

C4 Power system
technical
performance

C2 Power system
operation and control



Review of Advancements in Synchrophasor Measurement Applications



TECHNICAL BROCHURES
November 2025 - Reference 975

Review of Advancements in Synchrophasor Measurement Applications

CIGRE JWG C4/C2.62

Presenter: Athula Rajapakse



NASPI *Novel Applications for
Synchronized Power Instrumentation*
A DOE-EPRI Joint Initiative

Agenda

- Introduction
- Background of the working group and technical brochure
- Overview of chapters and representative contents
- Conclusions



TECHNICAL BROCHURE

Review of Advancements in Synchronphasor Measurement Applications

JWG C4/C2.62

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Background

- CIGRE has studied the industry developments and published several technical brochures on the application of synchrophasor measurement technology.
 - CIGRE TB 330 “*Wide Area Monitoring and Control for Transmission Capability Improvement*” - 2007
 - CIGRE TB 702 “*Application of PMUs for Monitoring Dynamic System Performance*” published - 2017
 - CIGRE TB 843 “*Life Cycle Testing of Synchrophasor Based Systems used for Protection, Monitoring and Control*” - 2021
 - CIGRE TB 917 “*Wide Area Monitoring Protection and Control Systems – Decision Support for System Operators*” - 2023.
- JWG C4/C2.62 started in June 2021 to provide update on applications

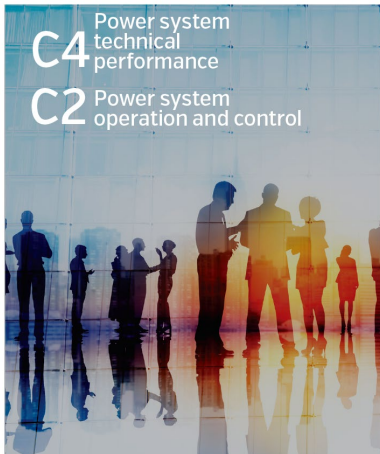
Rationale for the Review

- Recent revisions to standards and guidelines.
- Rapid increase of the number of utilities deploying synchrophasor systems and integrating them with EMS
 - Learning from wealth of real-world experiences
- Increased diversity of synchrophasor applications, specially for facilitating renewable energy integration
- Growing experiences in real-time protection and control applications
- Interest in distribution applications of synchrophasors

Aims and Scope of JWG C4/C2.62

- To provide an updated overview of synchrophasor technology including standard updates and distribution PMUs
- To provide an updated view of industry and academia experience on the concentration, archiving, and use of PMU data.
- To describe emerging applications and any technology gaps such as high dependency on reliable telecommunication, precise time synchronization, signal latency, etc.
- Elaborate and deliver application examples for new specific PMU applications
- To discuss and elaborate the end-user's experiences of deploying synchrophasor measurement systems and applications

Content of TB 975



**Review of Advancements in
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 **TECHNICAL BROCHURES**
November 2025 - Reference 975

1. Introduction
2. Advancements in the technology and standards
3. System architecture, data integration and protocols
4. Applications deployed in the industry
5. Potential applications
6. Outlook for next 5-10 years
7. Conclusions

168 pages

Content of TB 975



**Review of Advancements in
Synchrophasor Measurement
Applications**

 **TECHNICAL BROCHURES**
November 2025 - Reference 975

1. Introduction
2. **Advancements in the technology and standards**
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Advancements in the technology and standards

2. Advancements in the Technology and Standards

2.1 Synchrophasor-based Wide Area Measurement System

2.2 Standards

2.3 Time Synchronization

2.4 Phasor Measurement Units

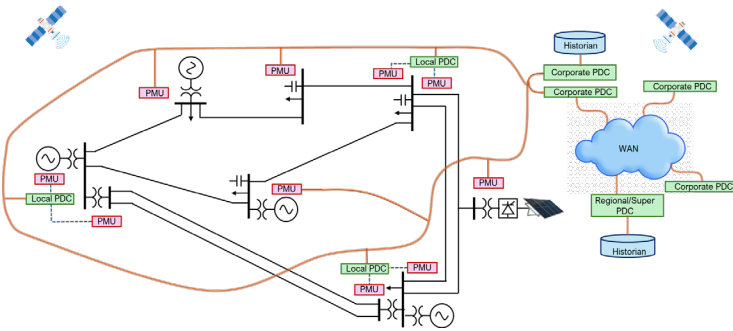
2.5 Data Concentration

2.6 Testing, Verification and Commissioning of PMU/PDC

2.7 Security and Certification of Synchrophasor Systems

2.8 Chapter Conclusion

2.9 References for Chapter 2



Content of TB 975



**Review of Advancements in
Synchrophasor Measurement
Applications**

 **TECHNICAL BROCHURES**
November 2025 - Reference 975

1. Introduction
2. Advancements in the technology and standards
3. System architecture, data integration and protocols
4. Applications deployed in the industry
5. Potential applications
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7. Conclusions

System architecture, data integration and protocols

3. System architecture, data integration and protocols

3.1 Data communication networks

3.2 System architecture

3.3 SCADA/EMS and WAMS integration

3.4 System architecture examples

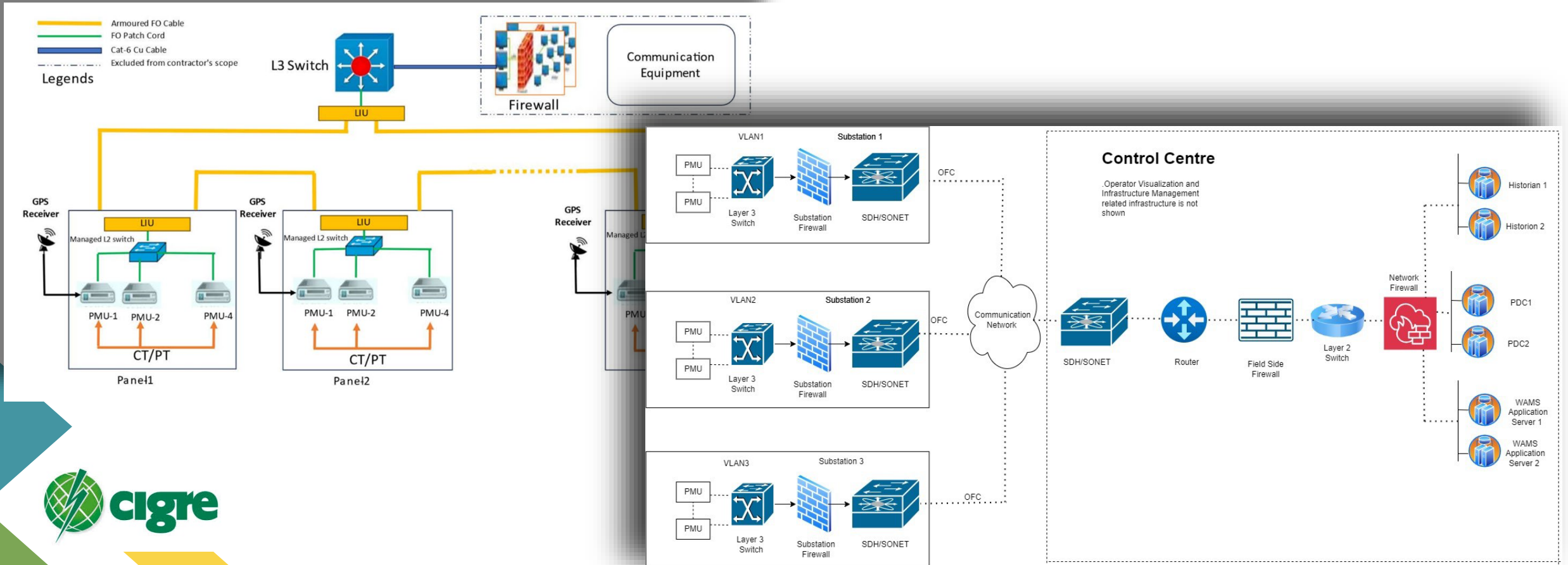
3.5 Data validation

3.6 Chapter conclusion

3.7 References for chapter 3

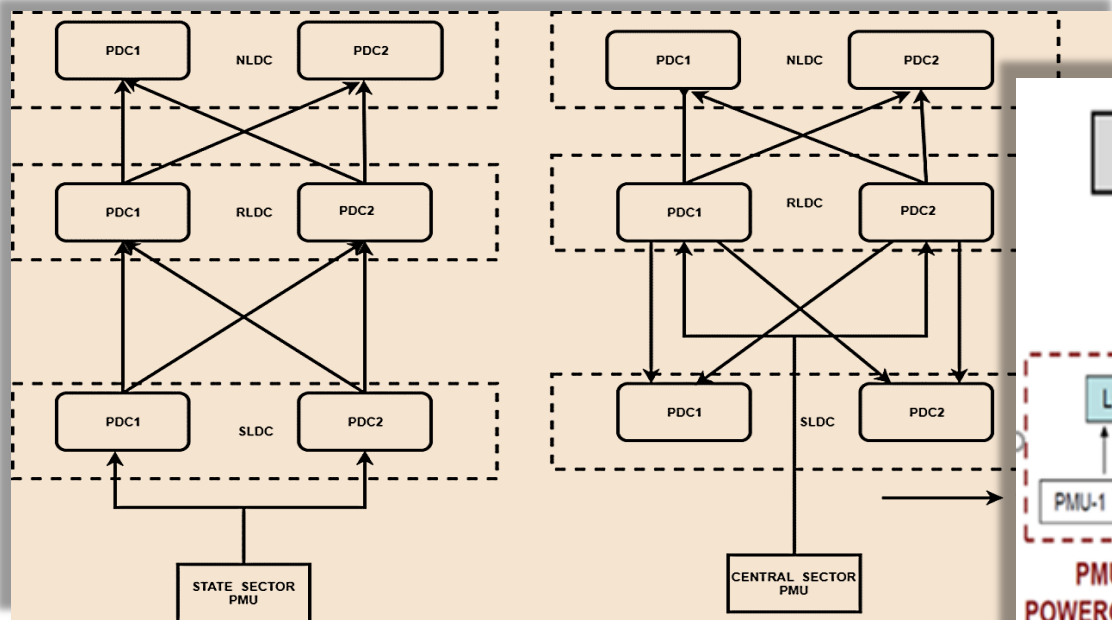
System Architecture

- Typical architectures used within substations and substations to control centres

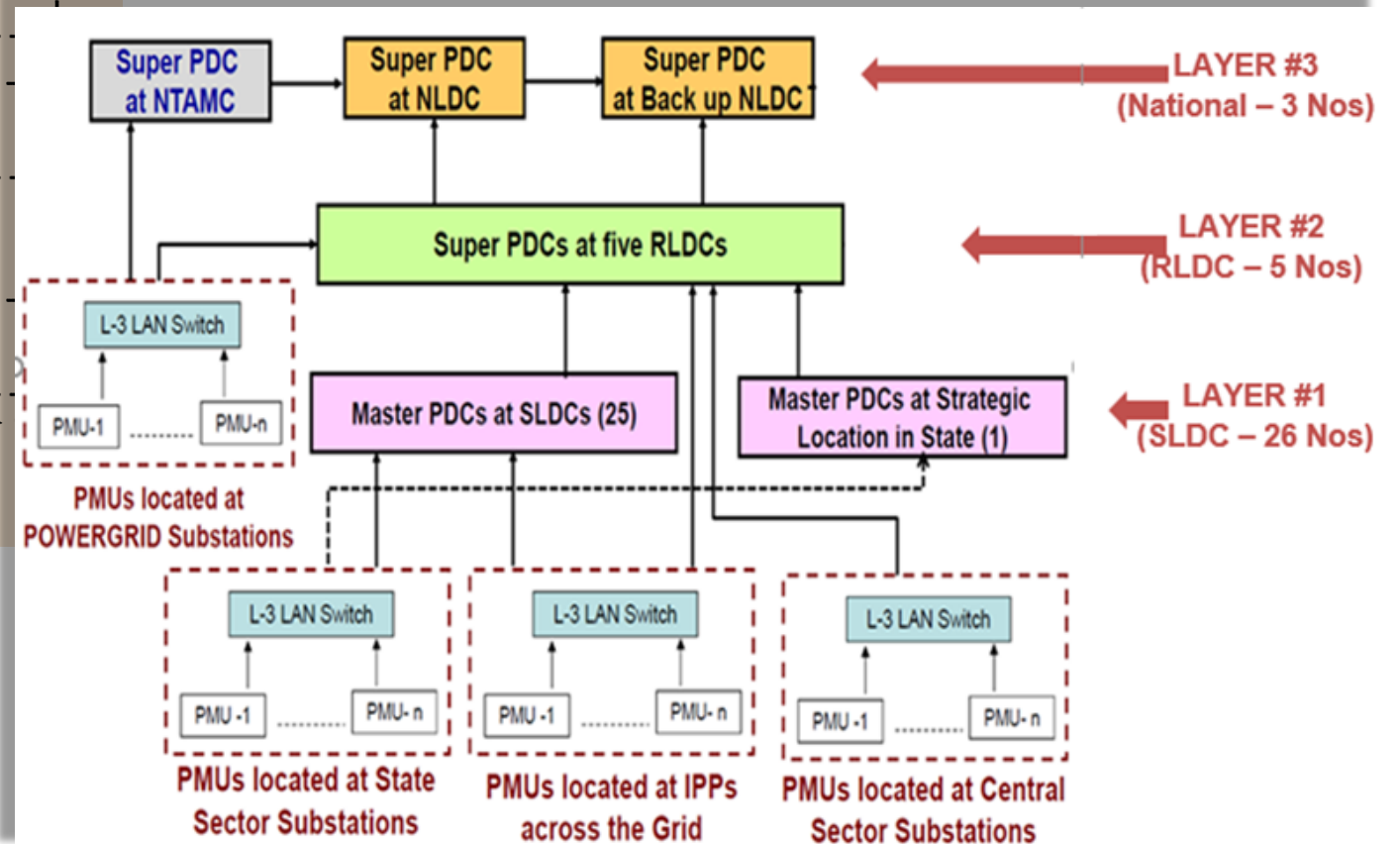


System Architecture Examples

■ Grid-India Real-Time Dynamic State Measurement System



LDC: Load Dispatch Centre
 S: State
 R: Regional
 N: National

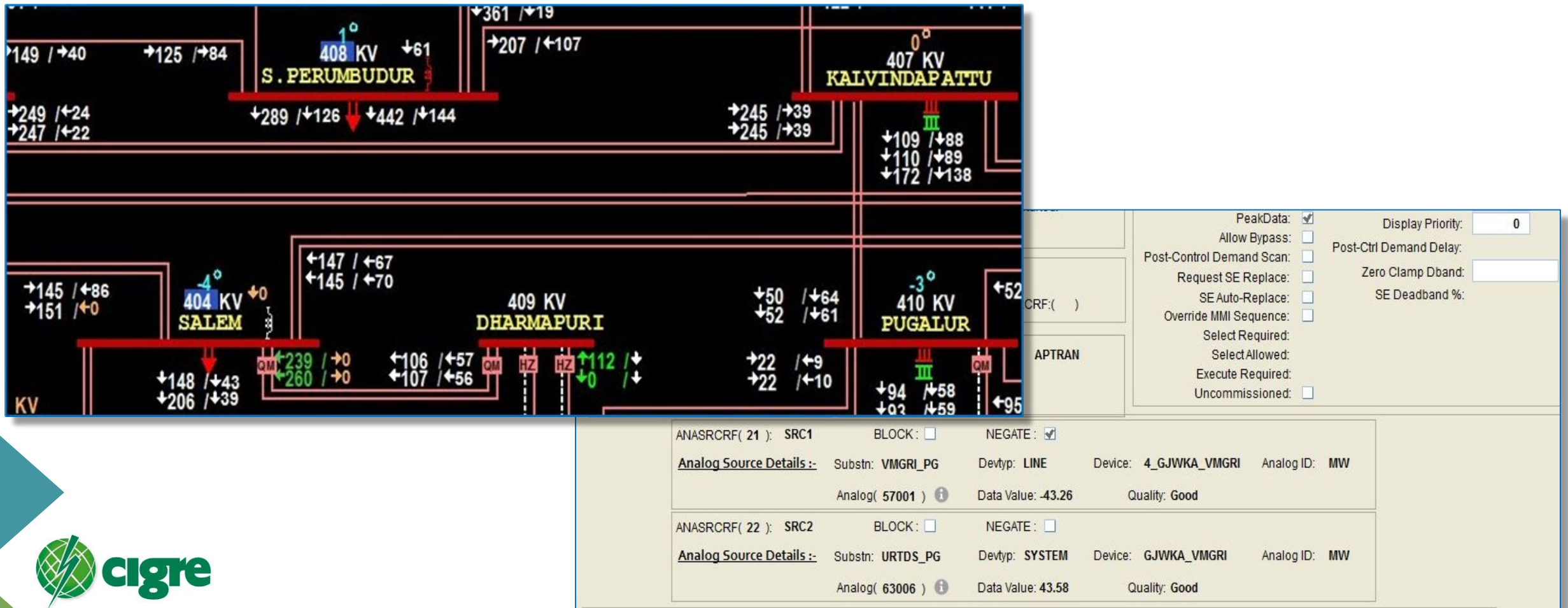


SCADA/EMS and WAMS Integration

- The integration of SCADA data and WAMS data in control centers enables a comprehensive view of the power system.
- Separate SCADA and WAMS data for power system monitoring divides the real-time operator's focus.
 - SCADA/EMS with their RTUs or substation automation systems (SAS), excel in control and integration of analogue and digital signals from all voltage levels.
 - PMUs provide precise, time-synchronized data, primarily at the EHV/HV levels, however, lack control features
- The next generation monitoring, visualization and control systems should be capable of integrating SCADA/EMS and WAMS into a unified module to maximize the benefits.

SCADA/EMS and WAMS Integration

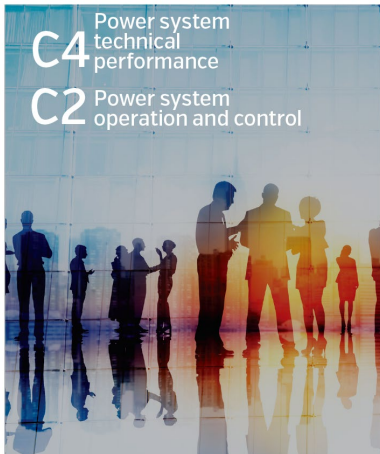
- SCADA screen showing phasor data – Grid India.



Chapter 3 conclusions

- Modern synchrophasor measurement system architectures with highly desirable features are emerging.
 - Layering, modularity, and other architectural constructs
 - Enable scalability, functional flexibility, and future-proofing.
- Optimum WAMS and SCADA systems integration is vital for electric grid resiliency and reliability
 - Comprehensive and integrated analysis of the grid's operational state
 - Enable early detection of anomalies and effective decision-making
- PMU data validation is highly important, and further research is needed for improving.
 - Robust, scalable, and adaptive data validation techniques,
 - Utilizing the AI technology.

Content of TB 975



**Review of Advancements in
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 **TECHNICAL BROCHURES**
November 2025 - Reference 975

1. Introduction
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Applications Deployed in the Industry

4. Applications deployed in the industry

4.1 Improved situational awareness

4.2 Post-event analysis

4.3 PMU-enhanced state estimation

4.4 Oscillation monitoring

4.5 Long-term voltage stability monitoring

4.6 Model validation and calibration

4.7 Controller tuning requirements and performance validation

4.8 Grid code compliance monitoring

4.9 Inertia estimation

4.10 System integrity protection schemes

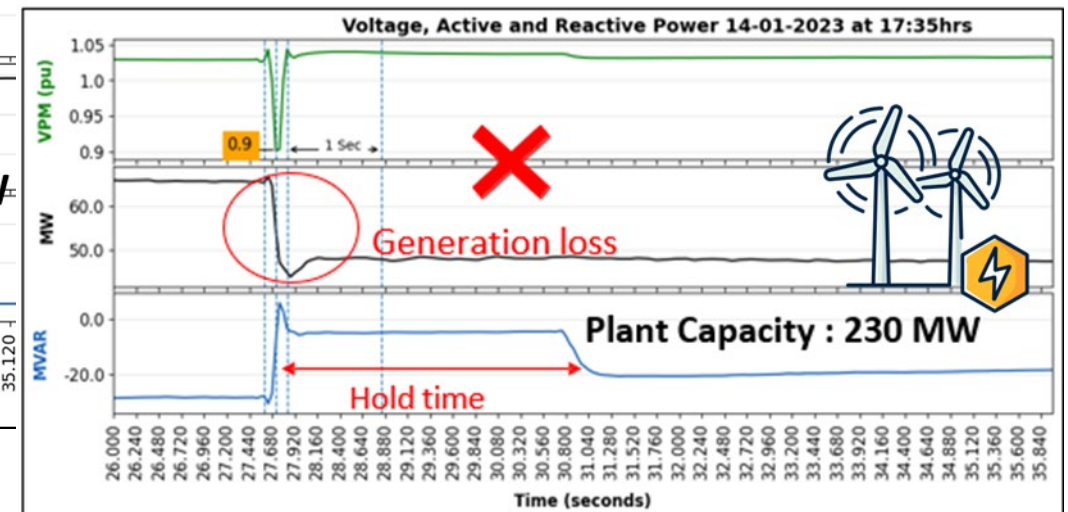
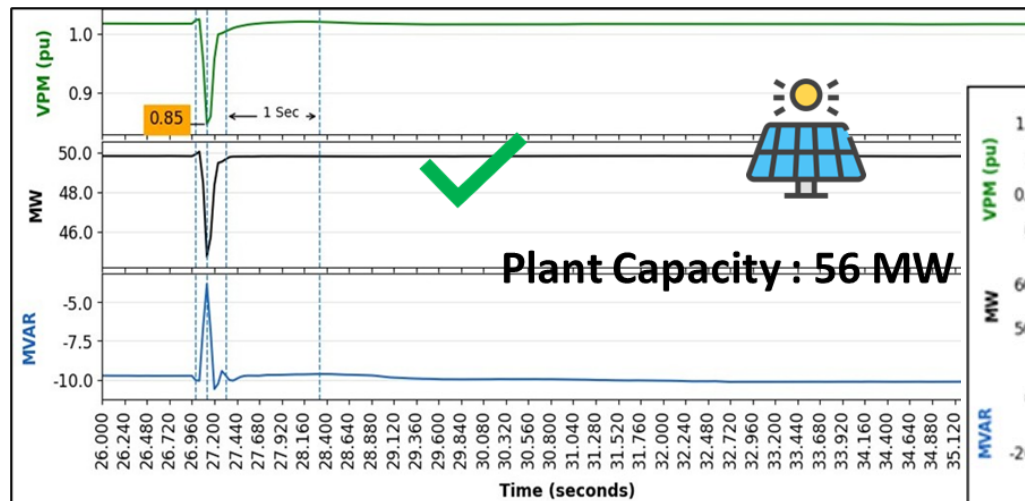
4.12 Wide area control systems

4.13 Chapter conclusions

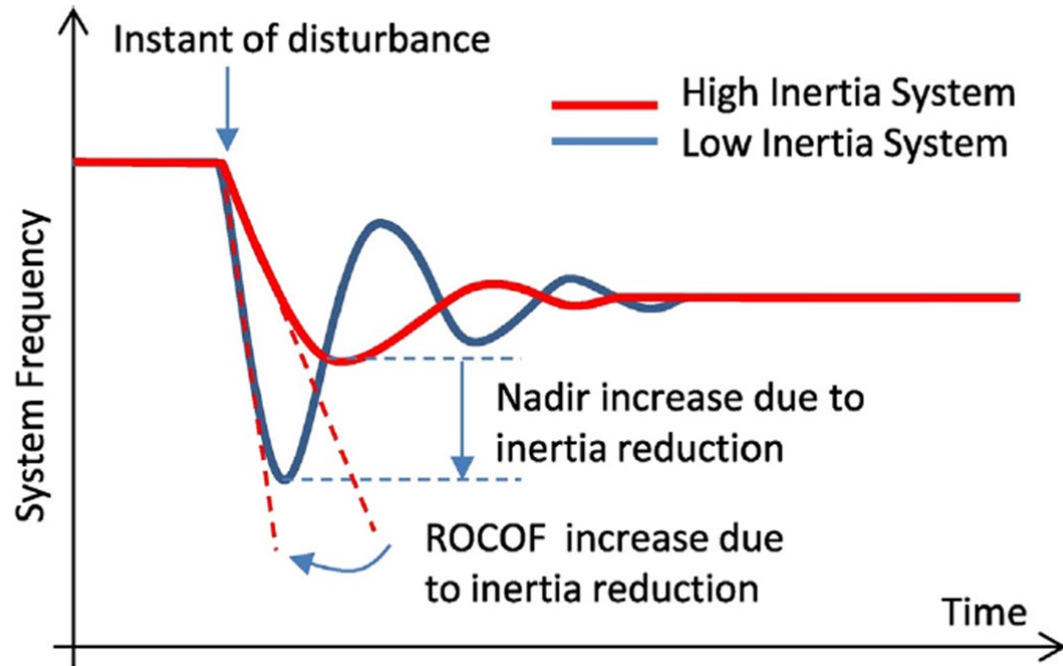
4.14 References for chapter 4

Grid code compliance monitoring

- Monitoring Fault Ride Through Response of Solar and Wind Power Plants.
 - Capability of electric generators to stay connected in short periods of lower electric network voltage has become one of the major grid connection requirements to be met by IBR.
 - PMUs installed on IBR based power plants were found very useful for monitoring the LVRT response as shown in Figure 4.46 [4.93].



Inertia estimation

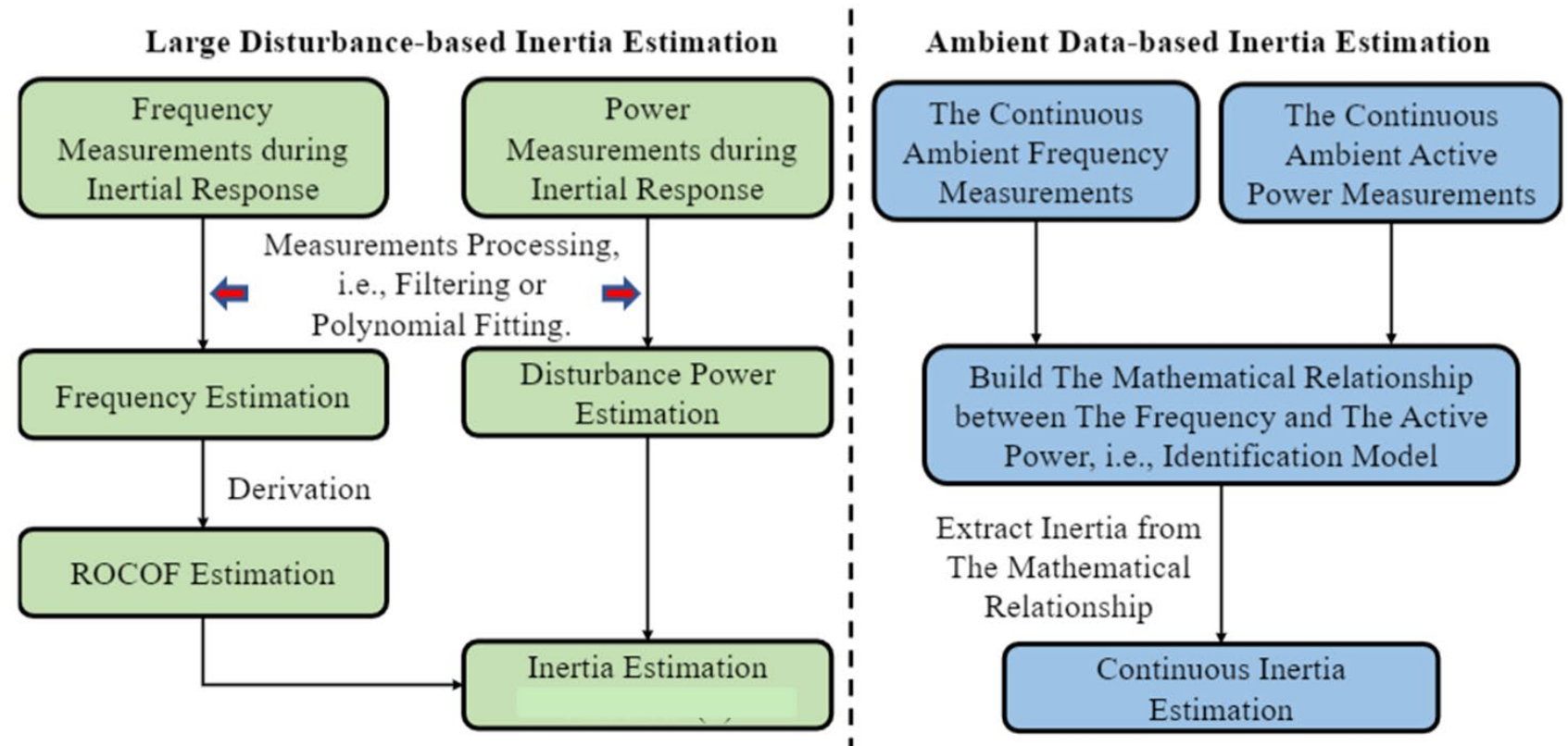


- The inertia is reduced with the replacement of conventional generators with renewable energy sources interfaced through power electronic converters.
- This reduction in inertia, in turn, reduces the time required for control action to prevent frequency excursions from violating security limits, and blackouts

Inertia estimation methods

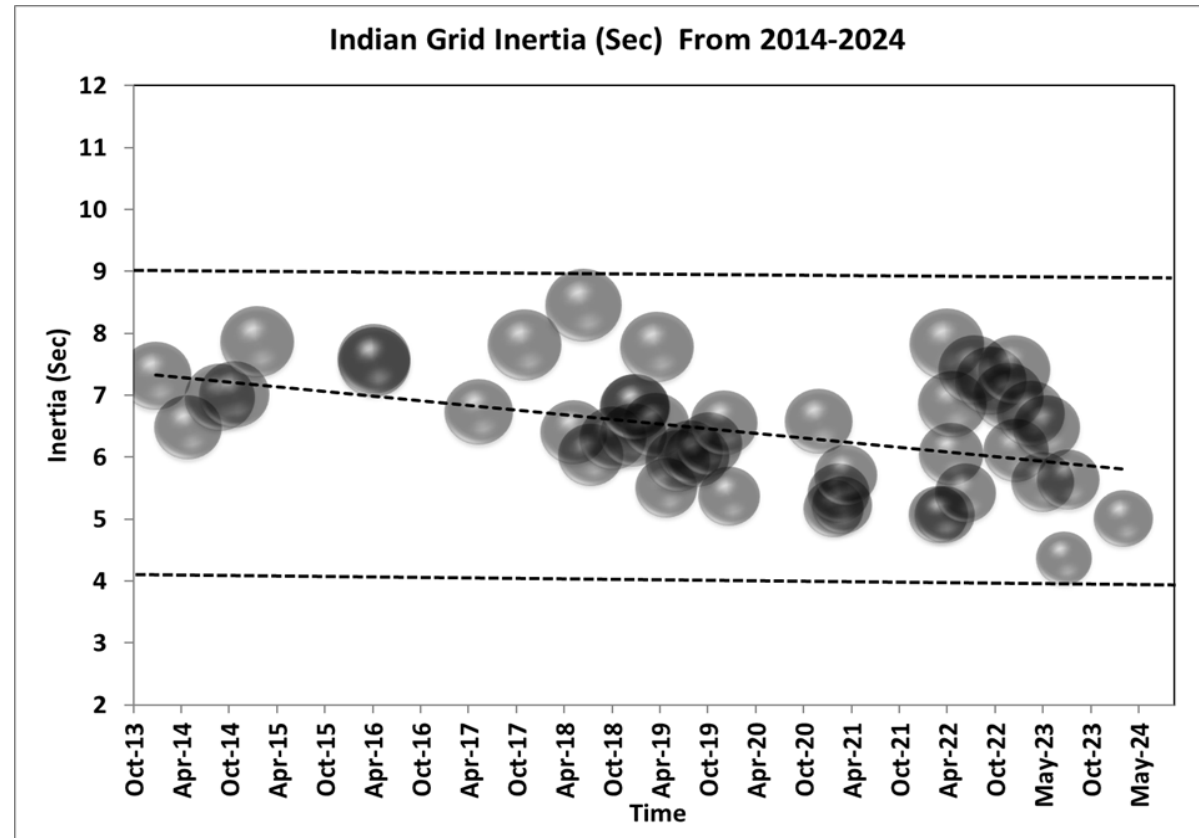
- Large disturbance-based (Swing equation-based)
- Ambient data-based (system identification-based)

$$\frac{d\omega_{COI}}{dt} = \frac{\omega_r}{2HS_{sys}} (\Delta P_e)$$



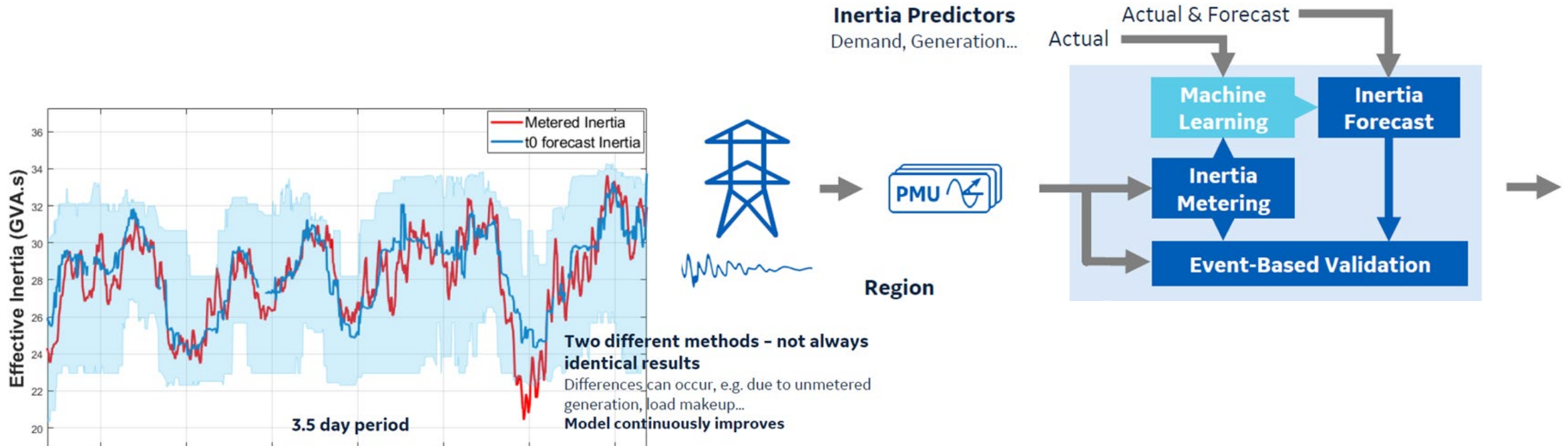
Inertia estimation examples

- Inertia calculated from synchrophasor data from Indian power system using a swing equation-based method



Inertia estimation examples

- Inertia monitoring and forecasting in Scottish Power Grid
 - Ambient measurements based inertia monitoring
 - Machine Learning-based inertia forecasting



System integrity protection schemes (SIPS)

- SIPS (SPS or RAS) is an automatic protection system designed to detect abnormal system conditions and take corrective actions to maintain system stability, acceptable voltages or power flows.
 - Action may include shedding loads or generation; changes to system configuration to maintain system.
 - Typically, event driven; specific triggering events are pre-defined
- Wide Area Monitoring, Protection and Control (WAMPAC) Schemes provides a generalized approach to developing system-responsive SPSs through measurement-based identification of the need for corrective actions.

South Australia WAMPAC Scheme



- SA-WAMPAC accommodates complex events by responding to stress measures observed using synchrophasors during a disturbance to trigger corrective actions.

- Power Imbalance:** Change of power imbalance within the South Australian region calculated from line flows, inertia and RoCoF.

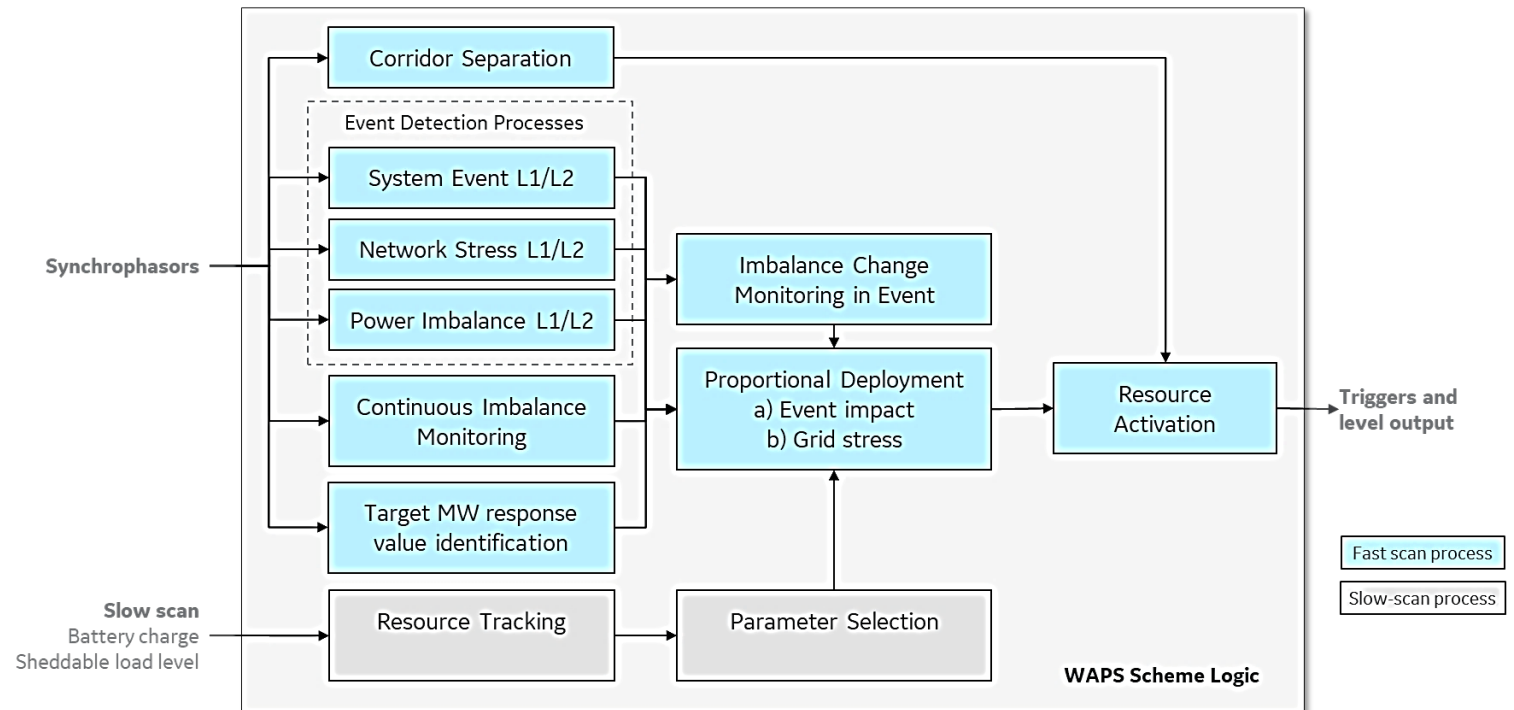
$$P_{imbal} = -P_{import} + k \cdot H_{SA} \cdot RoCoF_{SA}$$

- Network Stress:** Estimated from the angle difference between South Australia and the NEM and frequency difference.
- System Event:** Detects using RoCoF and/or frequency deviation and determines whether a response within South Australia improves or degrades stability.

South Australia WAMPAC Scheme

- SA-WAMPAC scheme will trigger a response in two levels
 - Level 1** event triggers response from the grid-scale BESS, but does not justify a load shedding.
 - Level 2** event is more severe, and load shedding is justified.

$$P_{WAPS} = P_{imbal} - P_{CorridorTarget}$$



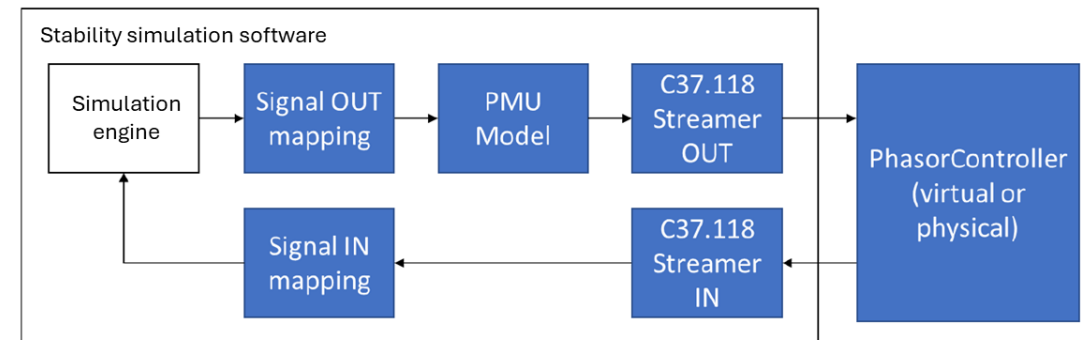
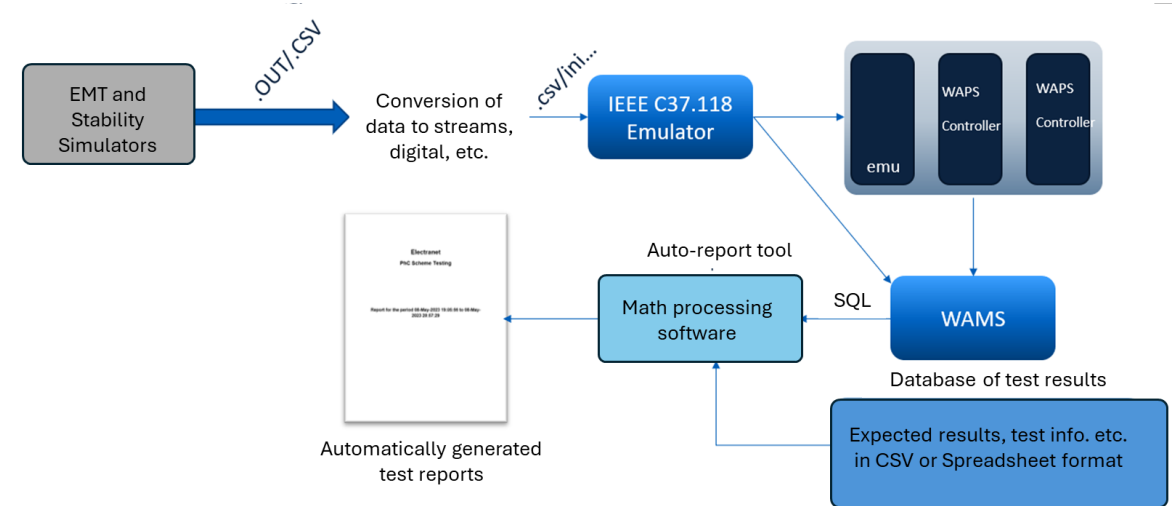
- Design



South Australia WAMPAC Scheme

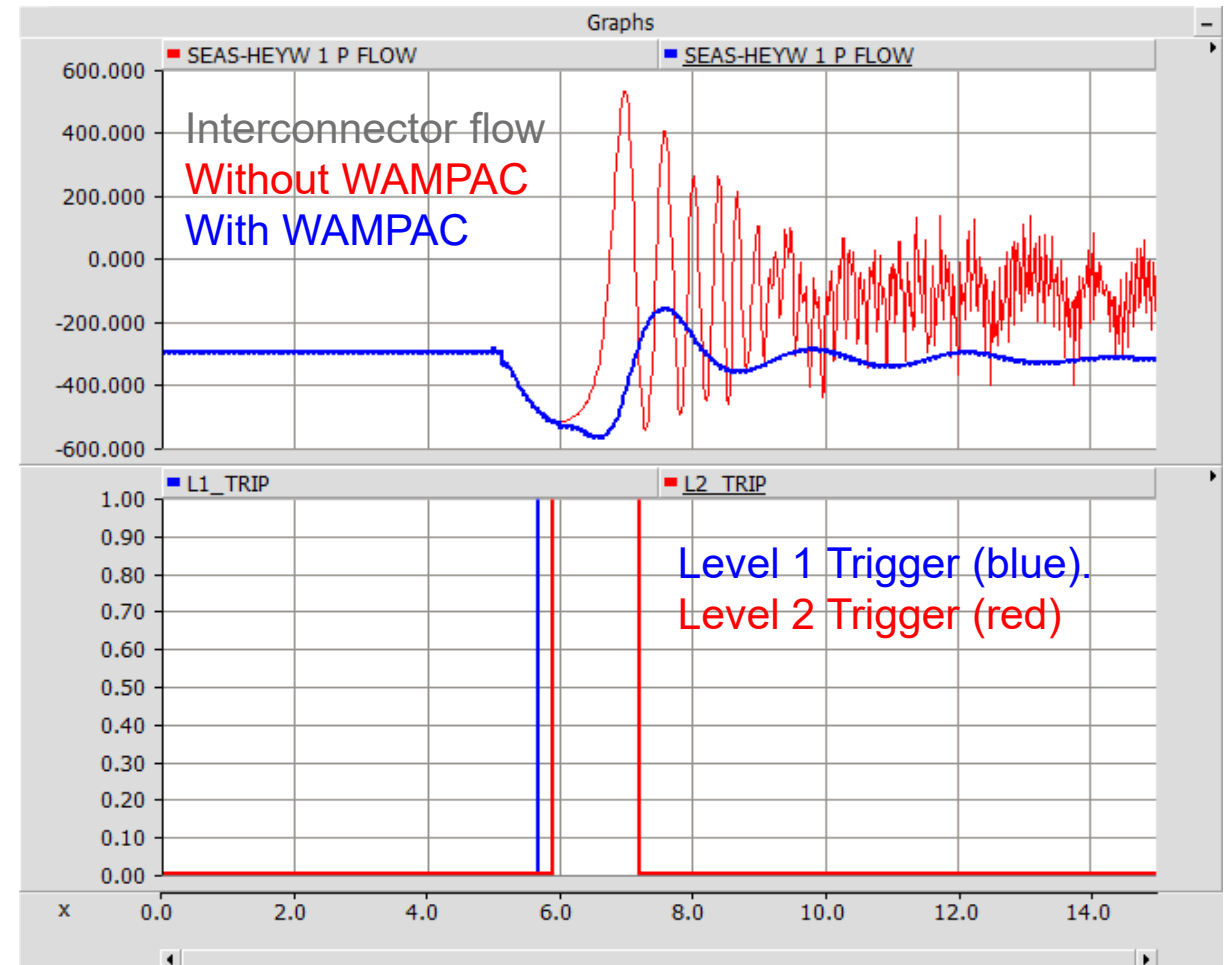
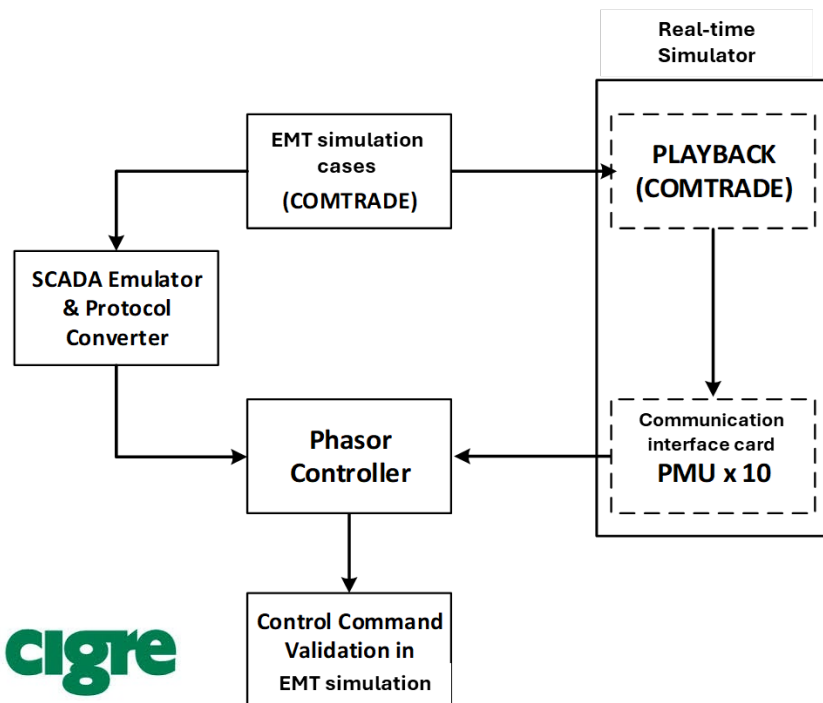
■ Testing of SA-WAMPAC

- Development and initial setting using a case library of simulated events and some real events measured using PMUs
- Initial testing of the SA-WAMPAC with the simulation data played back into the WAMPAC controller using a PMU emulator
- Closed loop testing with offline simulations and virtual or physical controller



South Australia WAMPAC Scheme

- Testing of SA-WAMPAC
 - Factory Acceptance Test and Model Validation with closed loop testing with real-time simulations

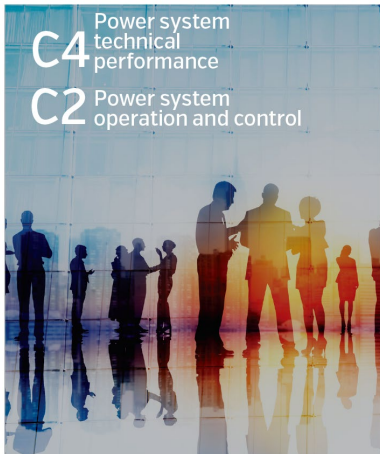


WAMPAC Response for loss of multiple asynchronous generation units simultaneously

Chapter 4 conclusions

- PMU data visualization for situational awareness is well-established; potential improvements with touch screens and virtual reality displays.
- Full linear state estimation using only synchrophasor data is yet to be implemented by a major utility.
- Oscillation monitoring has been widely used with enhanced capabilities in oscillation source location
- Usefulness of relatively new applications such as grid code compliance monitoring and inertia monitoring have been already demonstrated; further research is warranted for expanding and improving.
- A limited set of practical examples exist for wide area control systems and special protection systems; but not widespread.
- Wider dissemination of the accumulated experience from closed loop control systems can spur the growth such applications in the future.

Content of TB 975



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November 2025 - Reference 975

1. Introduction
2. Advancements in the technology and standards
3. System architecture, data integration and protocols
4. Applications deployed in the industry
5. **Potential applications**
6. Outlook for next 5-10 years
7. Conclusions

Potential Applications

5. Potential applications

5.1 Dynamic state estimation

5.2 Protection applications

5.3 Fault location

5.4 Short-term voltage instability detection

5.5 Transient instability detection

5.6 Fast frequency control

5.7 Asset management

5.8 Monitoring geomagnetic disturbances (GMD)

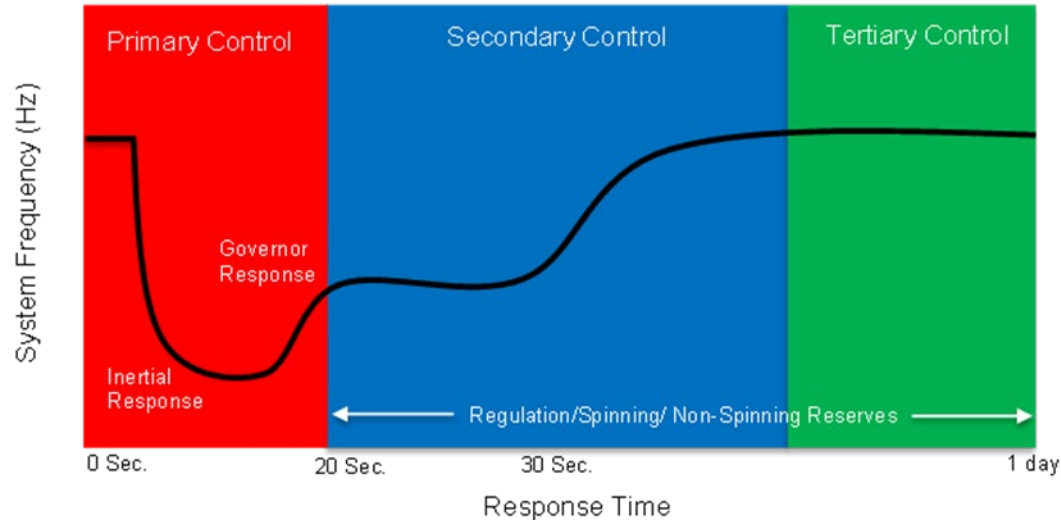
5.9 Use of digital twins for synchrophasor application validation

5.10 Dynamic line rating

5.11 Chapter conclusions

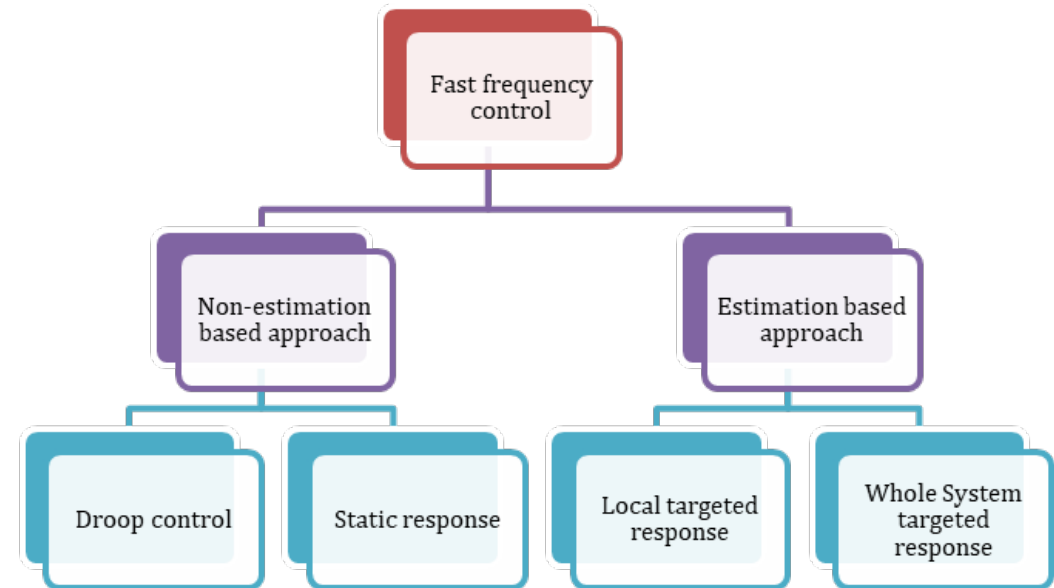
5.12 References for chapter 5

Fast frequency control



Secondary control: balancing service deployed in timescale of minutes; delivered via AGC and manual dispatch; recovers frequency

Tertiary control: reserve redeployment and reserve restoration following a system event .



- The estimation-based approaches use wide area measurements to estimate the power imbalance upon detecting an event
- Controller instruct targeted response:
 - the service providers are selected based on their locations/availability to provide a specific volume of response to correct the imbalance.

Fast frequency control

- Enhanced Frequency Control Capability Project in UK
 - A WAMAC system is developed to provide fast frequency response
 - This system uses PMU measurements to rapidly detect frequency disturbances and evaluate the location and magnitude of power imbalances.
 - Select the service providers and their response volume based on the capabilities and characteristics of different resources (e.g., wind, energy storage, demand, etc.)
 - The response targets the location of power imbalance and is fully delivered within less than one second from the initiating event.
 - The power imbalance is estimated by using swing equation with the initial system RoCoF obtained from PMU measurements and the system inertia.

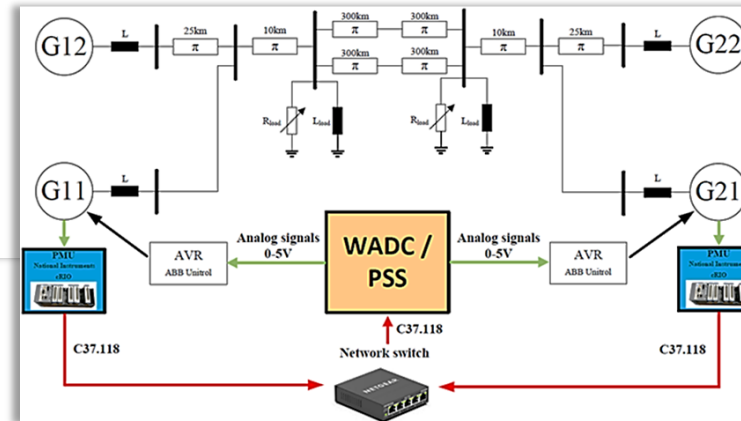
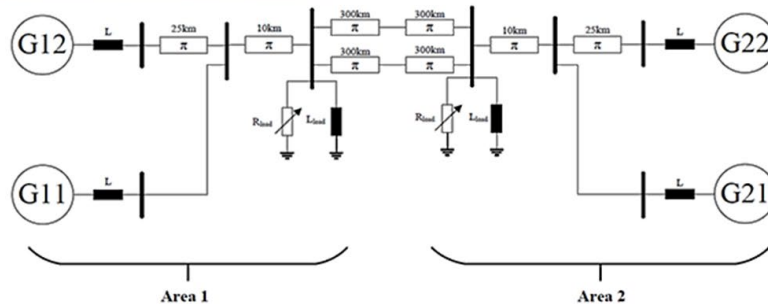
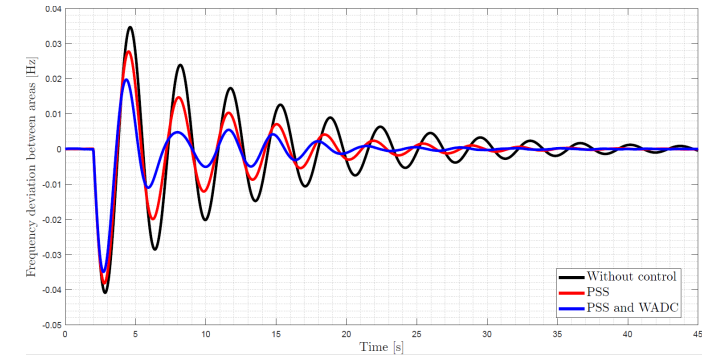
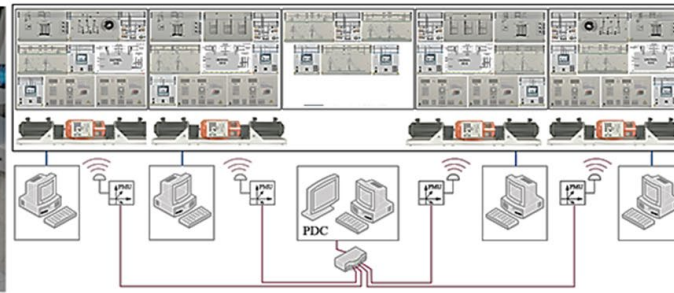
$$RoCoF(Hz/s) = \frac{f(Hz)}{2} \cdot \frac{\Delta P (MW)}{M (MVA \cdot s)}$$

Digital twins for synchrophasor application validation

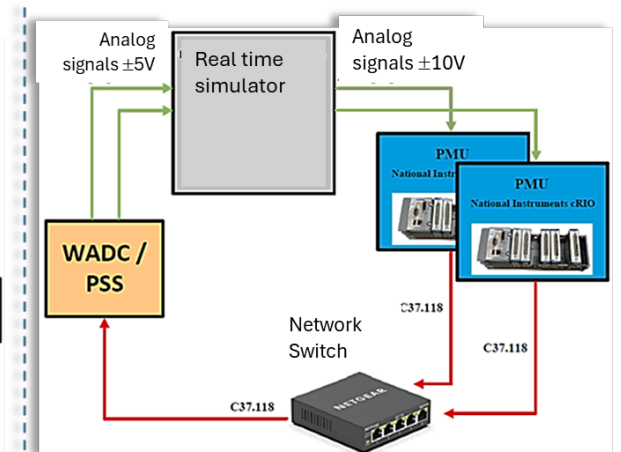
- Digital Twin in Power System (DTiPS) is a virtual representation of a real object and constitutes the description of its attributes and functional properties and is coupled with the real object accompanying it, from planning to disposal.
- The concepts of modelling and simulation and digital twins share common ideas, however, they differ in several aspects.
 - Modelling and simulation decouple the object of interest and the investigation of its behaviors and enable what-if analyses.
 - By contrast, the goal of a DTiPS is to tie the virtual model close to reality and potentially detect real world stimuli .
- The connection between the real object and virtual counterpart (twin) is usually established as a direct communication interface.
- Synchrophasors networks can naturally fits in this communication interface.

Digital twins for synchrophasor application validation

- Example of developing a digital twin system in a laboratory and using it for designing a wide area damping controller.



Real system
(implemented using hardware emulator)

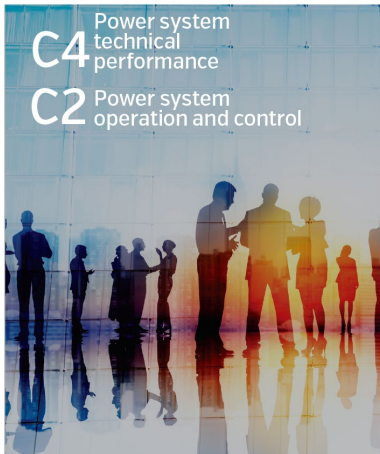


Digital twin
(Implemented using real time simulator)

Chapter 4 conclusions

- Development of many innovative synchrophasor applications can be found in the literature; it is a very active area of research.
- Some applications such as fault location and dynamic line rating have shown adequate performance and associated with relatively low operational risk.
- Applications such as fast frequency control have shown sufficient maturity by passing through thorough evaluations and pilot testing.
- Critical real-time applications such as transient and short-term voltage stability assessment, assets and system protection require further developments to ensure robustness and reliability under real operation.
- Dynamic state estimation may not be currently fully feasible for system wide application, but the current technology may be applied within a limited scope (ex. dynamic parameter estimation).
- Synchrophasor based ageing estimation is at an early stage and further research is needed to demonstrate its true potential.

Content of TB 975



**Review of Advancements in
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November 2025 - Reference 975

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6. Outlook for next 5-10 years
7. Conclusions

Outlook for Next 5-10 Years

6. Outlook for next 5-10 years

6.1 Cloud-based implementations

6.2 Role of data science, artificial intelligence and machine learning

6.3 Synergies with synchronized waveform monitoring

6.4 Technology gaps

6.5 Potential research areas for the future

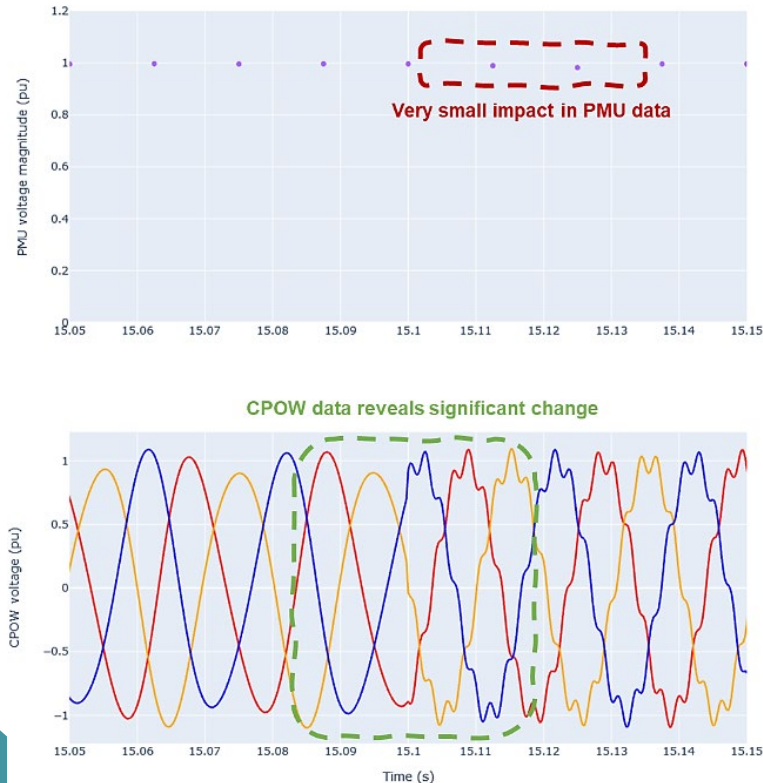
6.6 Chapter conclusions

6.7 References for chapter 6

Role of Data Science, AI and ML

- Massive amount of information derived from intelligent wide area monitoring systems provide rich insight into the power grid status
 - Human operators will not be able to respond to such large volumes of data in a timely manner.
- AI and ML technologies offers wide range of tools and techniques to use data for solving complex power system problems
 - Problems that are challenging to solve without making simplifying assumptions
- Generative AI and deep learning have a great potential to play a transformative role in future power systems planning, operation and monitoring.
 - Future research could lead to achieving self-healing objectives in bulk power systems.

Synergies with synchronised waveform monitoring



- Synchronized waveform measurements has a great potential for monitoring the fast phenomena and transient events in increasingly power electronic based power systems.
- Waveform data complements PMUs and conventional SCADA measurements by unlocking new monitoring, protection, and control applications
- Need solving of many practical issues
 - Development of appropriate standards;
 - Communication infrastructure and protocols;
 - System architectures that can handle the data volumes

Technology gaps

- Cyber security concerns
- Applications facilitating integration of renewable energy sources
- Standardization and interoperability
- Validation of AI and ML applications
- Electricity market-oriented applications

Potential research areas for the future

- Resilient Communication Networks
- Cloud Computing for Scalable Data Processing
- Quantum Computing for Grid Optimization
- Edge Computing for Real-time Analysis
- Advanced Linear State Estimation (LSE)
- Real-Time Contingency Analysis
- Advanced Forecasting Models
- Real-time Fault Level Estimation
- Oscillation Source Location in IBR Heavy Power Systems

Conclusions

- The field of synchrophasor measurement based wide area monitoring, protection and control has significantly advanced.
- Need to disseminate and share the experiences and lessons learned in using synchrophasors in closed loop control and protection systems.
- As increasing number of applications utilize AI and ML for making critical decisions, there is a need for developing systematic methodologies to evaluate their intended performance under practical conditions
- The synchrophasor technology is expected to play a crucial role in transformation of electricity grids to achieve net zero emission targets.



Thank you

Q&A session