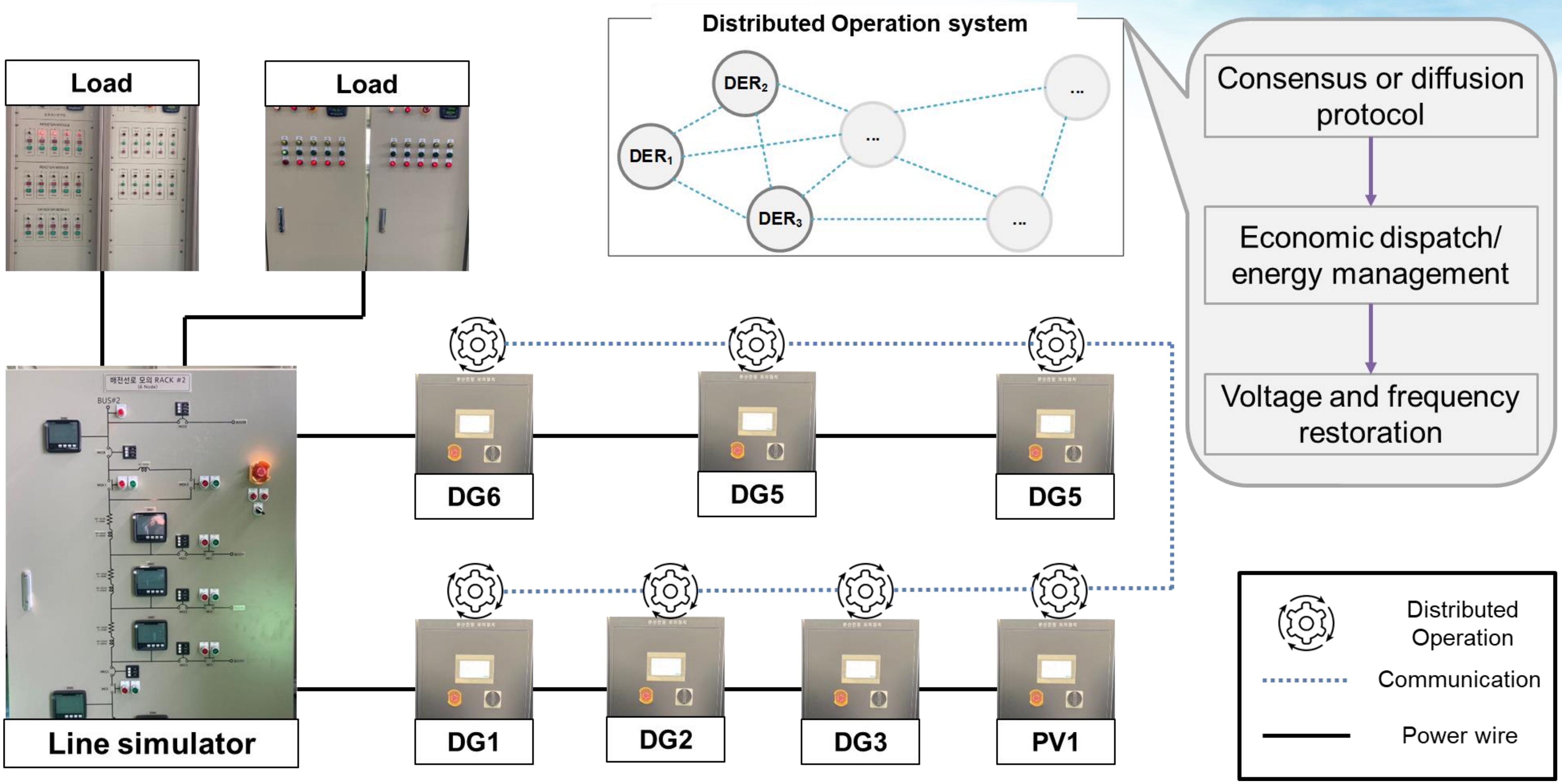
중앙집중식 제어방법과 유사한 SCO 패턴을 보임

운영비용의 경우 중앙집중식 대비 약 90% 성능을 보임

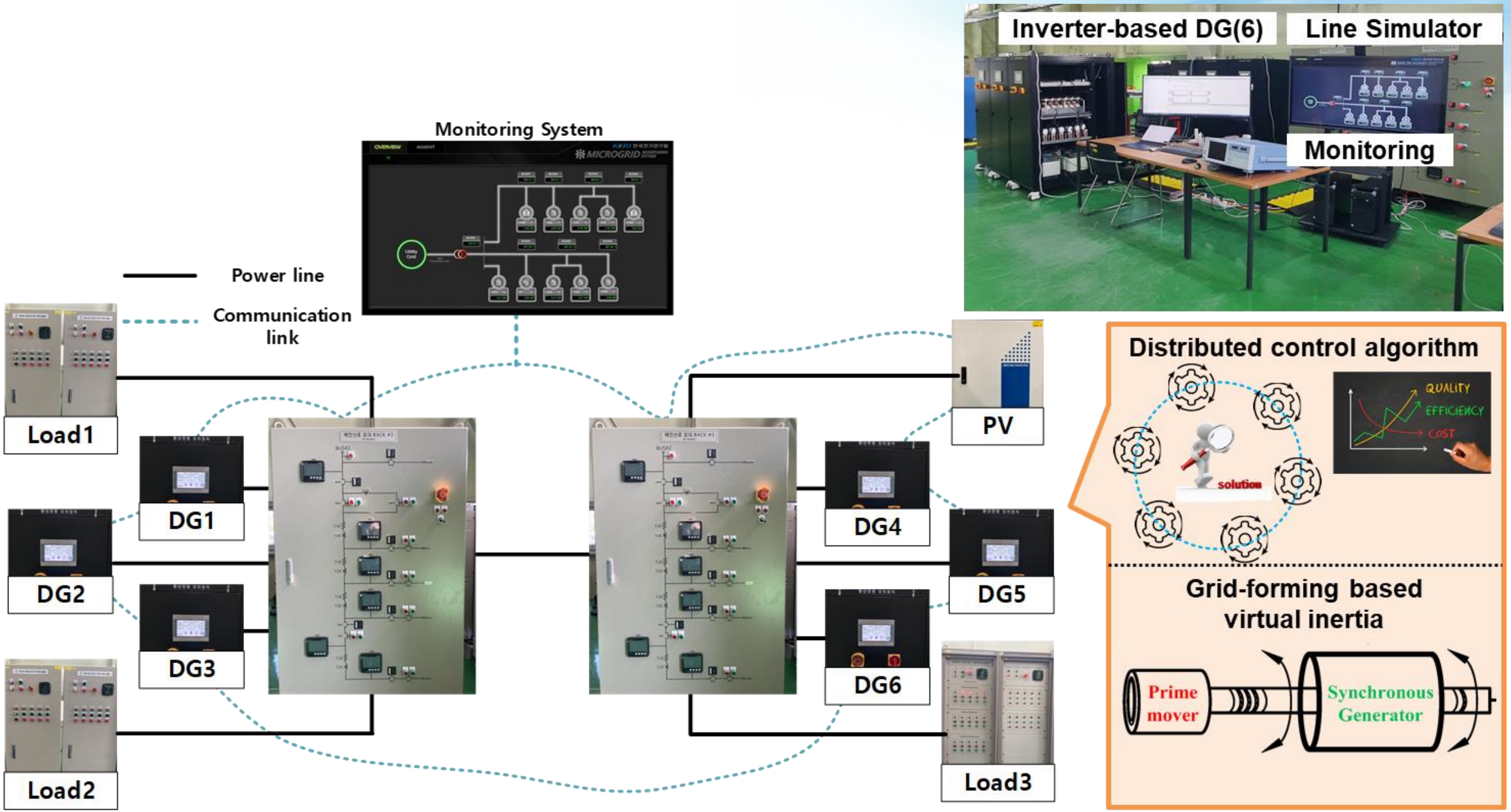
Control Scheme	Total Generation Cost
Centralized EMS	$ 766.8190
Proposed method	$ 808.5974
Difference	5.1668%

<ESS SOC>

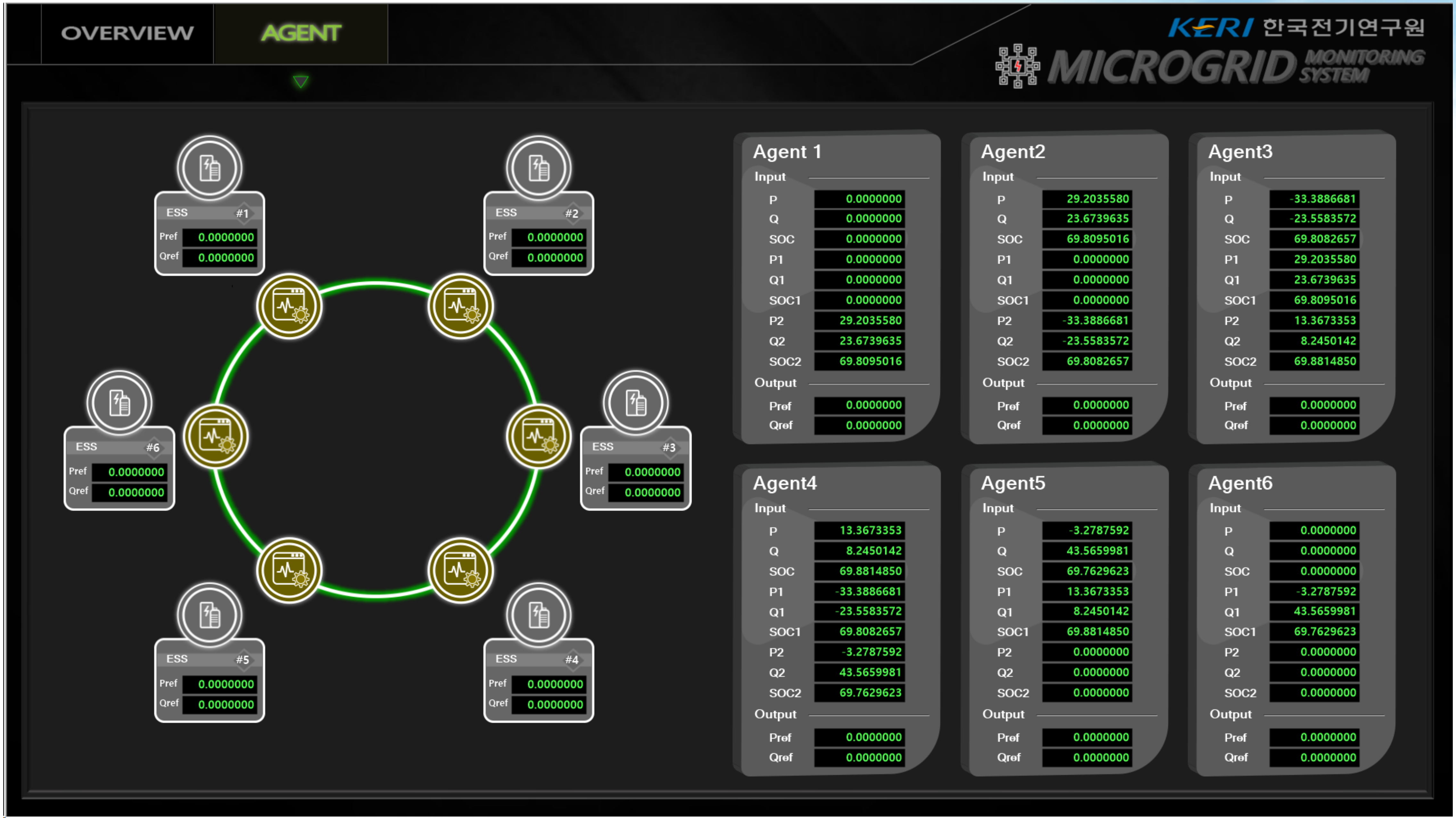
Pilot Plant (1)



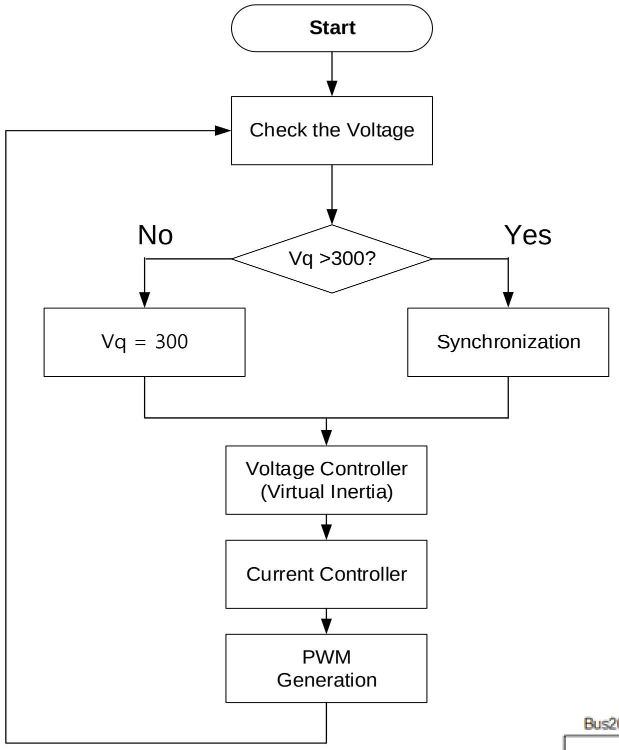
Pilot Plant (2)

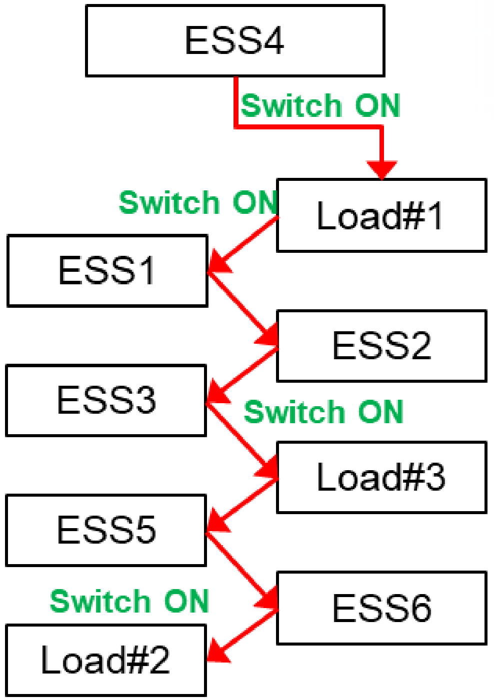


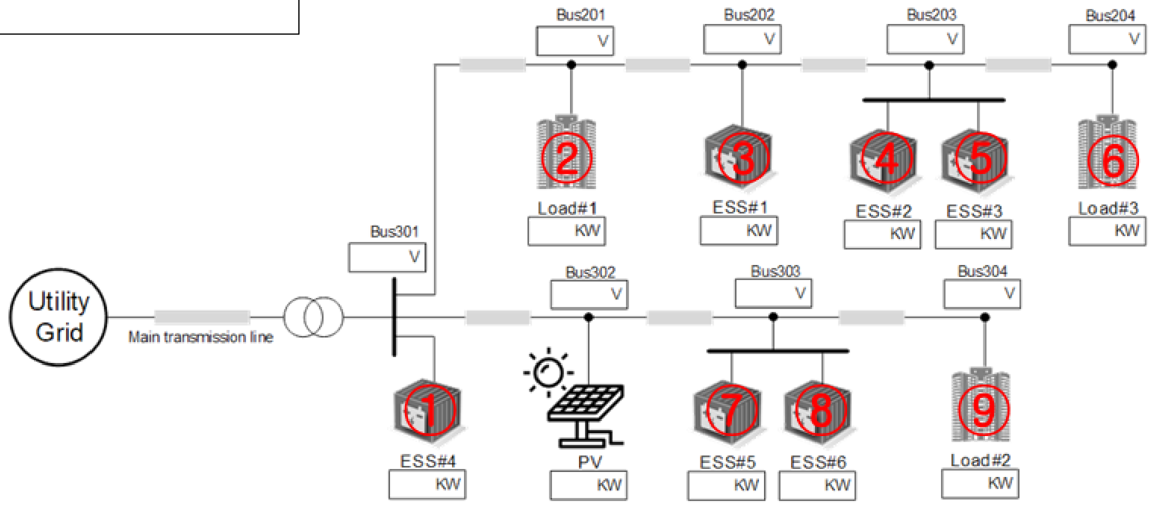
Monitoring System



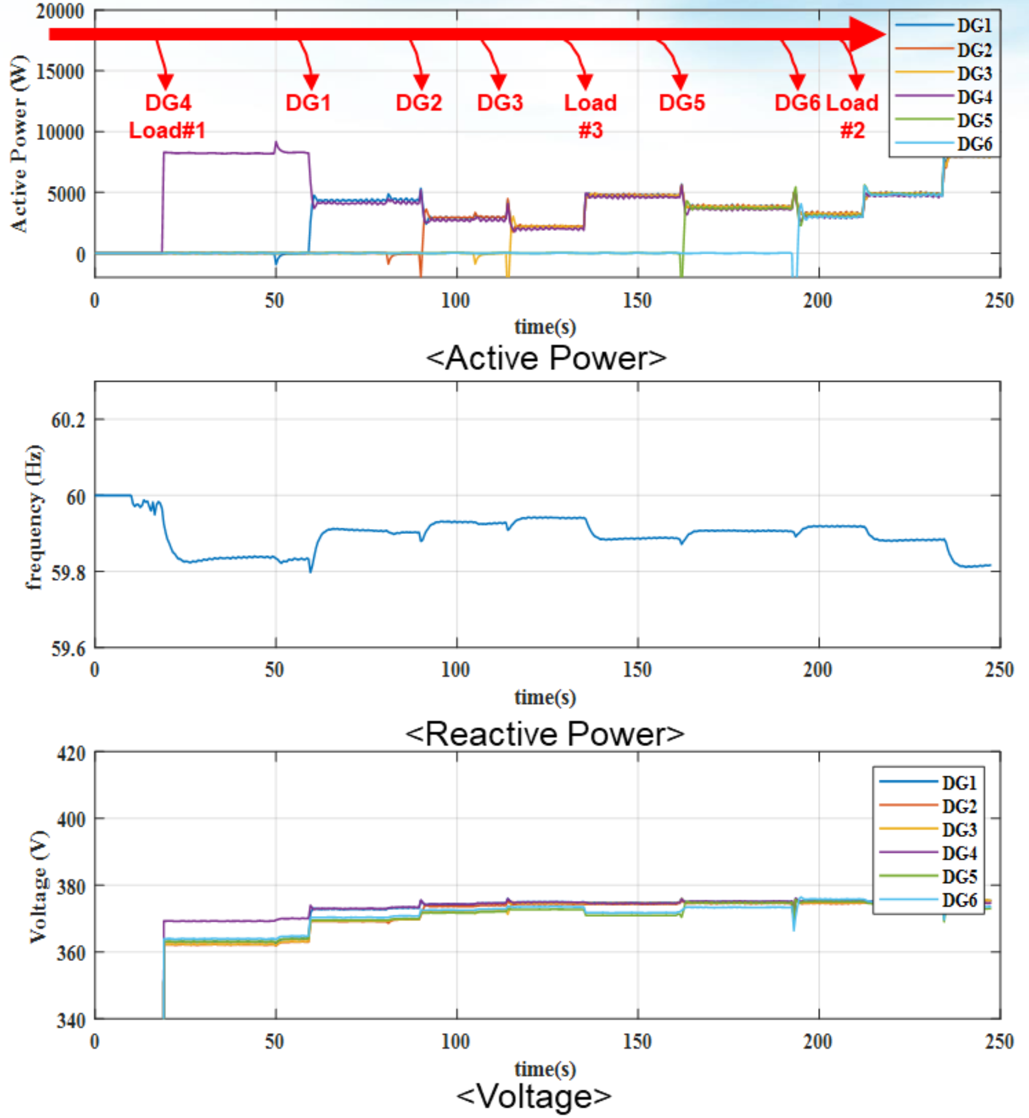
Black Start Test







Sequential DG connection

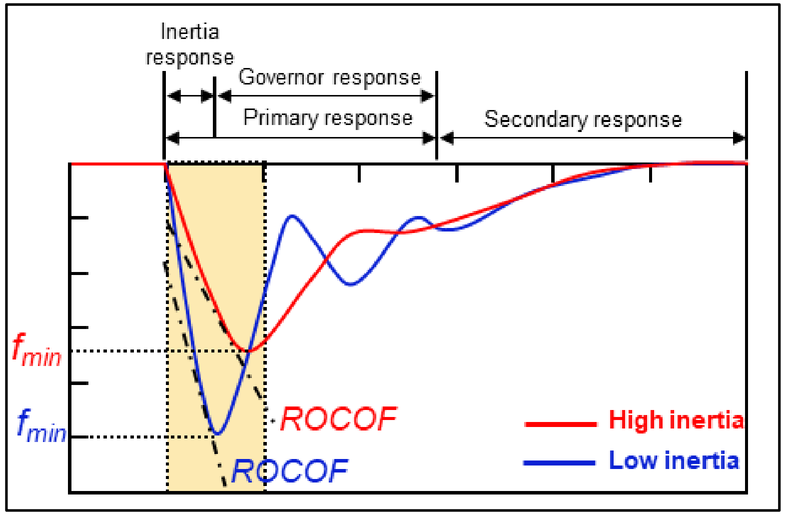


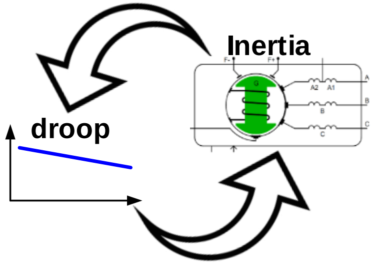
Experimental Scenario

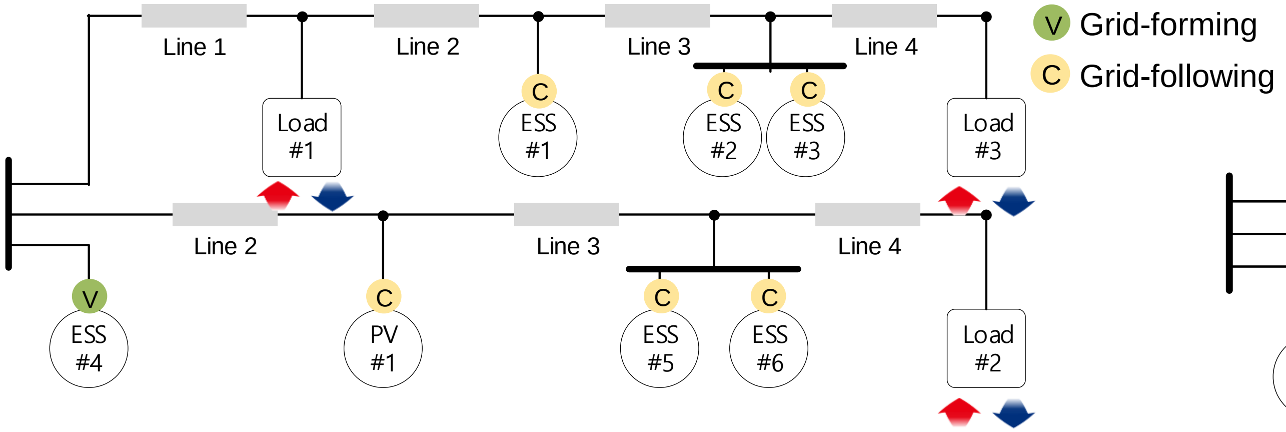
- Case 0
  - With/without virtual impedance
- Case 1 (single GFM inverter and the others GFL inverters
  - Load reduction & increase
  - Single GFM tripping
- Case 2 (multiple GFM inverters with virtual inertia)
  - Load reduction & increase
  - Single GFM tripping

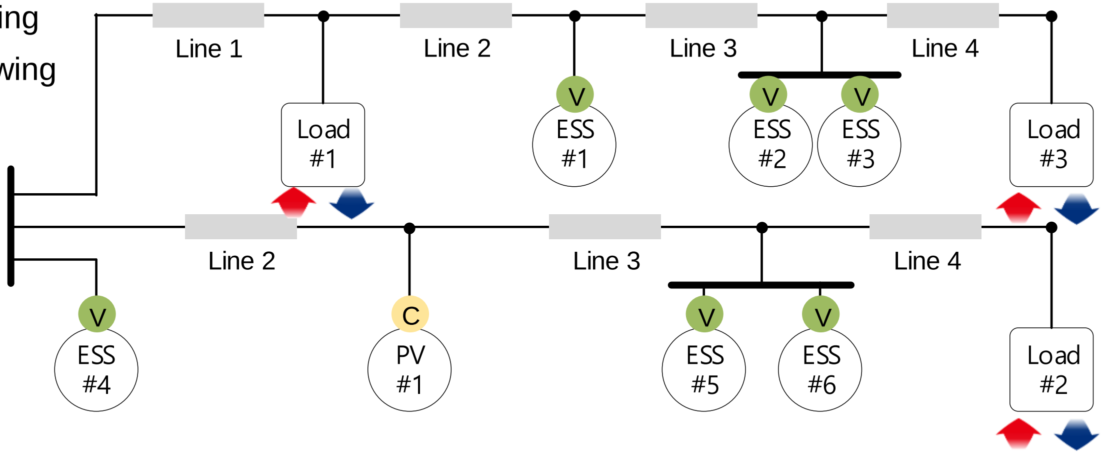
Check Point

1. **Frequency Stability(Nadir, ROCOF)**
2. **Resiliency(Grid-forming)**





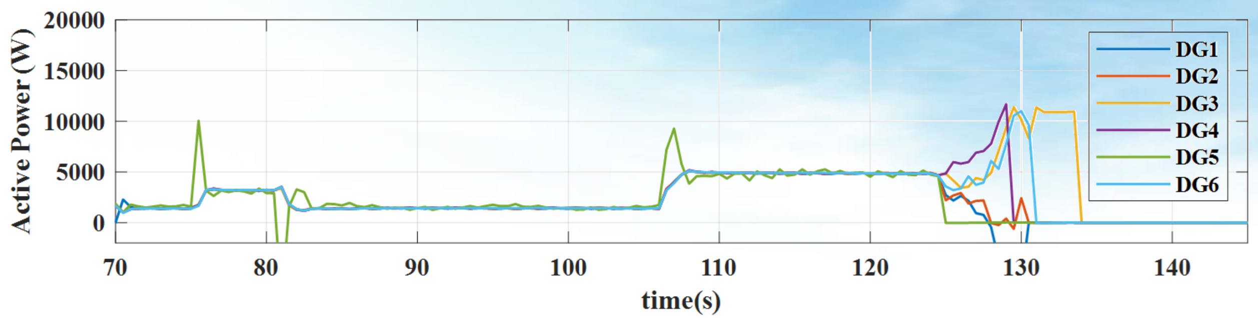




Test Results – Single GFM & Multiple GFL

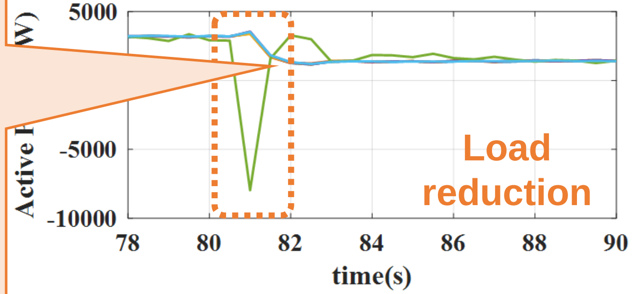
❖ Case1(Scenario)

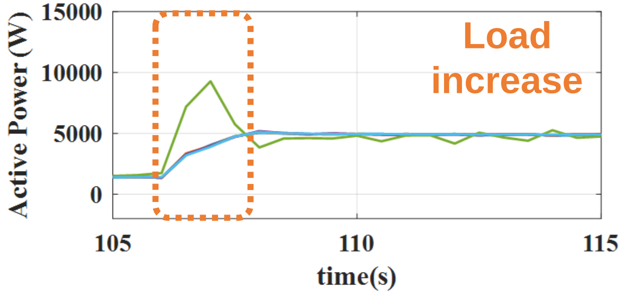
- ⊖ Load change
- ⊜ GFM inverter tripping

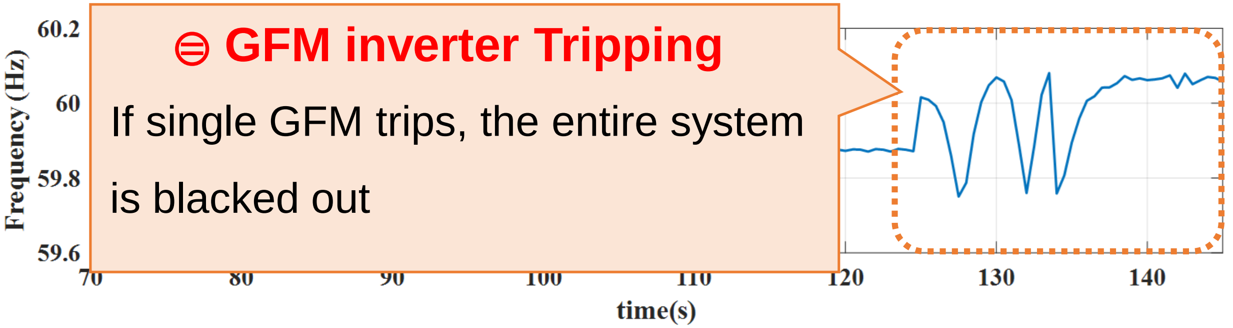


⊖ Load change

- GFM inverter operates first during load change because of the fast responsiveness of the GFM inverter

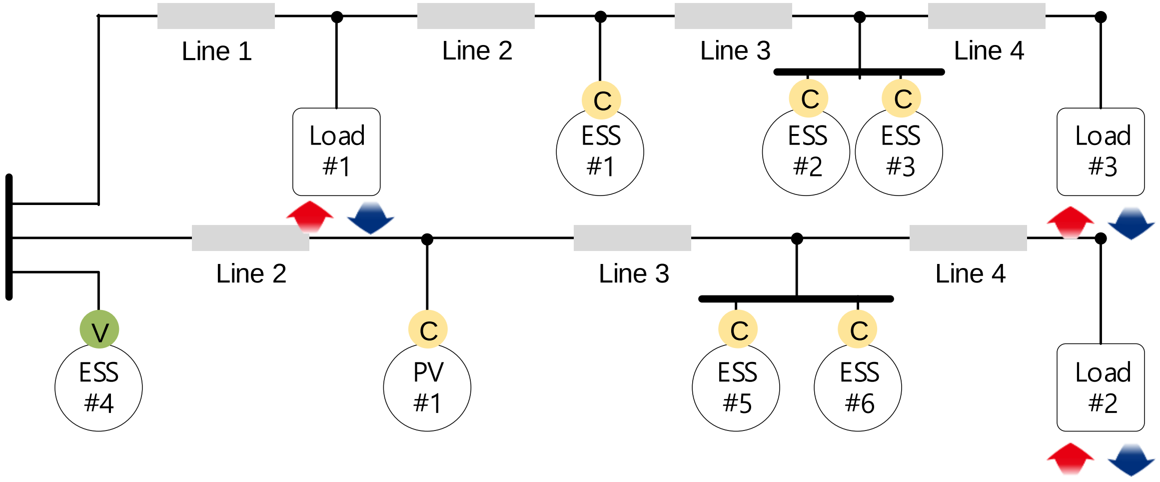


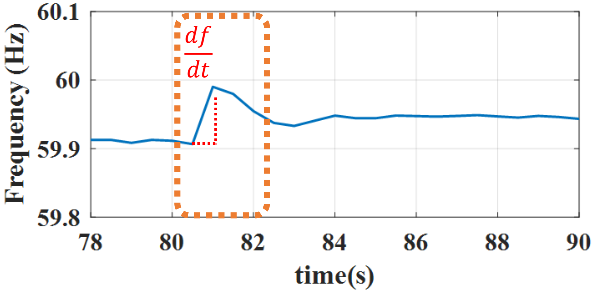


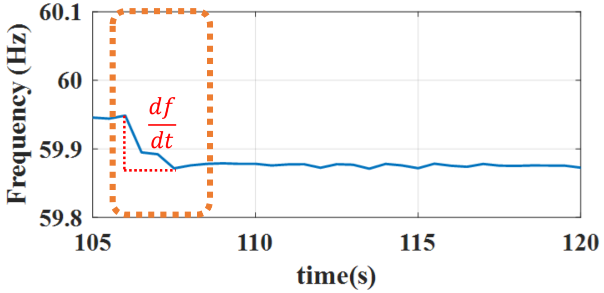


⊜ GFM inverter Tripping

If single GFM trips, the entire system is blacked out







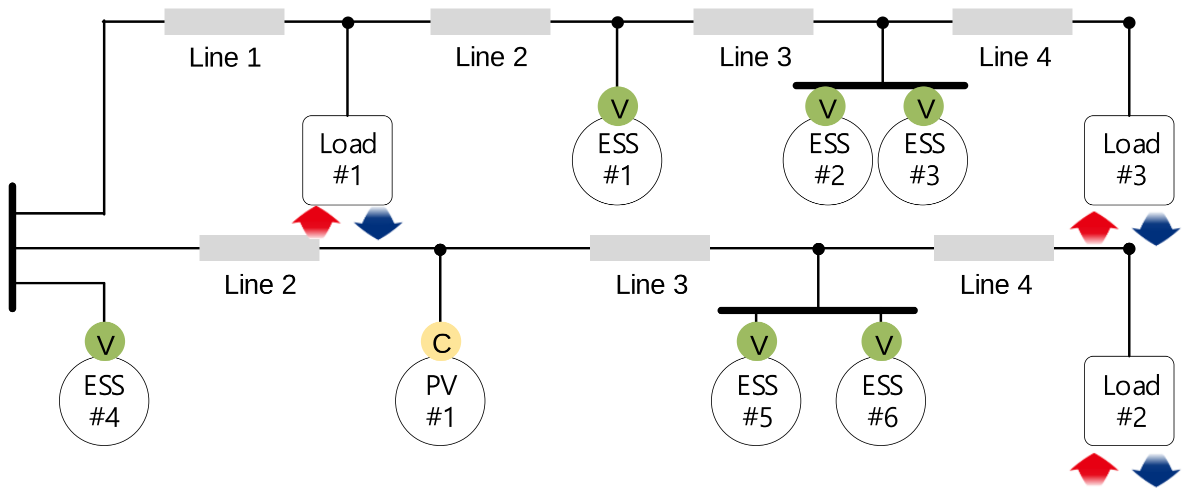
Test Results – Multiple GFM Inverter

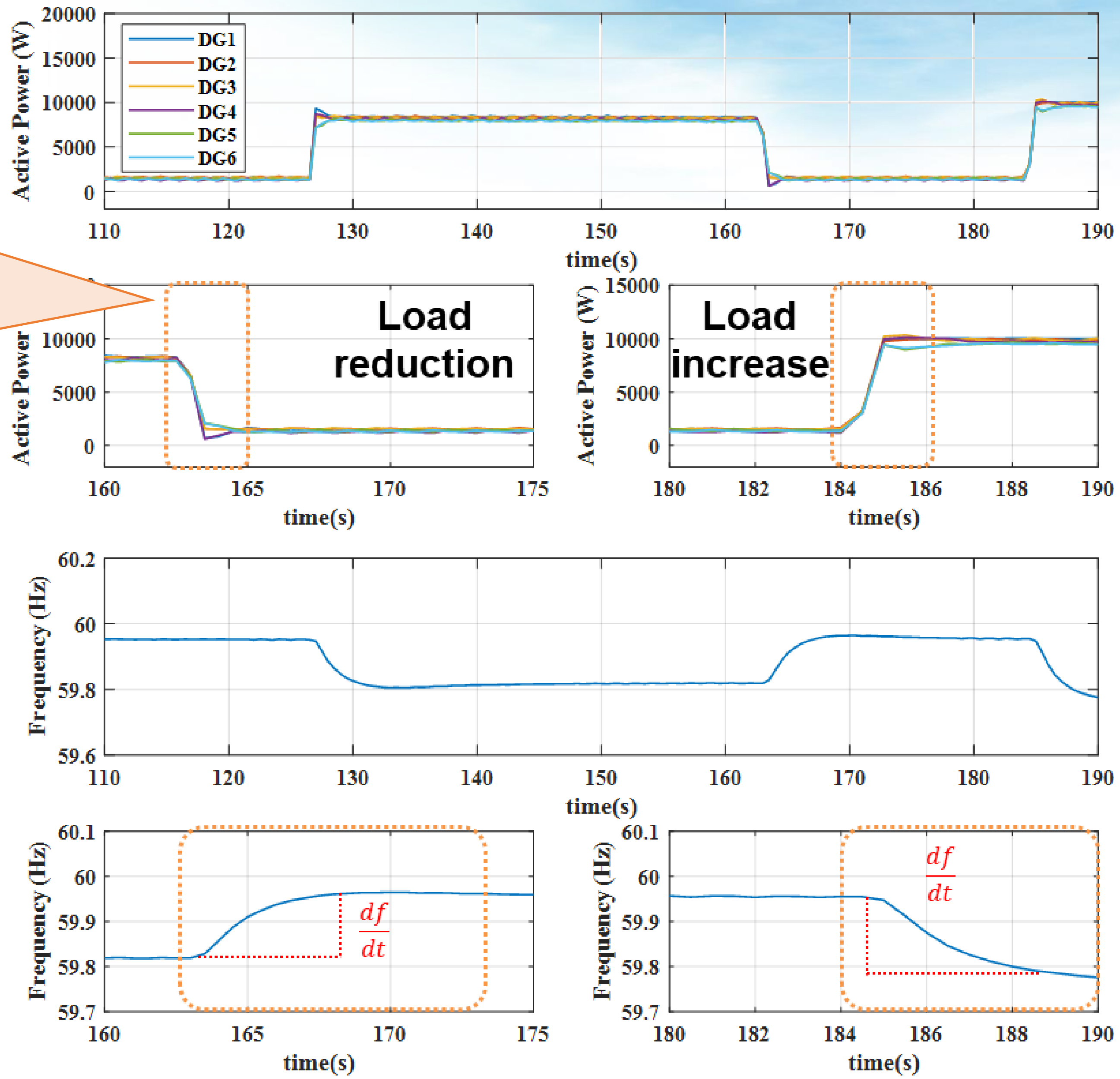
❖ Case2(Scenario)

⊖ Load change

Load change

- The frequency is controlled stably, because all GFM inverters operate at similar response time during load change,

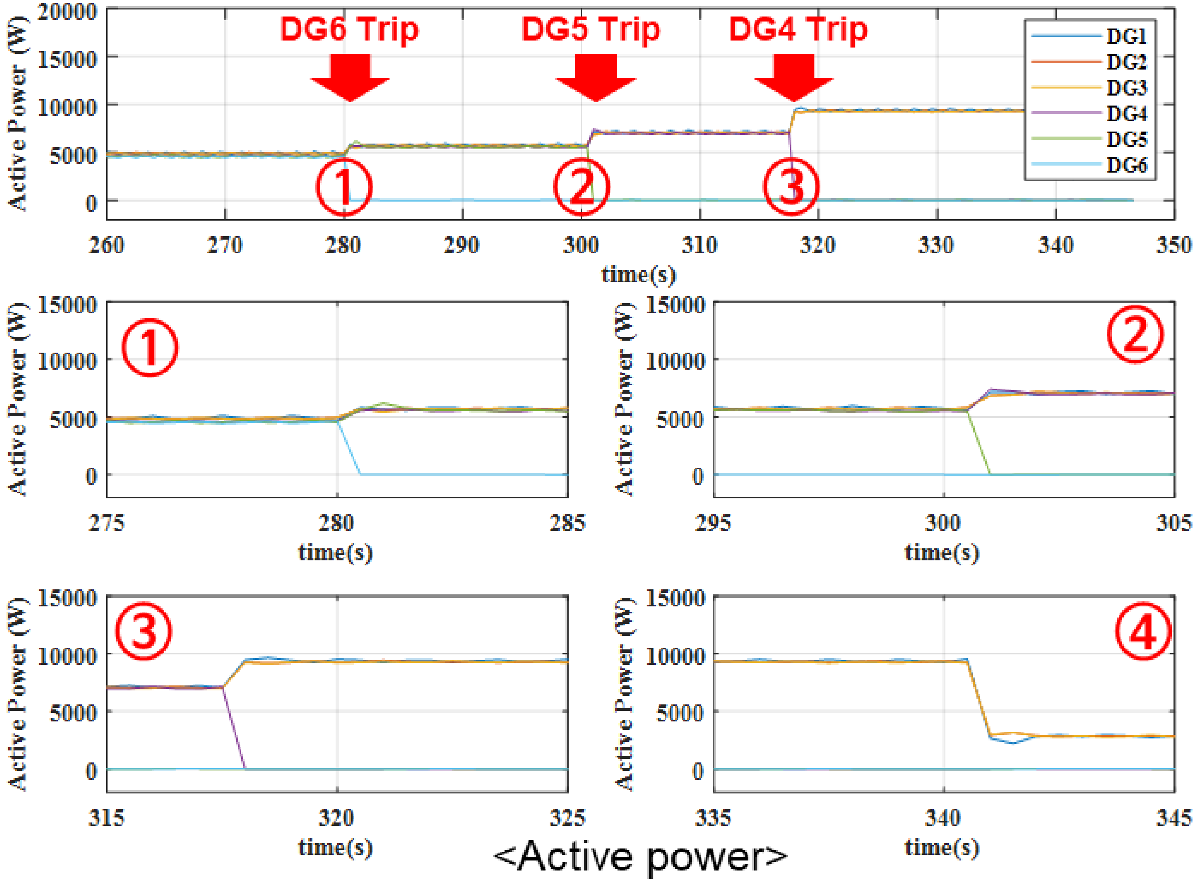




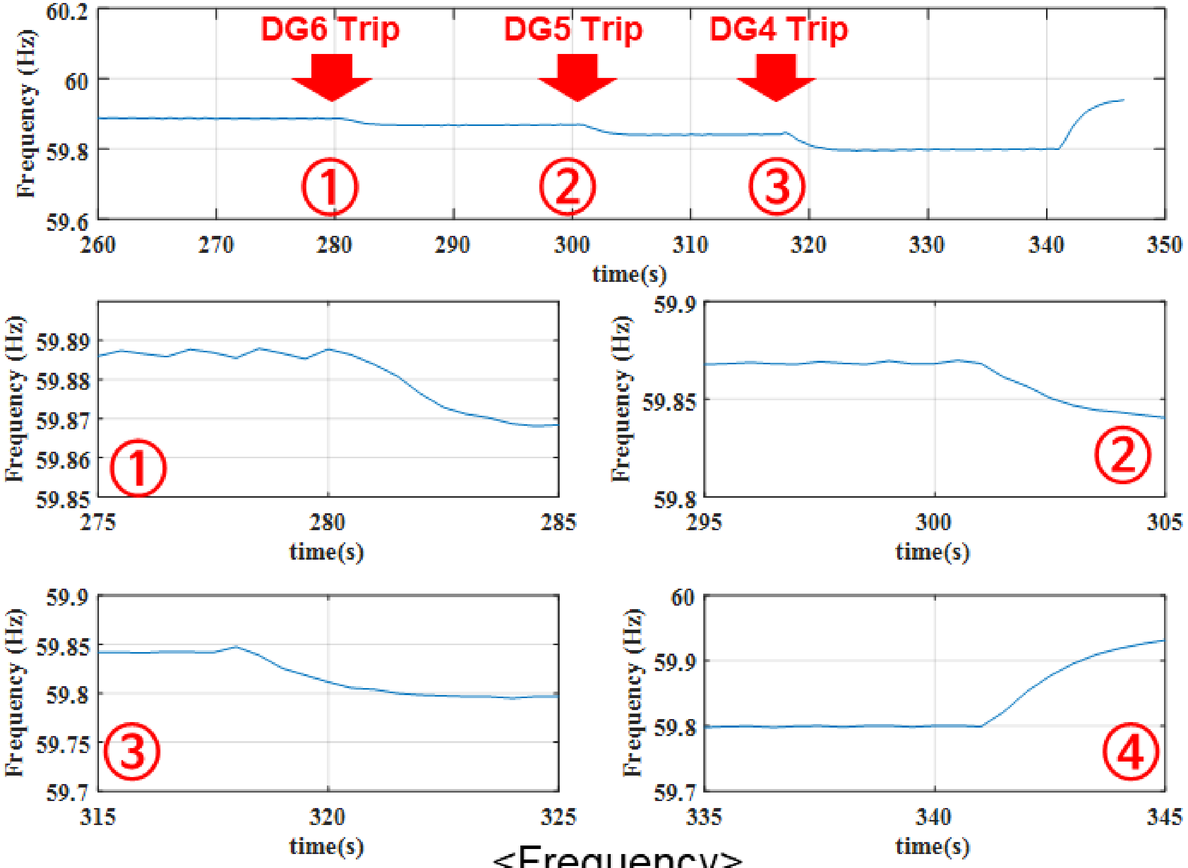
Test Results – Multiple GFM Inverter

❖ GFM inverter-based DG trip

- Scenario : The load amount is the same and DG is tripped sequentially
- The frequency and voltage can be maintained even if some DG trips because voltage is generated form multiple voltage sources.



<Active power>



<Frequency>

Test Results – Distributed operation function

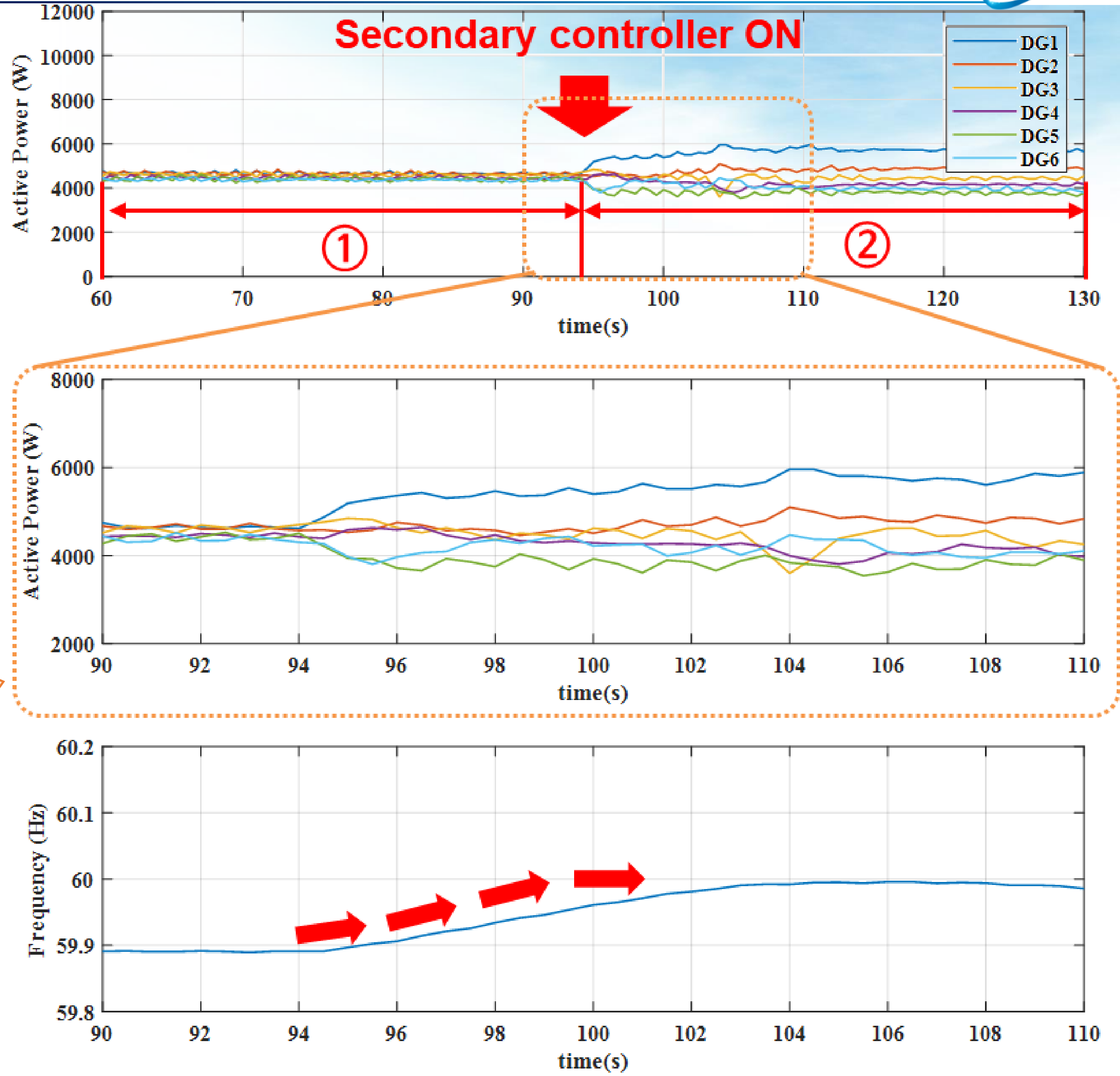
Incremental cost
$DG_1 < DG_2 < DG_3 < DG_4 < DG_6 < DG_5$

No.	A_i ($/kW2H)	$β_i$ ($/kWh)
DG_1	0.001562	3.82
DG_2	0.00174	3.99
DG_3	0.00186	4.15
DG_4	0.00196	4.53
DG_5	0.00208	5.09
DG_6	0.00219	3.11

⊖ **Section**: only primary controller operates

⊜ **Section:** Secondary controller ON

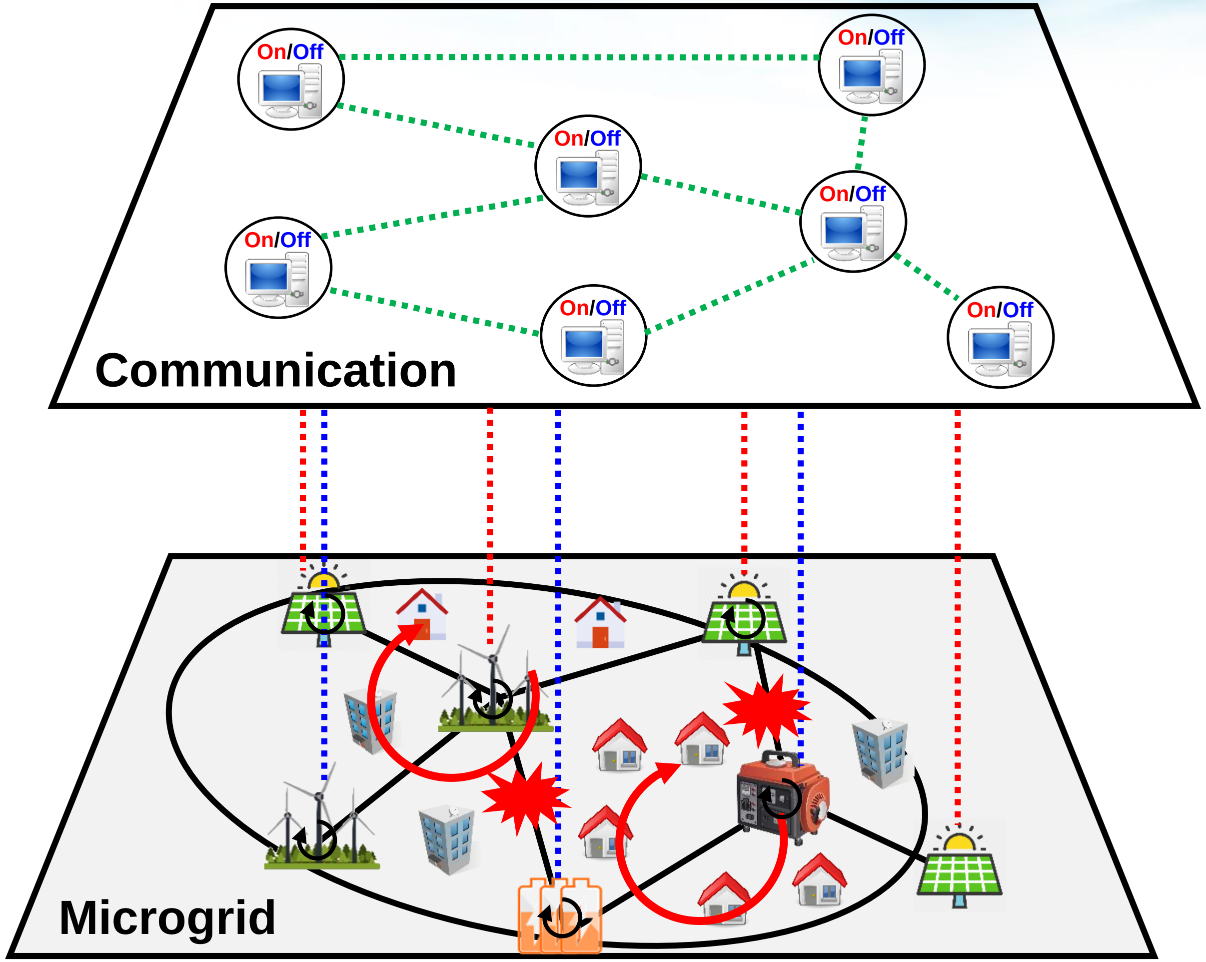
- Active power output change according to the incremental cost of each IBR



Conclusion

Development of Advanced Microgrid Technology

Phase1	Autonomous Operation using distributed strategy
Phase2	Autonomous restorative & self healing/auto configuration Self healing Auto configuration



Distributed Power System Research Center

Thank you

KERI