NASPI Work Group Meeting and Vendor Show 2025

Power system monitoring status of Korea based on PMU data and application

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(On behalf of
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& Kwangwoon Univ.)

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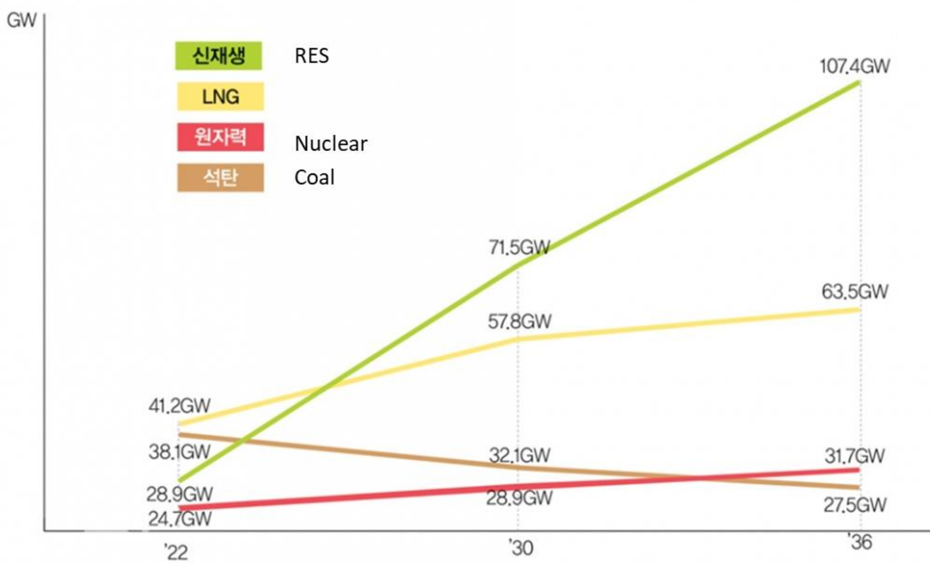
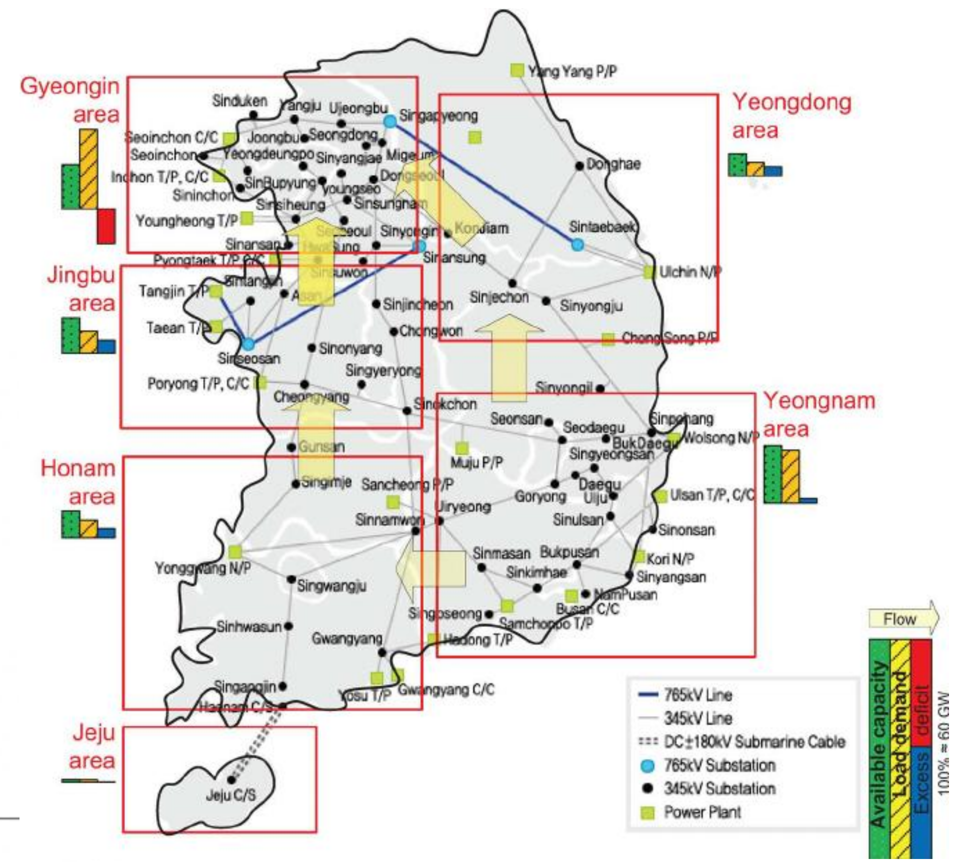
Ⅰ. Korea Power System Overview

□ KPS (Korea Power System) Overview

○ Total load : 102.3 GW in 2024
123.9 GW in 2038

○ Total RES : 17.4GW in 2024
125.9 GW in 2028

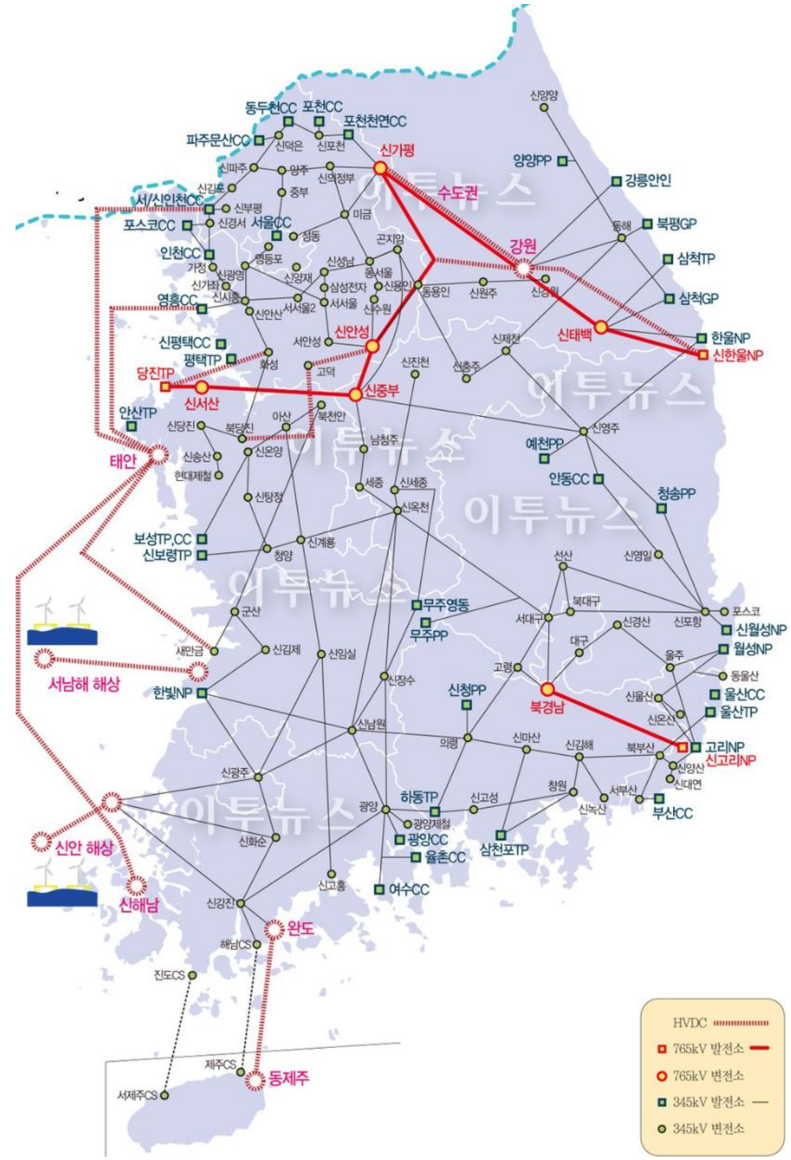




Ⅰ. Korea Power System Overview

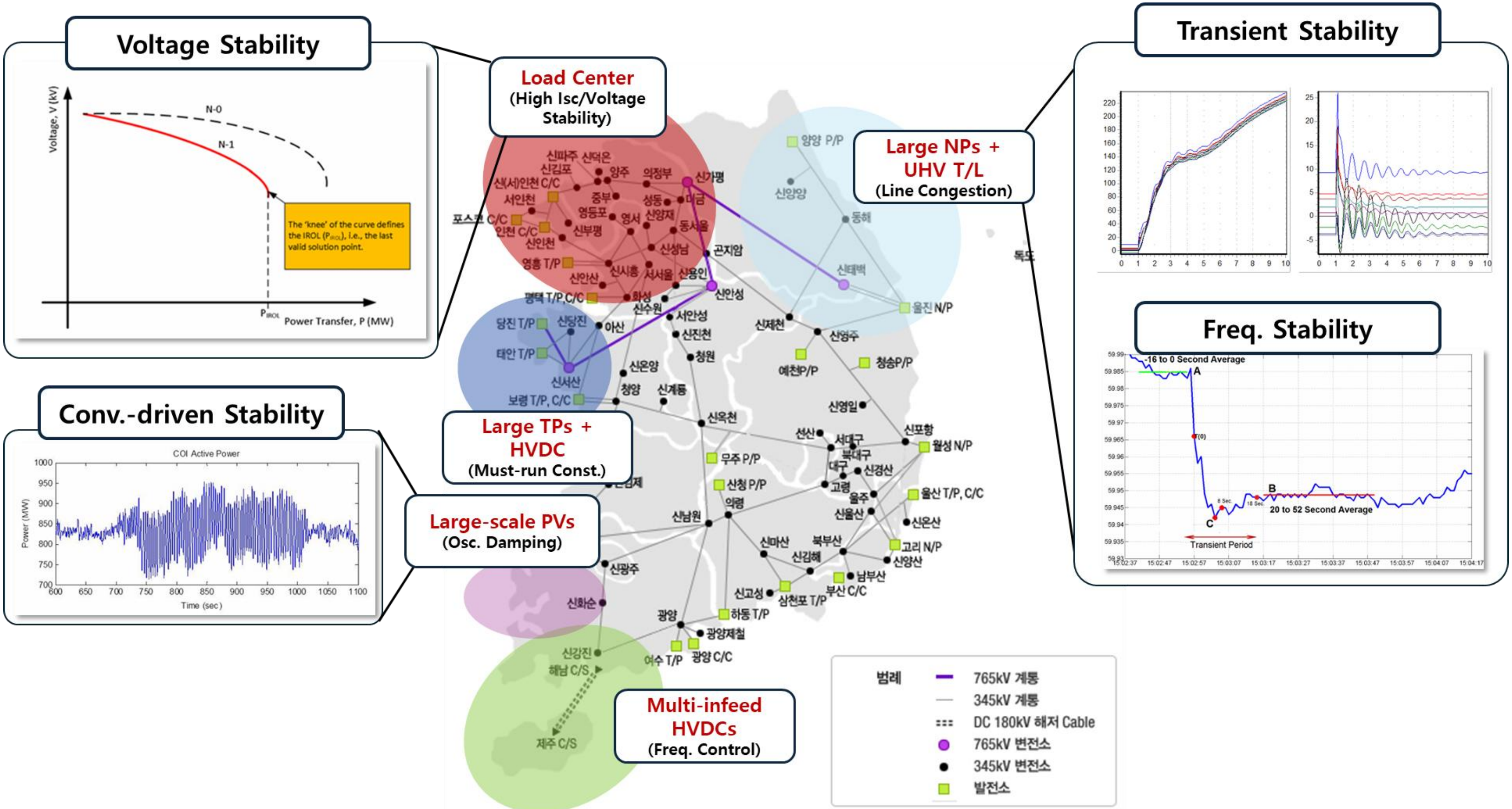
□ KPS (Korea Power System) Overview

- **Expansion of various IBR&Ds (Inverter-based Resources and Devices)**
  - · Rapid increase in RES due to carbon neutrality policy
  - · Increase of grid uncertainty : RES + Demand(EV, DC)
  - · New Grid Enhancing Technologies (GET) into the power grid: Control complexity
  - · Expansion of Power System Stability Evaluation Criteria: Resonance & Converter-driven Stability Evaluation

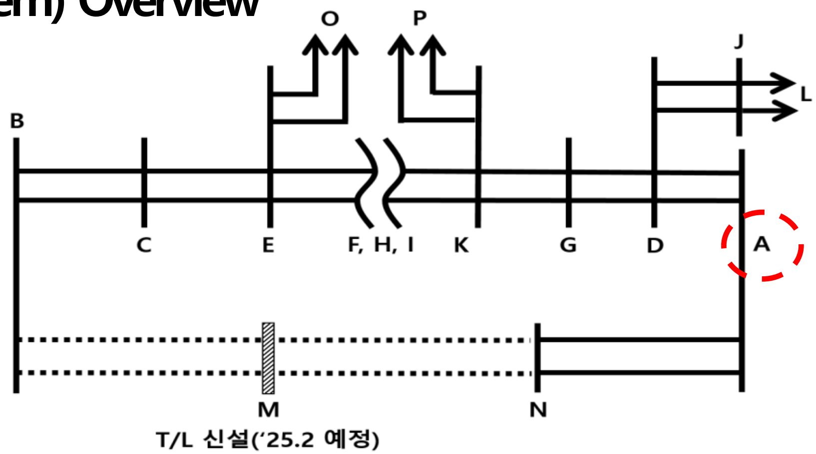


Ⅰ. Korea Power System Overview

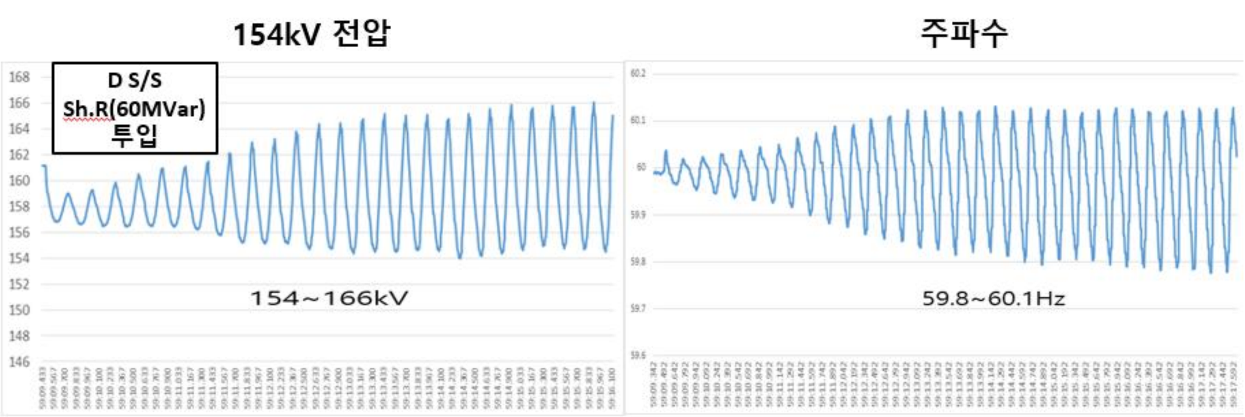
□ KPS (Korea Power System) Overview



□ KPS (Korea Power System) Overview



< A subs. SLD ('24.8) >



< J subs. PMU data ('24.4.13) >

RES nearby A subs.(단위 : MW)											
O	J	L	C	E	K	G	D	A	M	N	Total
160.8	124.4	279.8	141.0	187.7	179.6	151.9	148.8	701.7	96.0	120.3	2,292

Ⅱ. Power System Monitoring Status of Korea

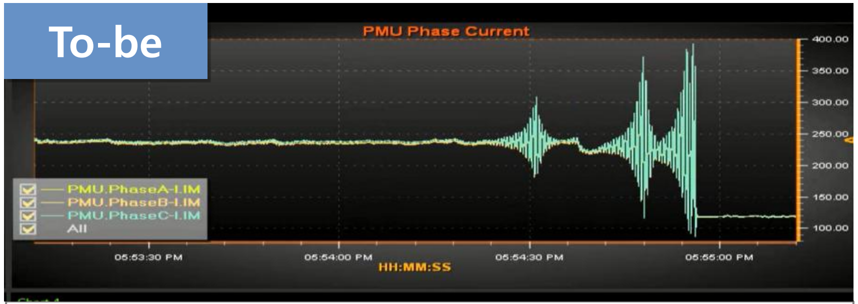
Current status (limitations of power grid monitoring/operation)

- Expansion of various IBR&Ds (Inverter-based Resources and Devices) Increased variability, complexity, and uncertainty in the power grid [Unprecedented rapid and large changes in the system operation environment]

As-Is

- IBRs increase in regeneration → **Oscillation** issue
- Measurement cycle 4~5 seconds analog data(**Phase Angle, Sync. X**)
- Independent network security weakness and sync. error

To-be



- PMU data for dynamic, transient monitoring (Excellent Dyr Visibility) 1/120 sec Digital Data + Phase Angle
- Adoption of **power standard time**, enhancement of **security/stability** and improvement of **precision**

[System Operation Paradigm change
WAMS→WAMAC→WAMPAC]

PMU-based high-precision monitoring, analysis, operation system

Ⅱ. Power System Monitoring Status of Korea

□ PMUs in Korea Power System

○ **Mainland : 36 location, 51 units**

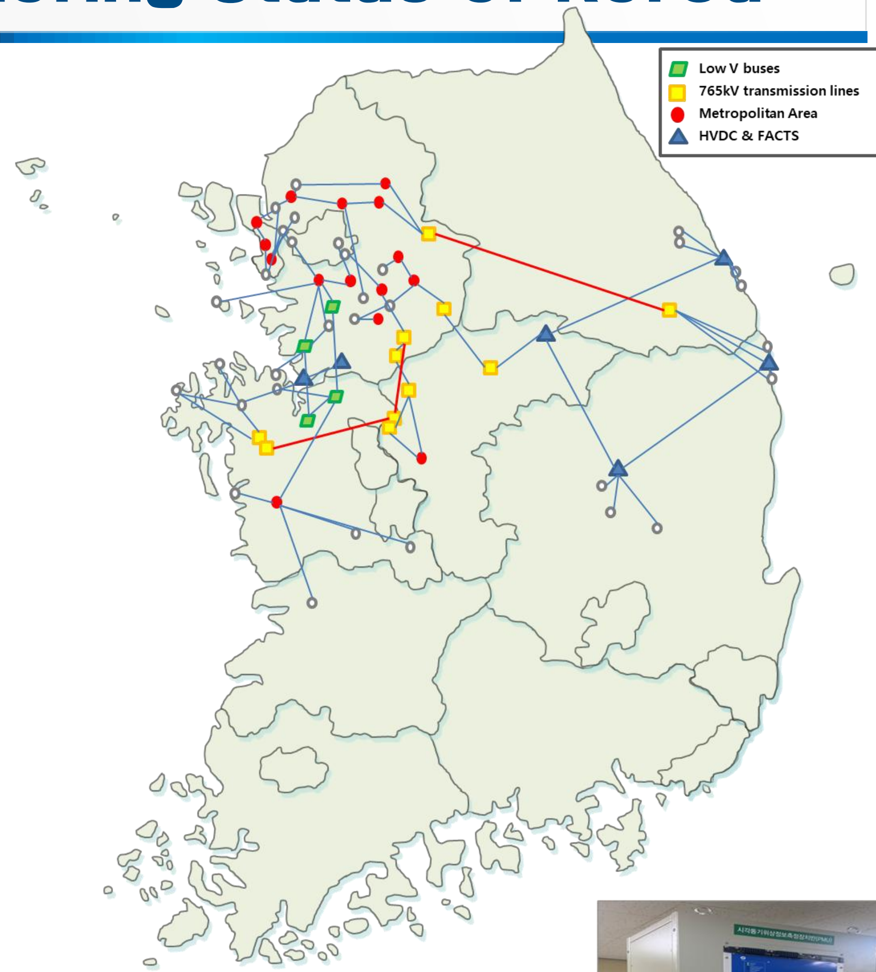
– Installed in 765kV T/L, metropolitan area, low V buses and IBDs

– Insufficient monitoring in Gangwon, Gyeongsang, and Jeolla areas

○ **Jeju island : 20 location, 22 units**

– Installed in 154kV substations, power plants, and special facilities (HVDC, FACTs)

- Precise monitoring of systems due to dense IBR&Ds



<Installation Example
- Seojeju C/S>

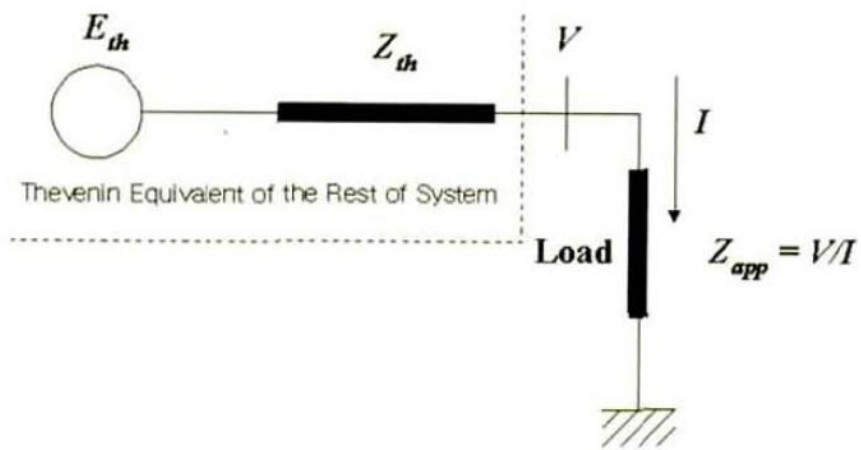
Ⅱ. Power System Monitoring Status of Korea

WAMS – Voltage Stability

- Voltage Instability Predictor (VIP)

· Compare Load Impedance and Thevenin Impedance of the System to determine the severity of the accident in terms of voltage stability

· Conditions to be stable on the voltage stability side: $\frac{|Z_{th}|}{|Z_{app}|} << 1 \qquad \text{(Z-index)}$

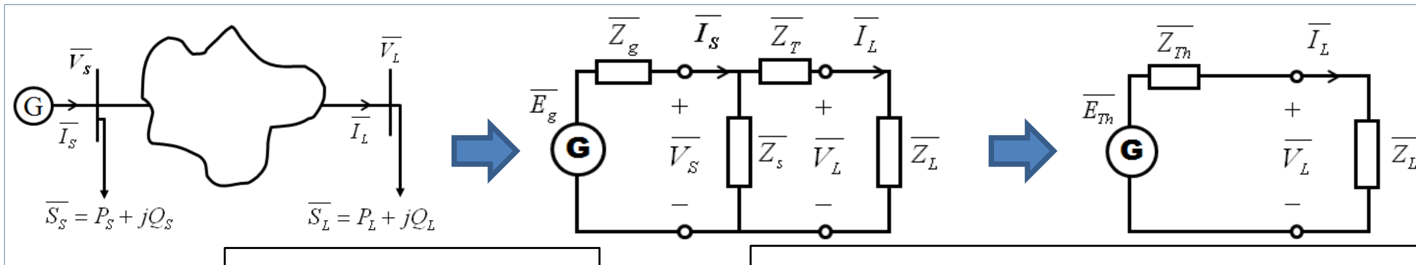


< Local bus and system network equivalent >

Ⅱ. Power System Monitoring Status of Korea

WAMS – Voltage Stability

- **Z-Index (WAVI : Wide Area Voltage Index)**



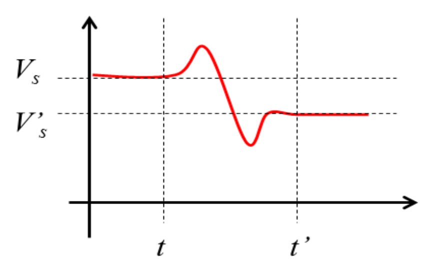
< T-equivalent >   < Thevenin Equivalent Circuit >

- Equivalent circuit configuration using VIP concept
- Z_T, Z_S, Z_L can be calculated by PMU data(V_S, I_S, V_L, I_L)
- Assumption : Z_g, E_g : Large-scale strong system
  E_g, Z_g : Not change rapidly and equals (t - t')

$$\frac{\overline{E}_g - \overline{V}_s}{\overline{Z}_g} = \overline{I}_s$$

$$\frac{\overline{E}_g - \overline{V}_s'}{\overline{Z}_g} = \overline{I}_s'$$

$$\rightarrow \quad \frac{\overline{V}_s - \overline{V}_s'}{\overline{I}_s' - \overline{I}_s} = \overline{Z}_g$$

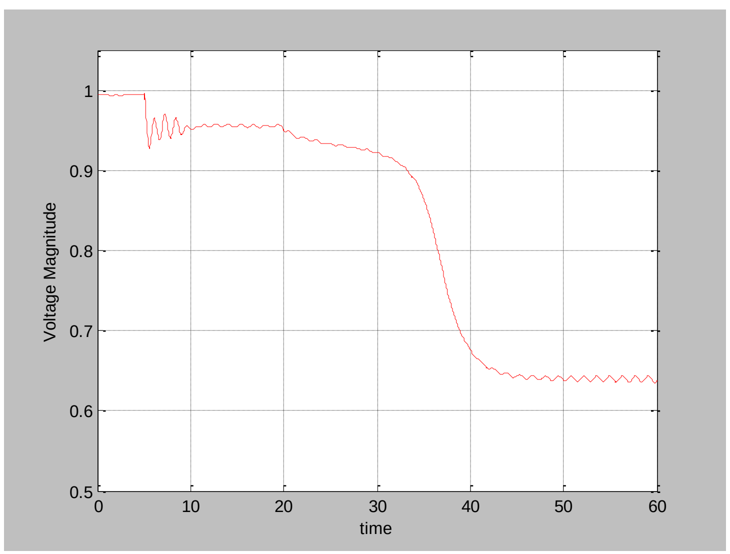


Ⅱ. Power System Monitoring Status of Korea

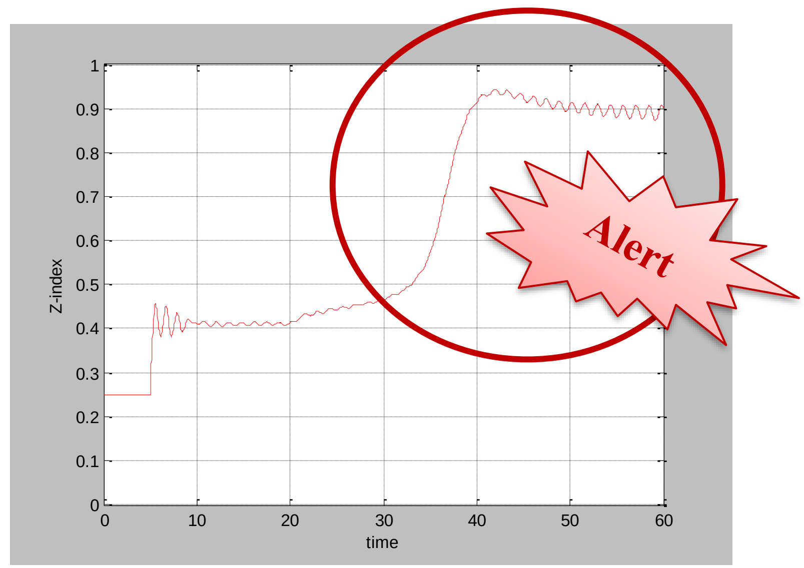
WAMS – Voltage Stability

- **Z-Index (WAVI : Wide Area Voltage Index)**

  - Determining the severity of an accident through a Z-Index graph
  - Application in KPS
    - Voltage instability scenario due to line fault and reactive power load increase
    - 5S: 345kV (Hwasung-Asan) Route Accident
    - 20s: Increased reactive power load (355 MVAR) in the metropolitan area



<Receiving End V>



<Z-index>

Ⅱ. Power System Monitoring Status of Korea

WAMS – Oscillation

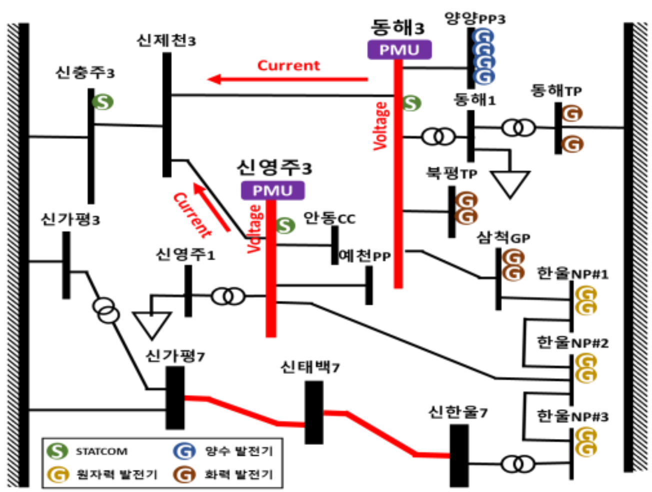
- **MLE (Maximum Lyapunov Exponent) Method**

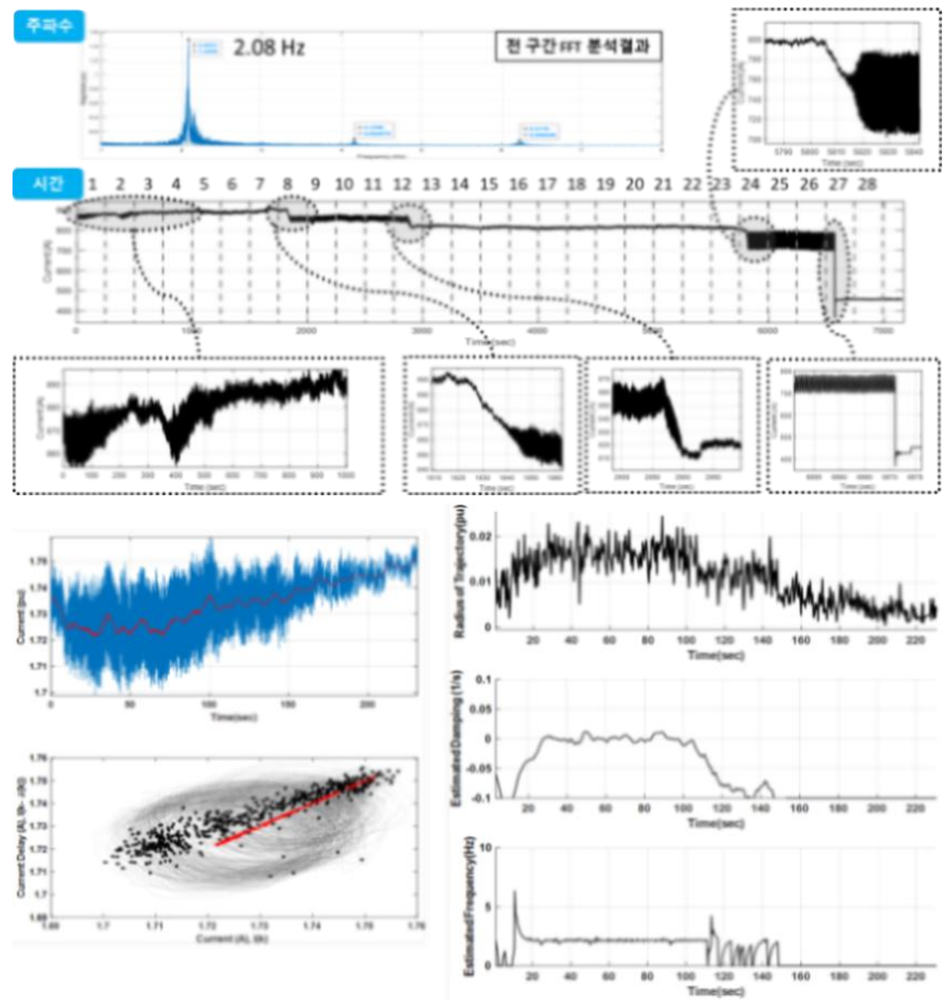
$$d(t) = \phi(t, z^* + d_0) - \phi(t, z^*)$$

$$d(t) = \frac{\partial \phi(t, z^*)}{\partial z} d_0$$

$$\Lambda(z) = \lim_{t \to \infty} \left[\frac{\partial \phi(t, z^*)}{\partial z^T} \frac{\partial \phi(t, z^*)}{\partial z} \right]$$

$$\lambda_i = \log \Lambda_i(z)$$





WAMS – Inertia Estimation

- **Offline inertial estimation**
  - Swing Eq. based P-f relationship

$$\Delta P = \frac{2\left(H_{sys}S_{sys}\right)}{f_0}\left(\frac{df}{dt}\right) \text{ where } H_{sys}S_{sys} = H_G S_G + H_R S_R$$

  - Natural Inertia of sync. Generators

$$\Delta P = \frac{2(H_G S_G)}{f_0}\left(\frac{df}{dt_G}\right) \text{ if } H_{sys}S_{sys} = H_G S_G$$

  - PMU-measured RoCoF is smaller since load inertia contribution

$$\boxed{\frac{df}{dt_{G,Limit}} > \frac{df}{dt_{PMU}}}$$

Ⅱ. Power System Monitoring Status of Korea

WAMS – Inertia Estimation

- **Online inertia estimation including load inertia**

  - The RoCoF contribution of sync. Gens can be calculated by SE datas

$$\Delta P = \frac{2(H_G S_G)}{f_0}\left(\frac{df}{dt}\right) \gg \left(\frac{df}{dt_{est}}\right) = \frac{\Delta P * f_0}{2(H_G S_G)} \quad \bullet\ \bullet\ \bullet \quad ①$$

  - The RoCoF including all elements can be measured by PMUs

$$\Delta P = \frac{2(H_G S_G + H_R S_R)}{f_0}\left(\frac{df}{dt_{PMU}}\right) \gg \left(\frac{df}{dt_{PMU}}\right) = \frac{\Delta P * f_0}{2(H_G S_G + H_R S_R)} \quad \bullet\ \bullet\ \bullet \quad ②$$

  - The contribution of other elements can be derived

$$\therefore \frac{①}{②} \quad \left.\begin{aligned} \left(\frac{df}{dt_{est}}\right) &= \frac{\Delta P * f_0}{2(H_G S_G)} \\ \left(\frac{df}{dt_{PMU}}\right) &= \frac{\Delta P * f_0}{2(H_G S_G + H_R S_R)} \end{aligned}\right\} \quad \boxed{H_R S_R = \left(\frac{\left(\frac{df}{dt_{est}}\right)}{\left(\frac{df}{dt_{PMU}}\right)} - 1\right) H_G S_G}$$

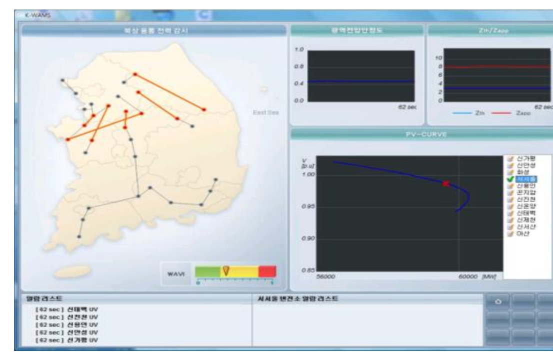
$$\therefore H_{sys} S_{sys} = H_G S_G + H_R S_R$$

Ⅱ. Power System Monitoring Status of Korea

- **K-WAMS**
  - Wide-area outage prevention (early detection and alarm of system instability)
  - Real-time, highly precisely measured voltage and current Phasor
  - Real-time system status monitoring/recording
  - Predictive analysis of system instability
  - Early warning system (prevention of large-scale power outages)

<Dashboard>

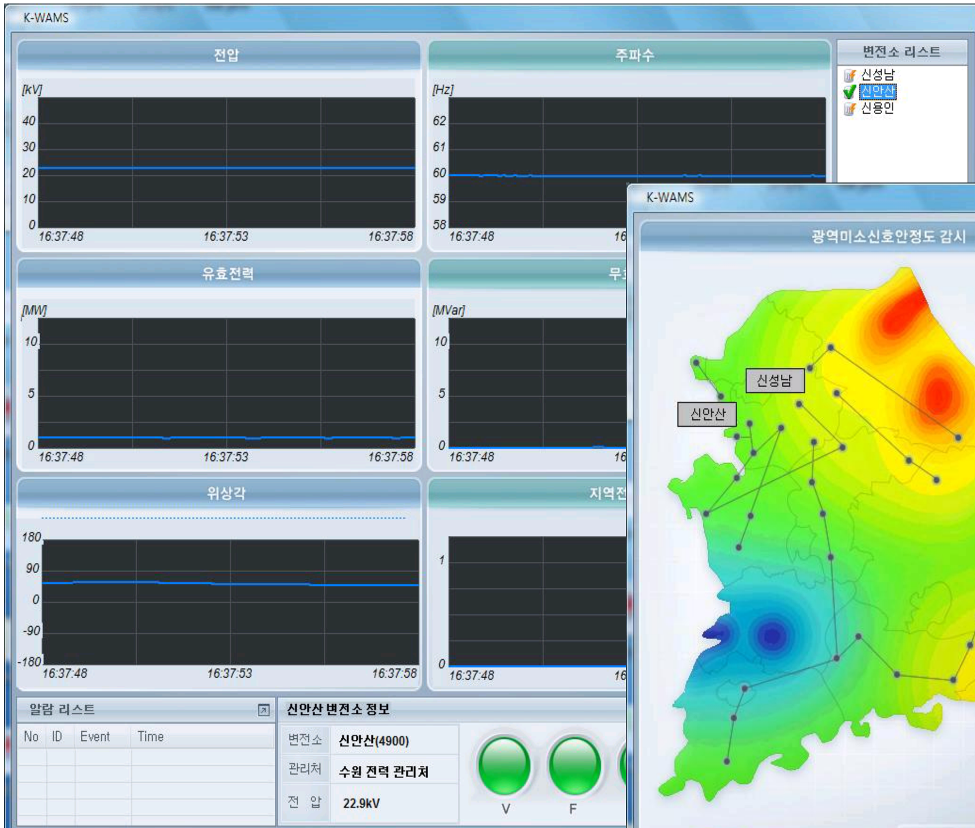
<Security Monitoring>



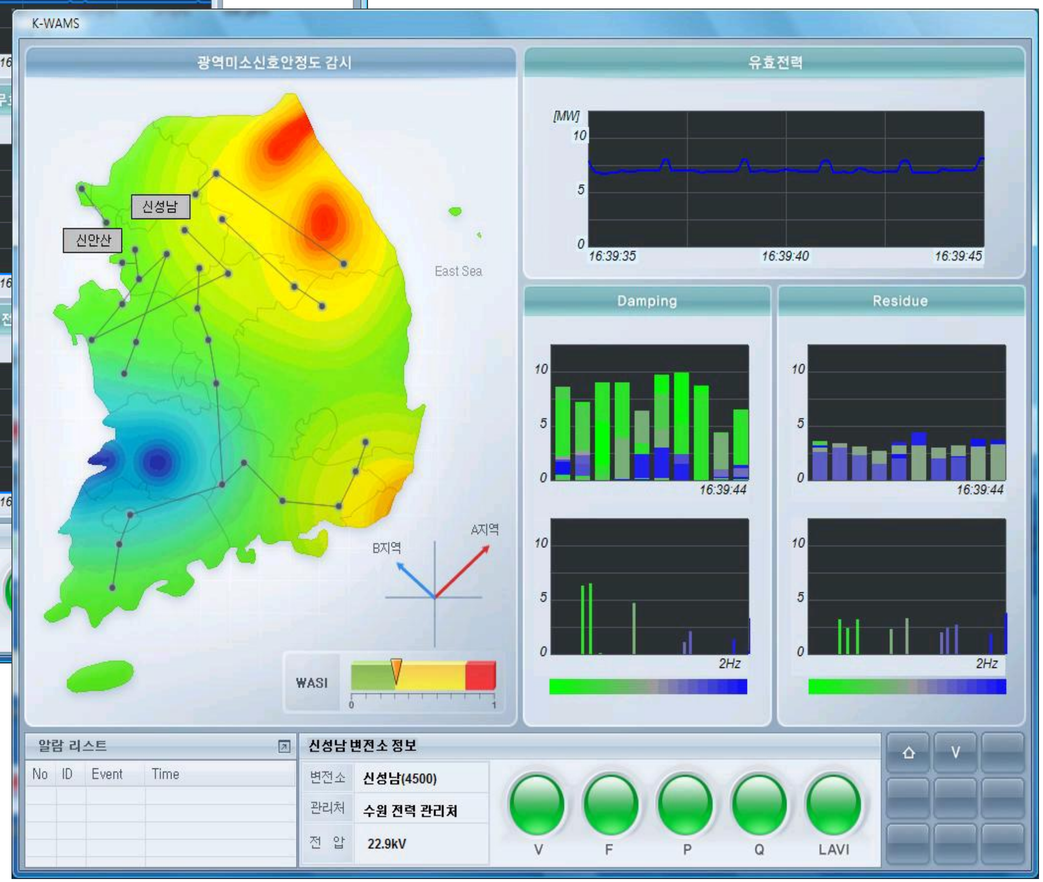
<Voltage Stability>

Ⅱ. Power System Monitoring Status of Korea

• Substation Monitoring

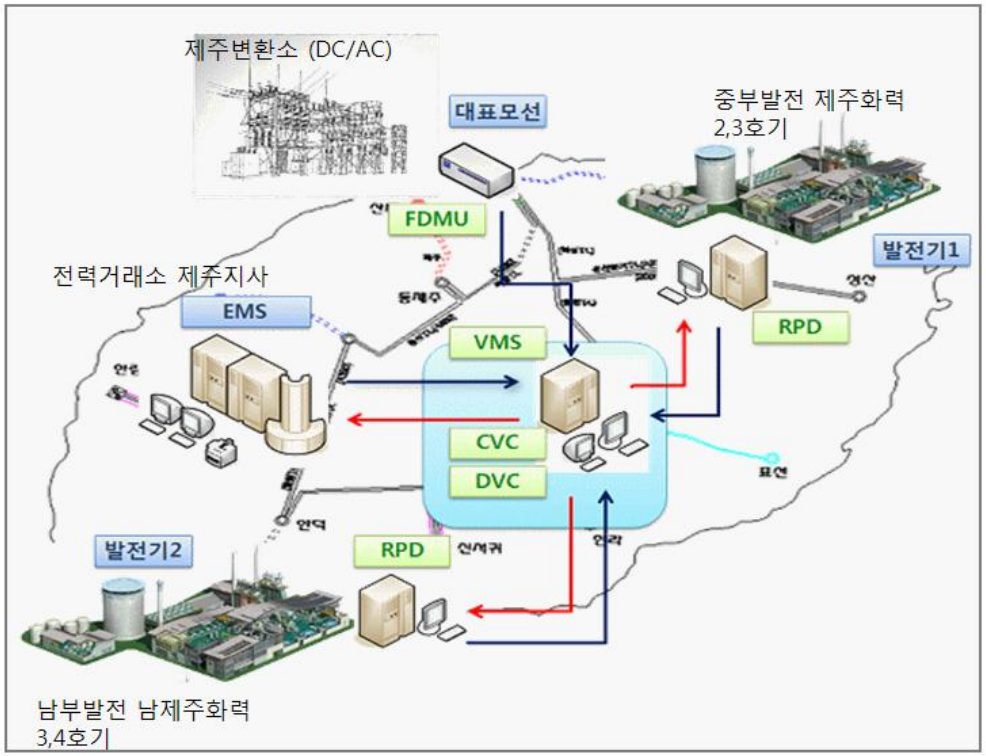


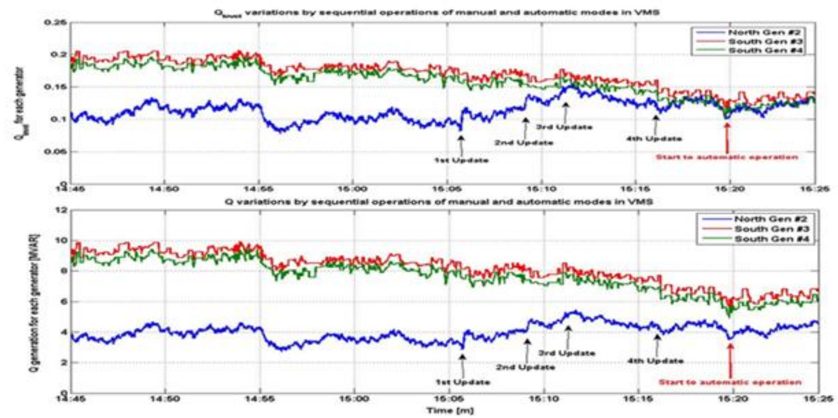
• Real-time Oscillation detection

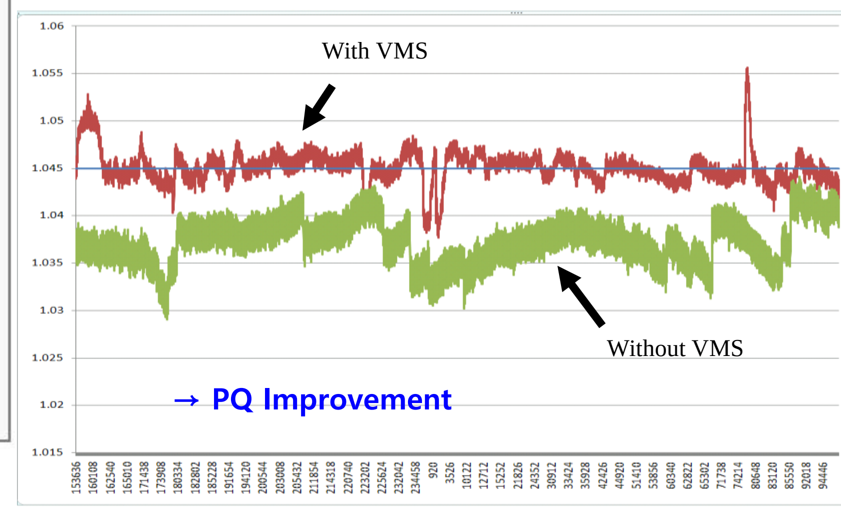


Ⅱ. Power System Monitoring Status of Korea

- Voltage Management System







Ⅲ. Research Advancement

① Situational Awareness

- Hybrid state estimation
- Real-time transient stability analysis
- Measurement-based inertia estimation

② Wide-area Monitoring and Control

- Wide-area hierarchical control
- Parameter estimation
- Failure type and location estimation

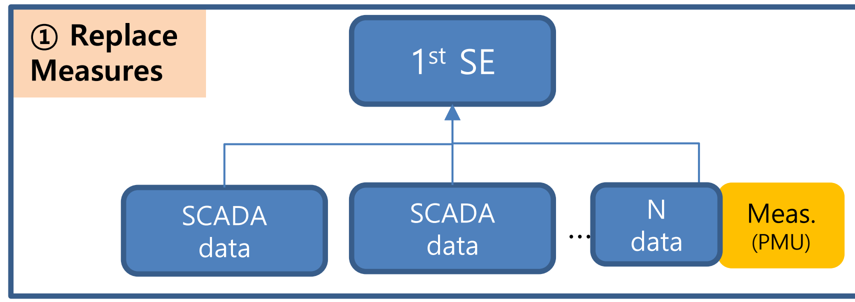
Ⅲ. Research Advancement

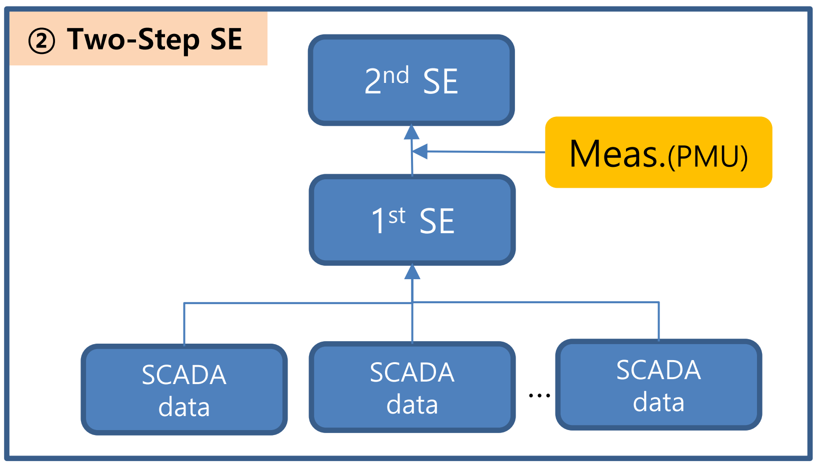
Situational awareness technology

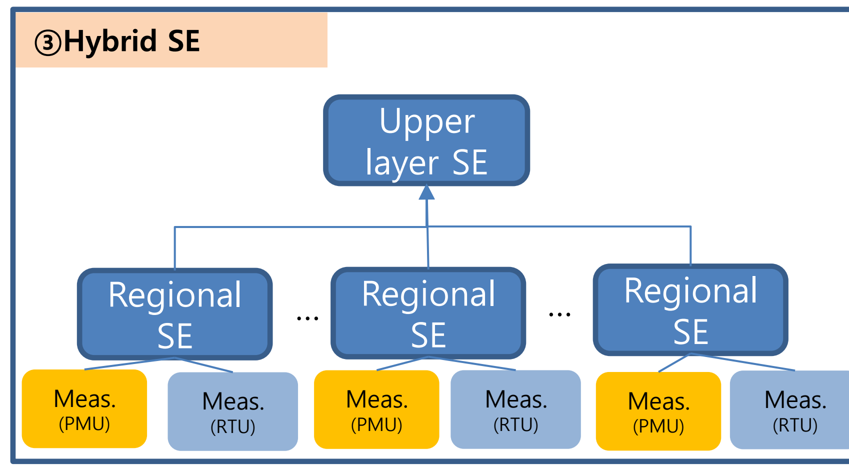
- **Hybrid state estimation**

Convergence, accuracy improvement using PMU data, and SCADA-based local condition estimation

$$\textbf{State} = \begin{bmatrix}\textbf{Obsv.}\end{bmatrix}\begin{bmatrix}\textbf{R} \\ \textbf{matrix}\end{bmatrix} + \begin{bmatrix}\textbf{error}\end{bmatrix}$$





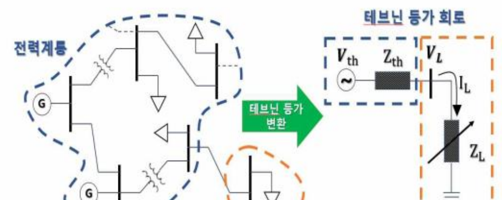


Ⅲ. Research Advancement

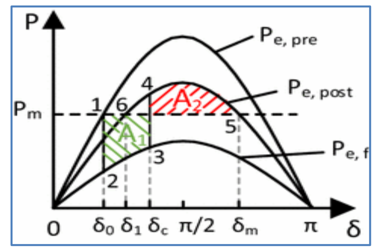
Situational awareness technology

- **Real-time transient stability analysis**

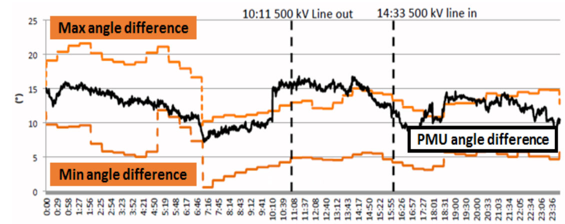
Development of a PMU-based transient stability analysis technique comparable to the EMS system results



Improve impedance estimation accuracy
(1) Improvement of the least squares method
(2) SE Information Integration



[Monitoring of Acceleration Energy Utilizing Estimated Impedance]



[Monitoring of phase differences between regions]

Transient Stability Analysis Method	Lyapunov	Prony	Equal Area Criterion	Hybrid
Input Data	PMU Measurement Data	PMU Measurement Data	PMU Measurement Data	PMU Measurement Data Computation Information
Analysis	Determining stability by accumulating the log of the relative change in data	Estimate the dominant component, its magnitude, and damping of discrete signal	Determining system instability through the power angle difference curve	
Feature	Limitations in the application of large-scale complex system	Requires prior selection of a threshold value	Difficulties in real-time system conditions due to the necessity of equivalent impedance calculation	Periodic table updates are required

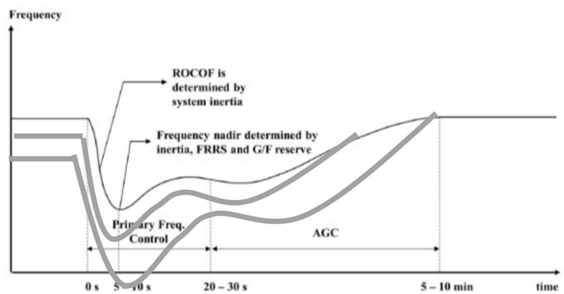
Ⅲ. Research Advancement

Situational awareness technology

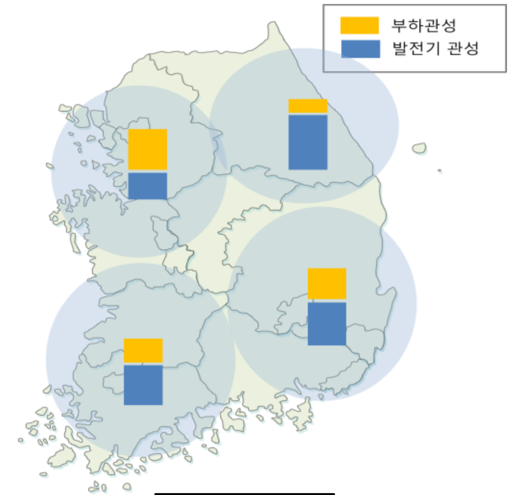
- **Measurement-based inertia estimation technology**

Improve accuracy through measurement-based estimation of the total inertia of the system, including load inertia

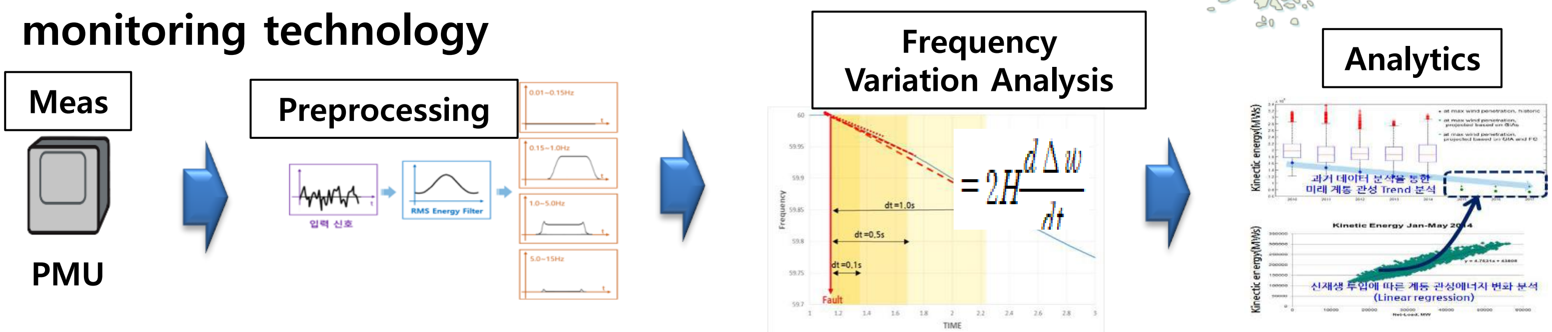
① Lowest critical inertia estimation based on event DB



② Estimation of inertia by region using generator distribution and load differentials



③ Development of measurement-based inertial monitoring technology



[Measurement-based inertia estimation procedure]

Ⅲ. Research Advancement

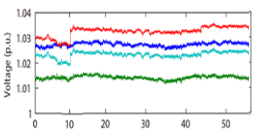
WAMAC technology

- **AI-based fault recognition technology**

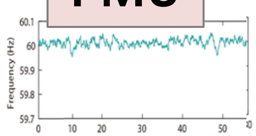
Classification of system fault situations and improvement of recognition accuracy

Data Acquisition → Preprocessing → Anomaly Detection → Training → Fault Identification

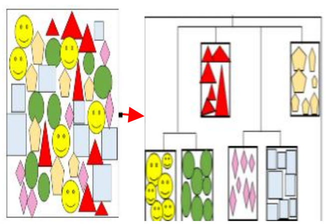
SCADA



PMU



Algorithm

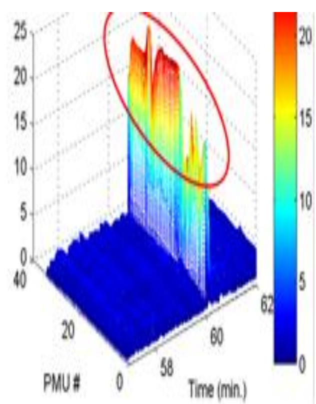


- **Normalization**
- **Noise filtering**
- **Dimension reduction**
- **Data classification**

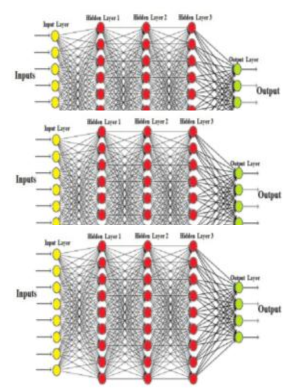
· Clustering algorithm

· Principal Component Analysis

· Noise filter



· Wavelet-Transform



· Deep neural network

· Convolutional neural network

T/L

ground(1p,2p,3p)
short(2p,3p)

Gen

Sync
IBRs

Intergrity

TR
CB

Ⅲ. Research Advancement

WAMAC technology

- **Regional and Inter-area grid control technology**

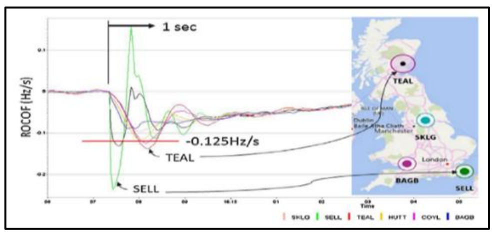
Optimal and adaptive power grid through segmentation and control by power grid characteristics

· Analysis of power grid characteristics by region

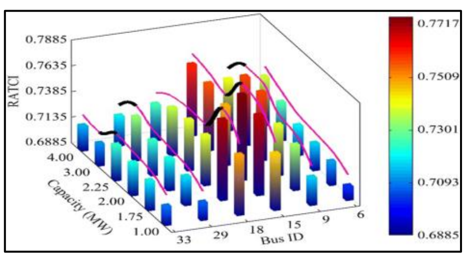
· Co-ord. control technology including distributed / feedback control of IBR&D

· **Control Range**

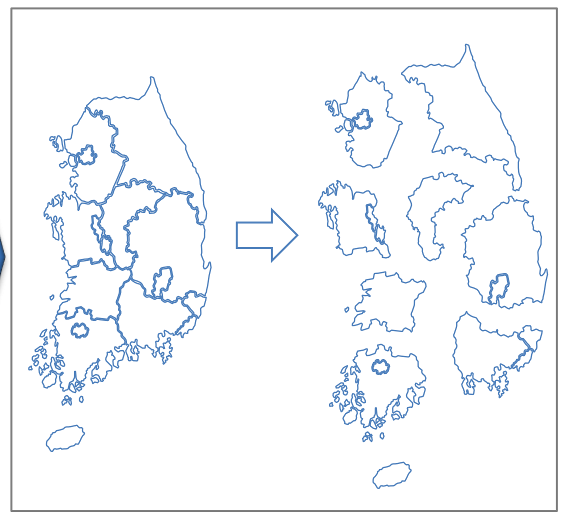
① Shunt R/C ② DNR (T/L and Bus) ③ SPS/Load ④ GETs



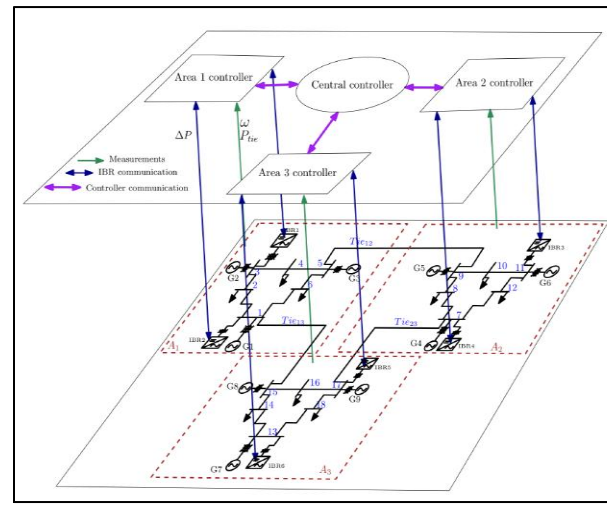
[Regional f/H characteristics]



[Regional V characteristics]



[Regional system characteristics based segmentation]



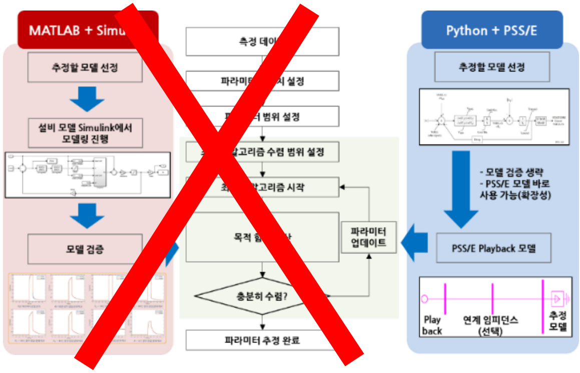
[Measurement-Based Adaptive Power Grid with Hierarchical Architecture]

WAMAC technology

- **Device Model Parameter Estimation**

Generic model comparable to manufacturer device models

· UDM : The manufacturer produces and supplies in consideration of the specificity of its product -> making it difficult for general users to use or change the model.



[Typical parameter estimation procedure]

PSS/e library model-based modeling

Appropriate Structure Selection to Reflect the Dynamics of UDM

Key parameter selection and estimation

Validation Parameter Estimation Model with EMT & PMU Data

IV. PMU Infra. Expansion Plan

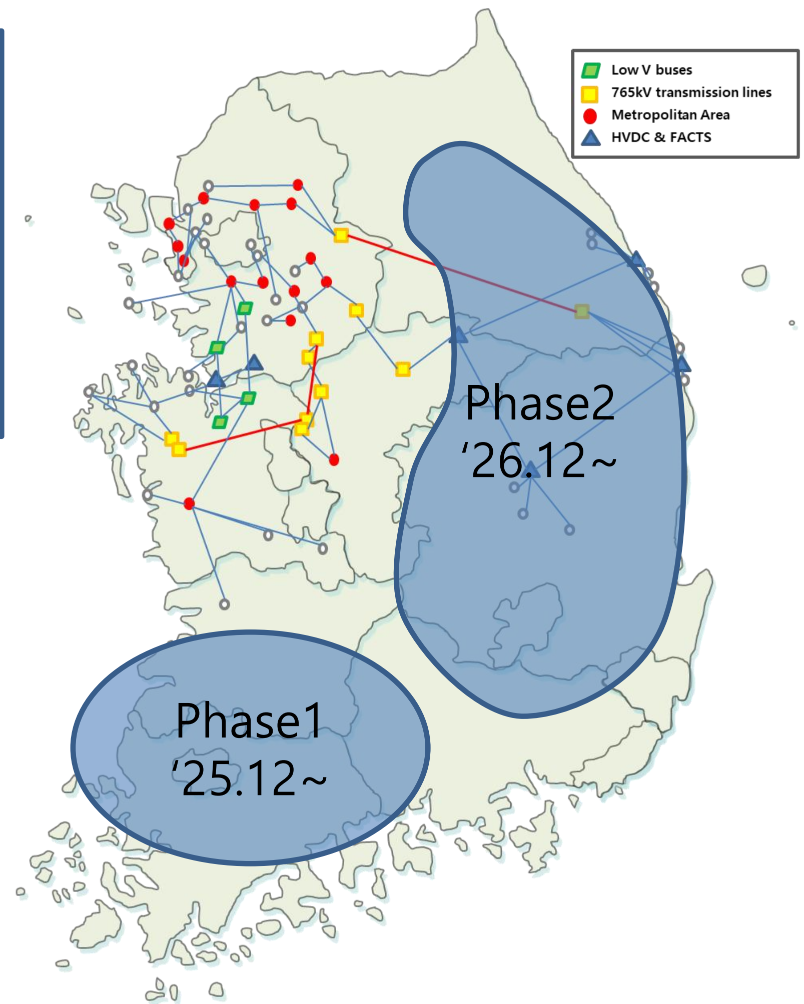
Blueprint

- **PMU & SCADA-mixed precise system monitoring, analysis, and operation system**

Paradigm Change	① WAMS → ② WAMAC → ③ WAMPAC
PMU	Precise monitoring of IBRs output fluctuations, evaluation of nonlinear vibration/stability, etc.
SCADA	Evaluation of voltage and transient stability, overload and fault current, etc.

Planning Phase

Phase 1 ('25~)	▪ **Initiated research project - Development of wide-area system monitoring and control (WAMAC) technology** ▪ Establishment of a preemptive high-precision monitoring system in the Honam region, which is a dense area of IBRs



THANK YOU

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