Next-level WAMS Based on Synchro-waveform to Address Emerging Stability Issues

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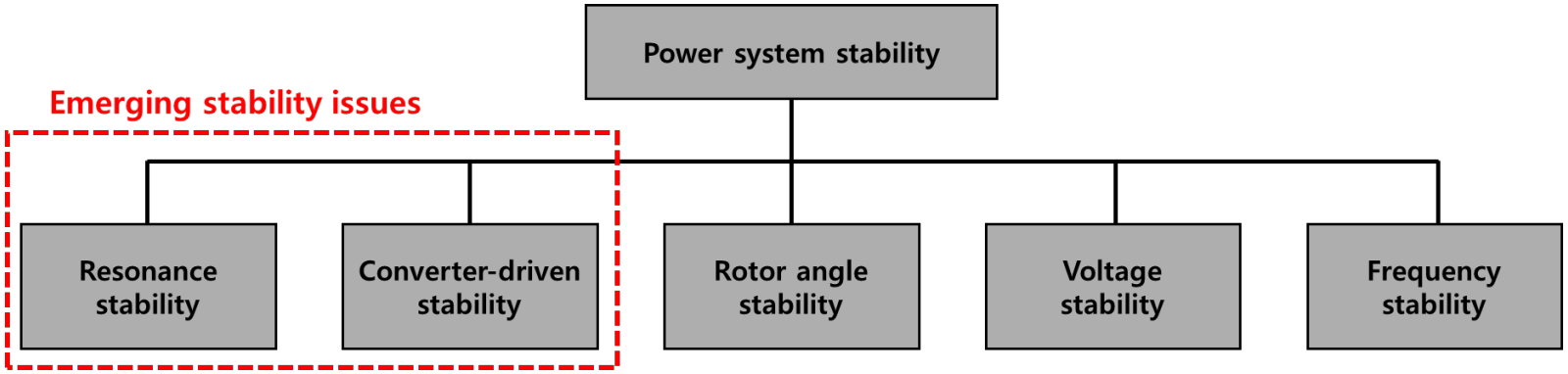
NASPI Work Group Meeting and Vendor (Minneapolis, Minnesota)

April 15-16, 2025

Contents

Emerging Stability Issues

- In 2021, IEEE revised and extended the power system stability classification.

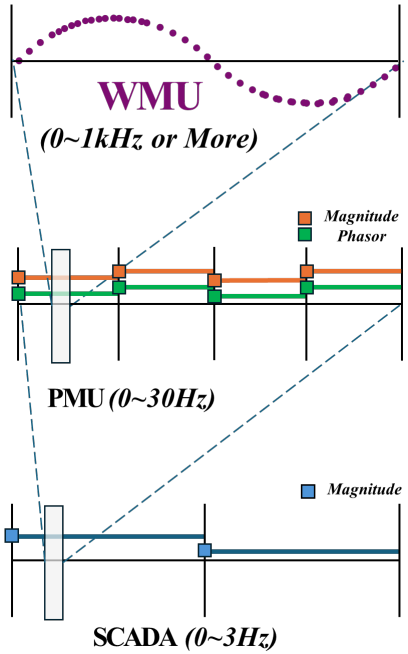


- Newly emerging resonance and converter-driven stability issues have necessitated the introduction of a high-resolution measuring device to capture emerging oscillation issues in the monitoring technique aspect.
- Integrating the new measuring device into the power system requires upgrading the existing wide-area monitoring system (WAMS).

Ref. N. Hatziargyriou et al., "Definition and Classification of Power System Stability – Revisited & Extended," in IEEE Transactions on Power Systems, vol. 36, no. 4, pp. 3271-3281, July 2021

Necessity of WMU

- WMU: the next-generation measuring device
  - A waveform measurement unit (WMU) is a high-resolution measurement unit utilizing synchro-waveform technology.
  - WMU's high waveform reporting rate enables the capture of power system oscillations (sub- and super-synchronous oscillations).

Device	Measuring data	Reporting rate	
WMU	Waveform	Max. 128 sample/cycle	
PMU	Phasor for nominal frequency	Max. 2 sample/cycle	
RTU	Scalar (magnitude)	1 sample for a few seconds	

Necessity of WMU for monitoring oscillation

- We briefly analyze extended dissipating energy flow (DEF), an oscillation source location method, to validate the necessity of WMU for monitoring oscillation.

$$\text{DEF:} \quad W_{ij}^{D} = \int \{\Delta P_{ij} d\Delta\theta_i + \Delta Q_{ij} d\Delta(\ln U_i)\}$$

  - $W_{ij}^{D} < 0$: Energy dissipation at node *i* suggests that the oscillation is being transmitted from near node *j*.
  - $W_{ij}^{D} > 0$: Energy absorption at node *i* suggests that the oscillation is being transmitted toward node *j*.

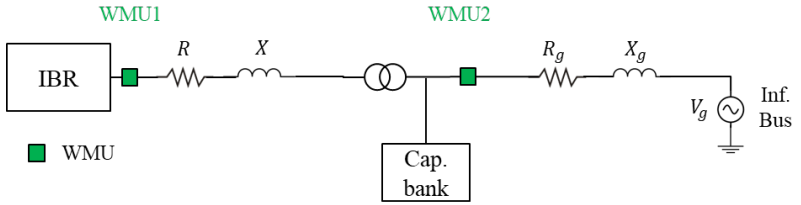
  - While DEF has traditionally been applied using PMU data, its application based on WMU measurements offers improved detection capability.

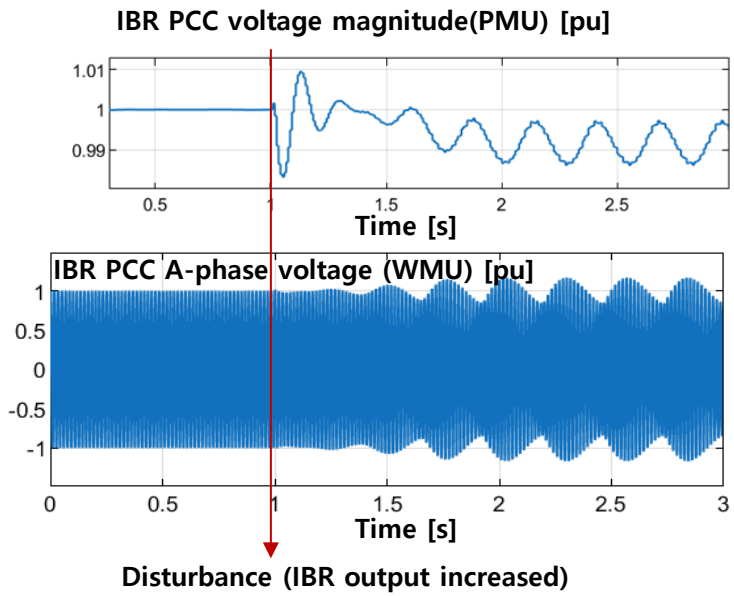
  - How are DEF by PMU and WMU different in detecting oscillations?
  - We analyze DEF on two oscillation cases to identify oscillation source location.
    - Case1: converter-driven stability (due to IBR PLL under weak grid)
    - Case2: electrical resonance stability (between IBR and series capacitor)

Ref. L. Chen, Y. Min and W. Hu, "An energy-based method for location of power system oscillation source," in IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 828-836, May 2013

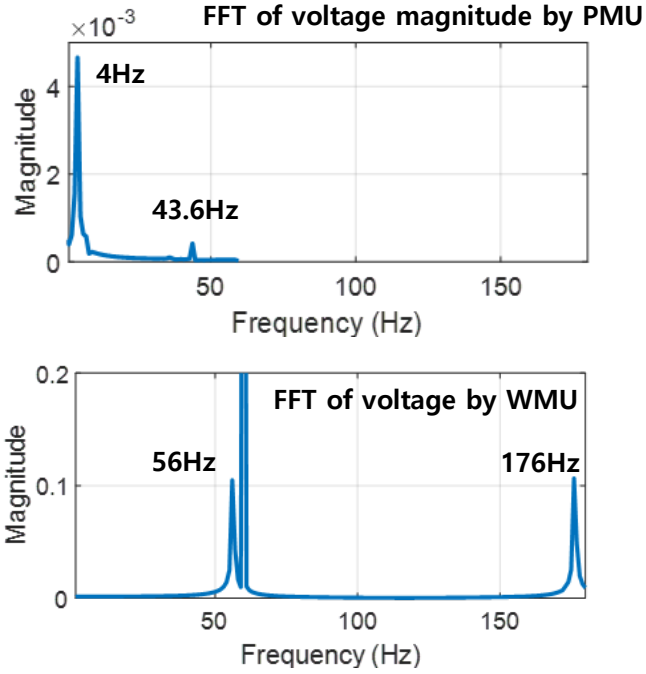
Necessity of WMU for monitoring oscillation

- DEF analysis - Case1: converter-driven stability
  - DDSSO* occurred by untuned control parameters of IBR PLL under a weak grid.
  - The IBR output suddenly increased at 1 sec, injecting a disturbance into the grid.





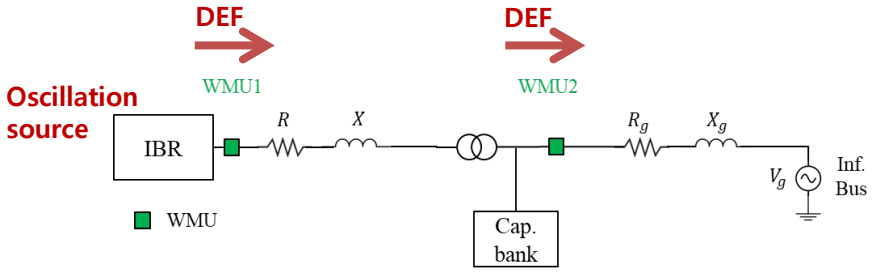
FFT

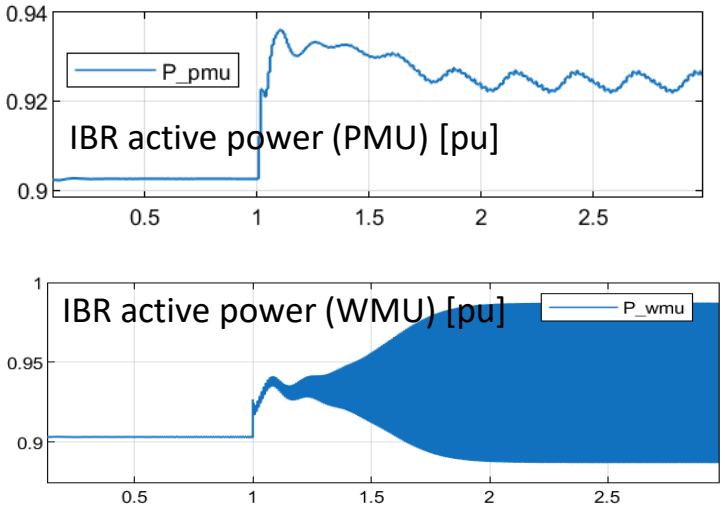


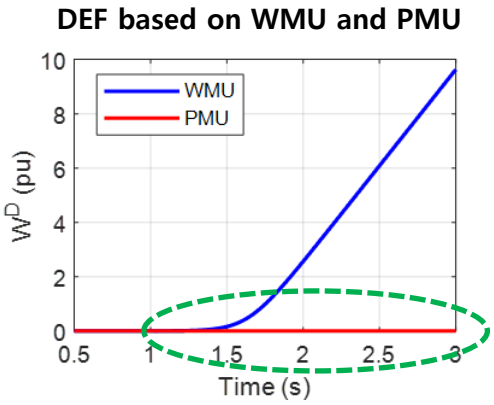
*DDSSO: Device Dependent Subsynchronous oscillation

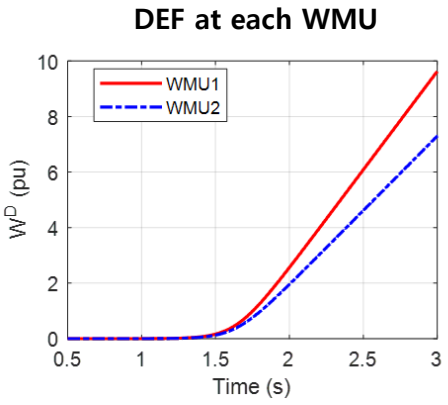
Necessity of WMU for monitoring oscillation

- DEF analysis - Case1: converter-driven stability
  - Comparing DEF using WMU and PMU
    - The WMU-based DEF analysis identified the IBR injection point as the source of the oscillation.
    - However, DEF using PMU figures out that the DEF is near zero.







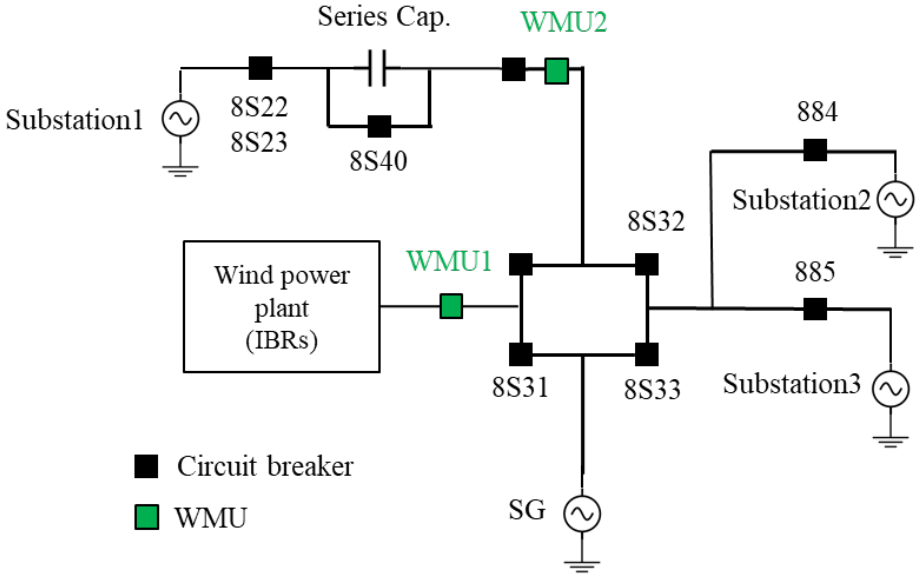


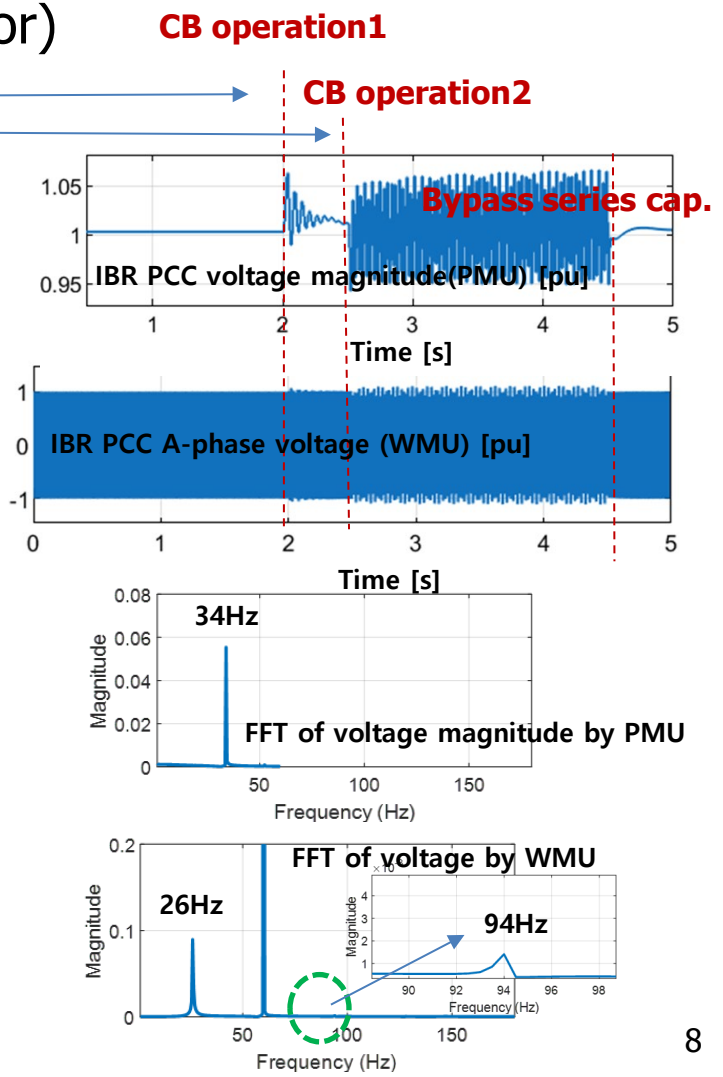
Necessity of WMU for monitoring oscillation

- DEF Analysis - Case2: electrical resonance stability (Interaction between IBR and series capacitor)
  - Circuit breaker 884, 885 opened at 2 sec.
  - Circuit breaker 8S31, 8S33 opened at 2.5 sec.

  ➔ The WPP is directly connected to the series capacitor, and it causes electrical resonance.
  - 8S40 closed at 4.5 sec to bypass series capacitor.

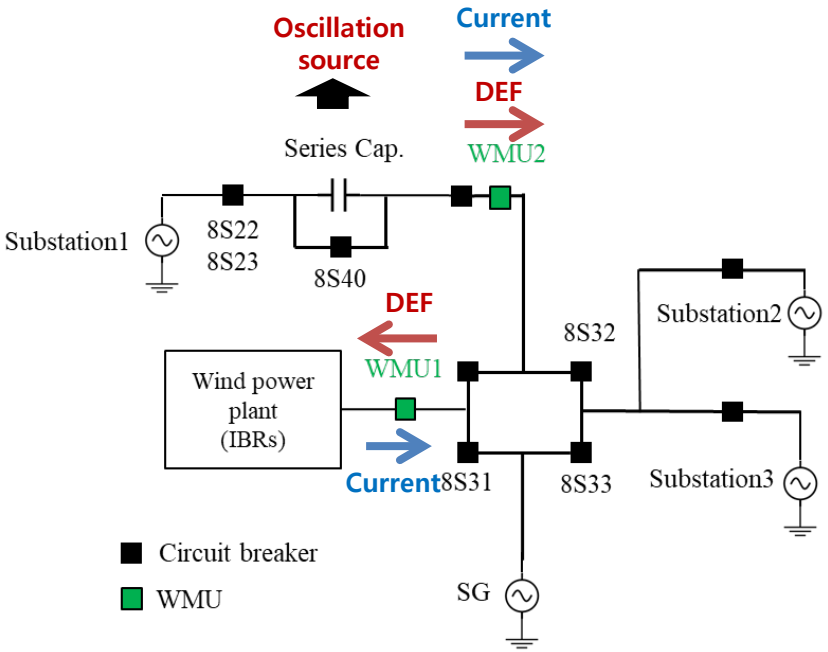
  ➔ It restored to the steady state.

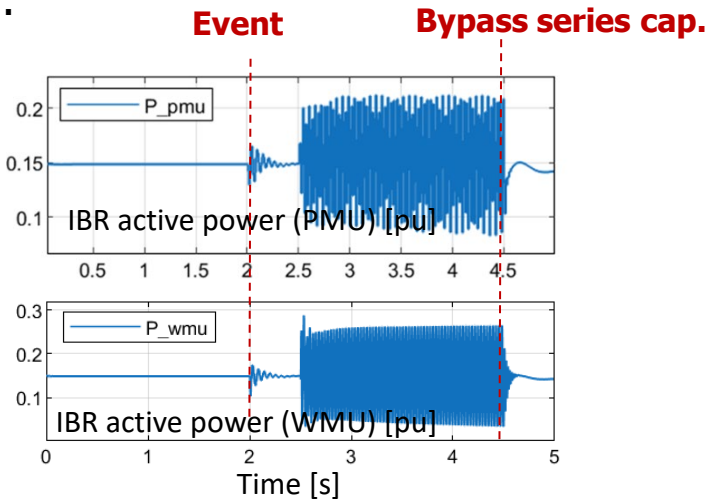


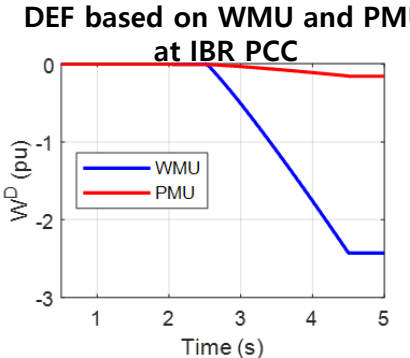


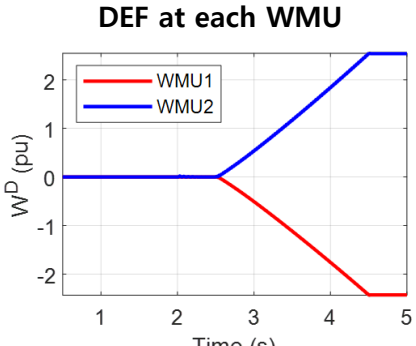
Necessity of WMU for monitoring oscillation

- DEF Analysis - Case2: electrical resonance stability (Interaction between IBR and series capacitor)
  - ➢ DEF using WMU captures oscillation severity clearly better than PMU.
  - ➢ The oscillation is damped when the series capacitor is bypassed. (4.5 sec)
  - ➔ The oscillation resource is eliminated.



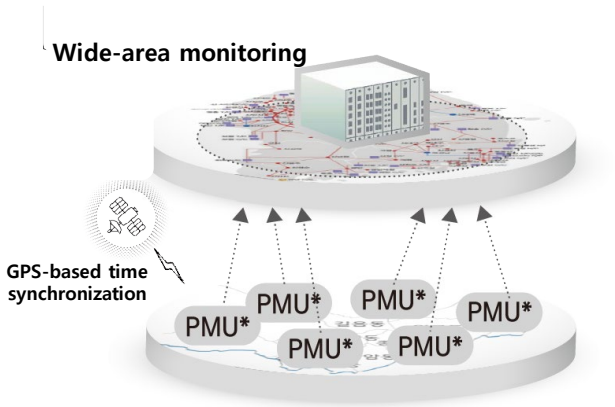
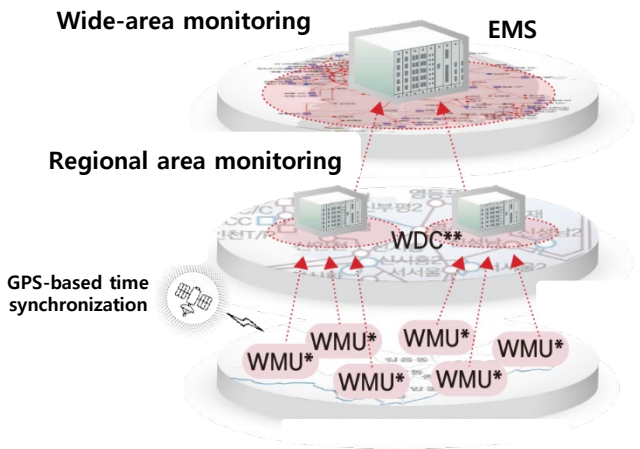






Future Techniques for WMU-based WAMS

- With the deployment of WMUs,
  the architecture of next-level WAMS is anticipated to evolve as below.

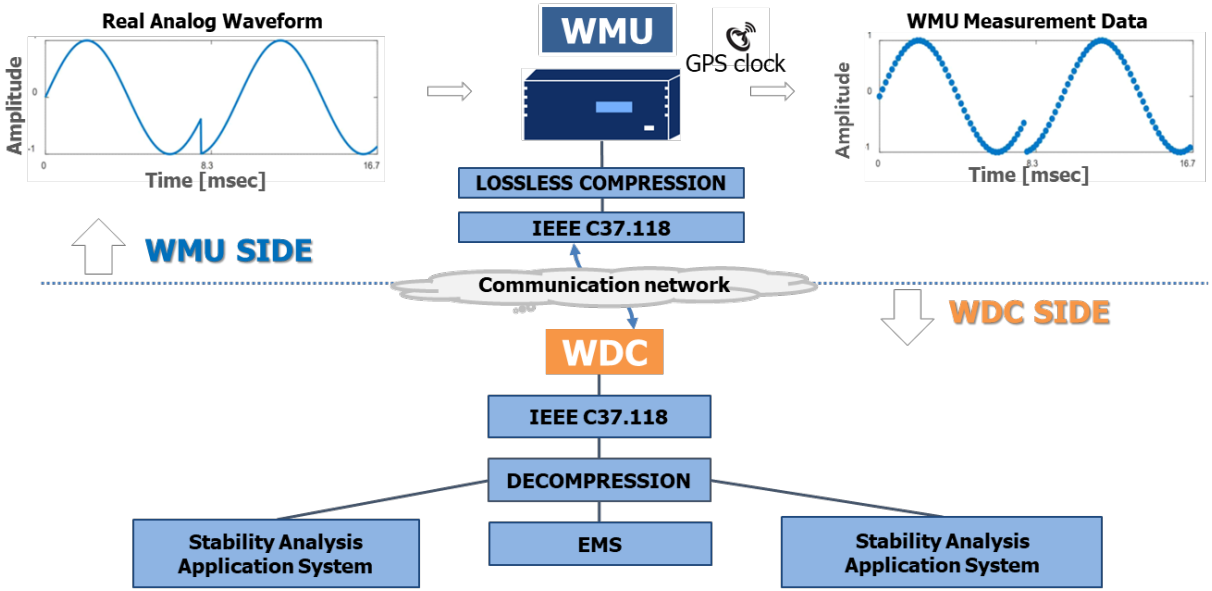
	As-Is	To-Be
	Monitoring Architecture based on PMU, SCADA	**Hierarchical monitoring architecture based on WMU, PMU, and SCADA**
Features	• Single-layer monitoring architecture • AC-centric power grid	• Multi-layer (regional and wide-area) monitoring architecture • Hybrid AC/DC power grid
Monitoring Structure		
Measuring device	▪ Data measurement using PMU and SCADA ➔ Phasor and scalar data	▪ Data measurement using WMU, PMU, and SCADA ➔ Waveform, phasor, and scalar data
Stability Monitoring	▪ Existing stability: voltage, frequency, transient stability ▪ Emerging stability: under 30 Hz oscillations	▪ Existing stability: voltage, frequency, transient stability ▪ Emerging stability: enables to monitor high-frequency oscillations

Future Techniques for WMU-based WAMS

- The Structure of WMUs and waveform data concentrators (WDCs)

WMU for High-Resolution Waveform Measurement

- **Main Function:** Continuous Waveform Recording, Seamless Data Capture, Outage Ride Through
- **Main Components:** High-speed ADC (Analog-to-Digital Converter) , Precise Time Synchronization, High-Speed Data Storage, High-Speed Communication

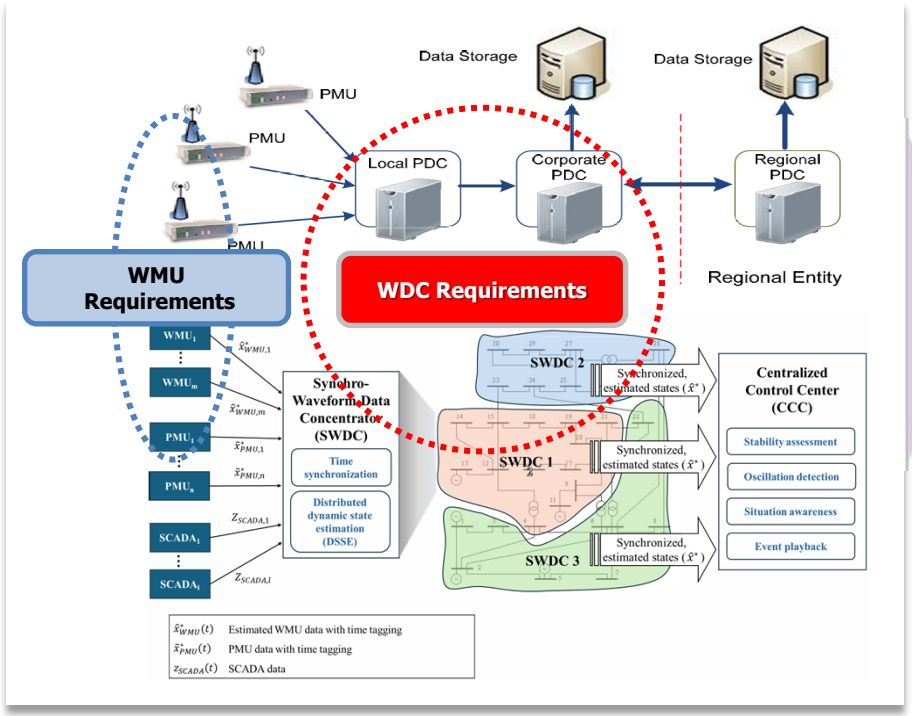


WDC for Aggregating WMU Data

- **Main Function**: Real-Time Data Collection from WMUs, Time Synchronization and Preprocessing, Data Transmission via Communication Protocols
- **Mian Components**: Data Acquisition Module, Communication Protocol, Time Synchronization Unit, etc.

Future Techniques for WMU-based WAMS

- Standardization of General Requirements and Communication Data Fields for WMU/WDC and WAMS
  - The new standard presents general functional requirements in terms of measurement and communication for achieving an advanced monitoring system



Standards for WMU, WDC, and WAMS

- **Functionality of Time-Synchronized Waveform Measurement in WMUs**
- **Communication Protocol and Data Exchange Between WAMS and WDC**
- **Architectural Model for Components, Communication, and Data Based on IEC**
- **Establishment of general requirements of WMU, WDCs**

Future Techniques for WMU-based WAMS

- A high-resolution WAMS Based on WMU
  - **Hybrid State Estimation-based** Online Situational Awareness and Playback

Online Situational Awareness

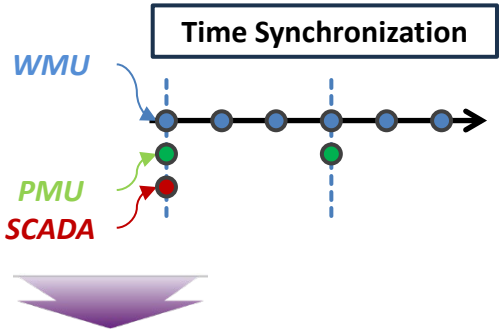
Domain Integration and Time Synchronization for Heterogeneous Data Integration

Time-domain

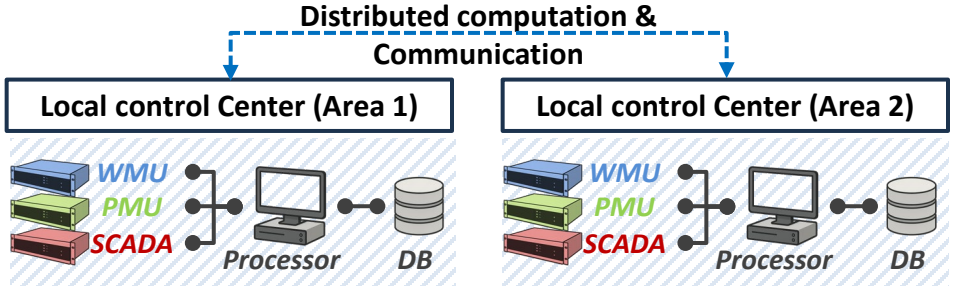
$$v(t) = V_m \cos(2\pi f t + \theta_v)$$
$$i(t) = I_m \cos(2\pi f t + \theta_i)$$

Frequency-domain

$$\dot{V} = V_m e^{j\theta_v}$$
$$\dot{I} = I_m e^{j\theta_i}$$

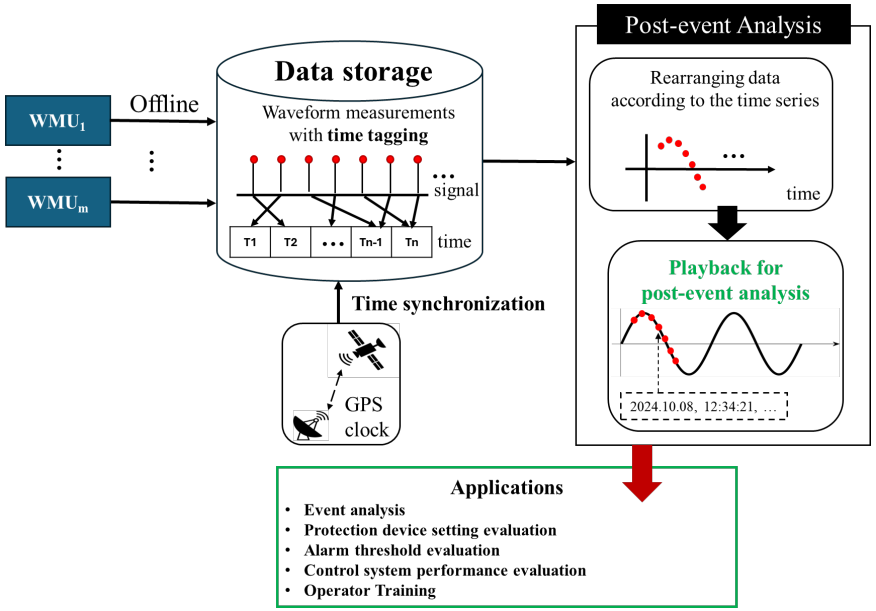


Online Distributed Hybrid State Estimation based on WMU·PMU·SCADA Data integration



Event Playback

WMU Data / HILS -based Offline Playback For Post-Event Analysis



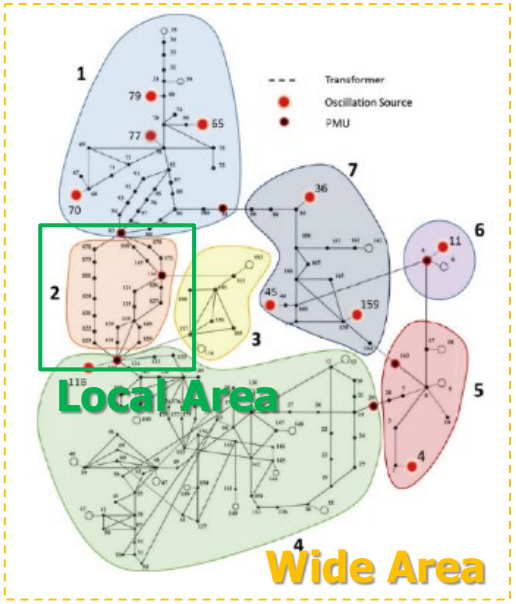
Architecture of event playback based on WMUs

Future Techniques for WMU-based WAMS

- WMU-based online wide-area situational awareness applications
  - Online High-Resolution Oscillation Awareness and Source Location

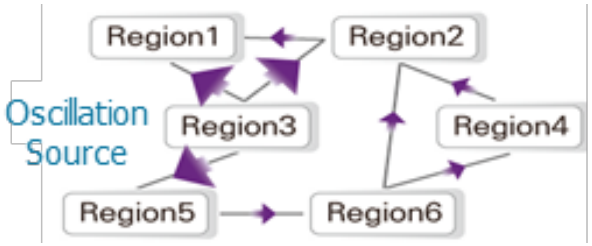
DEF-based Local and Wide-Area Oscillation Source Location Under Grid Partitioning and Hierarchical Monitoring System

The oscillation observable region of each WMU can be distinguished based on their respective locations

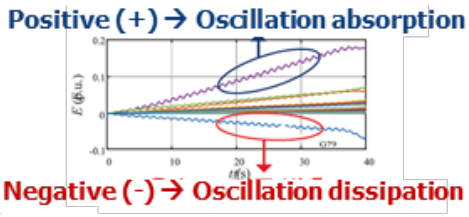


When oscillation occurs,

energy is dissipated from the oscillation source



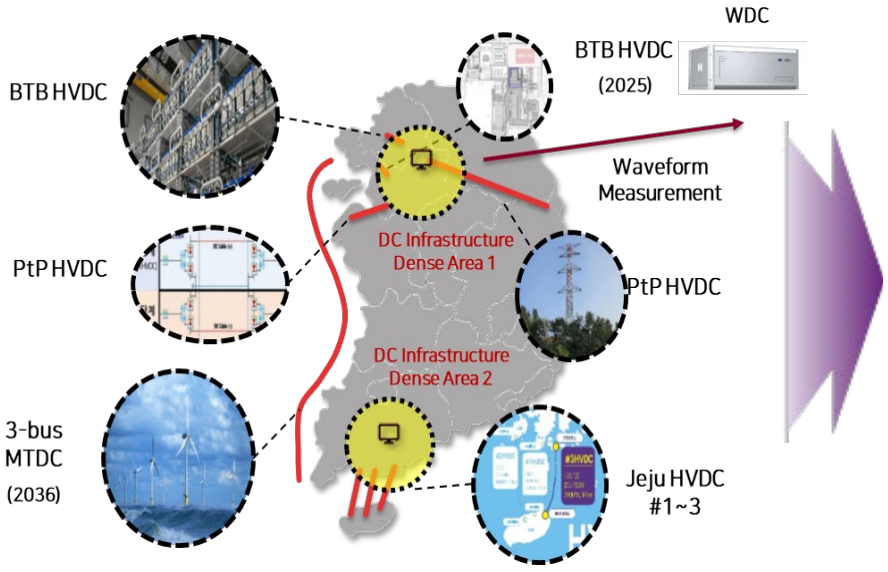
Using DEF, **the direction of energy flow can be calculated**, and the area with the highest energy deviation is identified as the oscillation source



Future Techniques for WMU-based WAMS

- WMU-based online wide-area situational awareness applications
  - Stability Monitoring Technology for Converter Infrastructure-Intensive Areas

WMU-based Situational Awareness Technology for Converter-Intensive Area Including HVDC and MTDC



- With the growing deployment **of large-scale DC transmission systems**, **interaction between converters** has become a key factor in oscillation stability issues

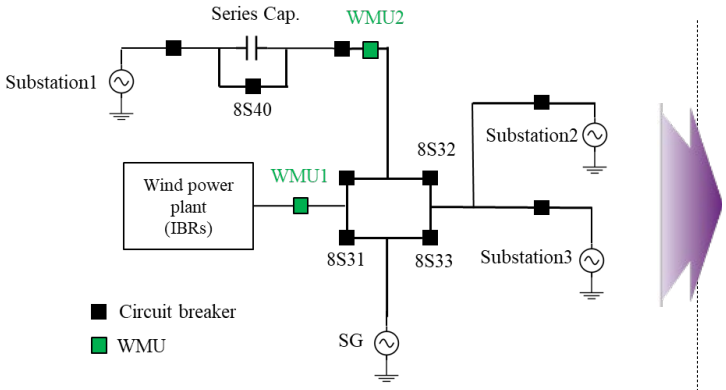
- Since **large HVDC/MTDC systems are often adjacent to large-scale renewable energy plants**, monitoring for oscillation instability is critical

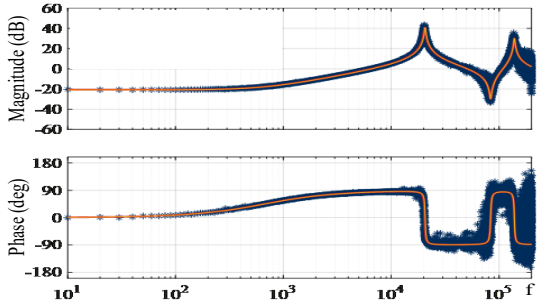
➔ **To ensure reliable operation, advanced situational awareness technology is needed through precise monitoring in DC infrastructure-Intensive Areas**

Future Techniques for WMU-based WAMS

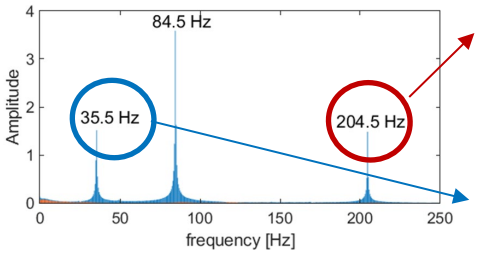
- WMU-based online wide-area situational awareness applications
  - WMU Data-based Converter-Driven Stability Monitoring Technology

Online Power System Impedance Estimation and Converter-Driven Stability Assessment / Root Cause Analysis





[Online Impedance Estimation]



High frequency (~kHz)

LCL filter | Current control | ...

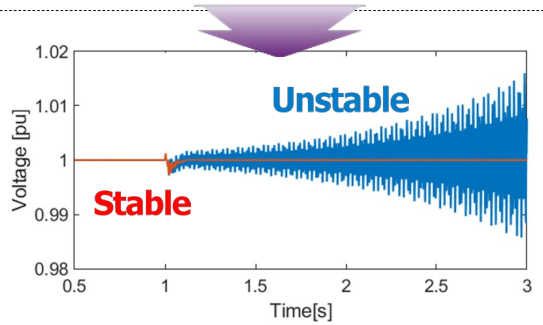
Grid Impedance

Low Frequency (<100Hz)

PLL | Voltage control | ...

Power control

[Identification Root Cause by Frequency]



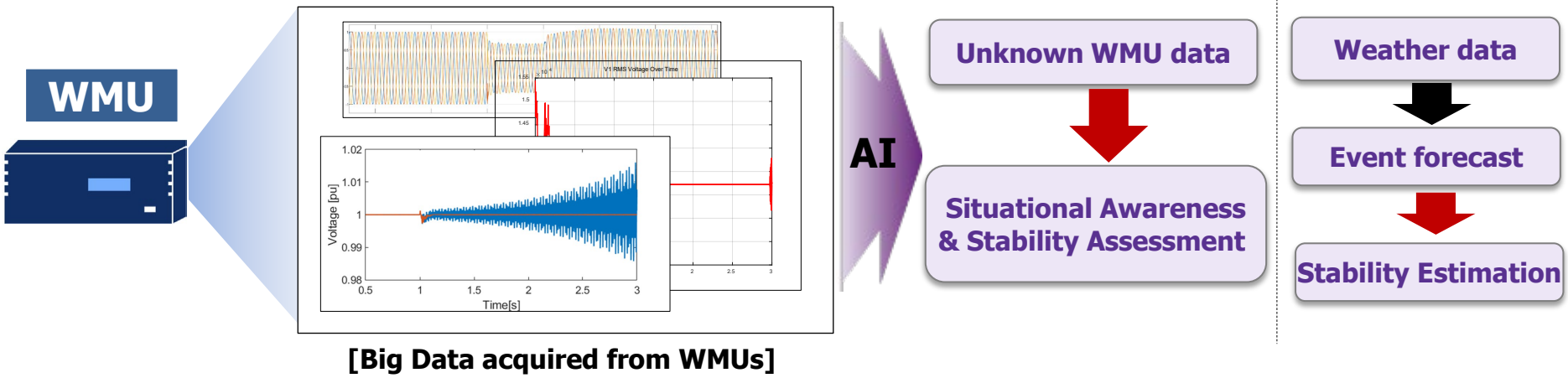
[Converter-Driven Stability Assessment]

Future Techniques for WMU-based WAMS

- WMU-based online wide-area situational awareness applications
  - AI- /Big Data-Driven Advancement of Stability Monitoring Technology

Event Forecast and Wide-Area based AI-driven Online / Offline Stability Technology Advancement

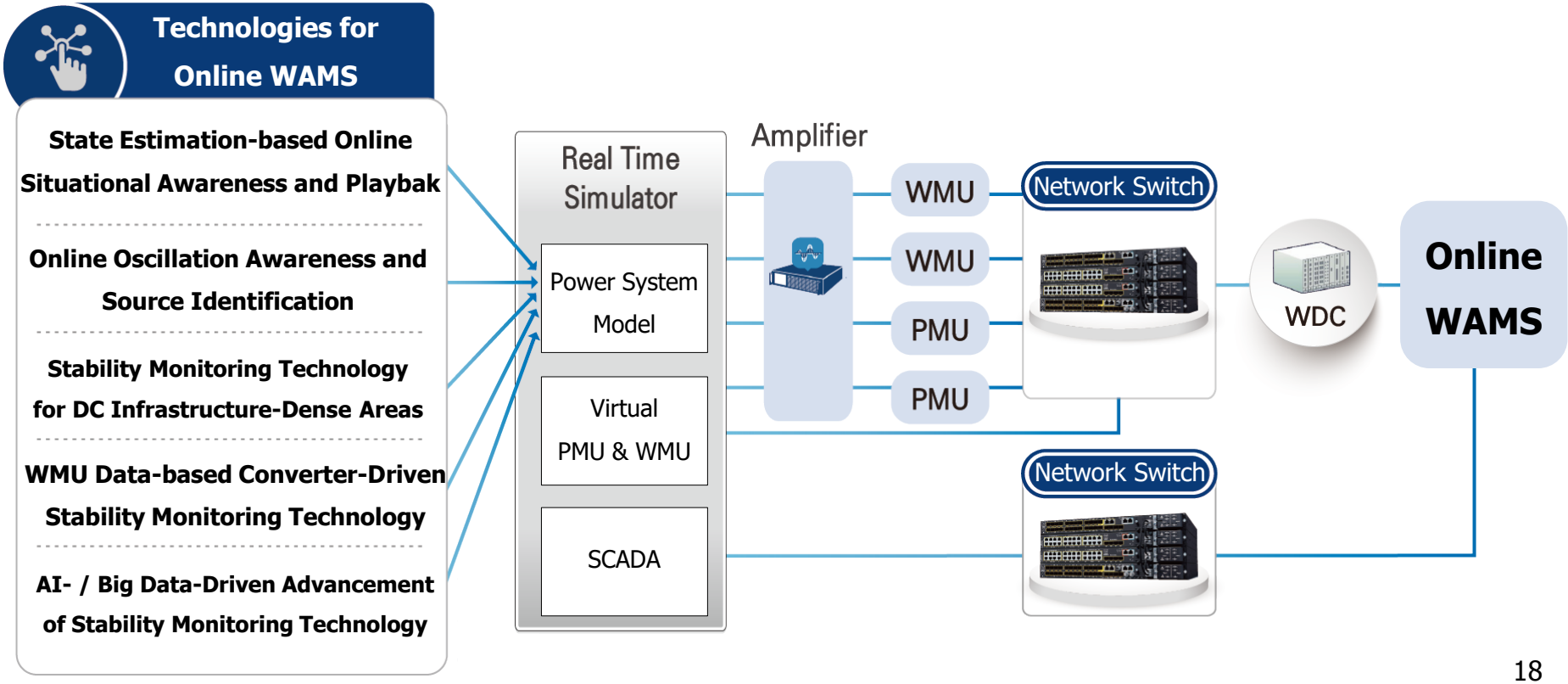
- **The integration of AI with big data acquired from WMUs** enables the advancement of WMU-based **WAMS**
- **(Monitoring Advancement) AI-based Data-driven WAMS advancement**
- **(Stability Estimation) Event forecast using weather data and stability estimation**



[Big Data acquired from WMUs]

Future Techniques for WMU-based WAMS

- The HILS validation of the devices and WAMS
  - HILS verification environment for **WMU**, **WDC**, and **WAMS**
  - **Local and wide area stability monitoring system** of Performance verification prior to field deployment



Conclusion

Challenges Facing Power Systems with High IBR Penetration

- With the increasing penetration of IBR, high-frequency oscillations have been observed
  ➔ Resonance and Converter-driven stability
- PMU cannot capture such high-frequency oscillation due to their limited sampling rate
- WMU can capture it by sampling raw waveform data with high sampling rate
- Despite its advantages, the application of WMUs still faces technical challenges such as the large volumes of data and significant communication burdens

WMU-based Next-level WAMS

- WMU-based WAMS requires continuous key technical and implementation challenges as follows:

① WMUs & Waveform Data Concentrators (WDC) for measuring and aggregating waveform data

② High-Resolution WAMS Featuring Hybrid State Estimation and Playback

③ Standardization of General Requirements for WMU/WDC and WAMS

④ WMU-based Online Wide-Area Situational Awareness Applications

Thank you

Q & A