

WAMS; PMUs; Renewable integration; Grid Stability with IBR

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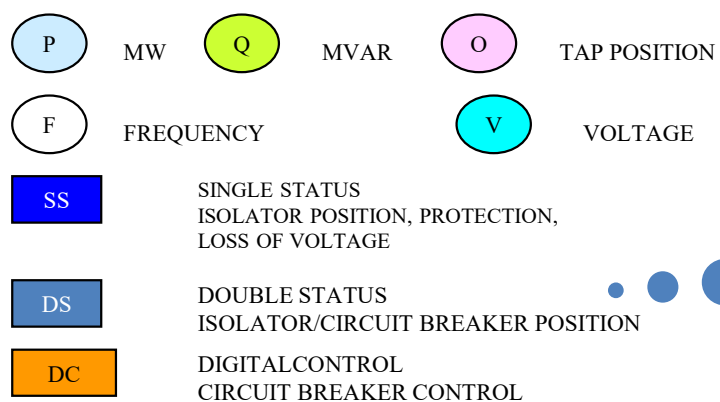
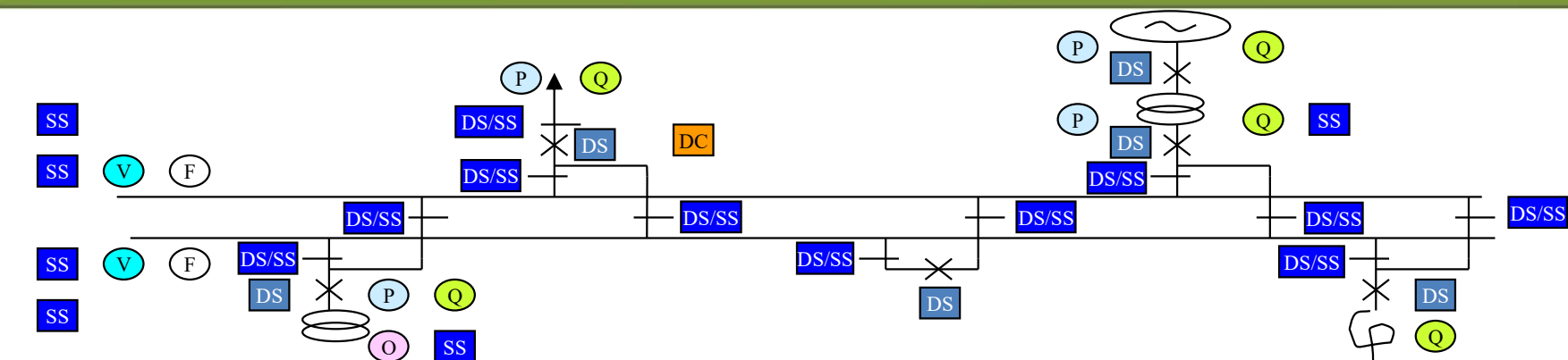
Control Strategy- Power System Automation

- Control Centre
 - Supervisory control and data acquisition
 - Balance **Generation** and **Demand** (dispatching)
 - Monitor flows and observe **system limits**
 - Coordinate maintenance activities, emergency response functions
- Localized (Power Plants, Substations)
 - Feedback controls (e.g., governors, voltage regulators, PPCs)
 - Protection (e.g., protective relays, circuit breakers)
- Key Priorities:
 - Safety
 - Protect equipment from damage
 - Reliability
 - Economics

Typical facts on Control Centre SCADA

- Voltage magnitudes, Current magnitudes, P flows, Q flows, Frequencies, Digital status of Devices(ISO, CB) and SOE.
- Reporting Rate: 4 second to 10 seconds
- Asynchronous sampling
- Cannot directly measure phase angles of voltage phasors(no common reference)
- Phase Angles estimated by fitting onto power flow models- state estimation(EMS).

Data Acquisition Principle



In SAS-based stations and stations with deployment of new RTUs, Isolators are also being modeled as Double-Status

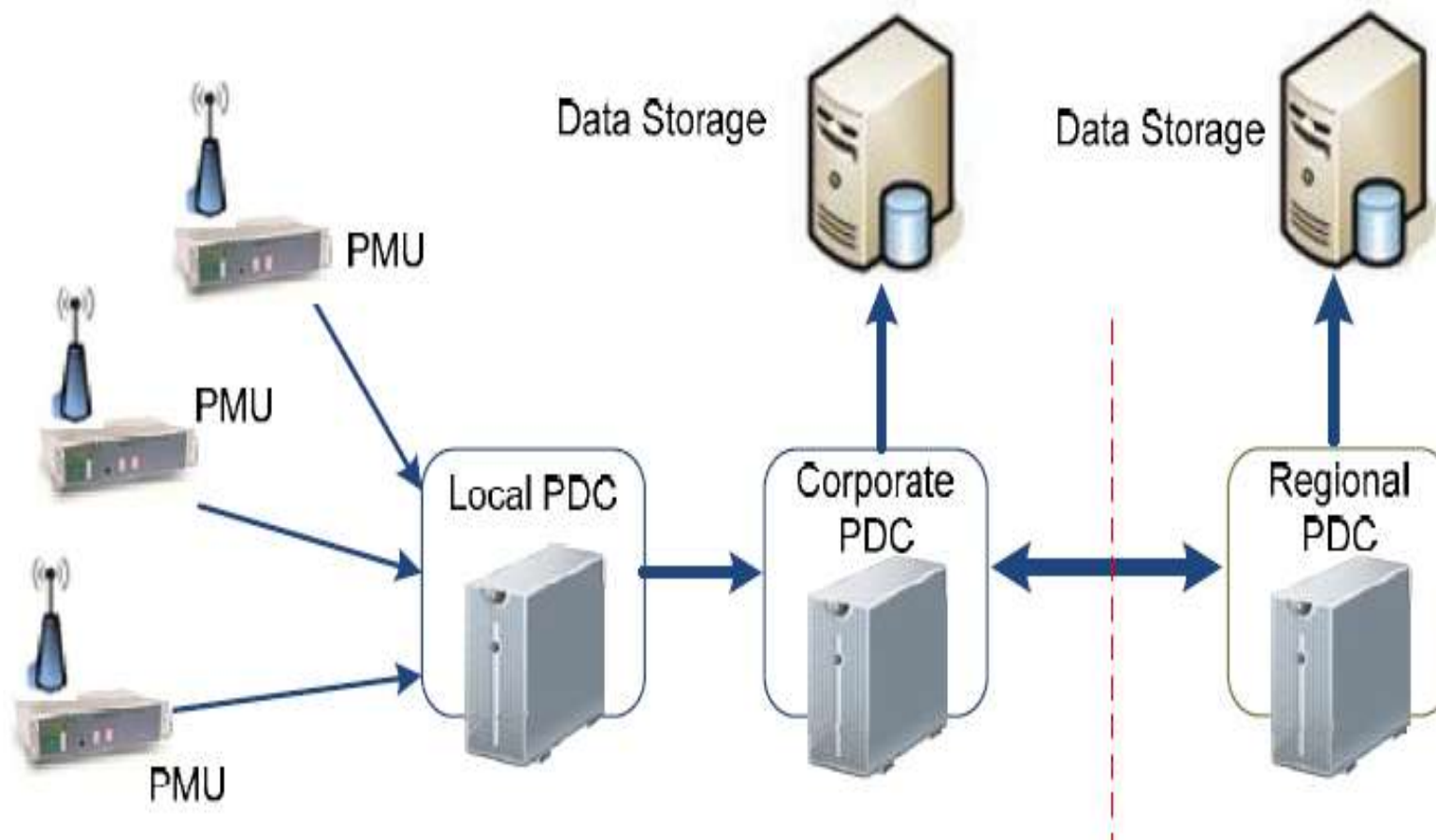
WAMS-Definition- Synhrophasor Technology

- It's a collective technology to monitor power system **dynamics in real time**, identify system **stability related weakness** and helps to design and implement **countermeasures**.(IEEE)
- It is based on **Phasor measurement units(PMUs)** which can deliver precisely time synchronized values of voltage and current phasors and other power system related quantities like frequency, ROCOF, breaker positions.

Components of WAMS

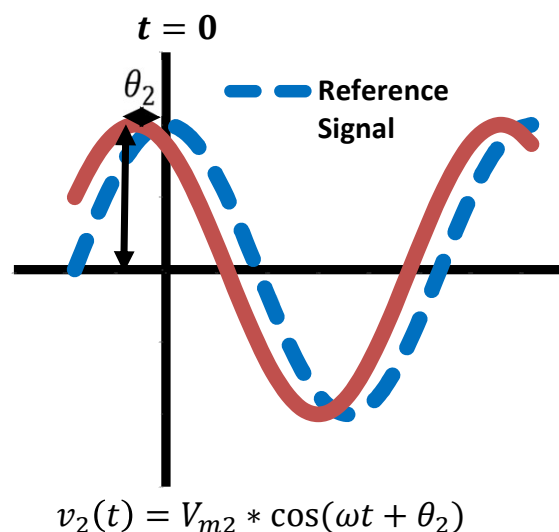
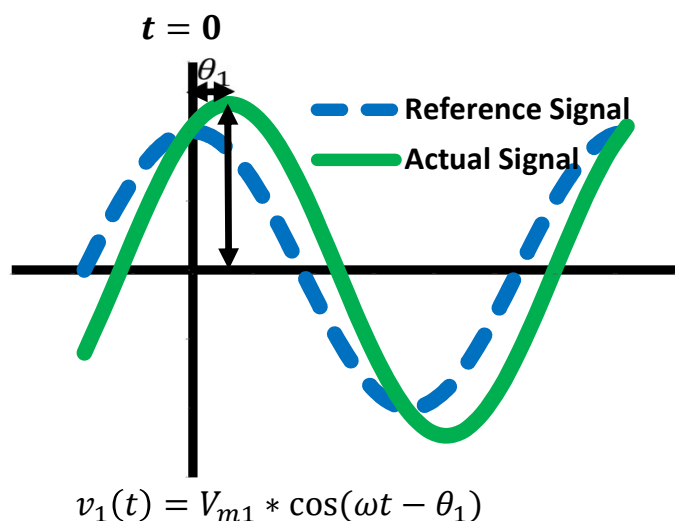
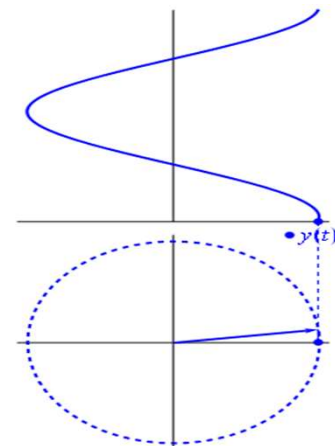
- Phasor Measurement Unit (PMU)
- Phasor Data Concentrator(PDC)
- Global Positioning System (GPS for Time Synchronization of the phasors)
- Communication channel (Preferably optical fiber cable)
- Visualization and analysis tools
- Wide area situational awareness system.
- Wide area protection and control

WAMS Use Case for Utility

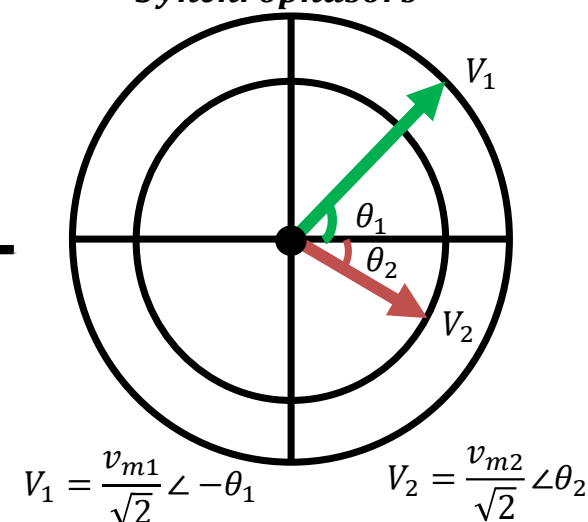


Synchrophasor

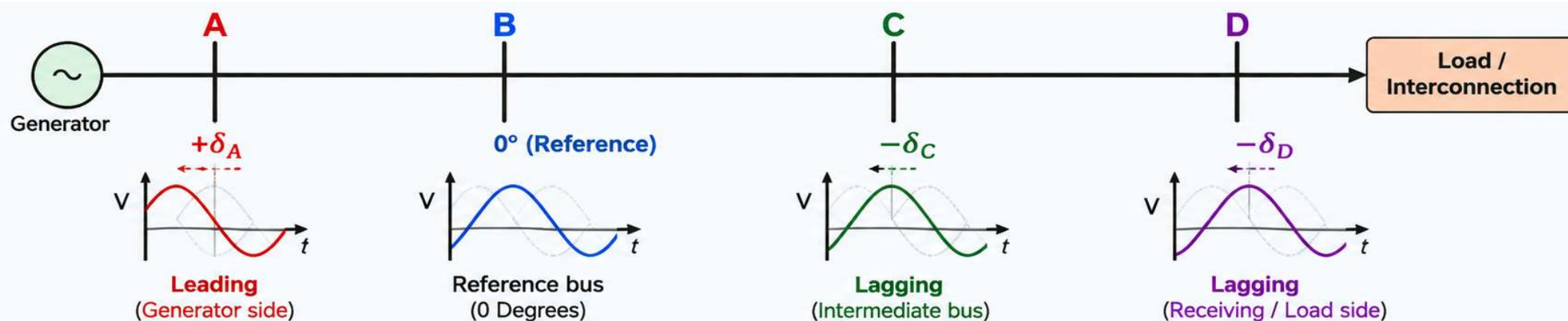
- Phasor synchronized with precise Time stamp is called Synchrophasor
- The Synchrophasor is defined relative to cosine function
- Considering two signals



Phase Angle Representation of Synchrophasors



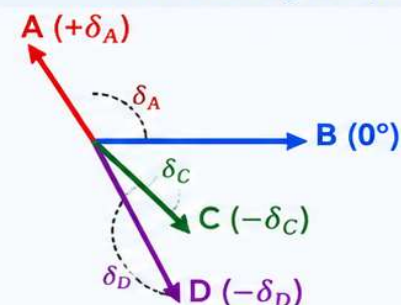
Synchrophasors for Grid Operations



Synchronized phasors (with common time reference) can be used for:

- Phase angle difference between transmission line terminals
- Phase angle monitoring across the interconnection
- Real-time estimation of effective power flow between the points
- Wide-area monitoring and system stability assessment

Phasor Diagram (referenced to Bus B)



Phase angle difference between two points (e.g. A and D):

$$\Delta\delta_{AD} = \delta_A - \delta_D$$

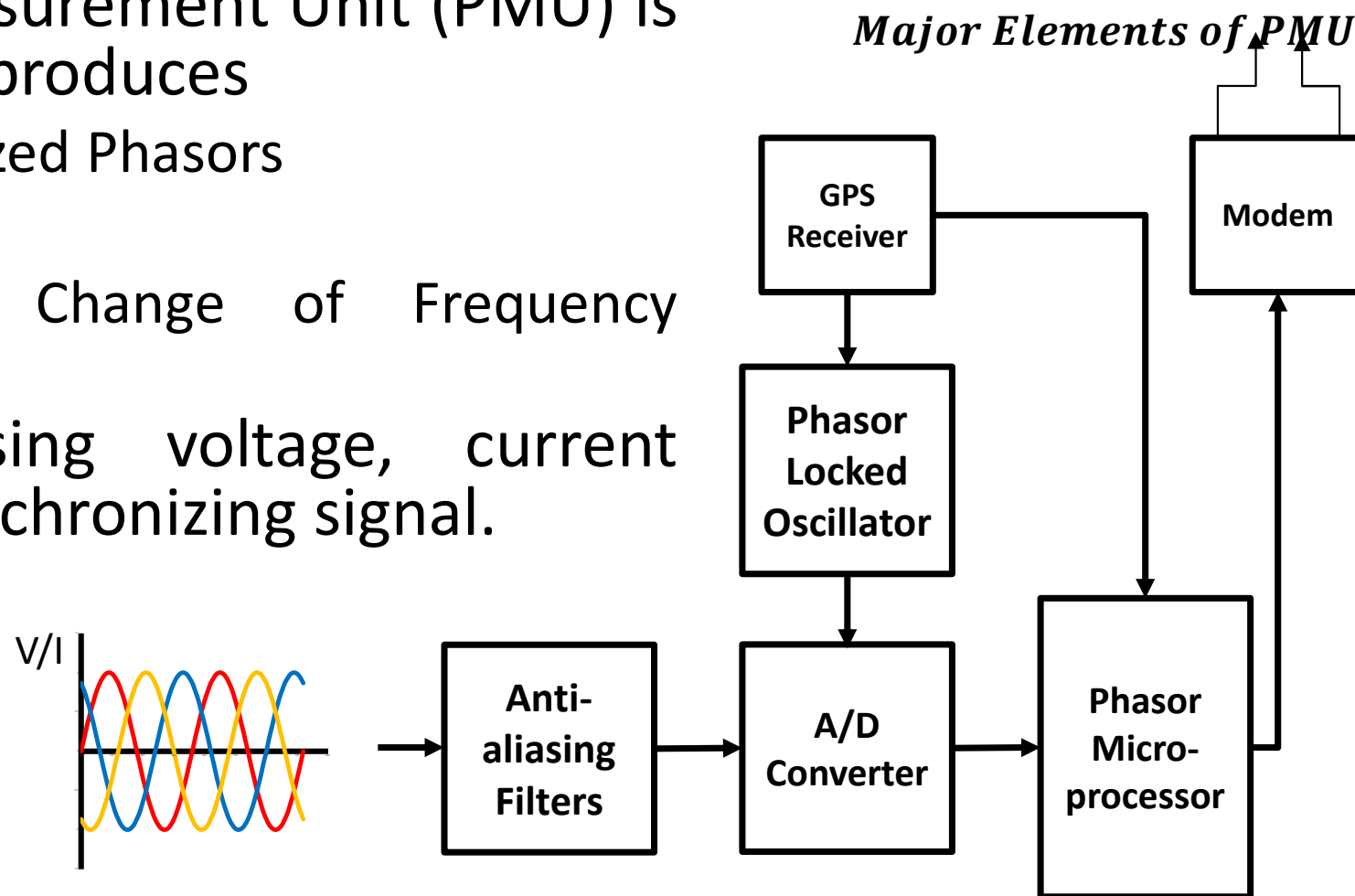
Positive $\Delta\delta_{AD} \rightarrow$ Power flow from A to D

Negative $\Delta\delta_{AD} \rightarrow$ Power flow from D to A

Accurate, time-synchronized phasor measurements enable real-time monitoring of angles and power flows across the grid.

PMU-Phasor Measurement Unit

- Phasor Measurement Unit (PMU) is device that produces
 - Synchronized Phasors
 - Frequency
 - Rate of Change of Frequency (ROCOF)
 estimated using voltage, current signals and synchronizing signal.



GPS- Global Position System

- ❖ GPS is a satellite system with 30 satellites launched for defense application by Department of Defense of USA.
- ❖ Primary application is for navigation purpose.
 - Accurate determination of location, anytime anywhere
 - For a moving object location is time dependent.
- ❖ GPS system provides a 1pps with accuracy of 1 ms

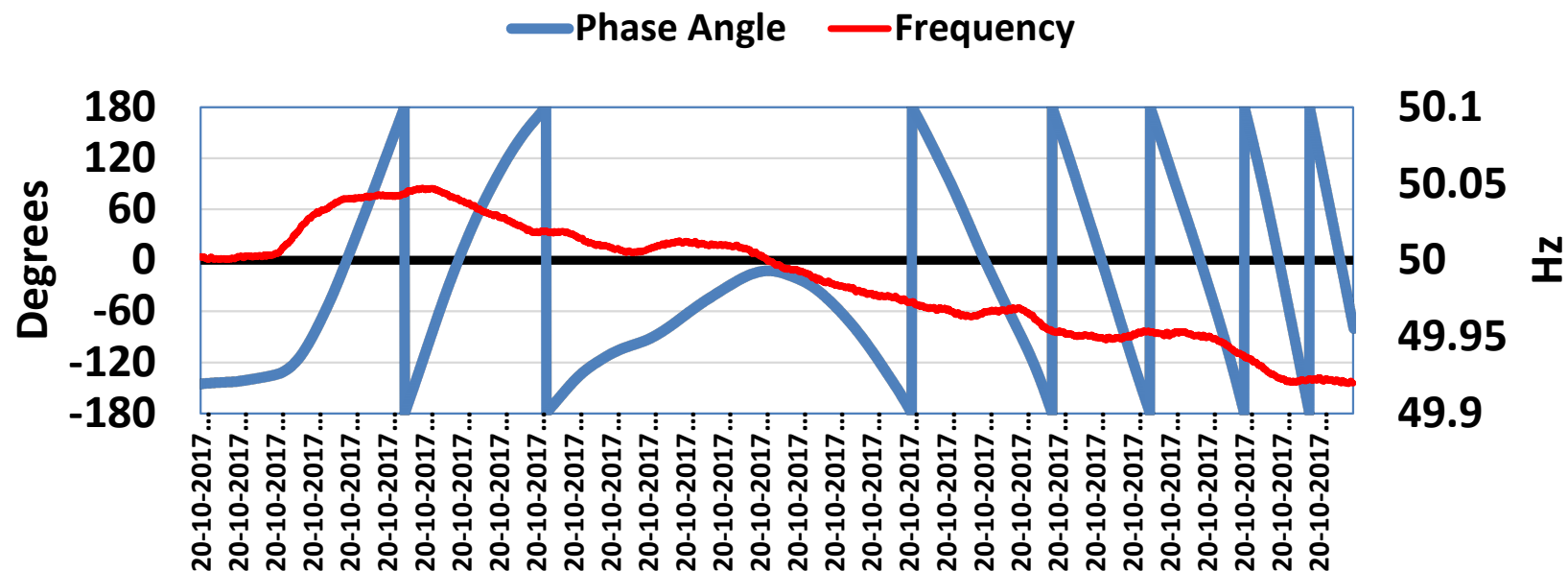


Figure: Reference:
<http://www.gpsmagazine.com>

Visibility of 3 satellites is required for time synchronization

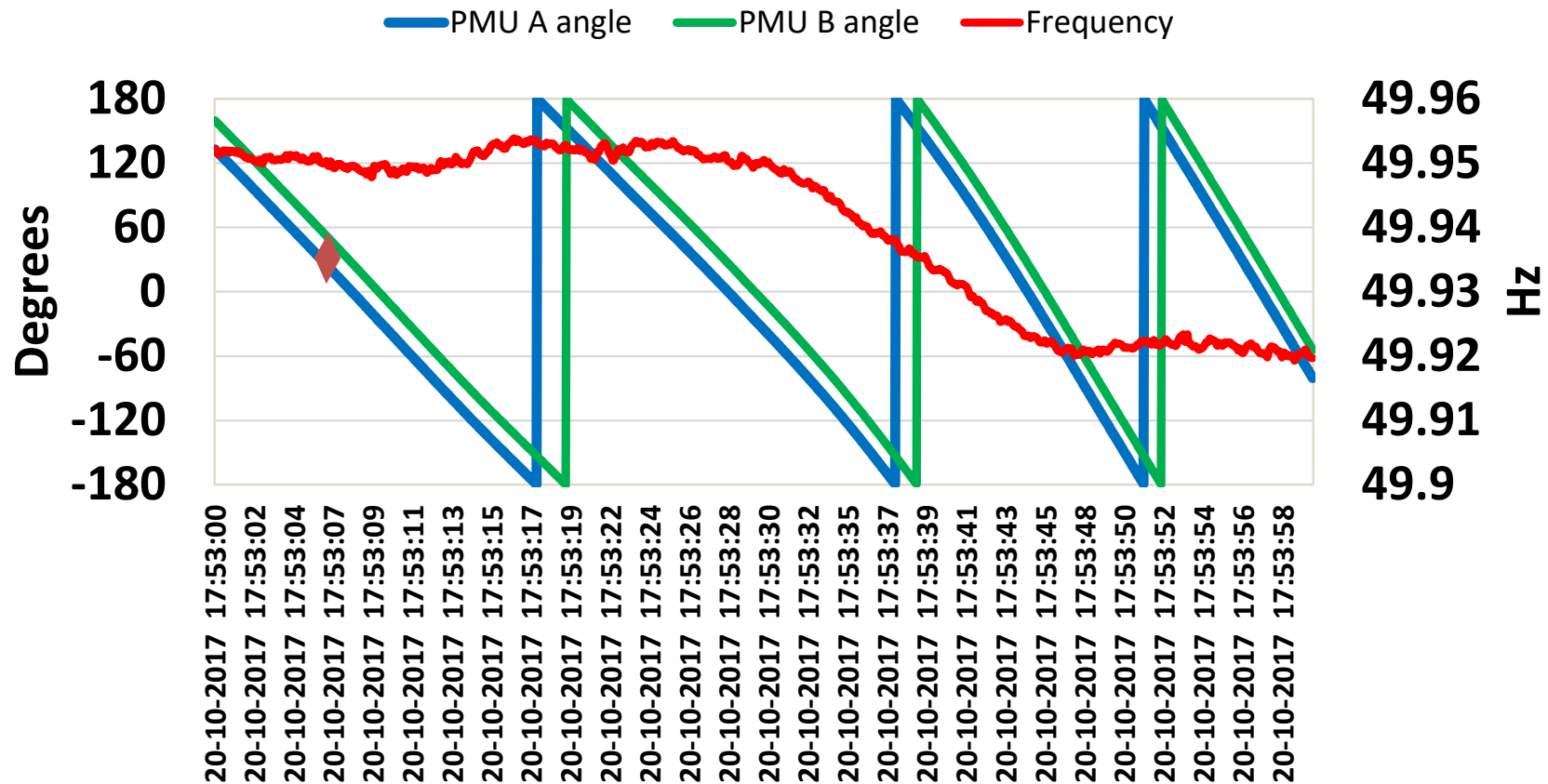
Phase angles in Reality

Phase Angle Variation w.r.t Frequency

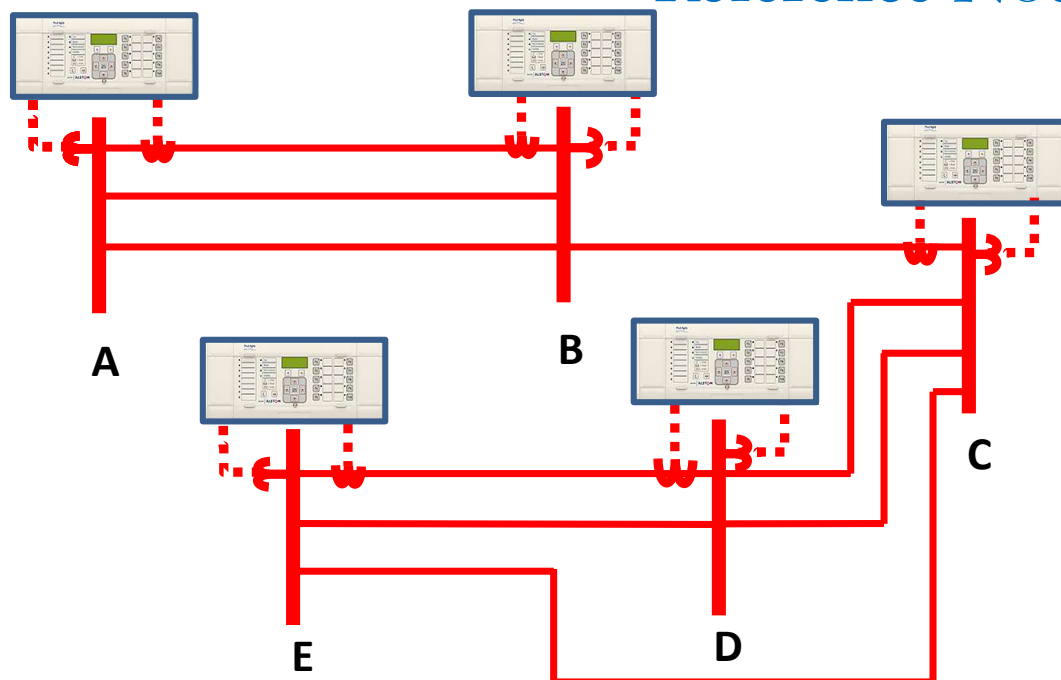


Phase Angle Difference between two Nodes

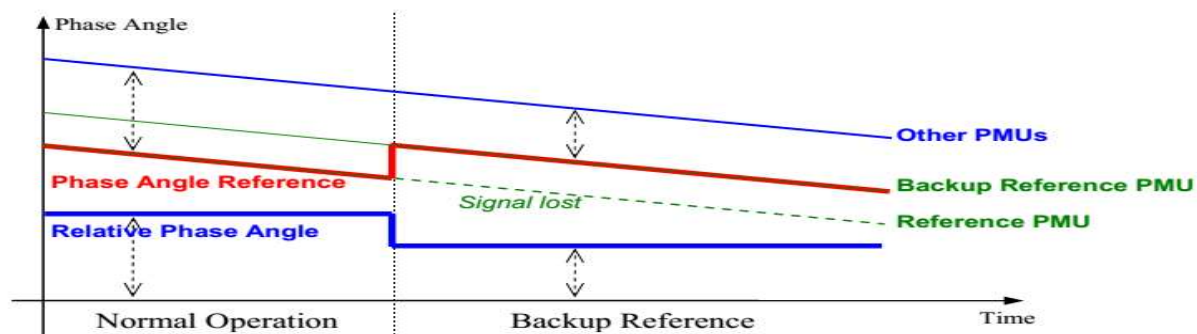
Angular Difference between Phase angles



Reference Node selection in WAMS



Reference PMU	Angular Difference
A	A-B
	A-C
	A-D
	A-E

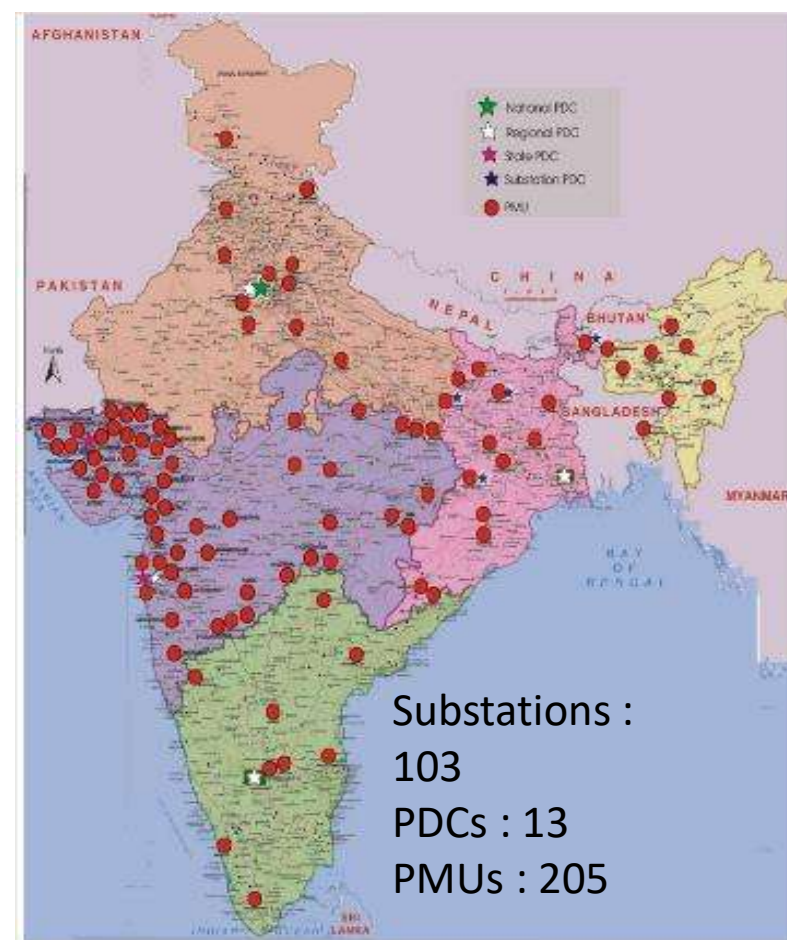
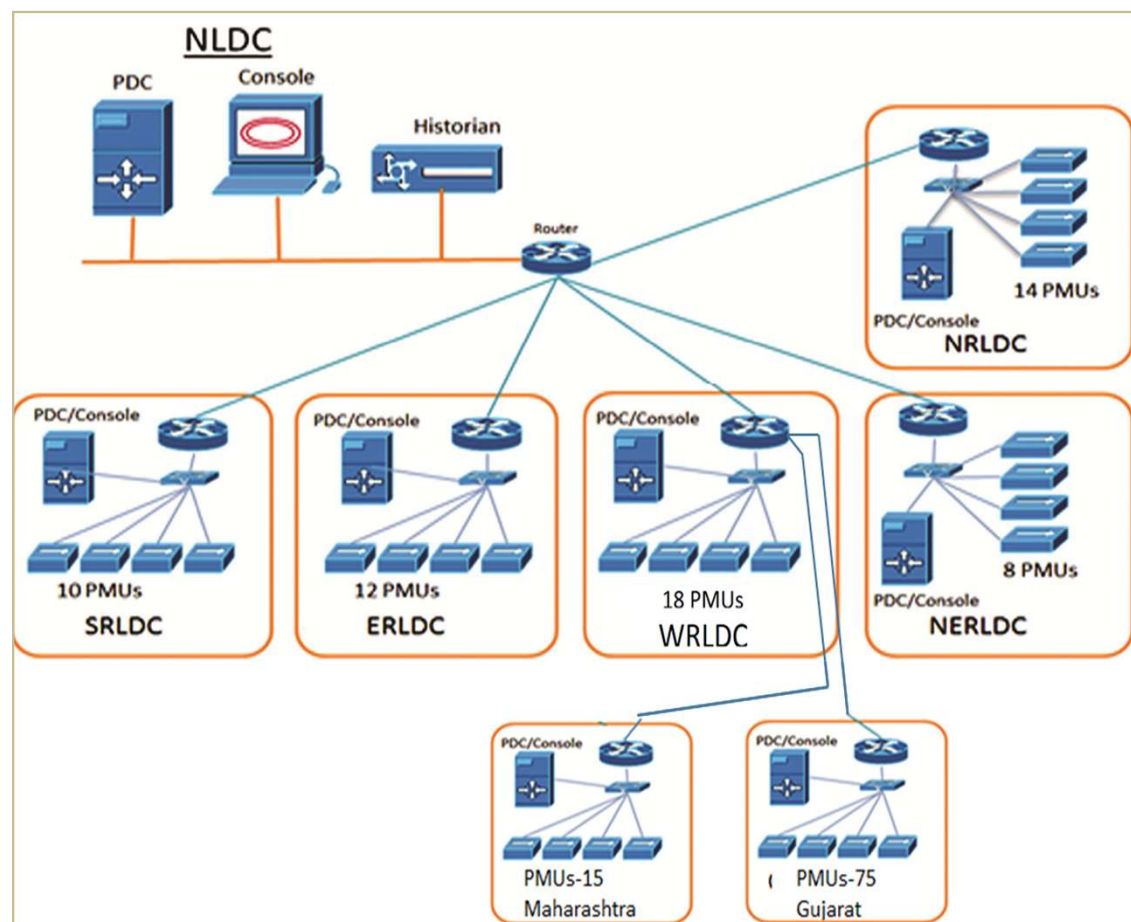


PMU Vendors

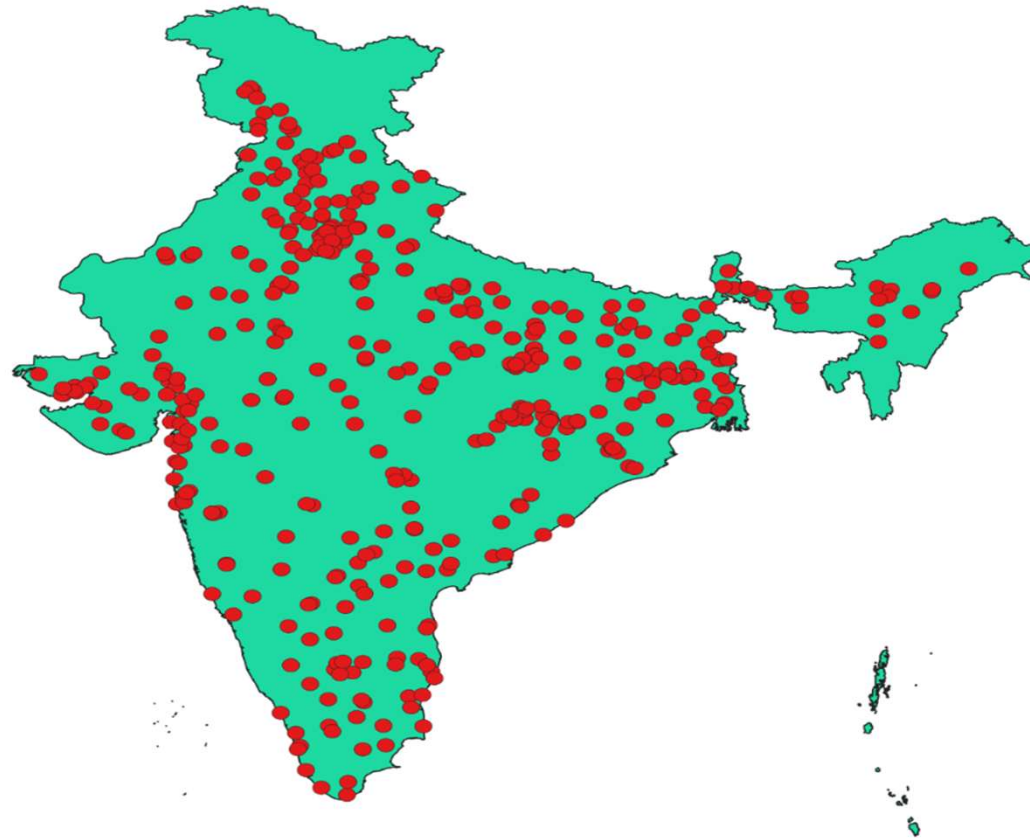


WAMS Pilot Projects in India 2016

State Level → Regional Level → National Level



PMU Locations in India- Large Scale



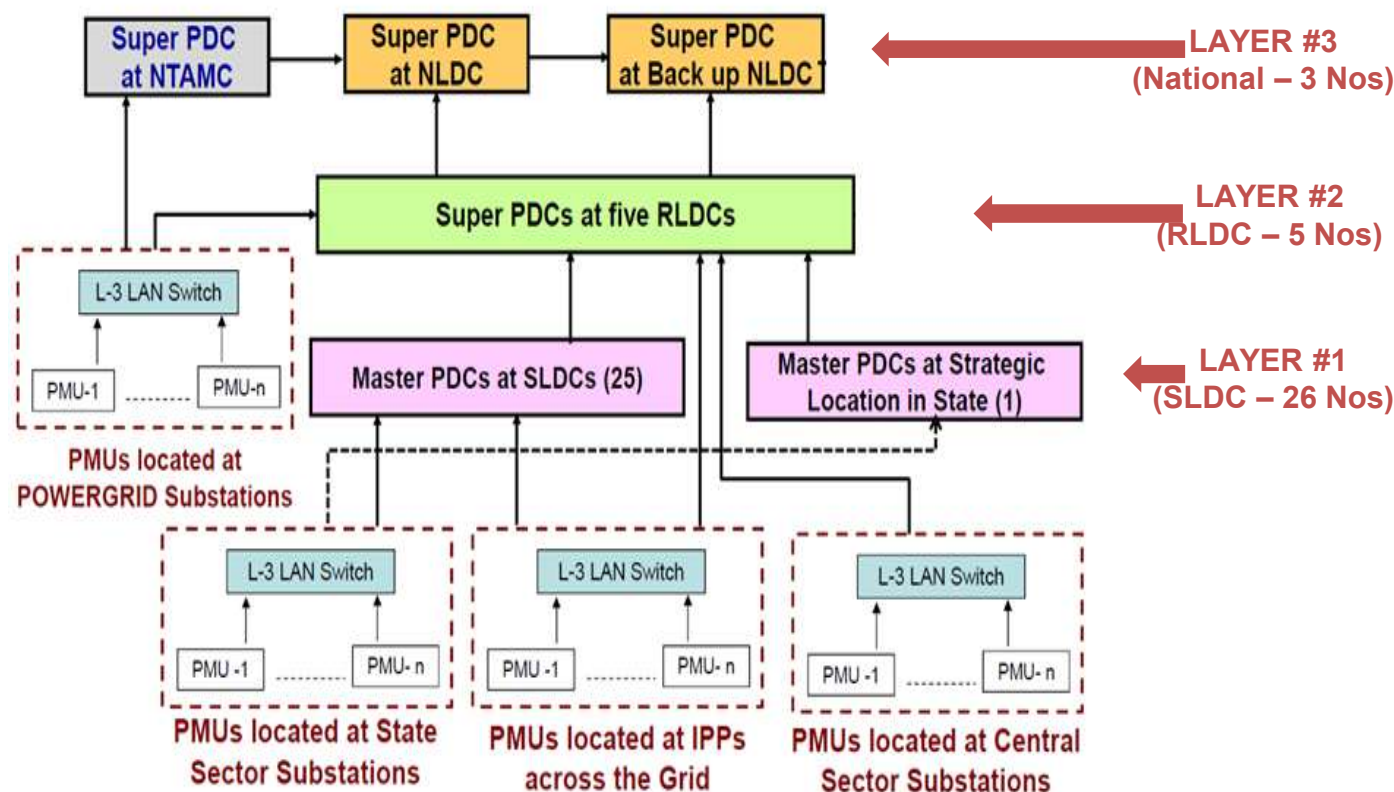
WAMS in Large Scale- URTDSM

SCOPE

- **3 Level Hierarchical System** – National, Regional, State
- 34 Control Centers, 351 Substations, 1100+ PMUs, 30K Phasor Measurement with sample rate of 25 samples per sec, 500 TB storage.



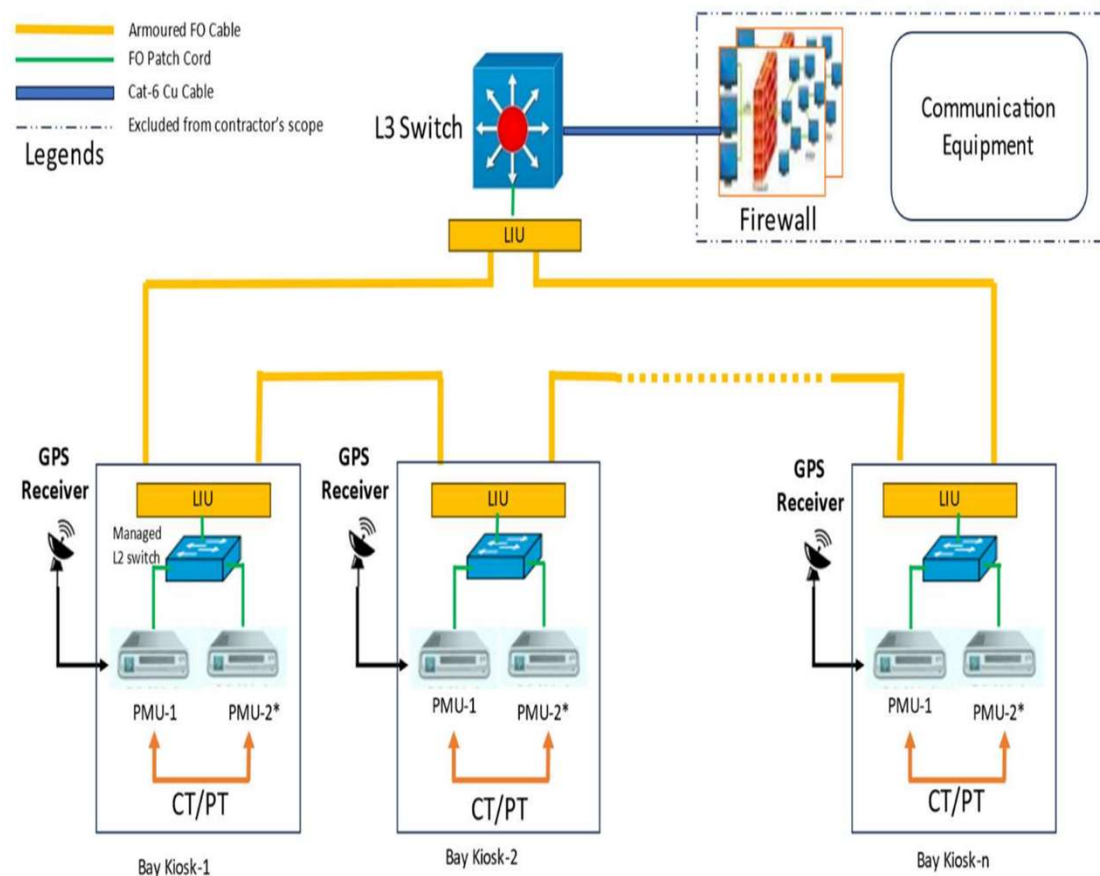
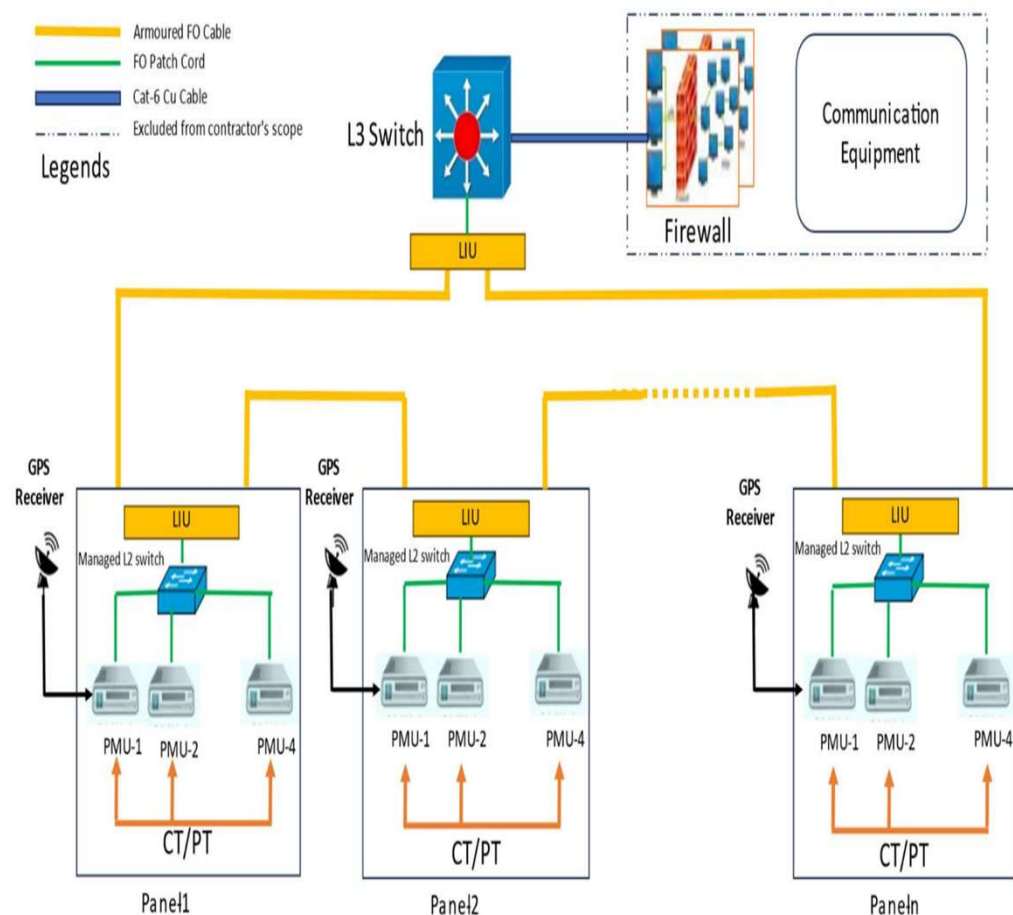
URTDSM System Hierarchy



WAMS Large Scale Deployment in India

- Installation of 1400 PMUs at around 351 Substations / Generating stations 400 kV stations in State and ISTS grids
 - Generating stations at 220 kV and above
 - HVDC terminals and inter-regional and inter-national tie lines
 - Both ends of 400kV and above transmission lines at State and ISTS sector
- Installation of 34 PDCs at control Centre's.
- Transmission of PMU data over fiber optic communication network

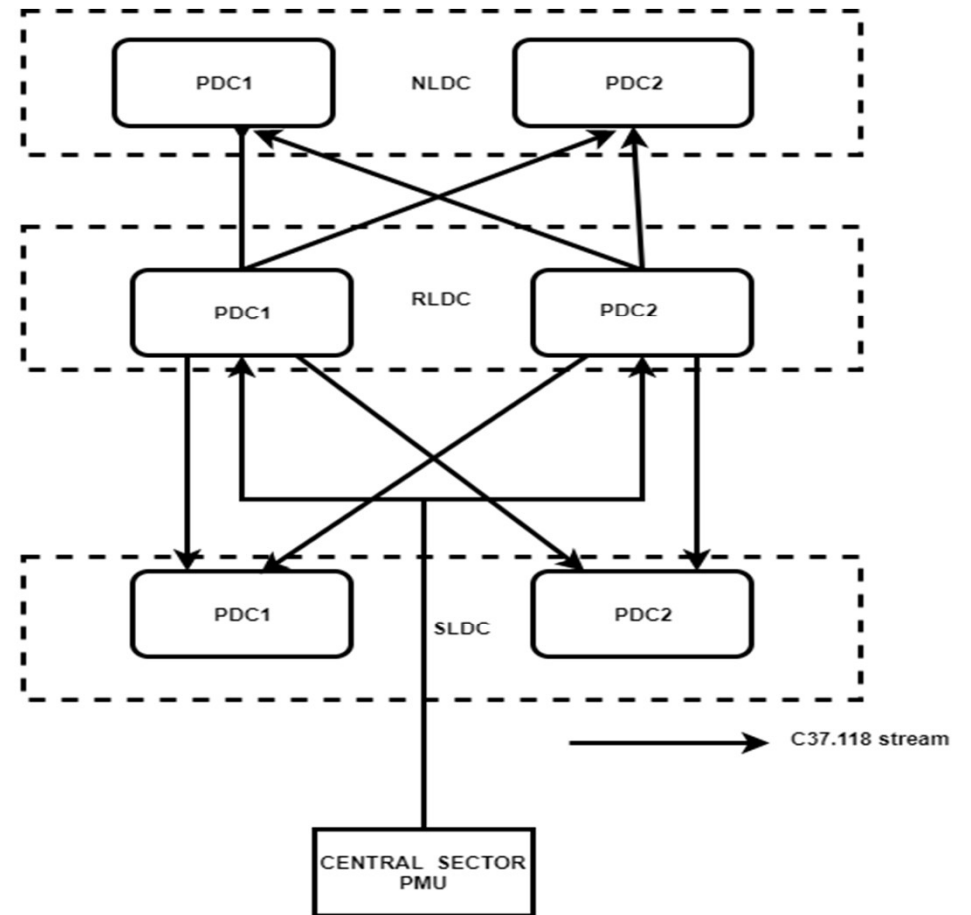
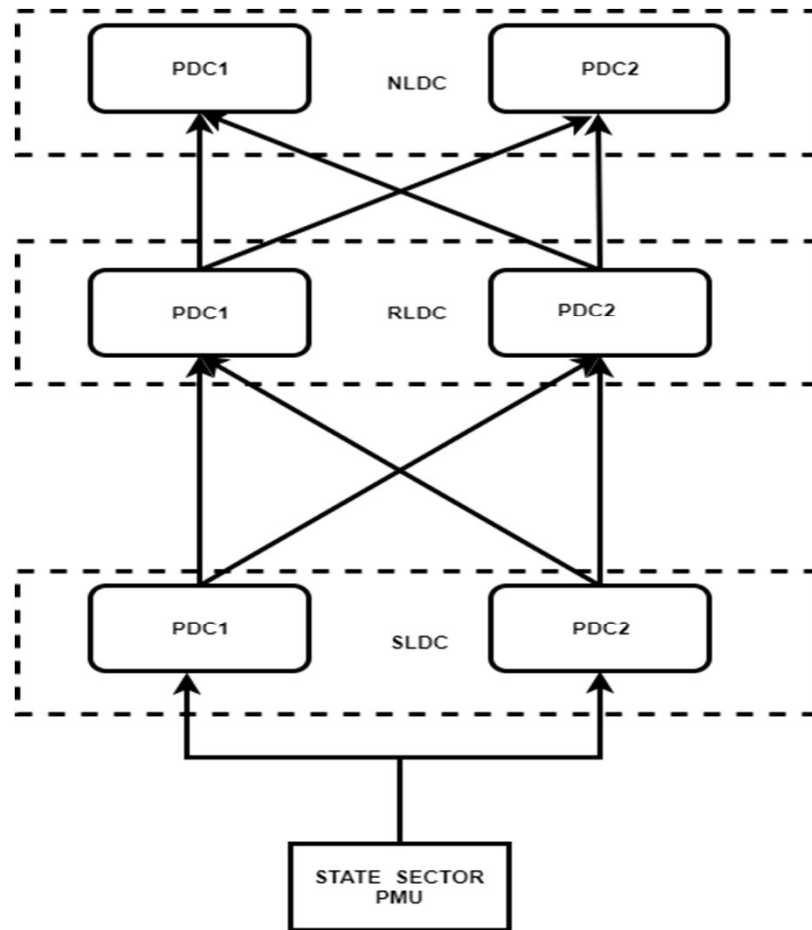
Typical PMU Architecture in a substation



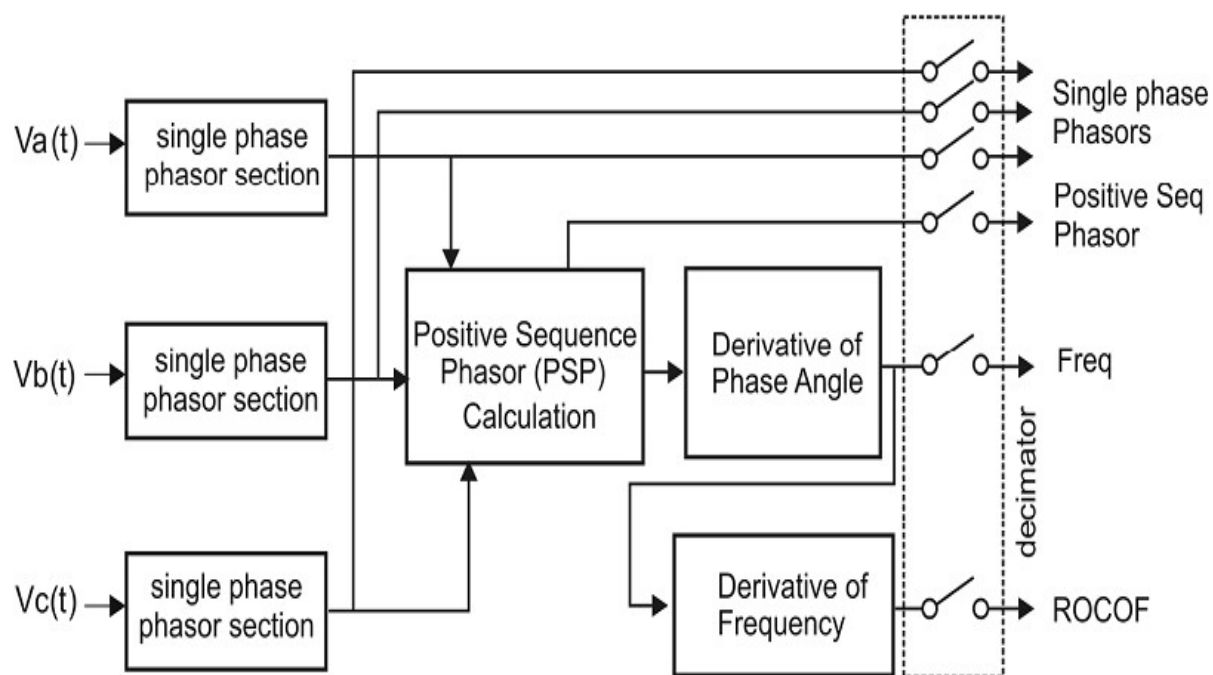
Substations having Control and Relay Panels

Substations having Bay Kiosks

WAMS Redundancy in Data flow



PMU Reference Signal Processing



$$X_2 = \{X_0 + X_1 + X_2\}.$$

$$X_b = \{X_0 + \alpha^2 X_1 + \alpha X_2\}.$$

$$X_c = \{X_0 + \alpha X_1 + \alpha^2 X_2\}.$$

Source: IEEE Standard for Synchrophasor Measurements for Power Systems," in *IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005)* , vol., no., pp.1-61, 28 Dec. 2011

Synchrophasor Standard...

- ▷ First standard IEEE1344-1995
- ▷ Second standard C37.118-2005
 - ▷ TVE test & error limits, steady-state phasor only
 - ▷ Comprehensive messaging for communication
- ▷ C37.118 split into 2 standards
 - ▷ Supports harmonization with IEC standards
 - ▷ C37.118.1-2011 for measurement
 - ▷ C37.118.2-2011 for communication
- ▷ C37.118.1a amendment
 - ▷ Corrects & clarifies 2011 standard
- ▷ 2018: IEC/IEEE 60255-118-1

Other Standards & Guides

- ▷ **PMU – IEEE C37.242-2021**
 - ▷ PMU installation & testing
 - ▷ Measurement & timing-system evaluation
 - ▷ Synchronization and performance testing
- ▷ **PDC**
 - ▷ IEEE C37.244-2013 – Guide: PDC functions, operation & testing (Inactive-Reserved)
 - ▷ IEEE C37.247-2019 – Standard: PDC functions, performance & evaluation
- ▷ **Communications – IEEE C37.118.2-2024**
 - ▷ Synchrophasor data communication
 - ▷ PMU ↔ PDC ↔ Applications
 - ▷ Message formats & data exchange

Other Standards & Guides

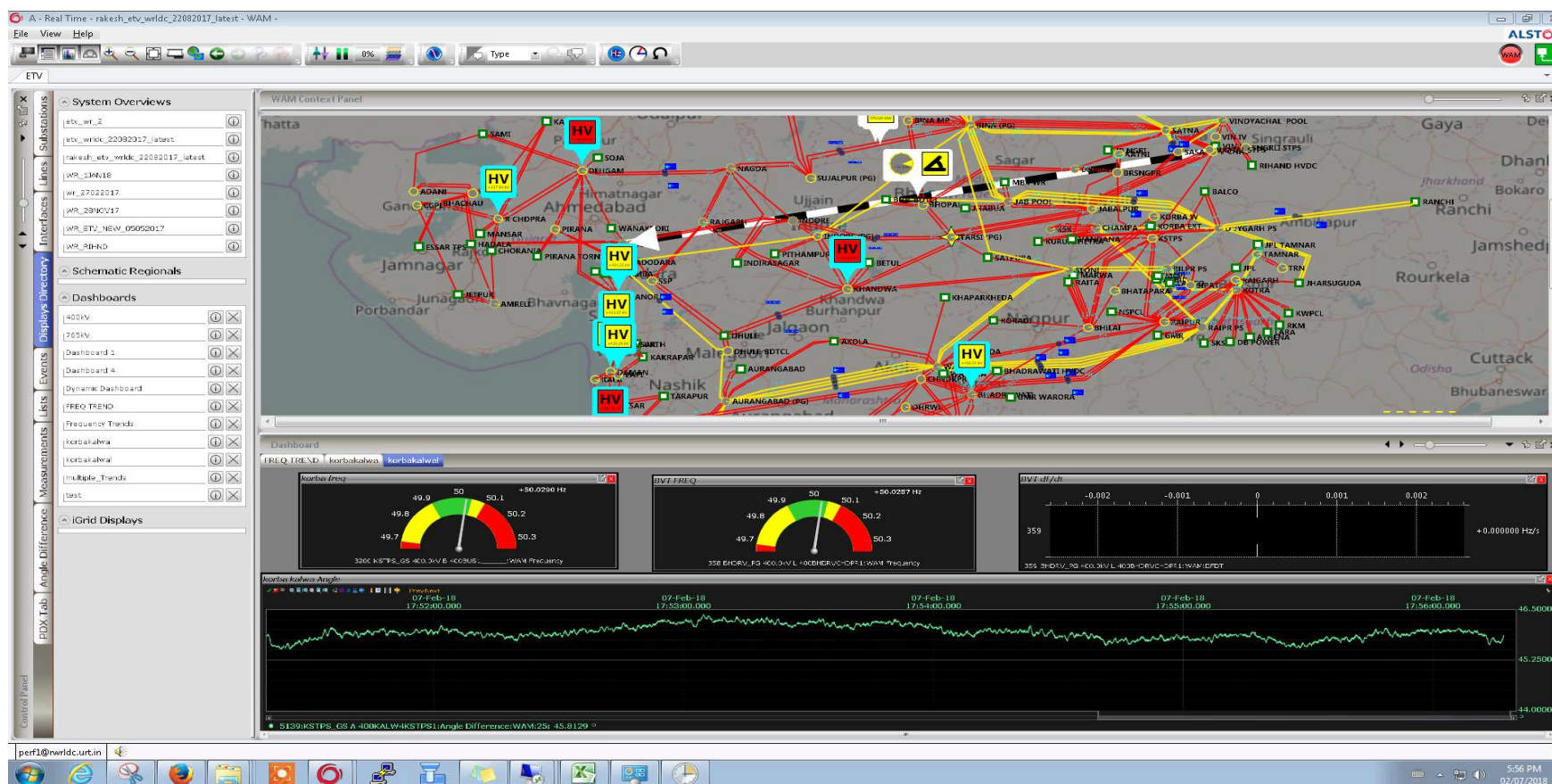
- ▷ **STTP – IEEE 2664-2024**
 - ▷ Streaming Telemetry Transport Protocol
 - ▷ Real-time power-system data streaming
 - ▷ Publish–subscribe architecture
 - ▷ Built-in security & lossless compression
 - ▷ Scalable, configurable & IP-based
 - ▷ Applicable to PMU/PDC and other streaming measurements

Operator User Interface- Trending



Operator User Interface Subsystem

Information that will be shown geographic display includes positive sequence voltage **magnitude and angle**, positive sequence current magnitude and angle, angle differences, MW and MVAR line and interface flows, frequency, df/dt, oscillatory modes, which will refresh every one second.



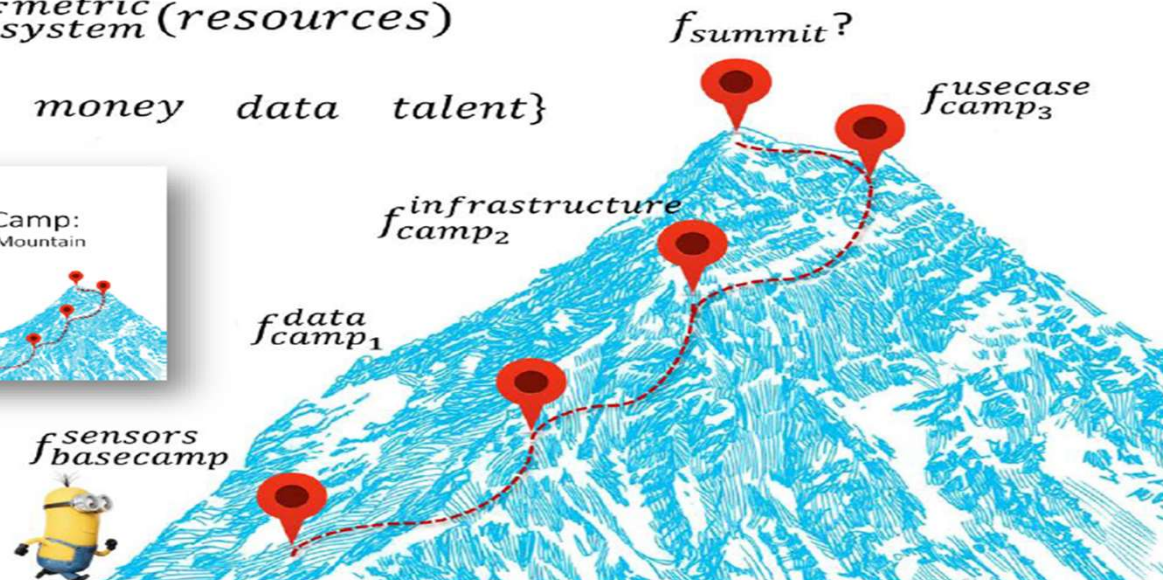
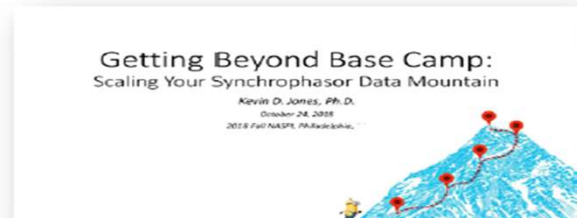
Scaling Mount Synchrophasor

Scaling Mt. Synchrophasor

The common objective function for each dimension of scaling is to drive down the cost of analytic experimentation.

$$\text{outcome} = f_{\text{system}}^{\text{metric}}(\text{resources})$$

$$\text{resources} = \{\text{time} \quad \text{money} \quad \text{data} \quad \text{talent}\}$$



Source: Presentation by Kevin D. Jones in NASPI

Challenges of Phasor Data



Streaming Data

- High speed, real-time
- Continuous analysis
- Specific historical context

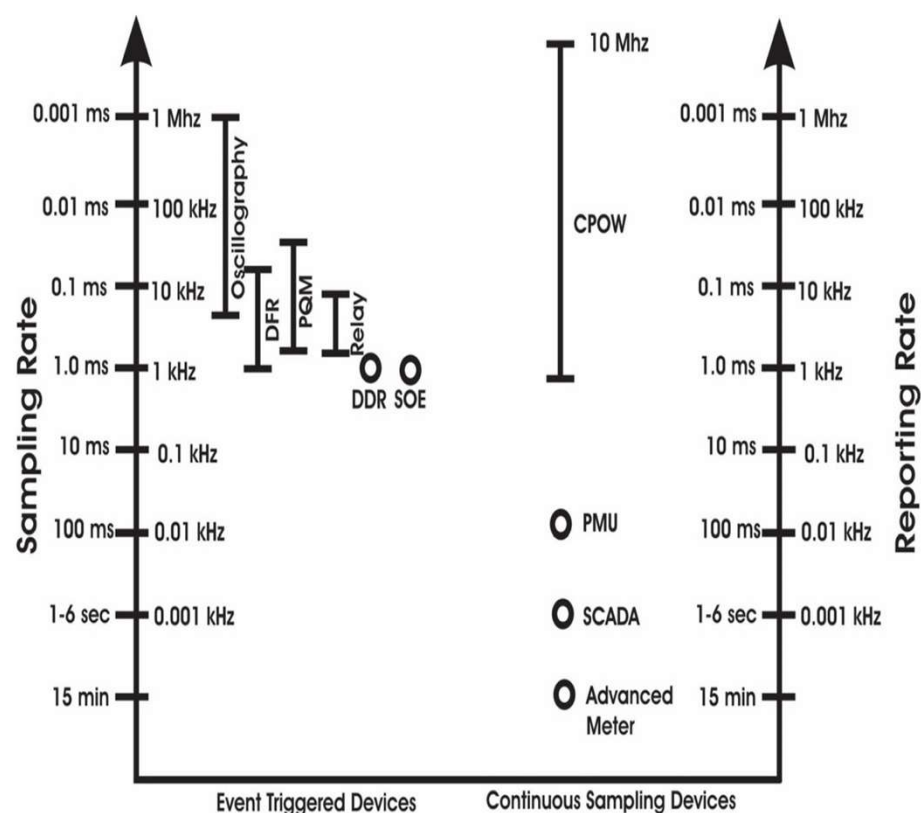


Big Data

- Large volume
- On-demand analysis
- Full historical context

Source: Presentation by Tom Anderson in NASPI WG April 2019

Grid Monitoring Devices Future ?

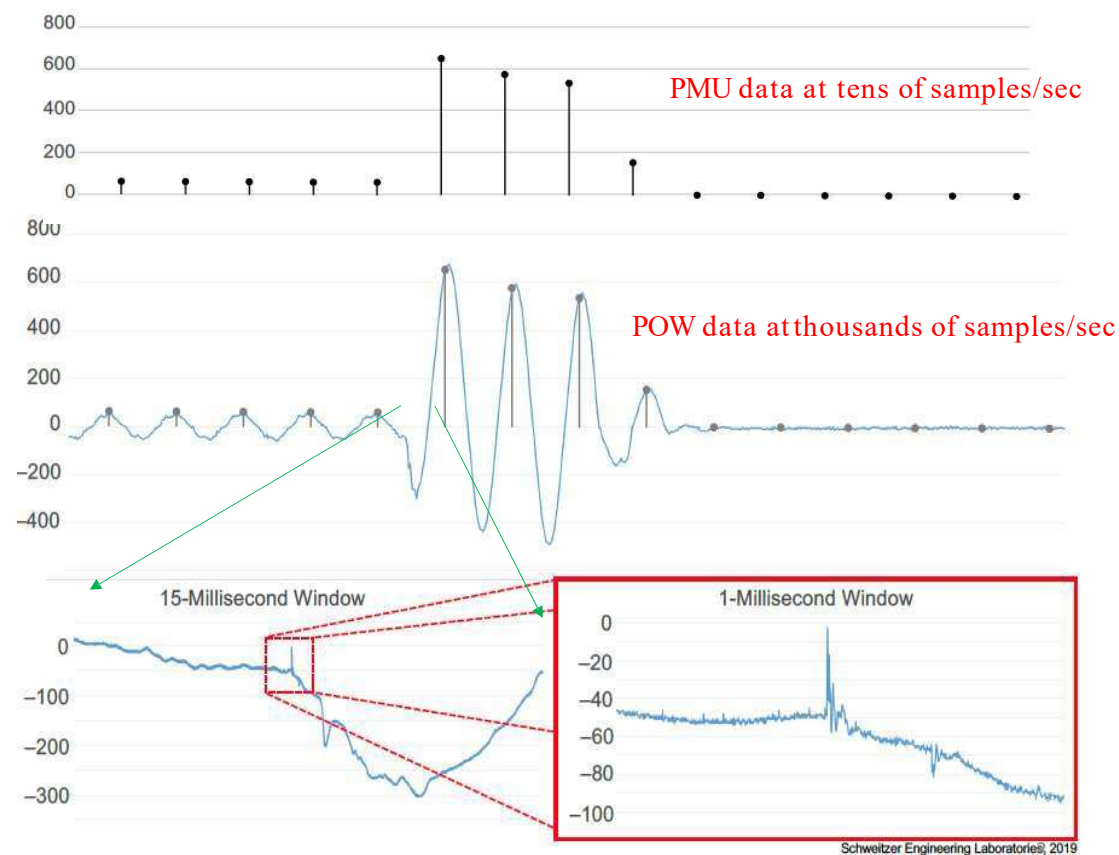
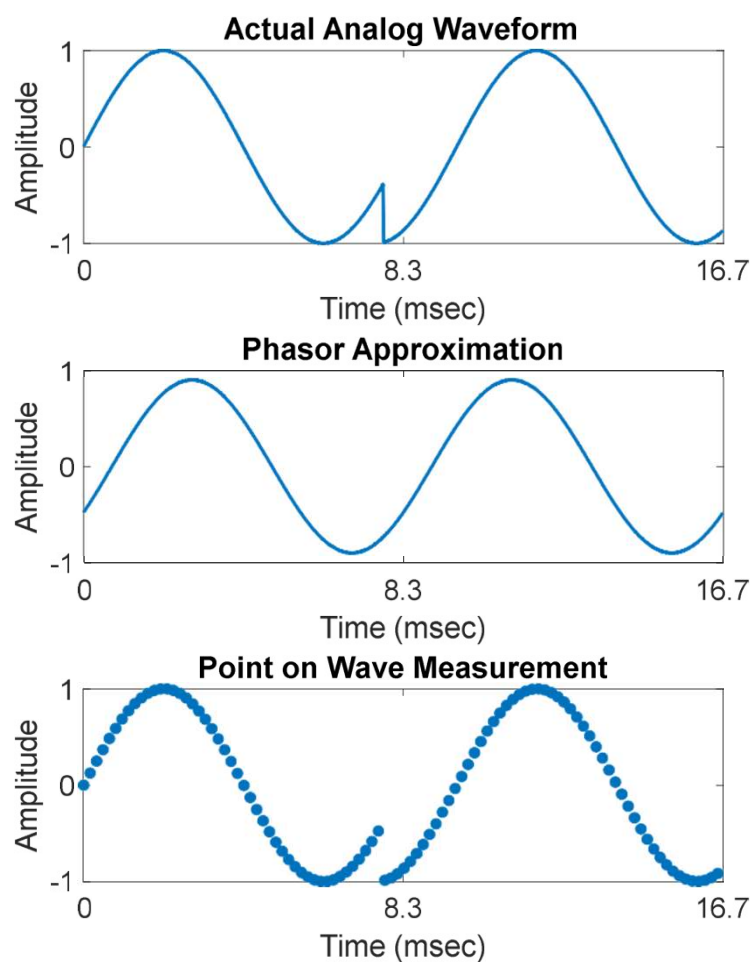


TIME PERIOD	GRID EVENTS	GRID APPLICATIONS
Nanoseconds	• Arcing faults	
Microseconds	• Lightning strike • Switching of inductive or capacitive loads, transformers	• Breaker restrikes • Harmonics higher than 16th
Milliseconds	• Harmonics • Faults	• Fault-induced delayed voltage recovery of air conditioners • Solar PV inverter trip and recovery • Meter error • Relay operation • Fast frequency response
Seconds	• Load shifts • Load flow changes • Generation dispatch	• Governor, exciter automatic voltage response (electromechanical transient) • Inertial response to frequency loss
Minutes	• System stability	• Power swings • Time of use meters • System peak
Hours	• Load variations	• Generation schedules

Source: HIGH-RESOLUTION, TIME-SYNCHRONIZED GRID MONITORING DEVICES Alison Silverstein, Alison Silverstein Consulting Dr. Jim Follum, PNNL North American Synchrophasor Initiative Technical Report March 20, 2020

Grid Monitoring Devices Future ?- WMU/CPOW

Compare PMU to POW fidelity
to actual waveform



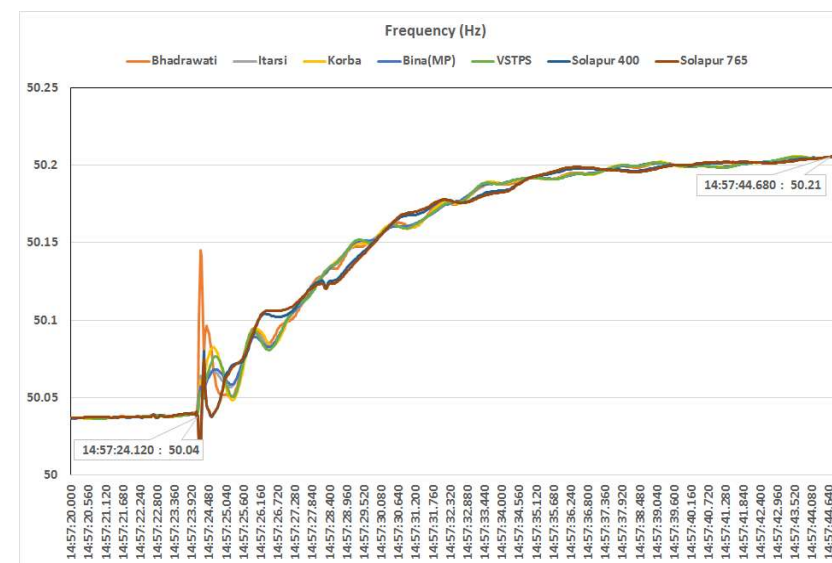
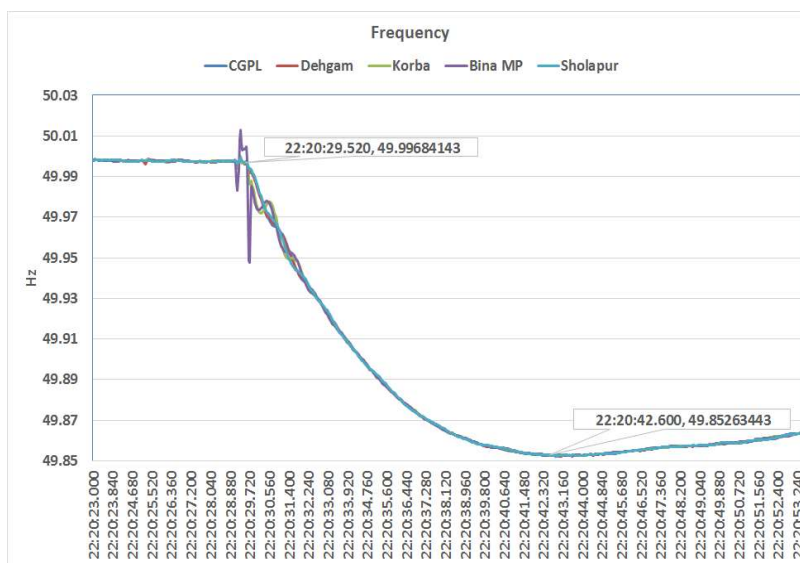
Source: Greg Zweigle, SEL, NASPI Work Group Meeting, 10/30/19

1. Real Time Event detection and Restoration support



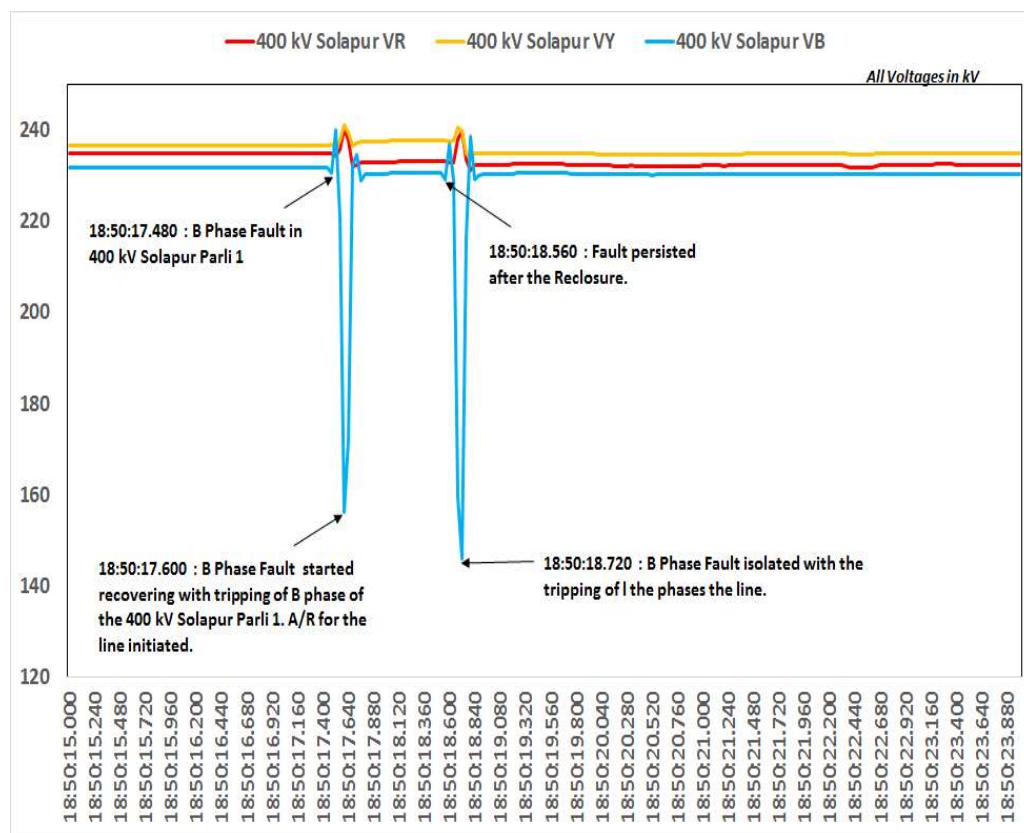
Generation and Load Loss Event

- Any load or generation loss event is characterized by sudden change in frequency.
- Generation Loss :Frequency Drop
- Load Loss : Frequency Rise.

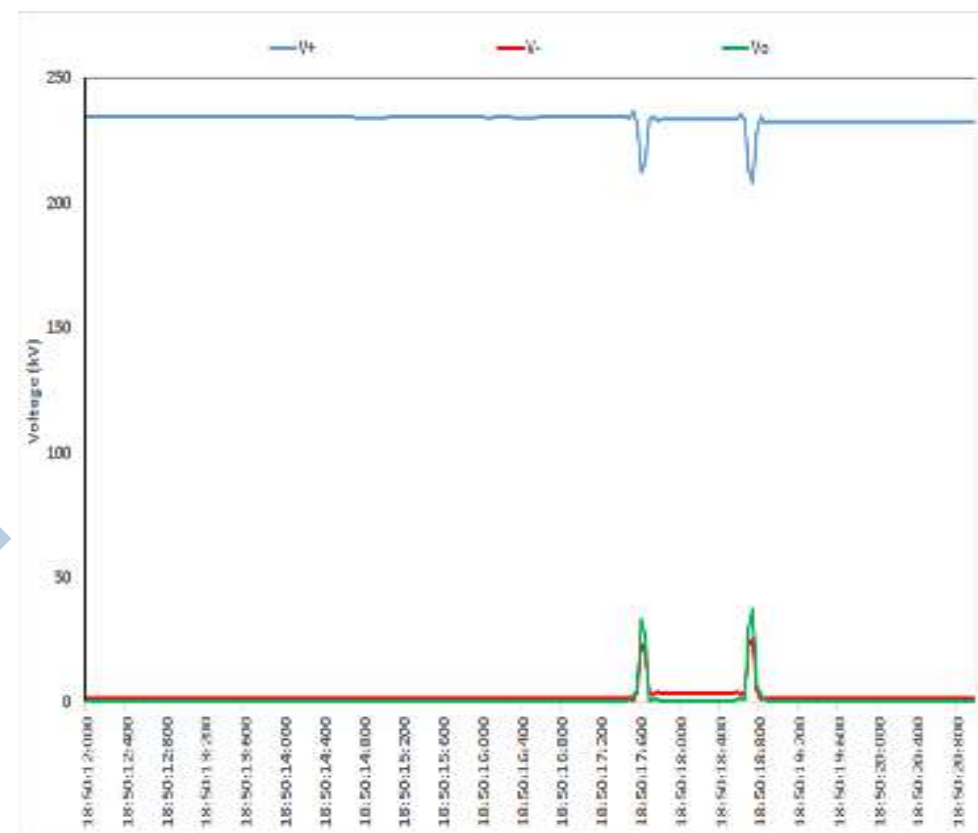


Single Phase to Earth Fault

- Case Study : B Phase to E/F on a line whose one end Bus voltage is measured from PMU.



Bus Voltage phase Magnitude



Bus Voltage Sequence Component Magnitude

Auto-Reclose Validation..

▷ Single phase to earth fault on transmission line with **unsuccessful A/R**

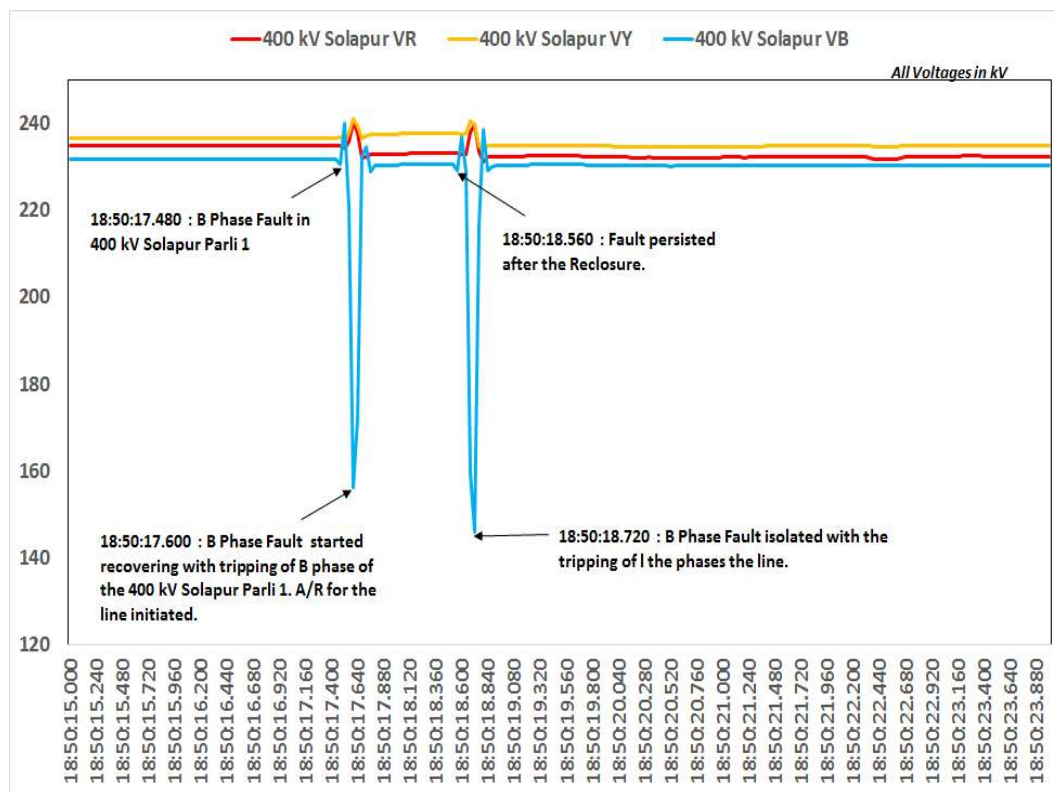


Fig : Voltage of 400 kV Sholapur bus from Synchrophasor data during single phase to ground fault on 400 kV Solapur-Parli circuit 1

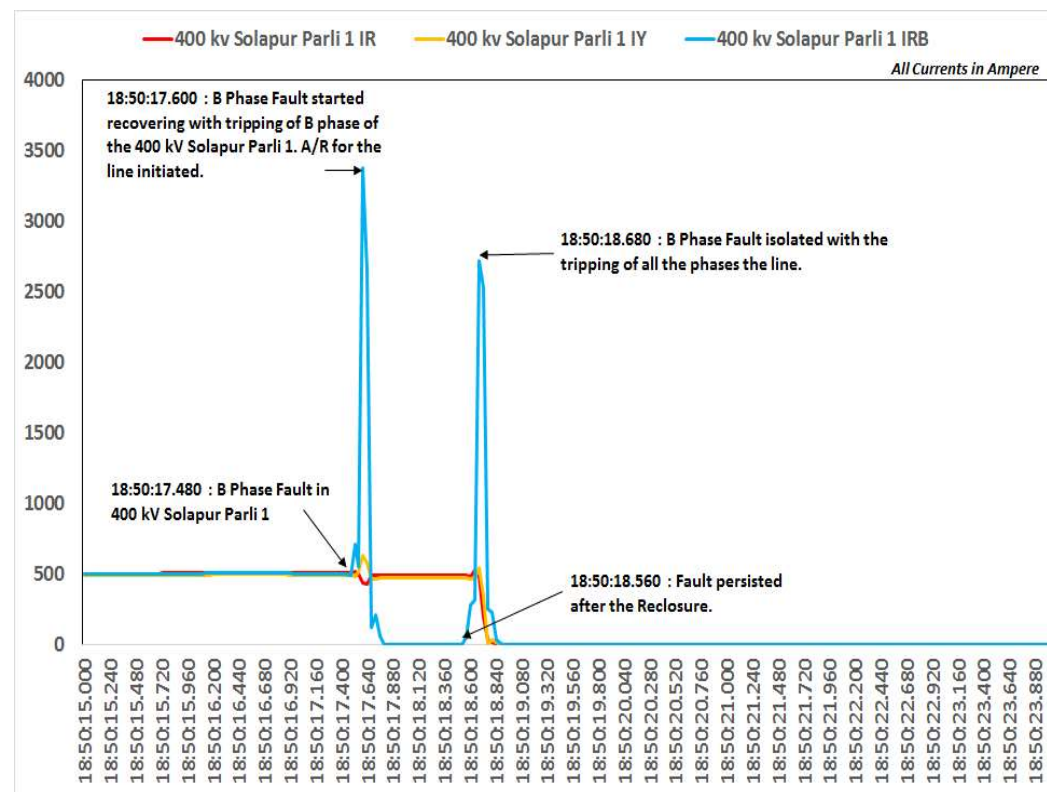


Fig : Current through 400 kV Solapur-Parli circuit 1 observed from Sholapur end

Auto-Reclose Validation

▷ Single phase to earth fault on transmission line with **successful A/R**.

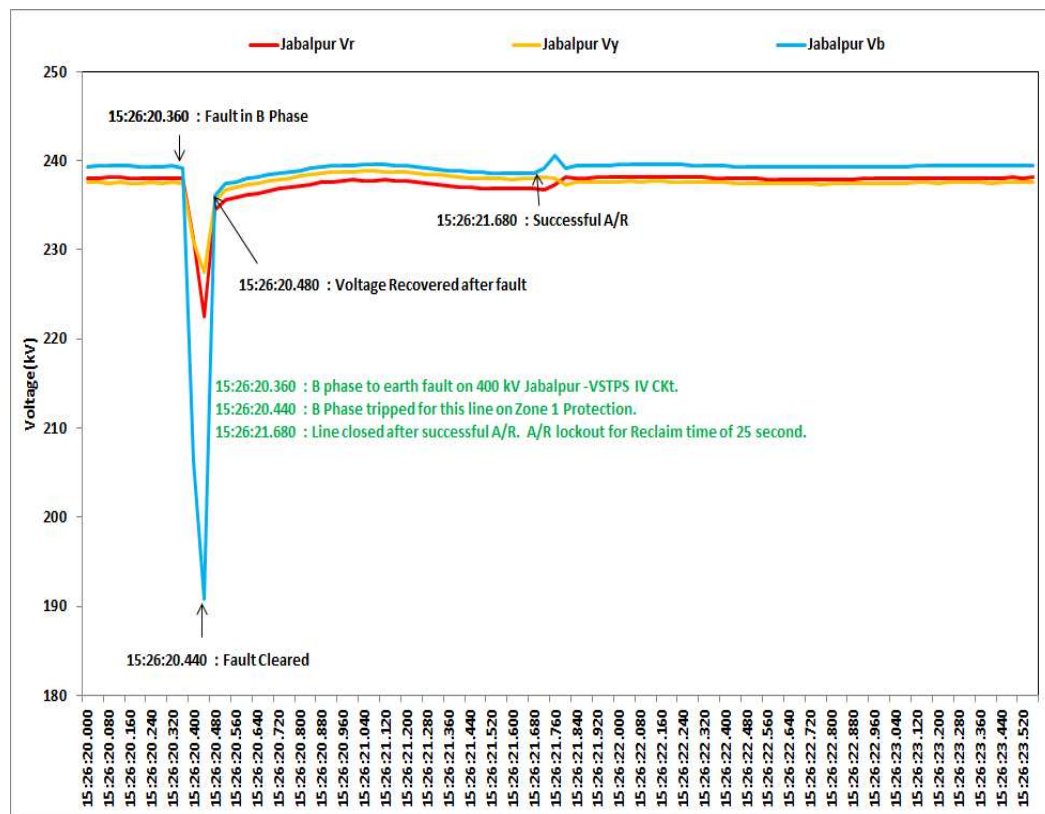


Fig : Voltage of 400 kV Jabalpur bus from Synchrophasor data during single phase to ground fault on 400 kV Vindhyachal-Jabalpur circuit 4.

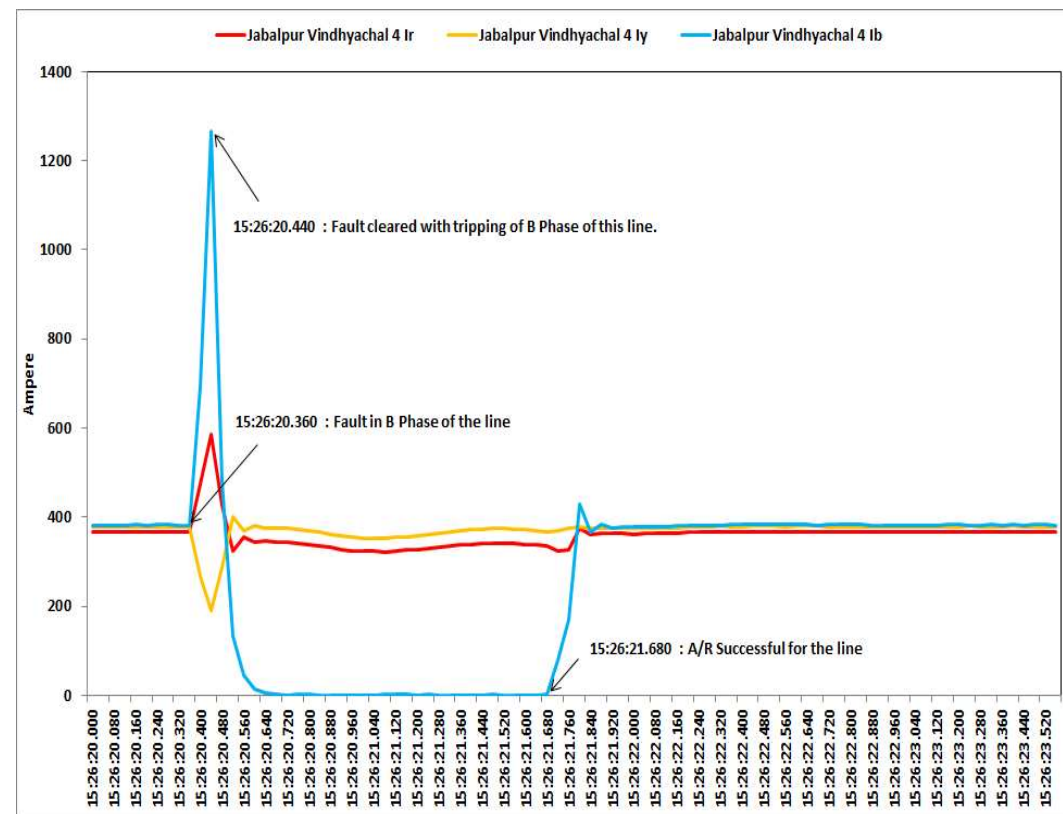
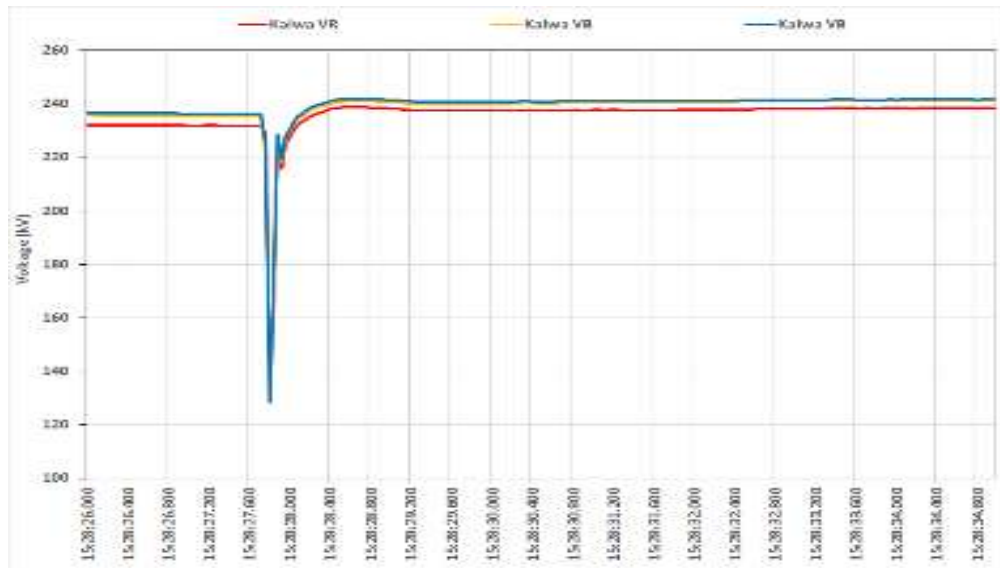


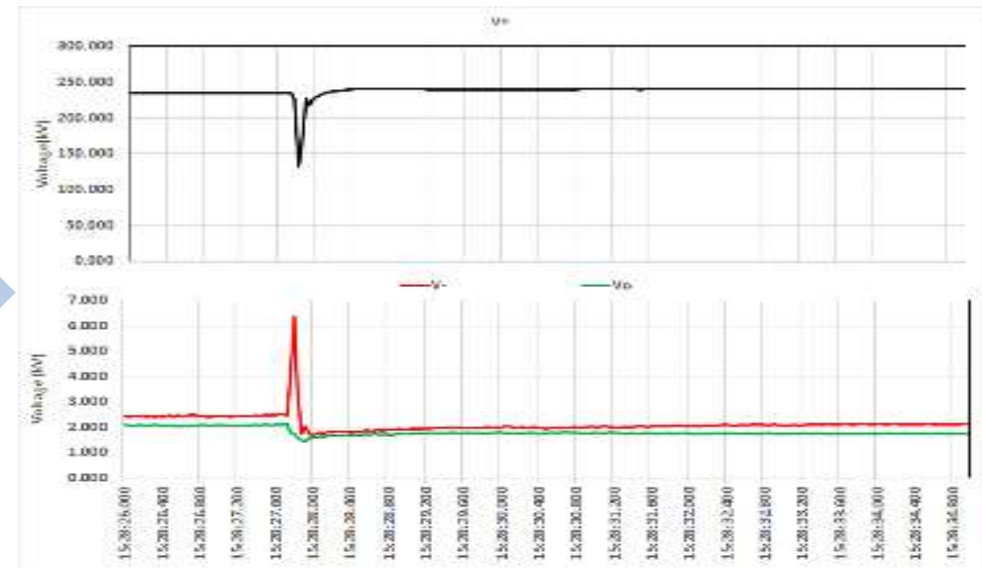
Fig : Current through 400kV Vindhyachal-Jabalpur circuit 4 observed from Jabalpur end

Three Phase Fault

- One of the rarest phenomenon and very few cases observed.
- The impact of three phase fault is hazardous particularly when they occur near to a load center.
- Case study : A three phase fault on 220 kV circuit at one of the sub-station where PMU is available at 400 kV voltage level.



Bus Voltage phase Magnitude



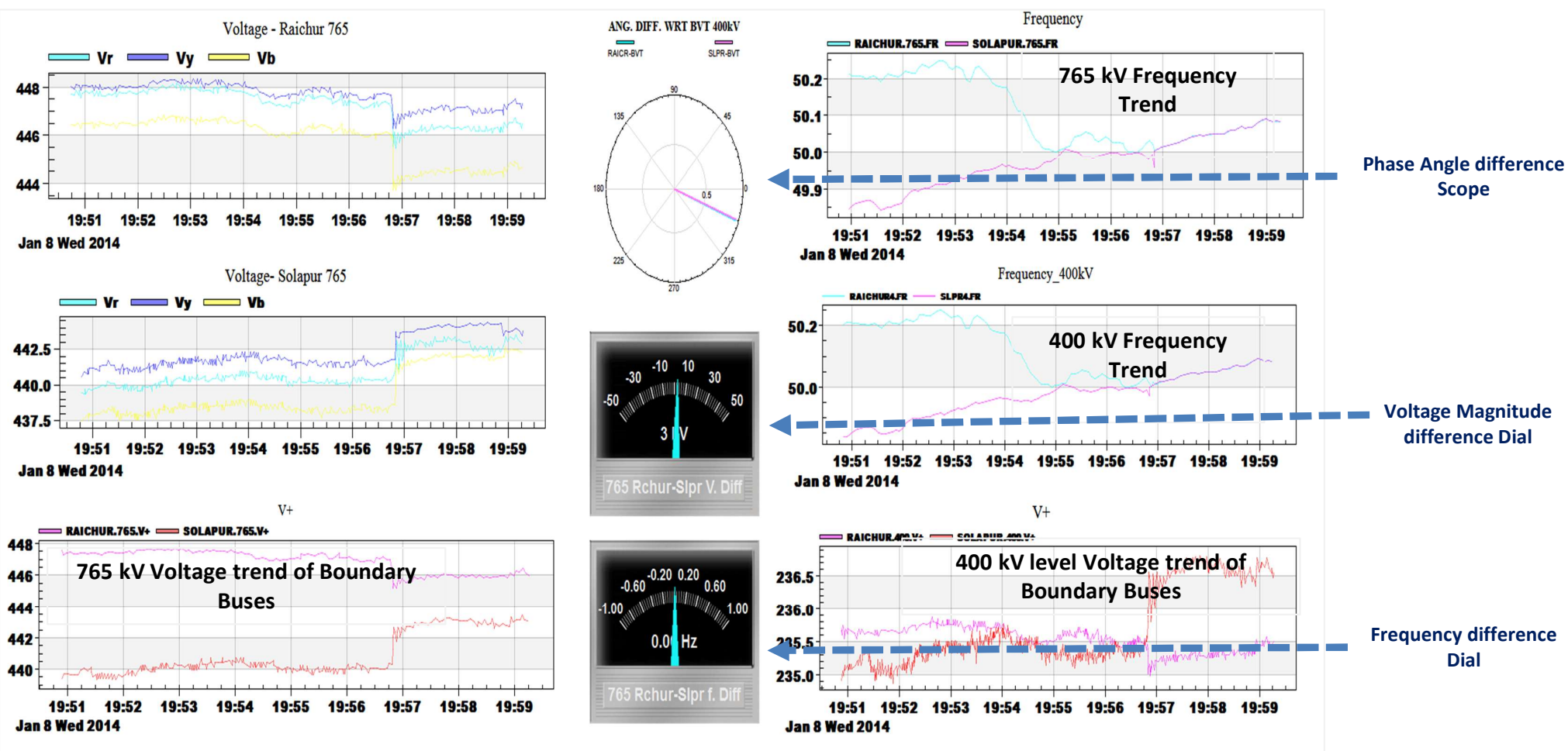
Bus Voltage Sequence Component Magnitude

2. Islanding Detection and Decision Support for Synchronization

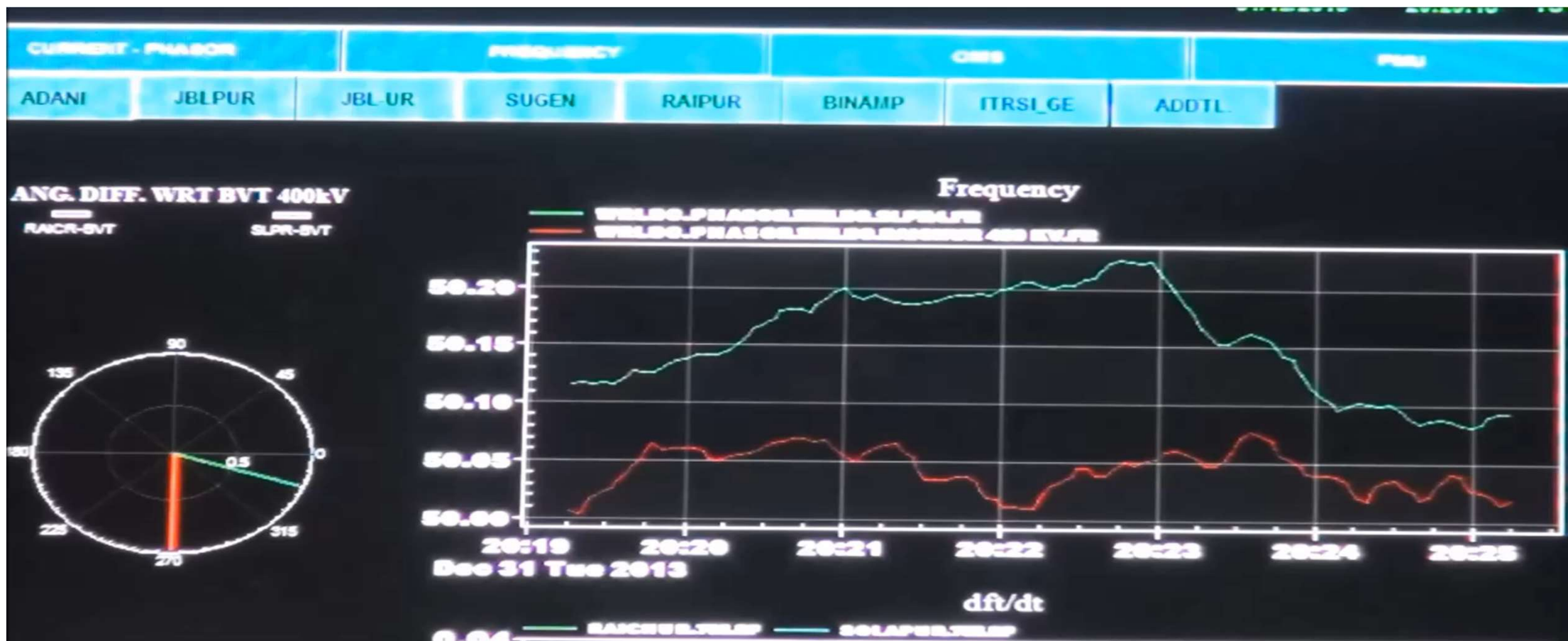
Remote Synchroscope for Control Centre using Synchrophasors

- ▷ PMU installed on both end of the Tie Line
- ▷ Bus PT and Line CT given as input to PMUs
- ▷ Optical fiber communication between PMU to Regional Control Center.
- ▷ Displays for visualization / Decision making
 - Frequency Control
 - Voltage Control
- ▷ Real-time view at Regional/National Control Centre
- Instruction for activation of auto-synchronization at sub-station issued from Control Centre

Dashboard at Operator Console in Regional/National Control Centre



Grid Synchronization : One of the First Use Case Across World



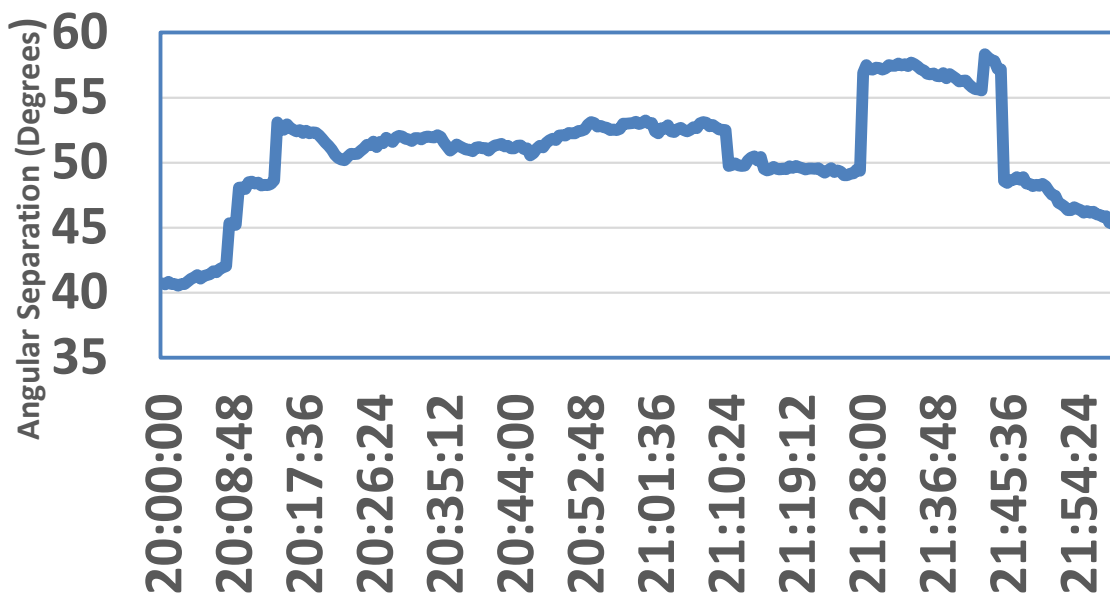
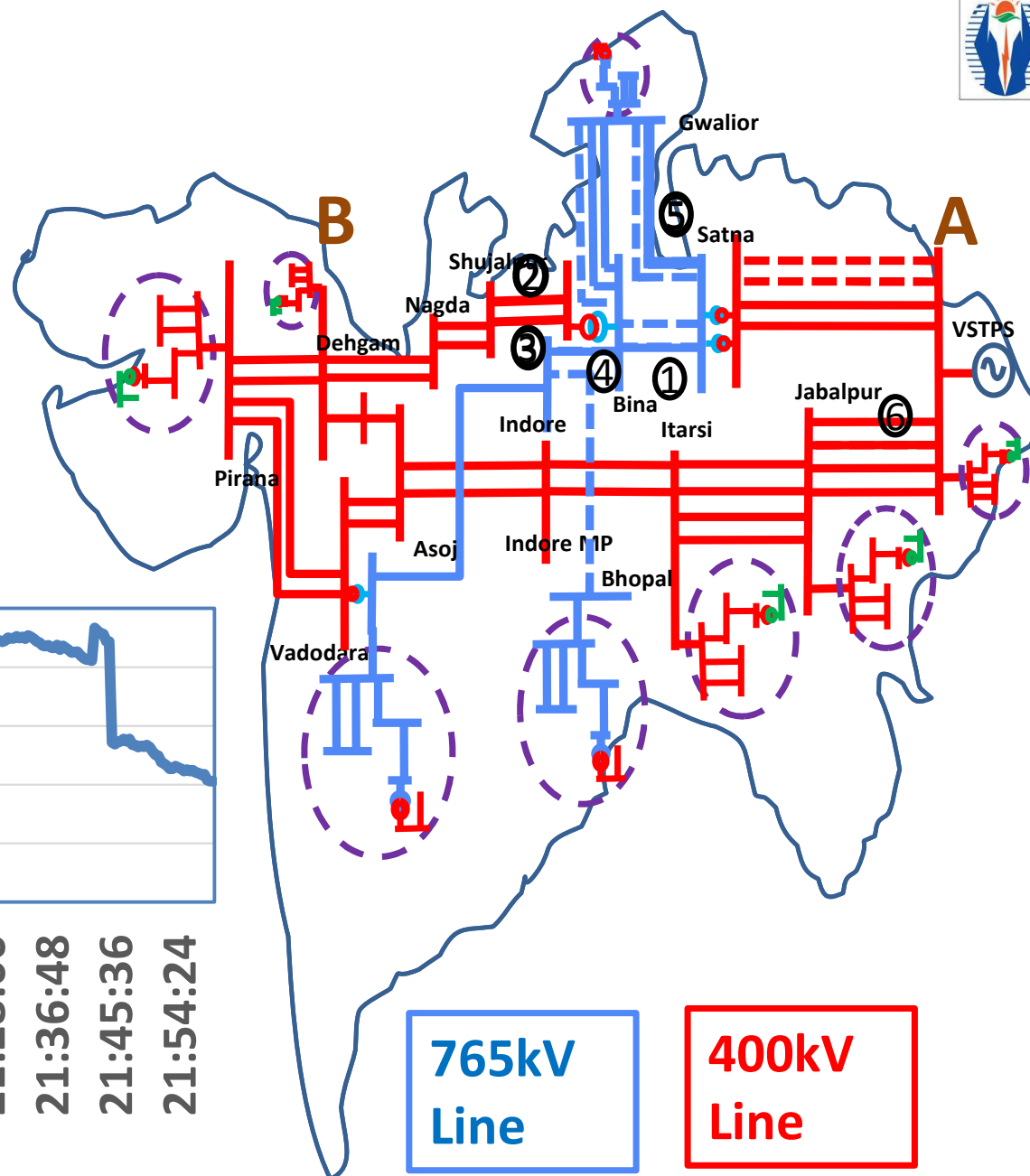
3. Angular Separation Monitoring



Normal and Alert Grid Operation

$$P = \frac{V_s V_r \sin(\delta)}{X}$$

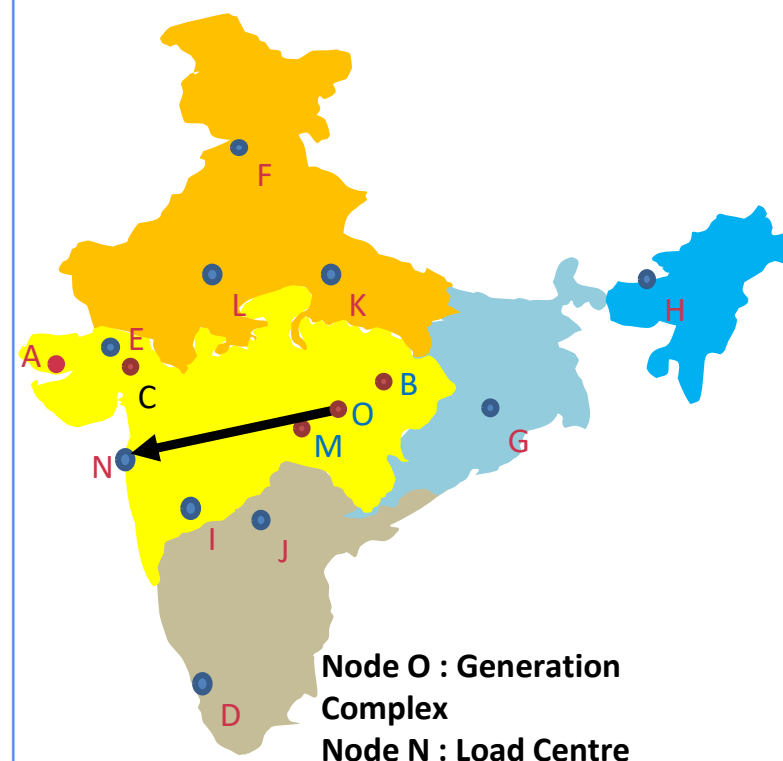
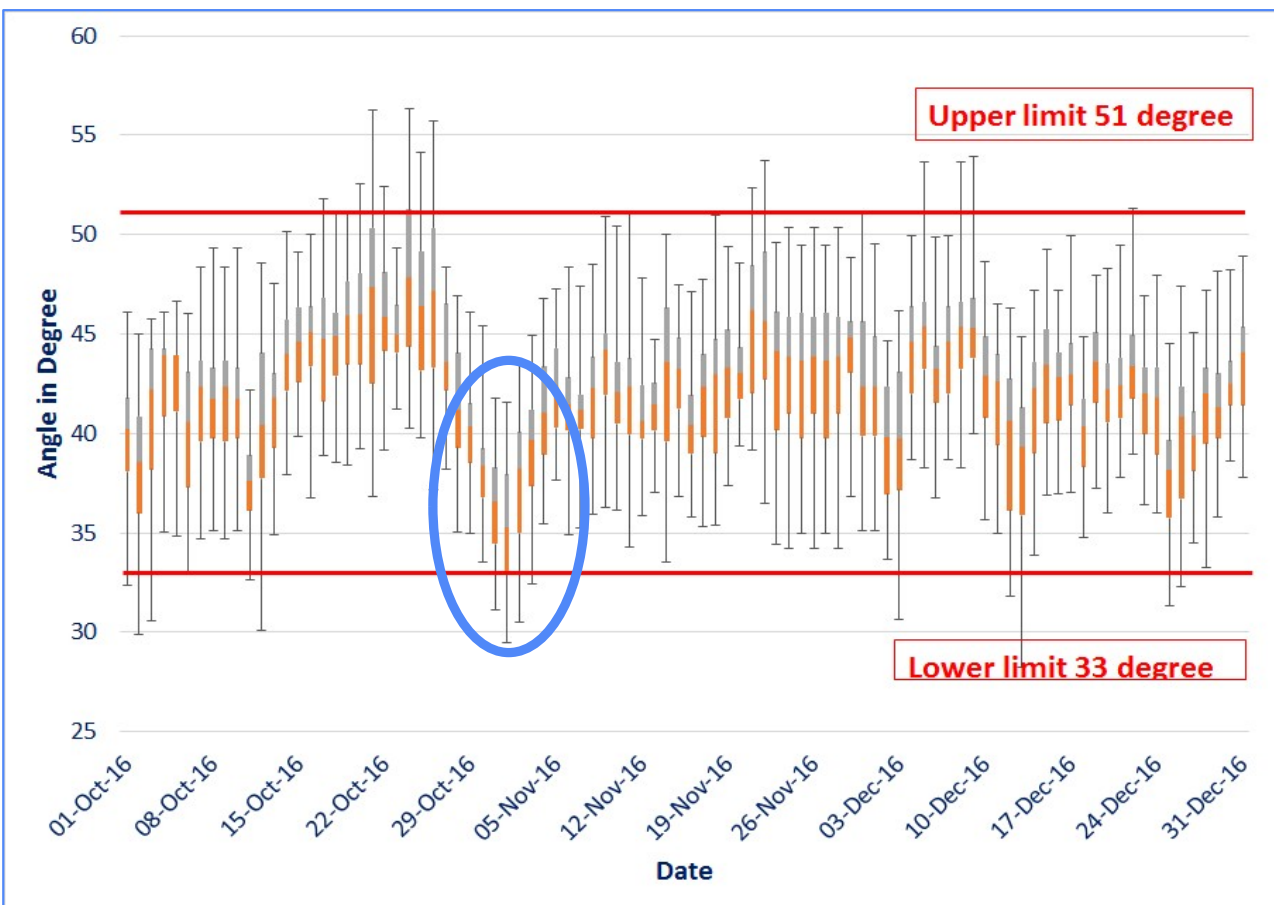
$$\delta = \sin^{-1} \left(\frac{PX}{V_s V_r} \right)$$



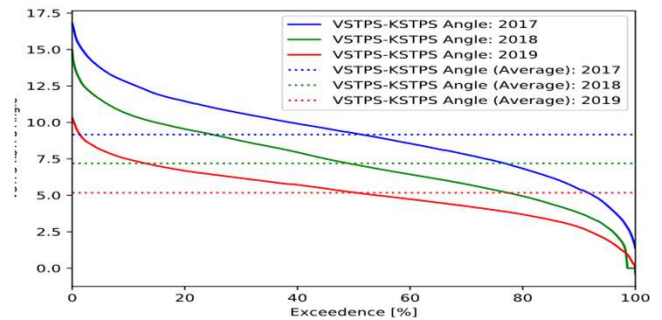
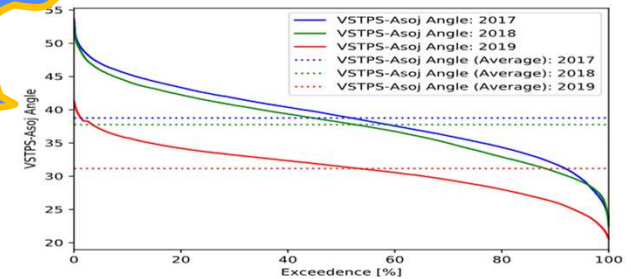
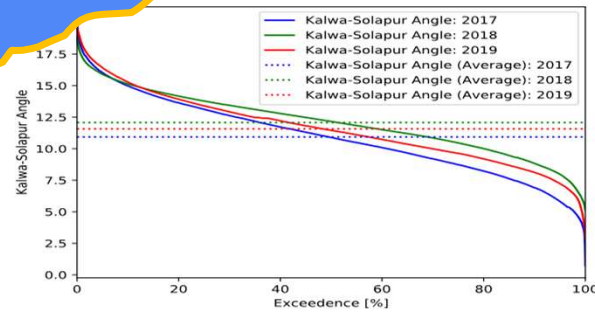
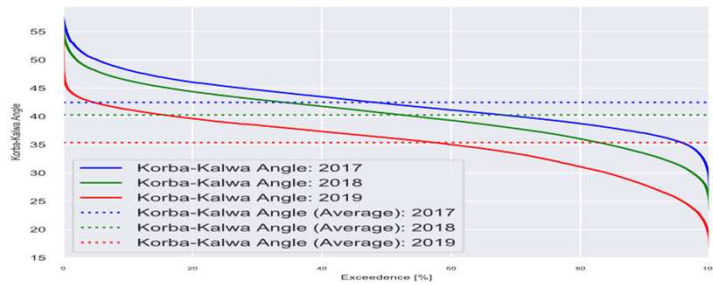
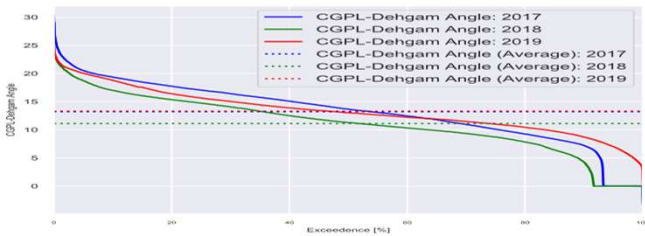
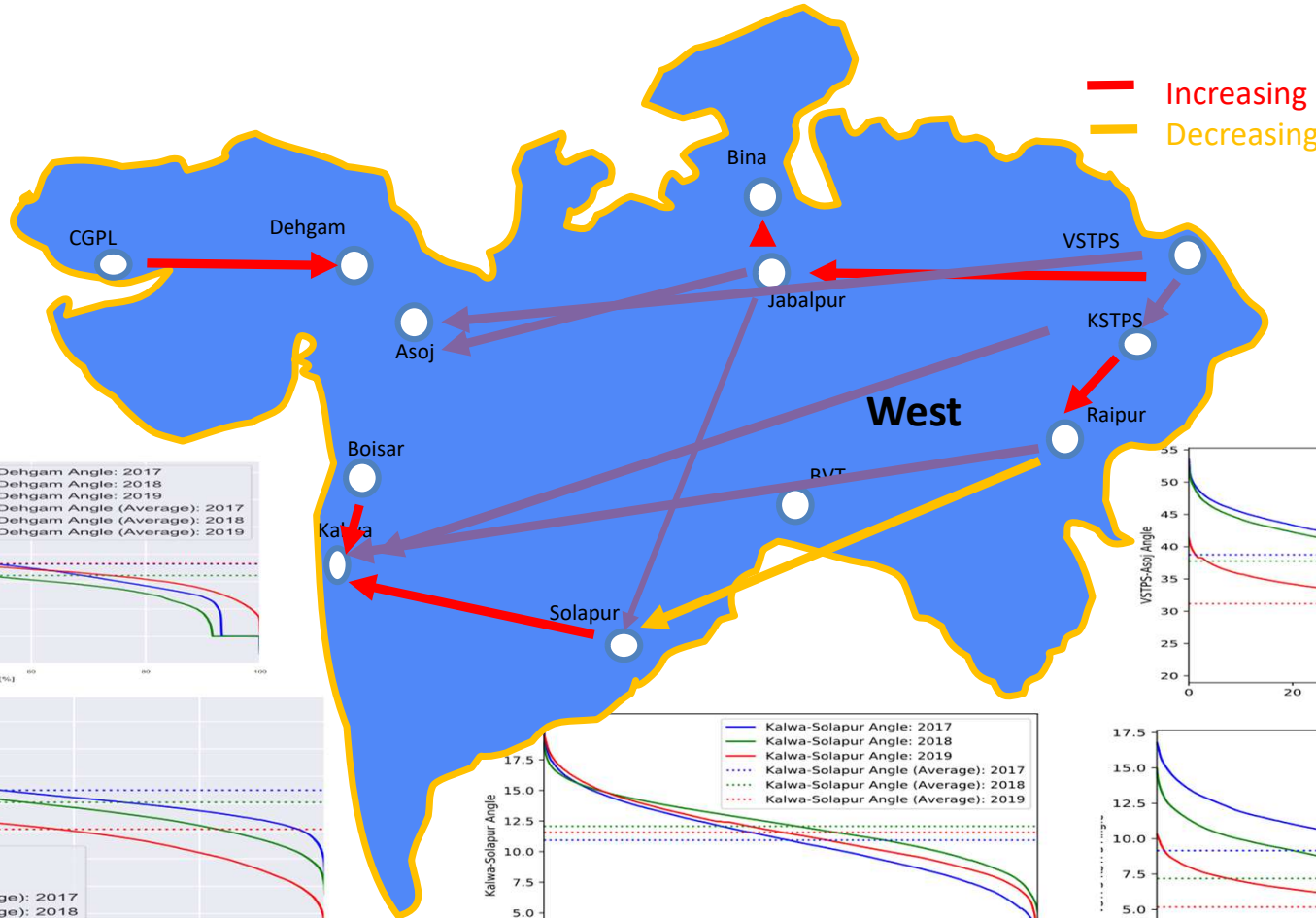
765kV
Line

400kV
Line

Typical wide angle pair for baselining



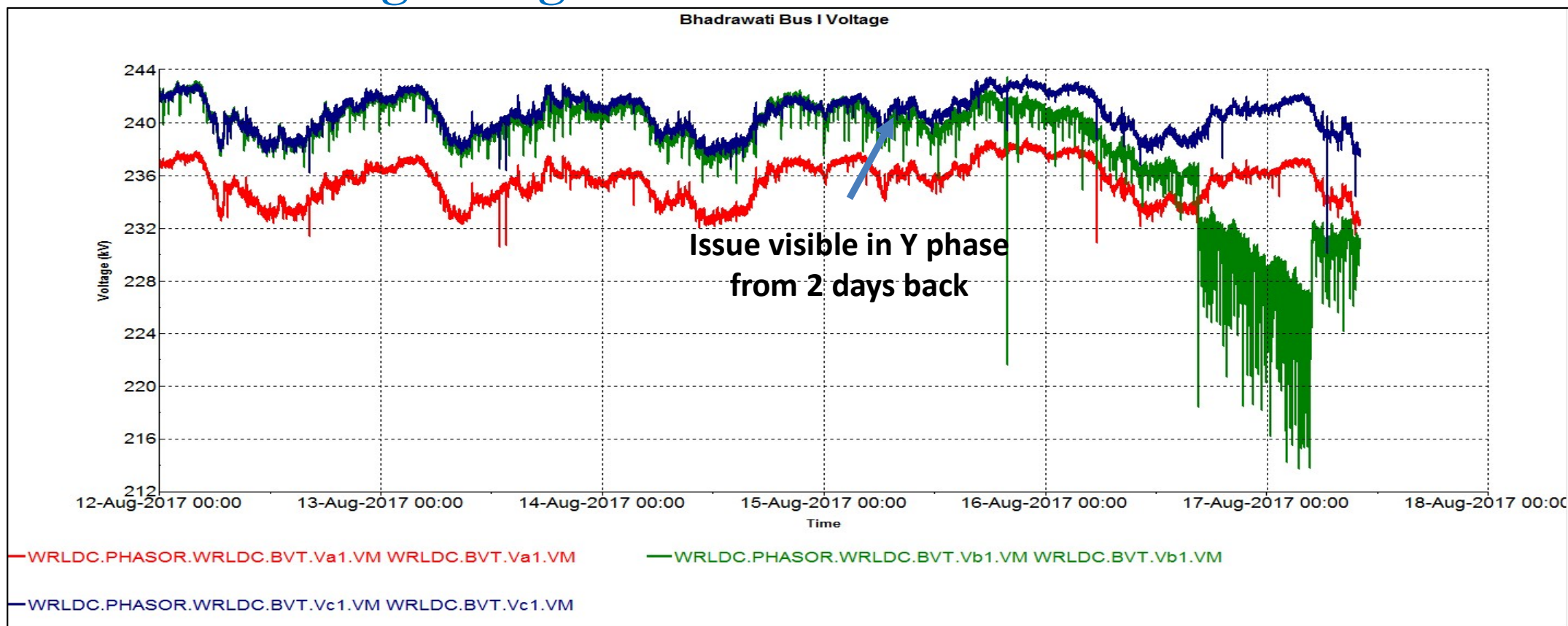
Angle Baseline for feedback to Planners



4. Failing CT/PT Detection



Failing Voltage Transformer: Our Own Case



**Case of Western Regional Grid :
Bhadrawati Y phase Bus 1 CVT Issue**

5. Oscillation Monitoring



Power System Responses

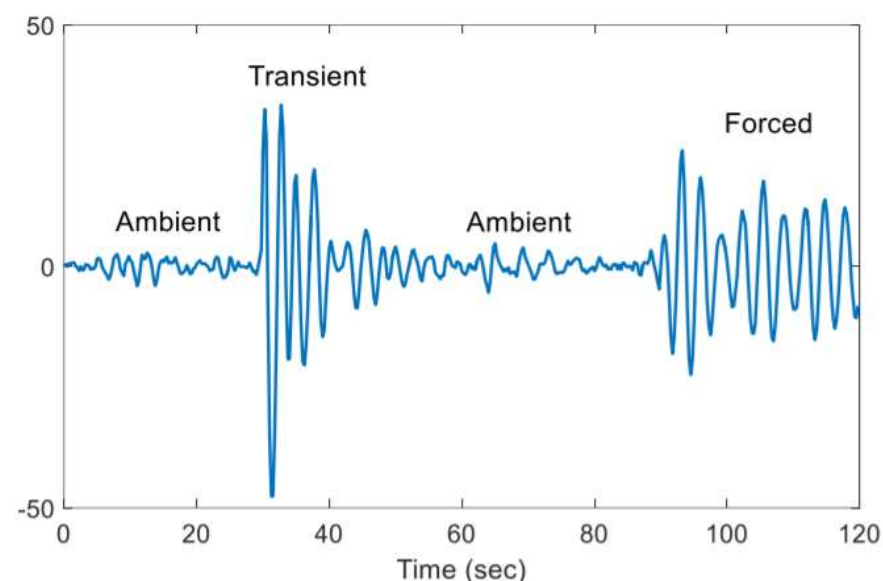
Power systems display variety of responses based on Initial condition and input.

Natural Response: A Natural Response is an oscillation characterized by the oscillatory modes only.

Ambient Response: System Response to small random changes. (Load changes)

Transient Response: System Response immediately after a sudden disturbance (Faults, line/ Generator/ Load Trip)

Forced Response: System response associated with an external input or a malfunctioning apparatus.

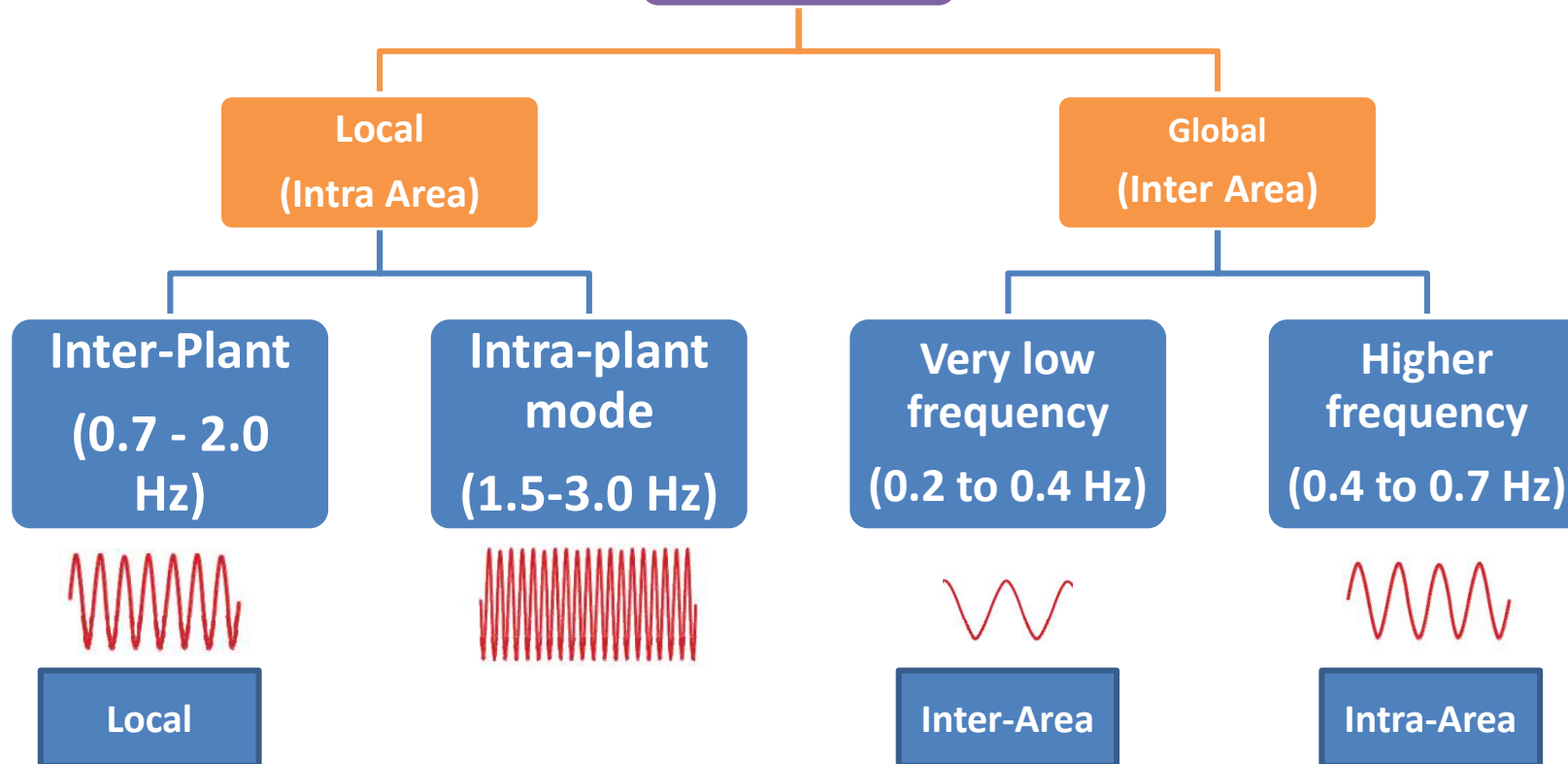


Modes of Oscillation

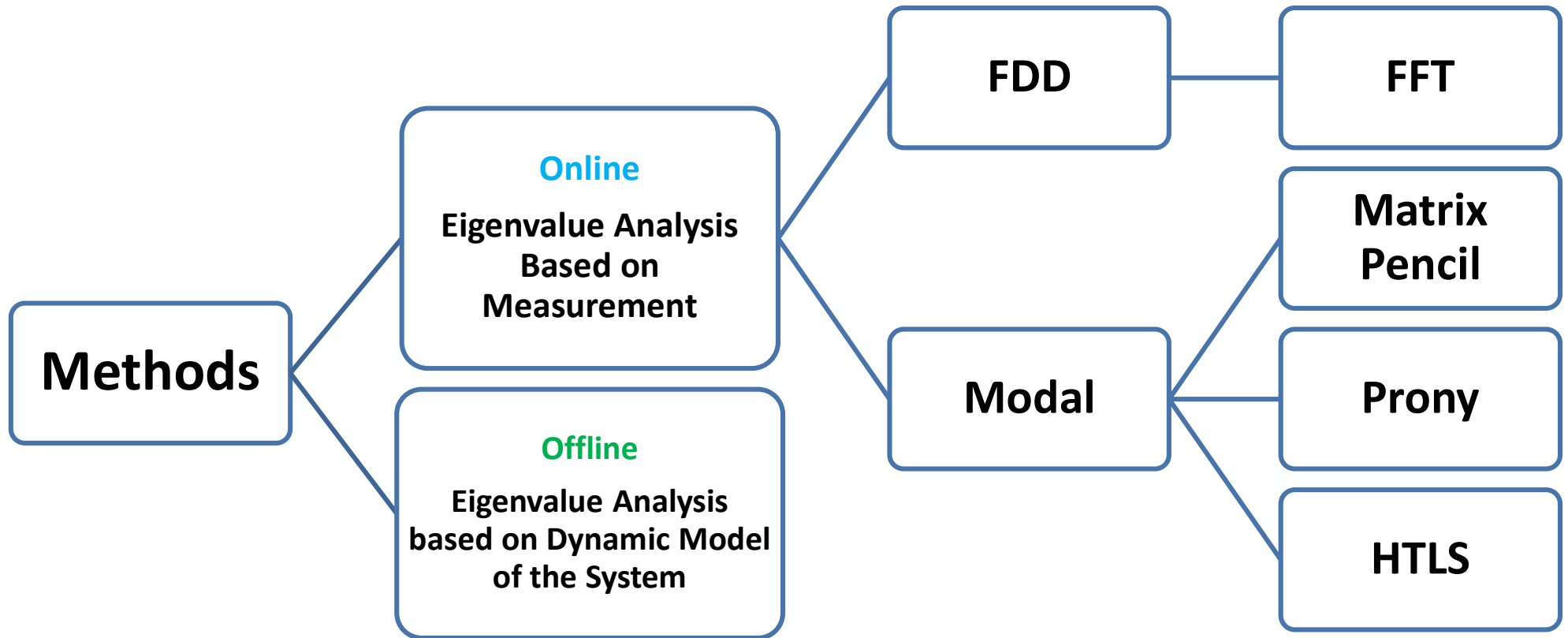
Electro-mechanical Oscillation : Mostly associated with Electro-mechanical Interaction in generating units

Small Signal Stability

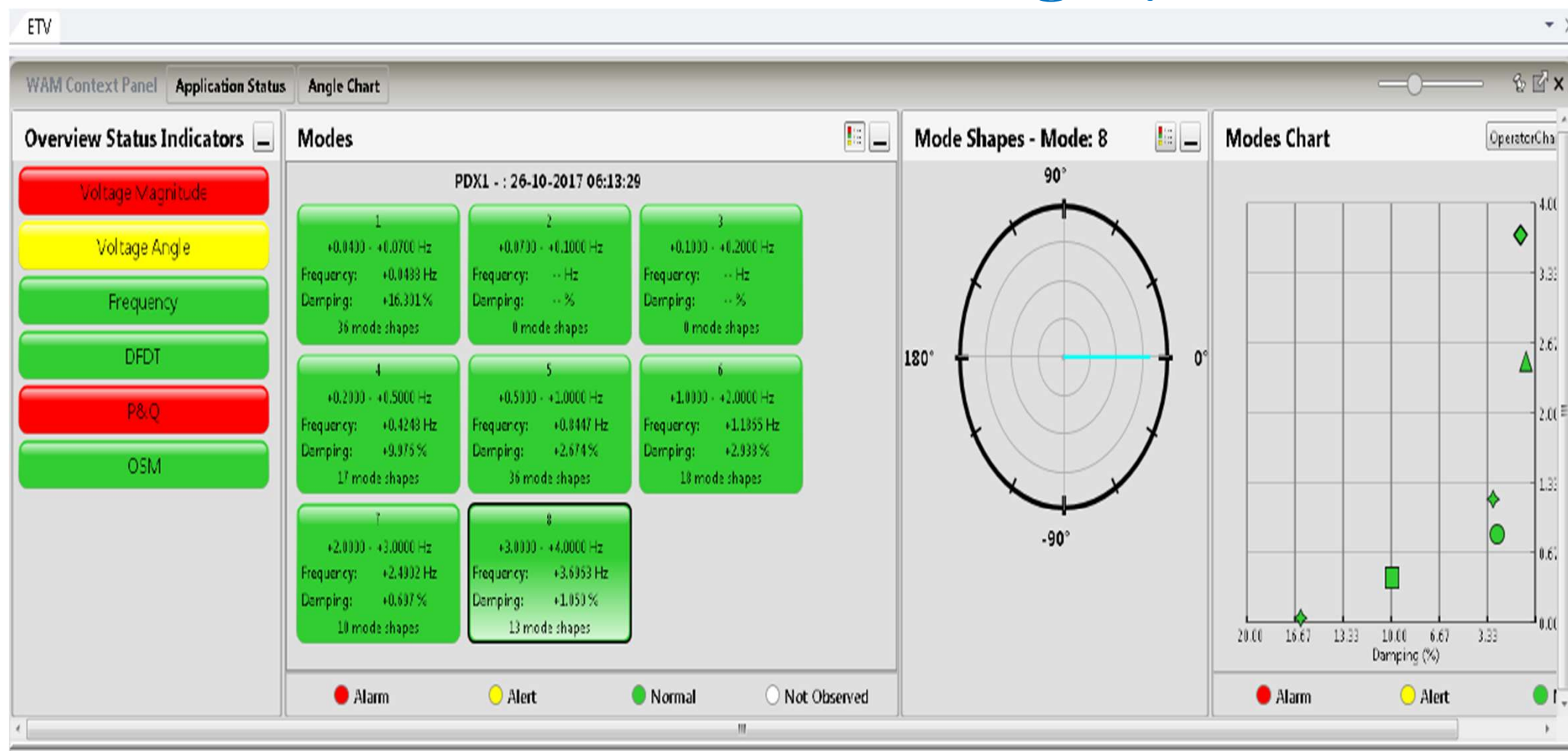
Low Frequency Oscillation : As frequency is Lower than Designed Frequency of Power system.



LFO Detection and Analysis

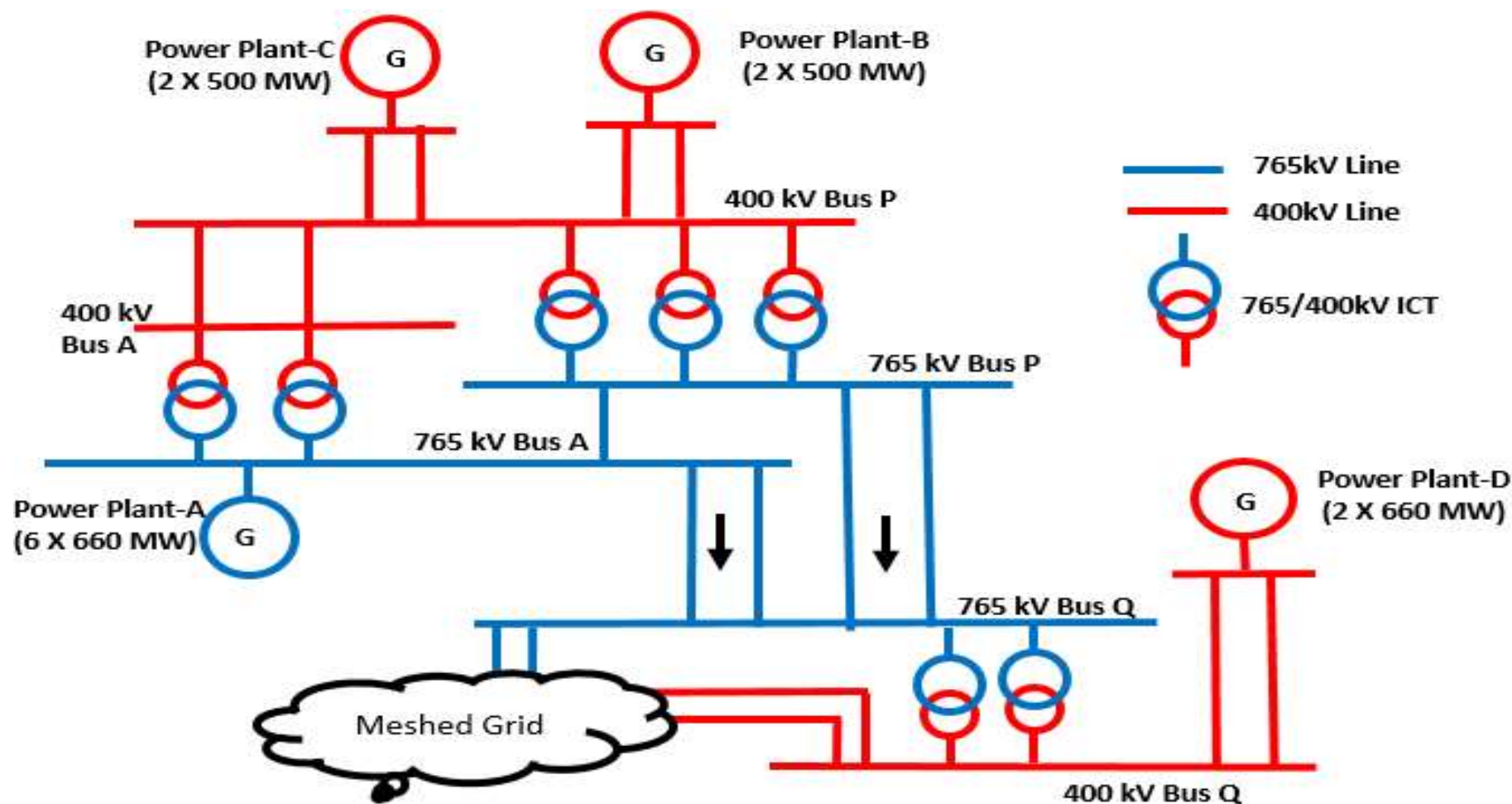


Oscillation Monitoring System

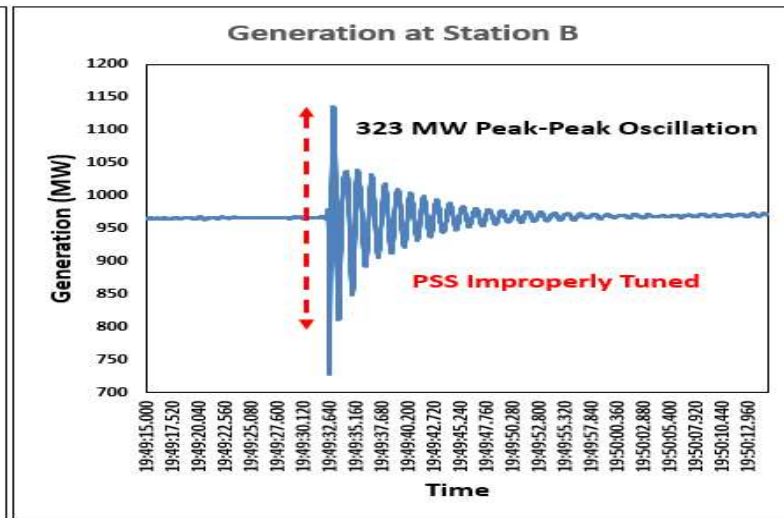
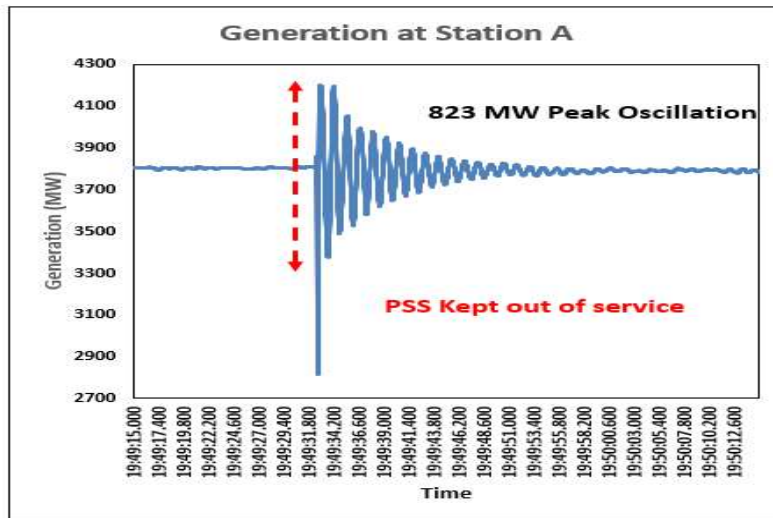




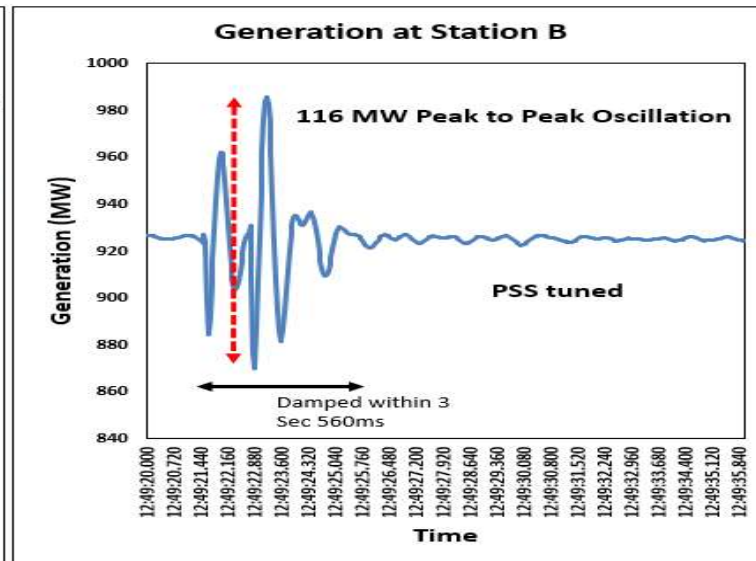
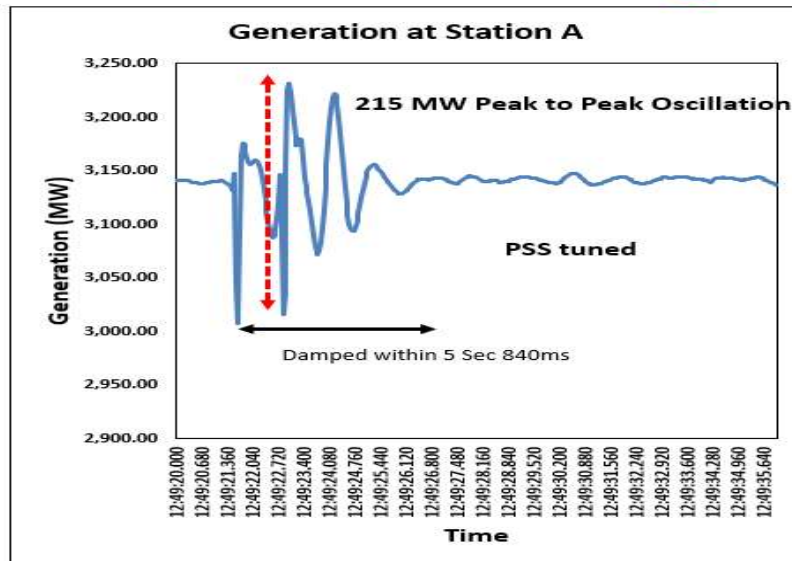
How Power System Stabiliser (PSS) Improve Damping : Example



**Before PSS
Tuning**

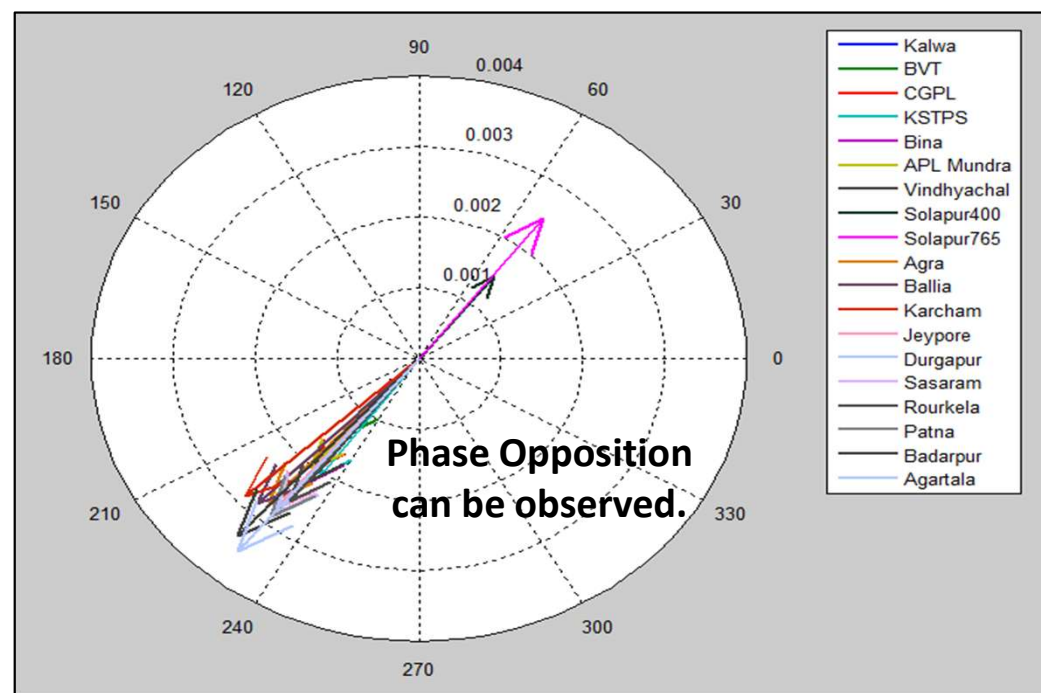
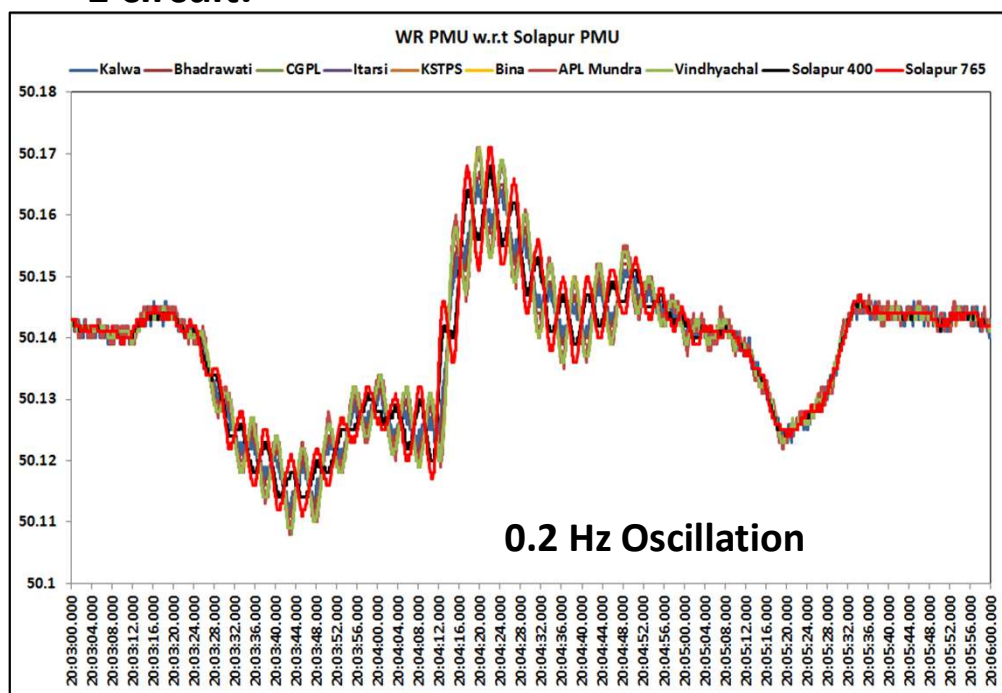


**After PSS
Tuning**

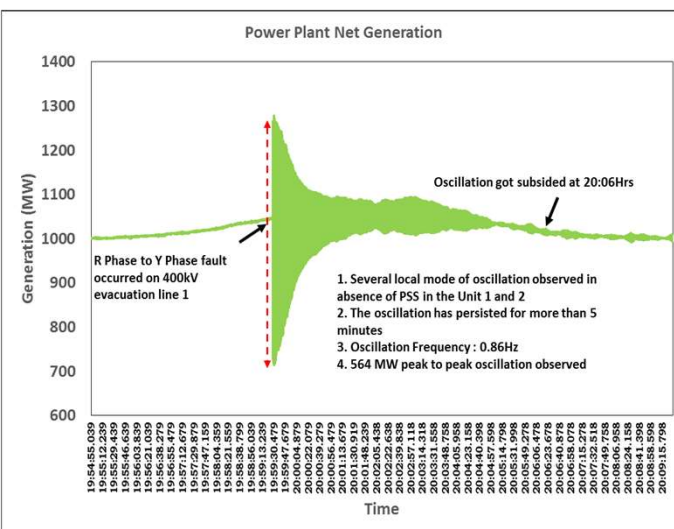
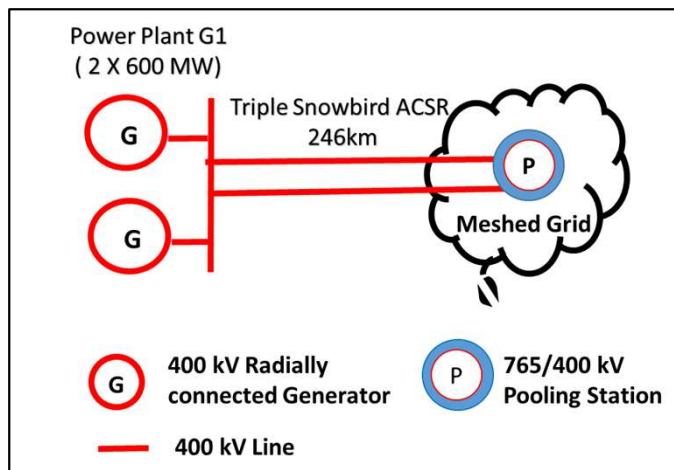


Inter –Area Oscillation : 0.2 Hz in NEWS Grid

- Here all generators align in two groups
- Two groups oscillate in phase opposition with each other.
- Major reason is weak tie link between two grids.
- E.g. 0.2 Hz oscillation between NEW and SR grid after synchronization through 765 kV Solapur-Raichur 1 circuit.



Use Case : LFO Detection at Power Plant

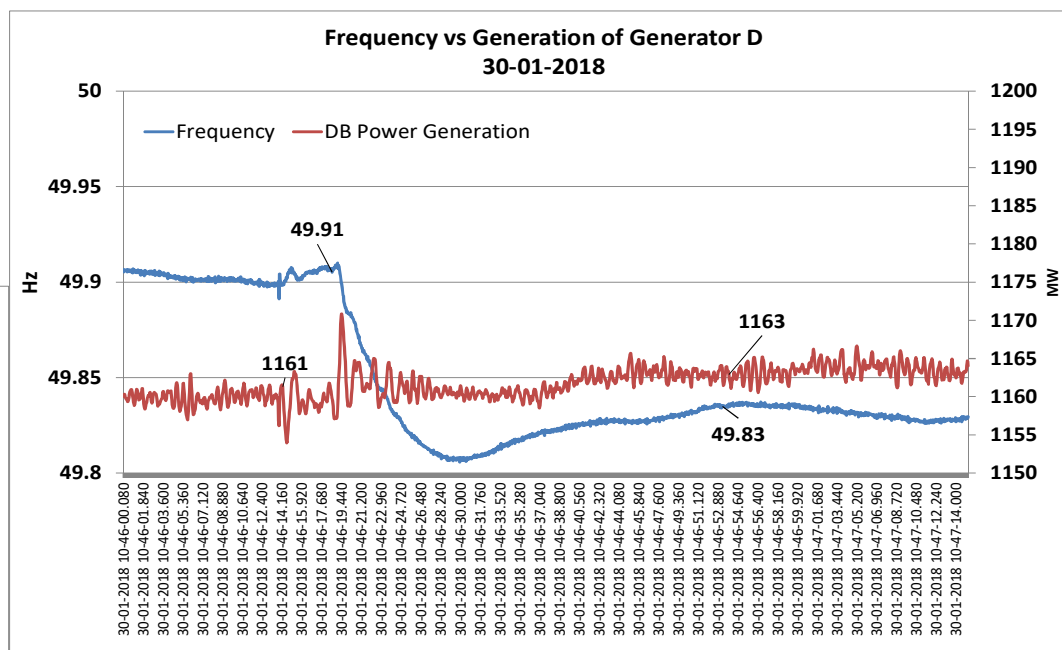
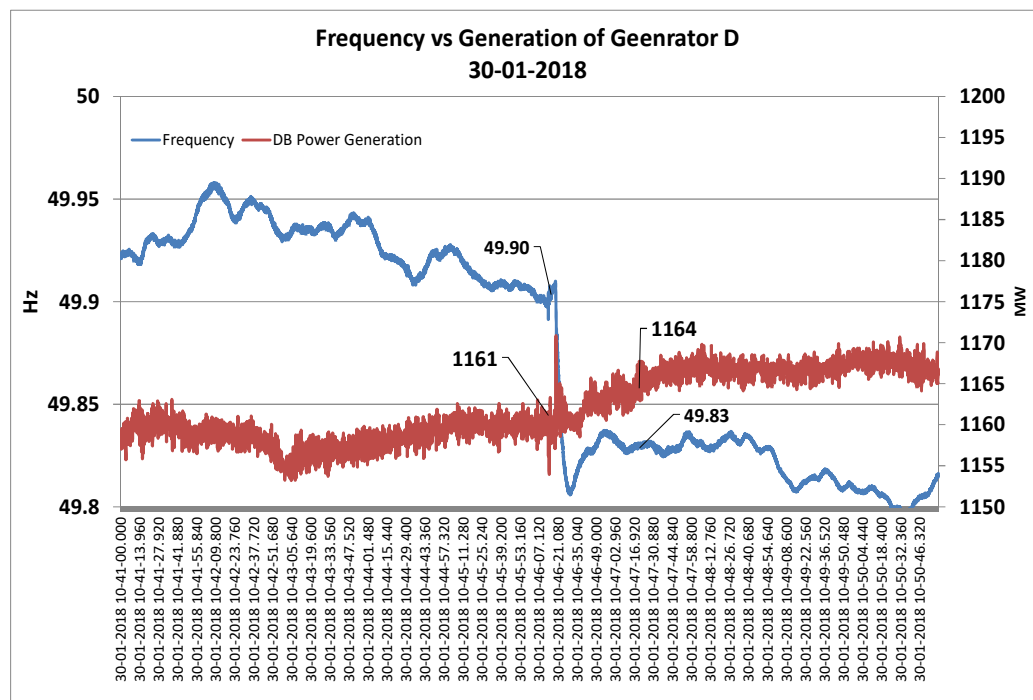


6.

Frequency Response Monitoring through PMU

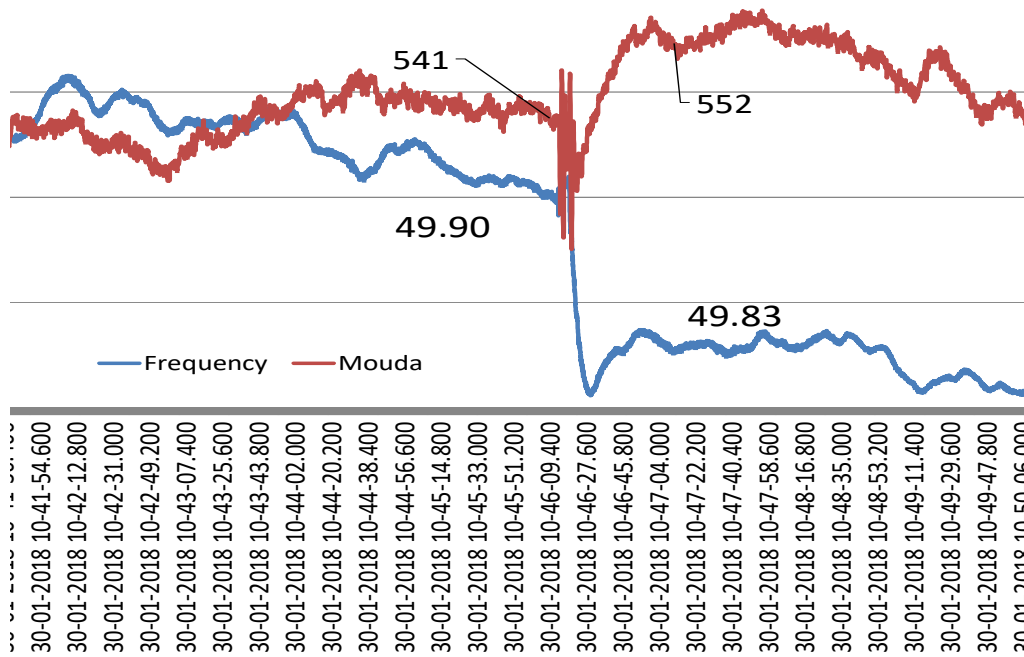


Frequency Response through Synchrophasor

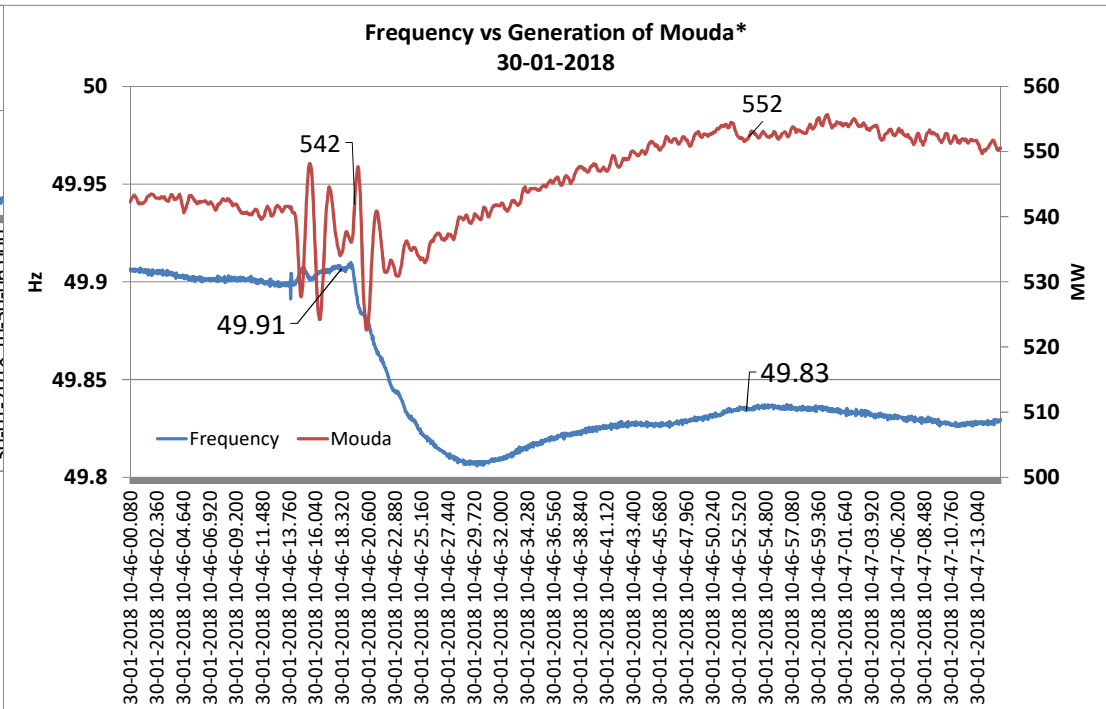


Frequency Response through Synchrophasor

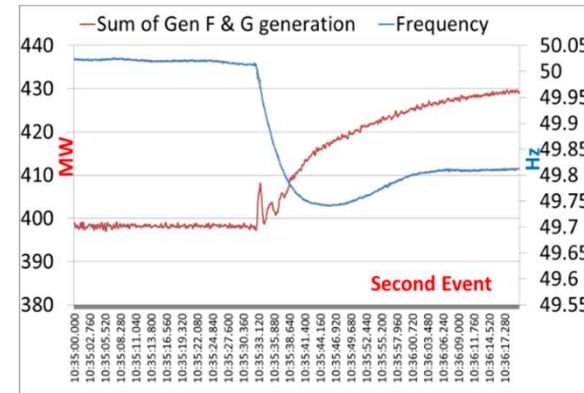
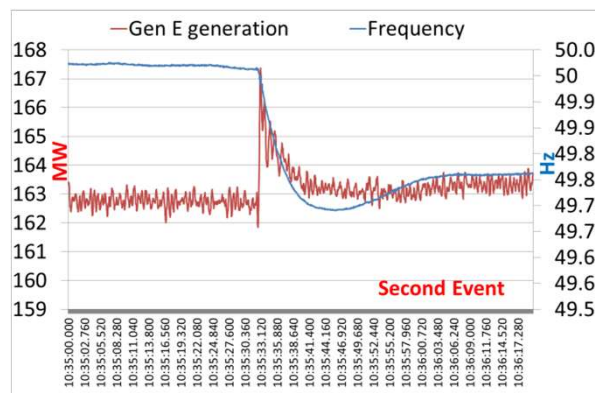
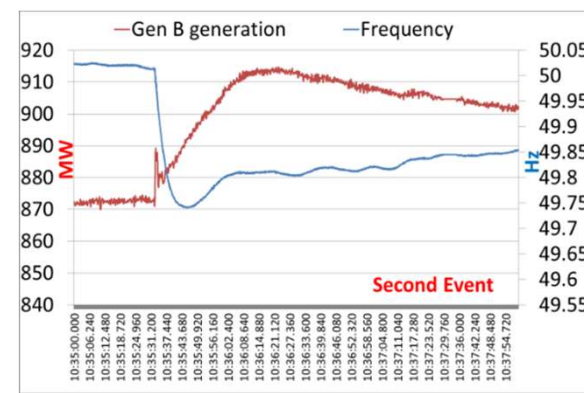
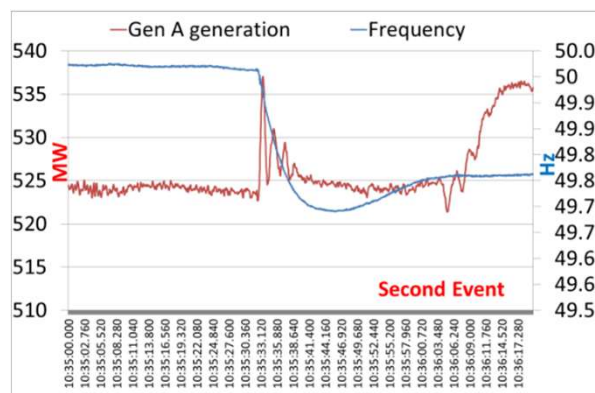
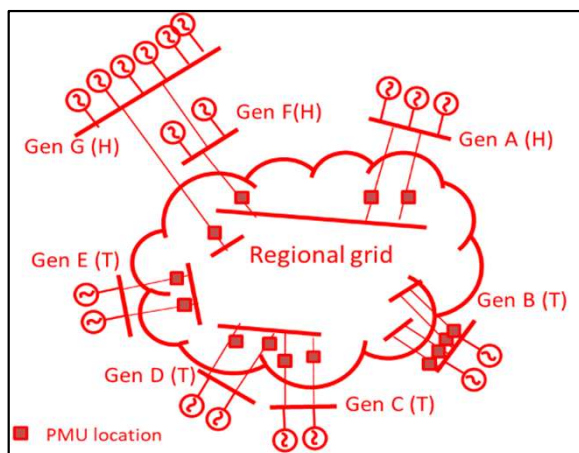
Frequency vs Generation of Mouda*
30-01-2018



Frequency vs Generation of Mouda*
30-01-2018



Governor Response Monitoring

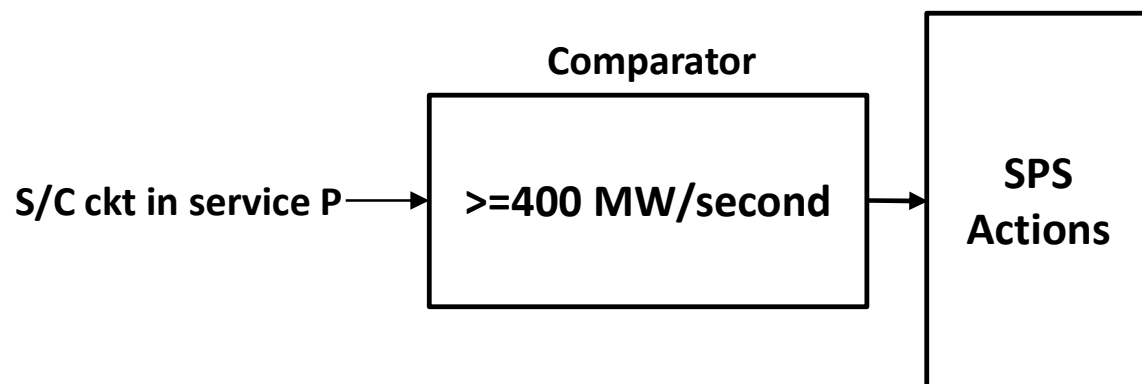


7. Performance Evaluation and Review of SPS

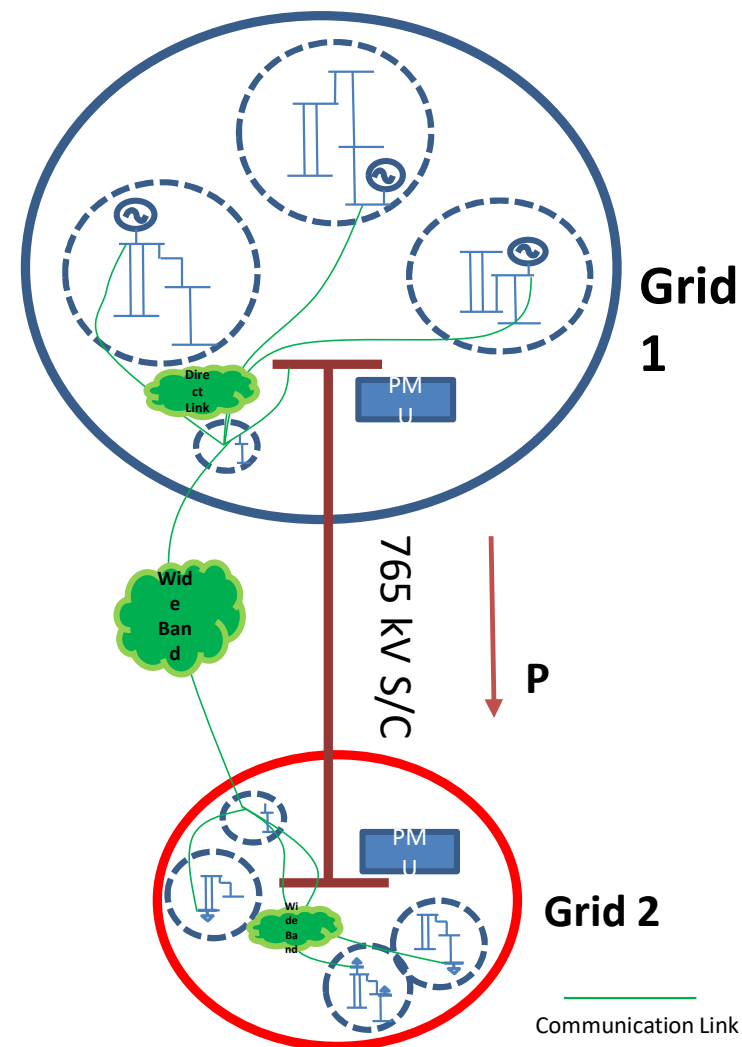


Assessing Dependability of the SPS

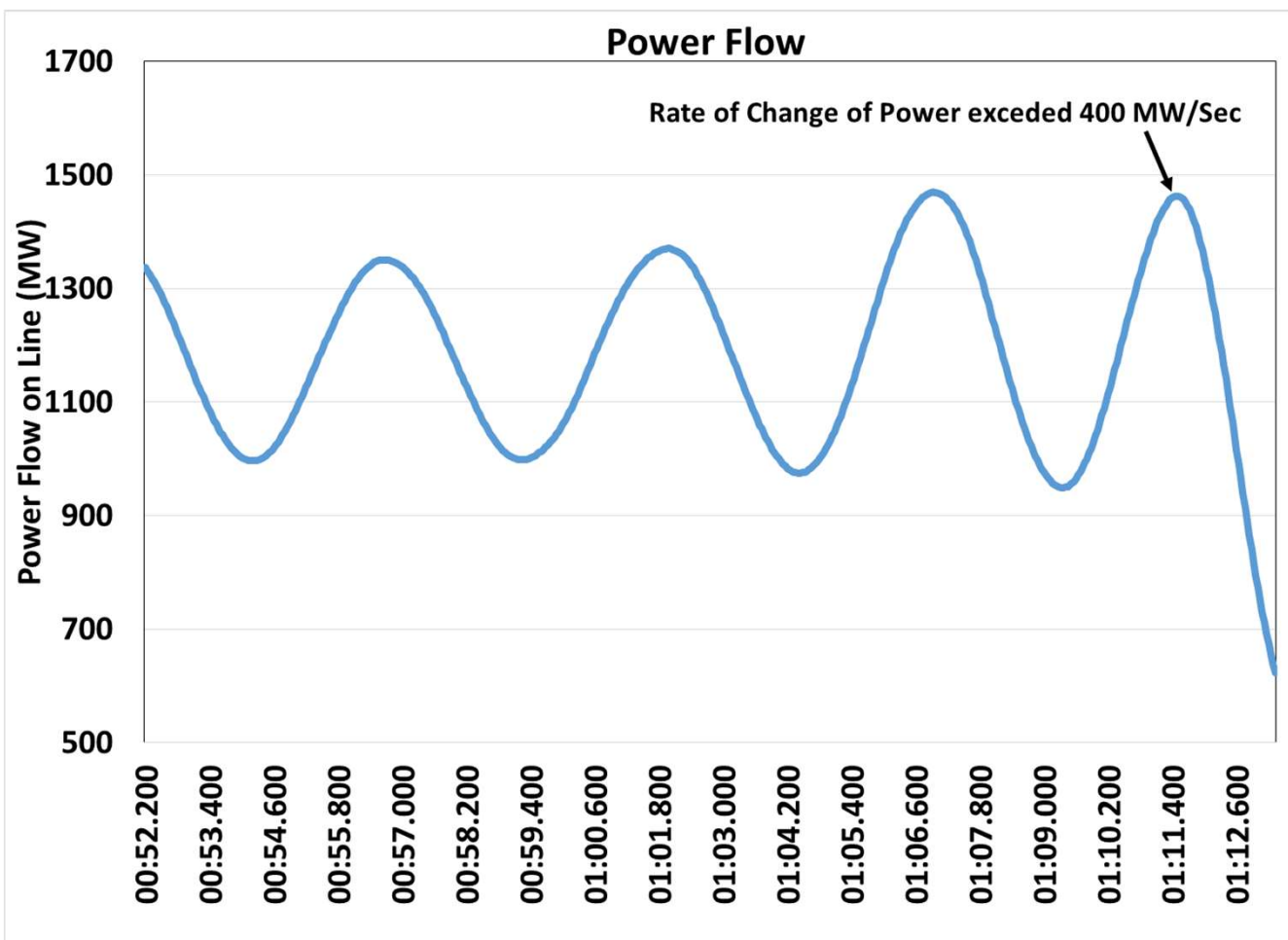
- One Analog, Two Digital Inputs



- SPS Actions
 - Generation Rejection in Grid 1
 - Load Rejection in Grid 2



Assessing Dependability of the SPS contd.

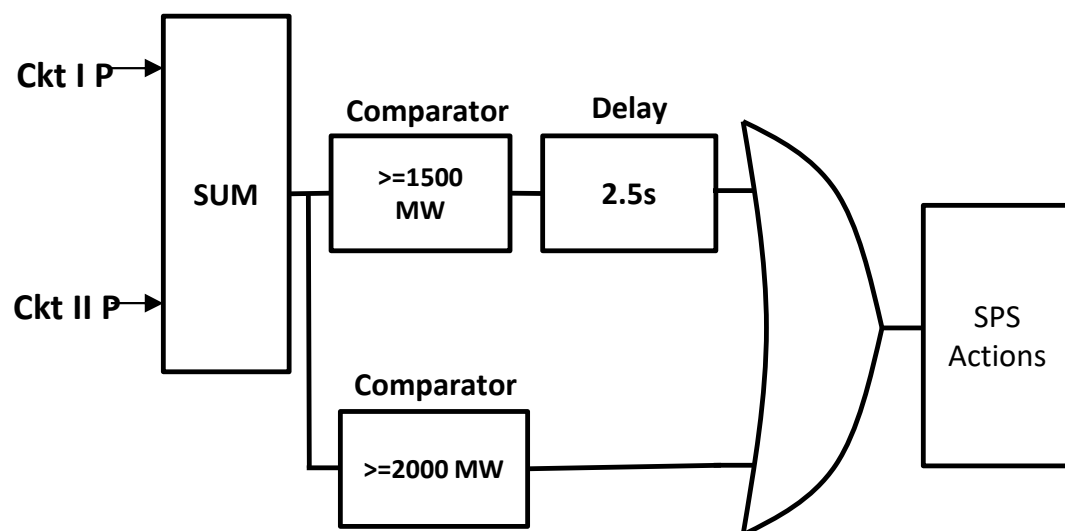


- **Number of Operations : 24***
 - Successful Operations : 21
 - Unsuccessful Operations : 0
 - Unnecessary Operations : 3
 - Failures : 0
- **SPS is disabled**
 - SPS triggered irrespective of power flow direction

*Up to Dec-15

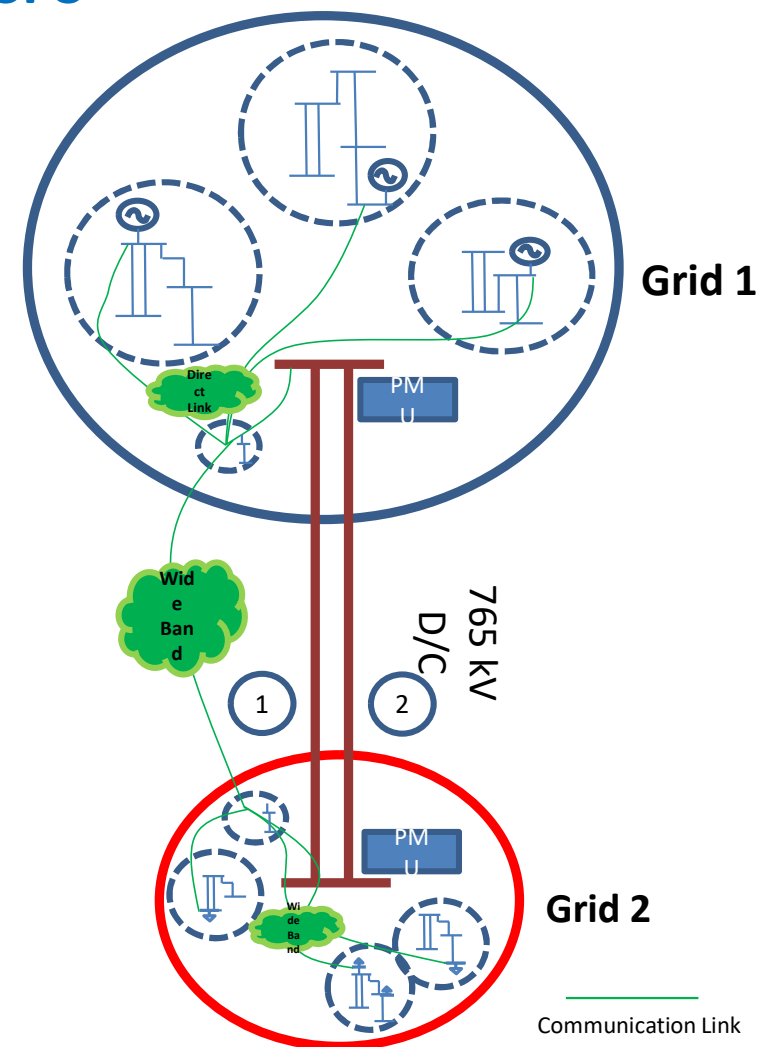
Assessing Dependability of the SPS

- Two Analog Inputs

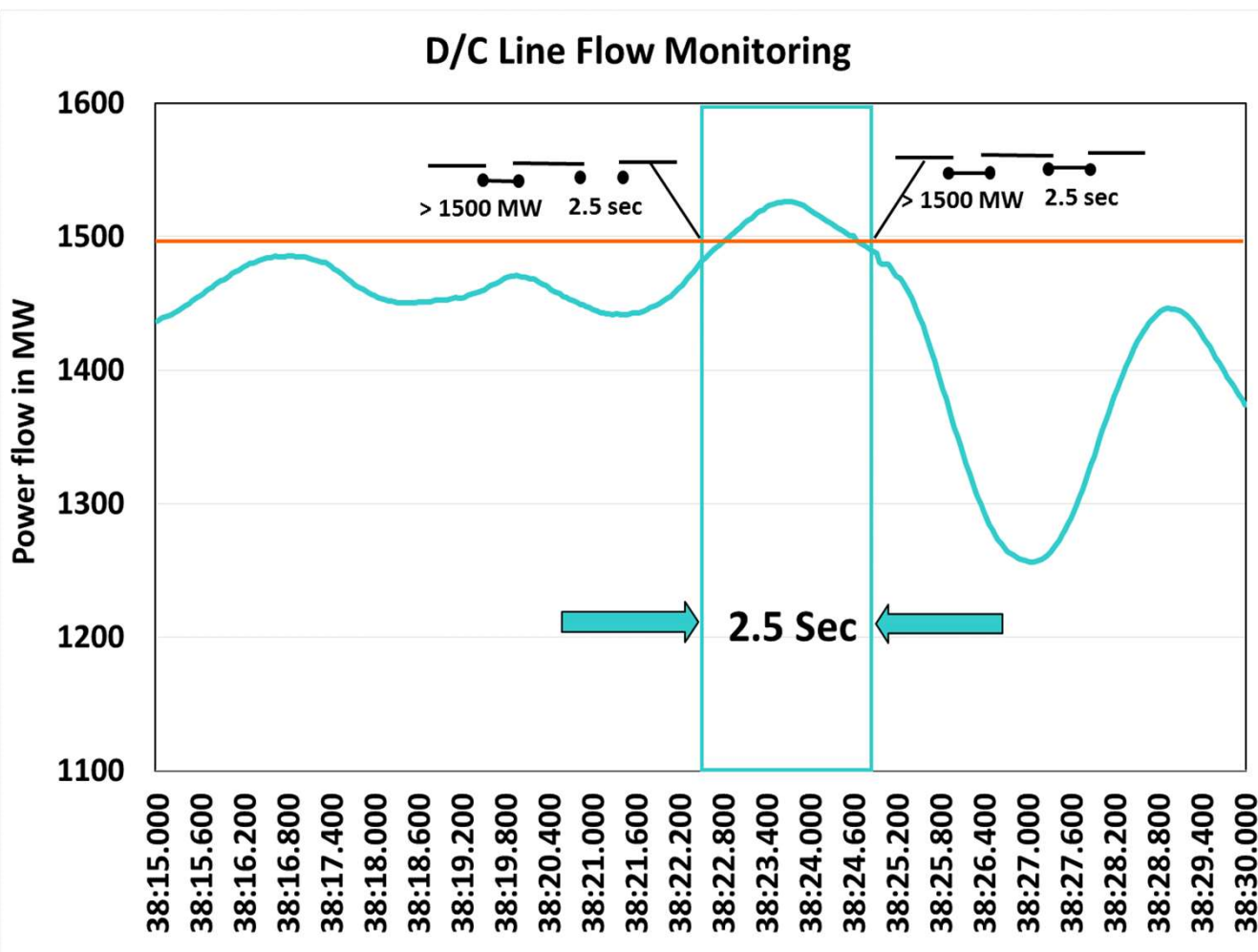


- SPS Actions

- Generation Rejection in Grid 1
- Load Rejection in Grid 2



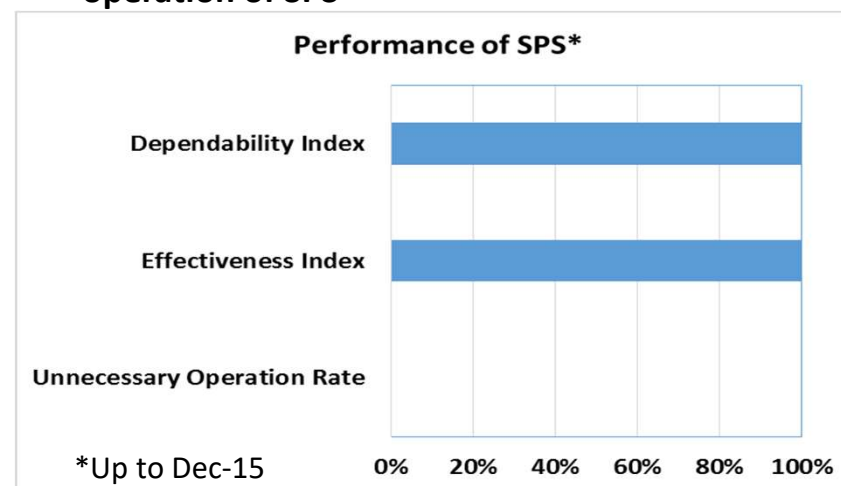
Assessing Dependability of the SPS contd



- **Number of operations : 15**

- **Successful Operations : 15**
- **Unsuccessful Operations : 0**
- **Unnecessary Operations : 0**
- **Failures : 0**

- **Introducing time delay reduced frequent operation of SPS**



IBR Monitoring Using Synchrophasor

- **PMUs are placed on**

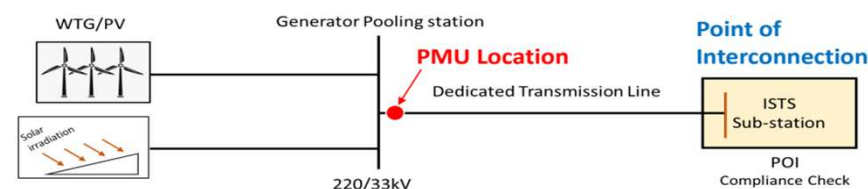
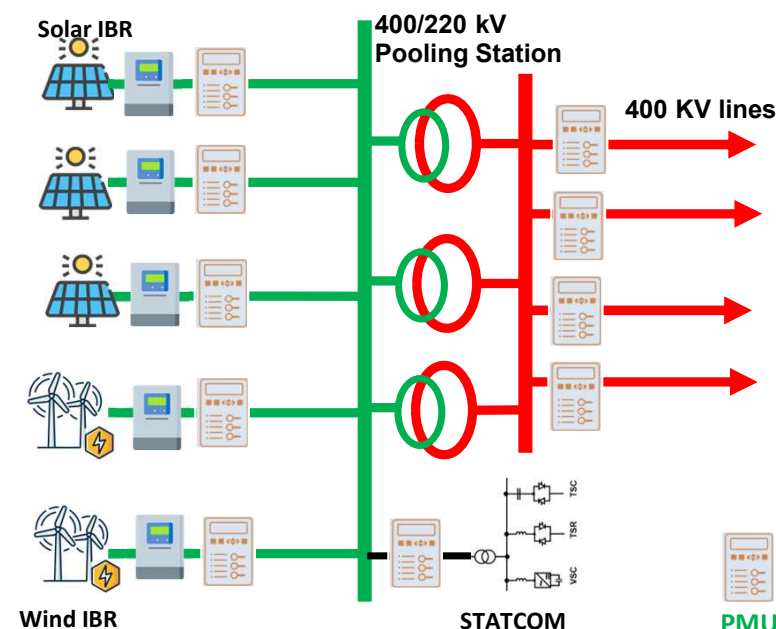
- At Point of Connection (PoC)
- At STATCOM within IBR Plants

- **Enable to capture**

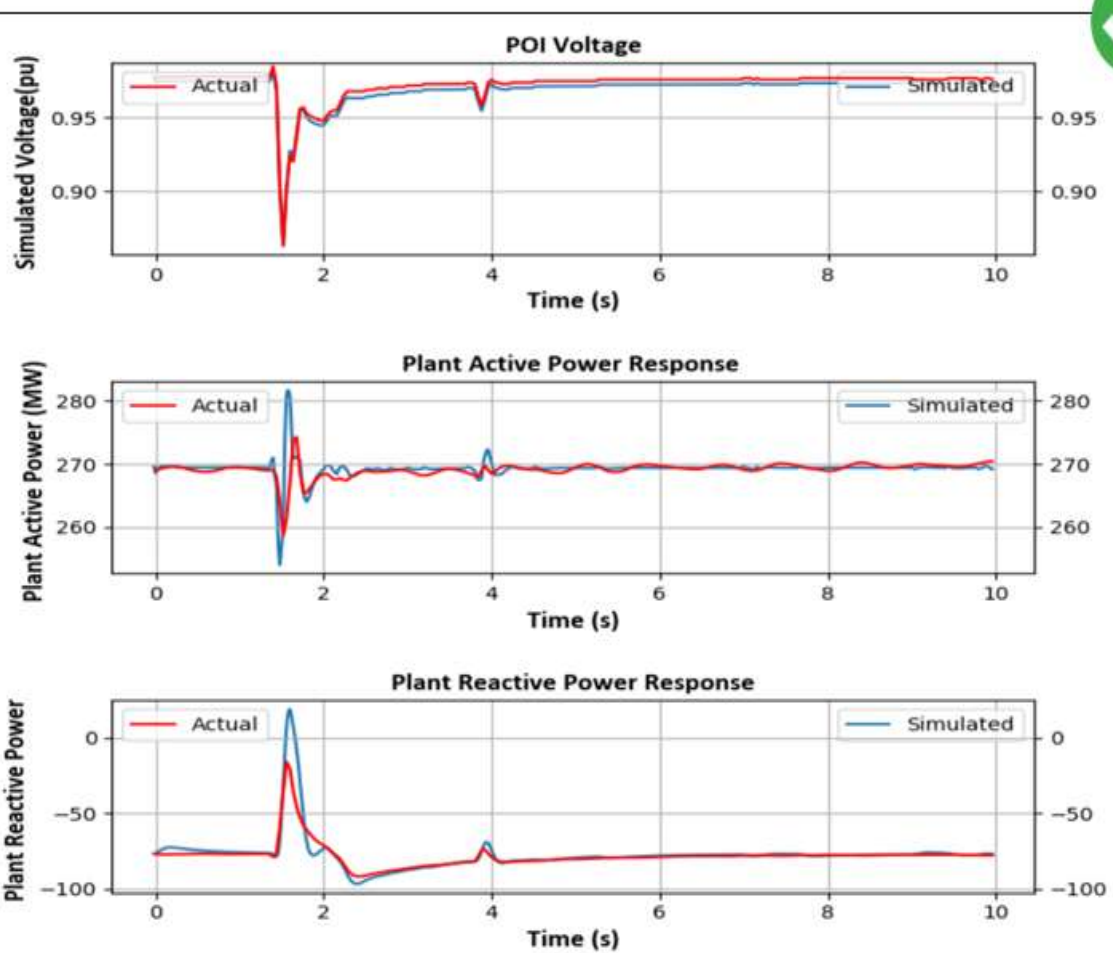
- Dynamic performance of entire plant and its Power Plant Controller
- Power Plant Active Power P , Reactive Power Q , Voltage, Current, Frequency and ROCOF

- **Utilization for IBR**

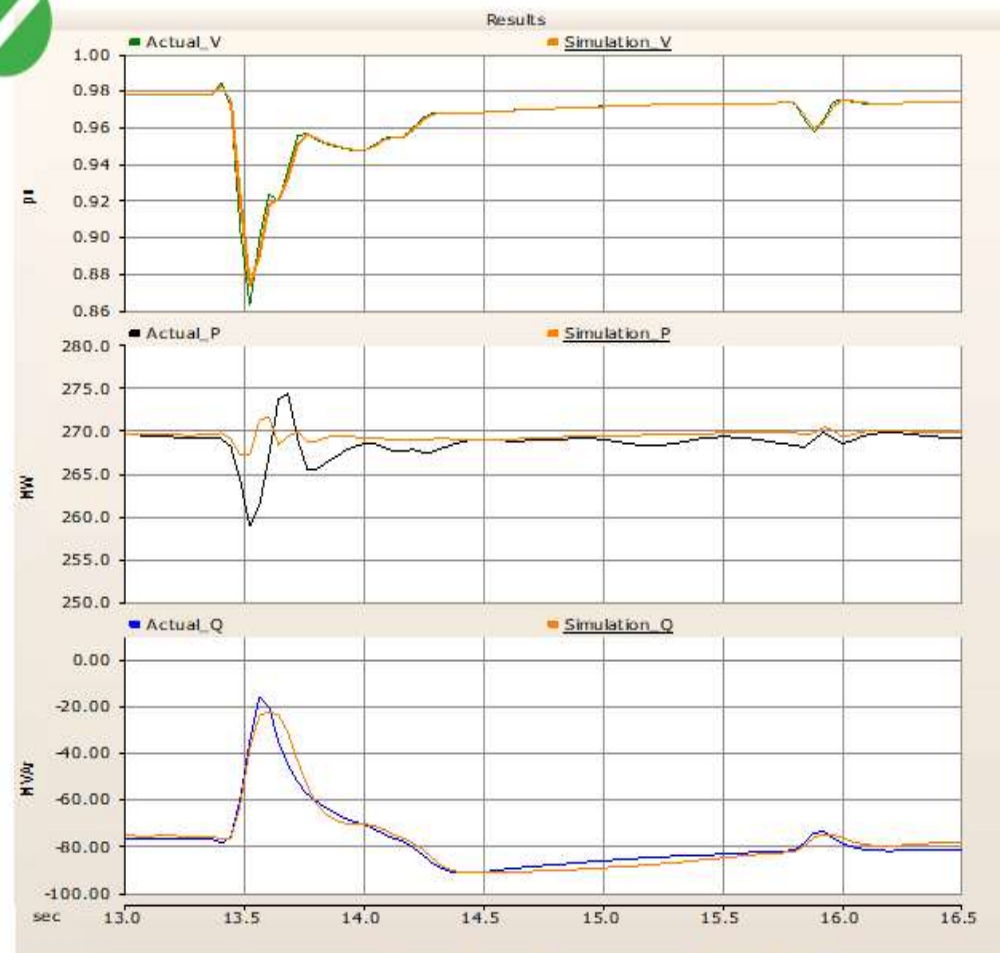
- Grid Compliance Testing and Model Validation
- Validation of Plant performance during event
- Oscillation Event analysis
- Grid Event Analysis



Actual vs Simulation- Performance

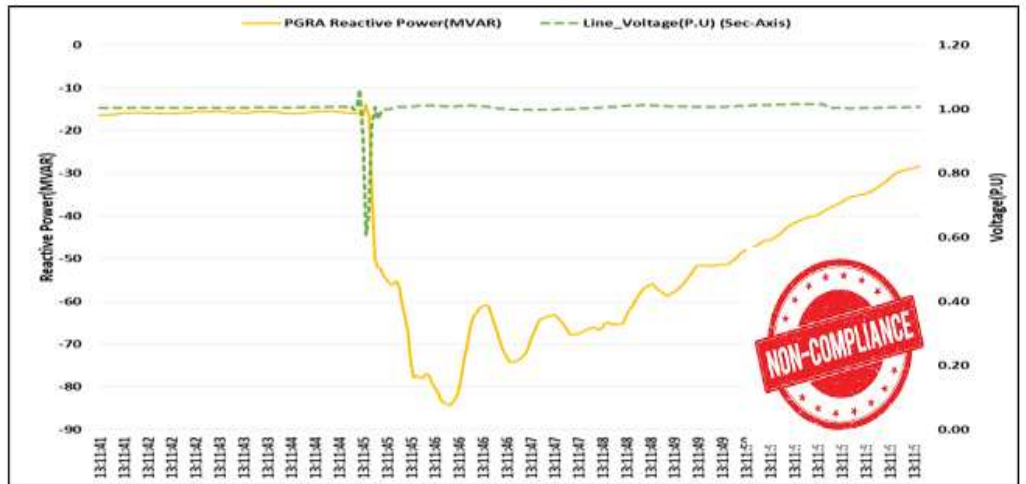
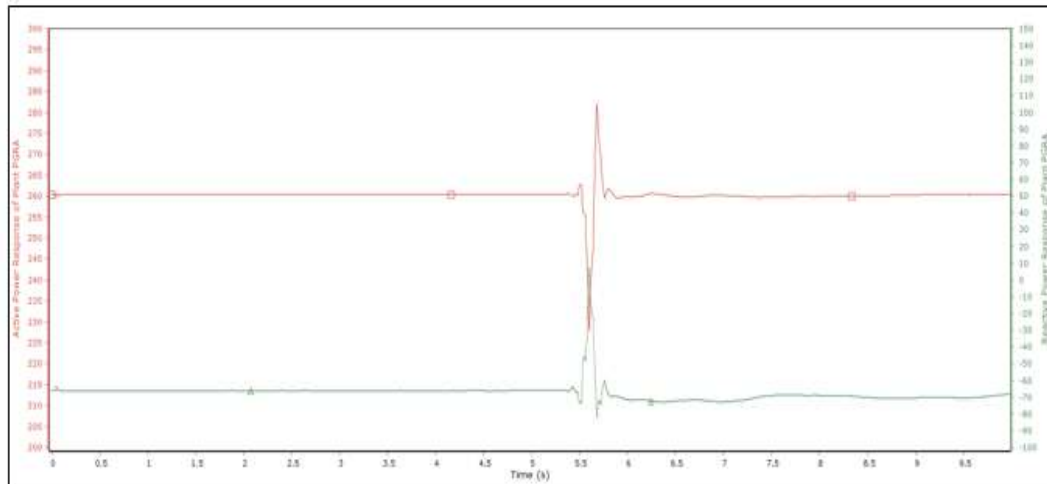
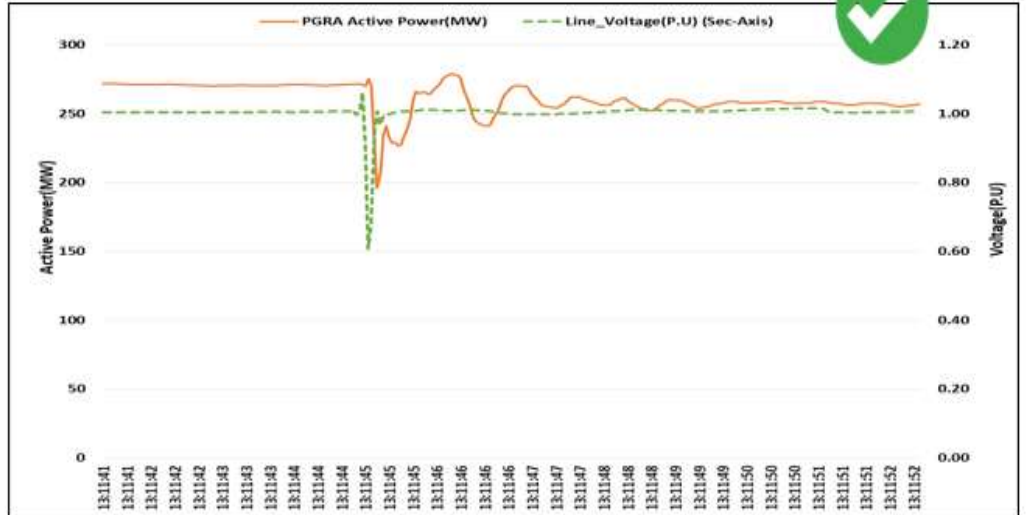
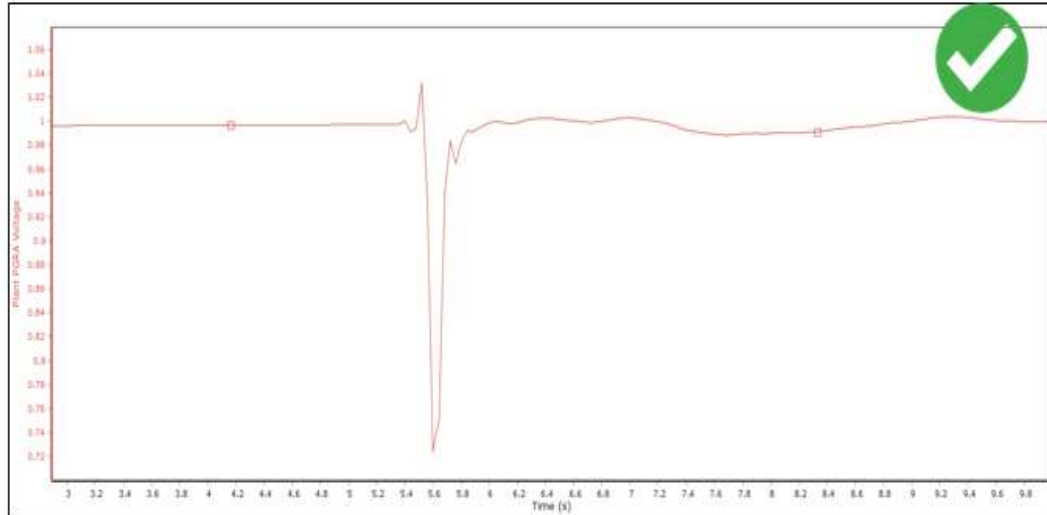


Actual vs. Simulation results (RMS)

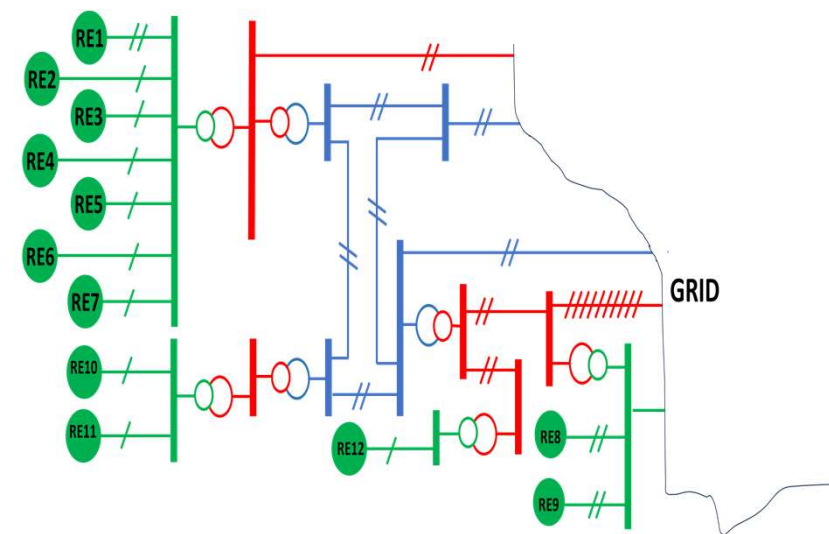
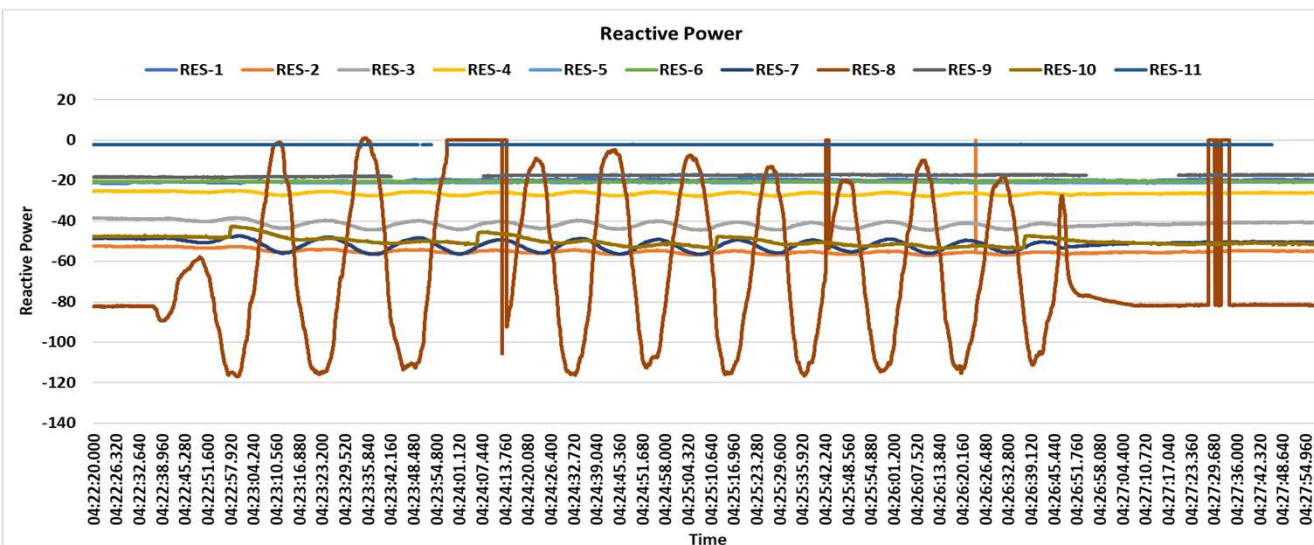
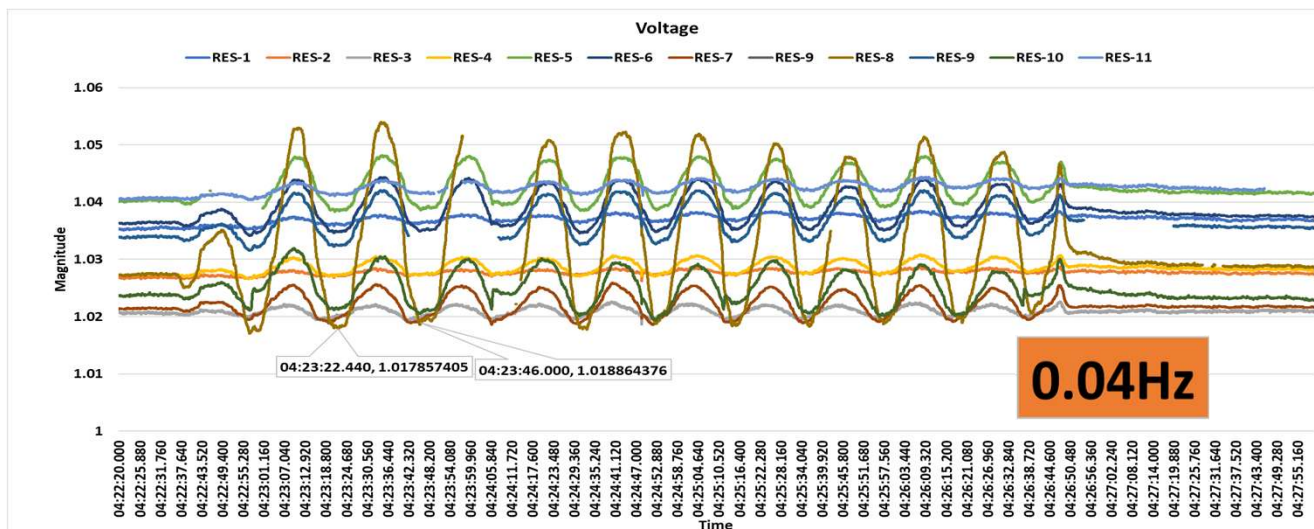


Actual vs. Simulation results (EMT)

Actual vs Simulation- Performance

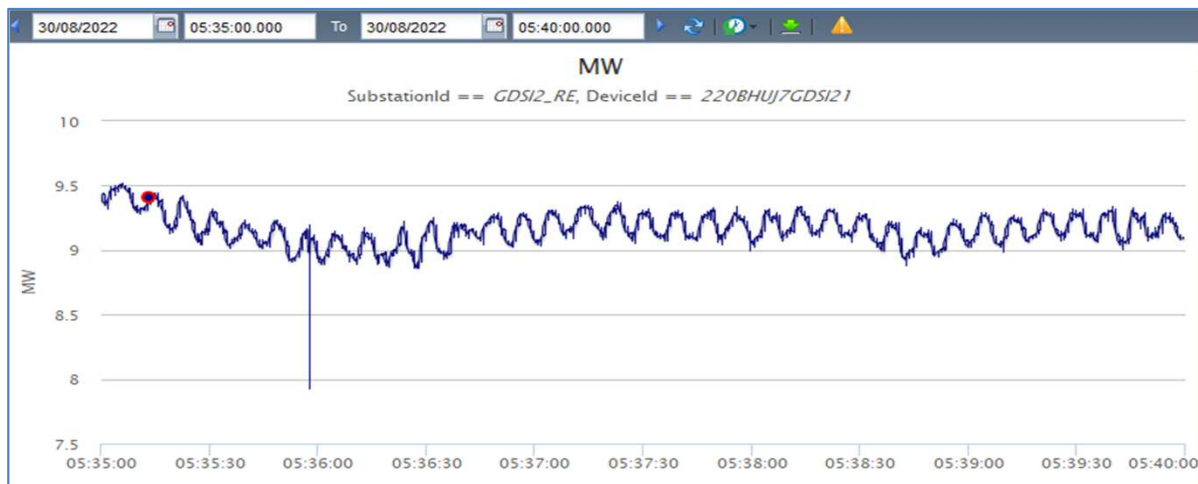


Oscillations: Reactive Power



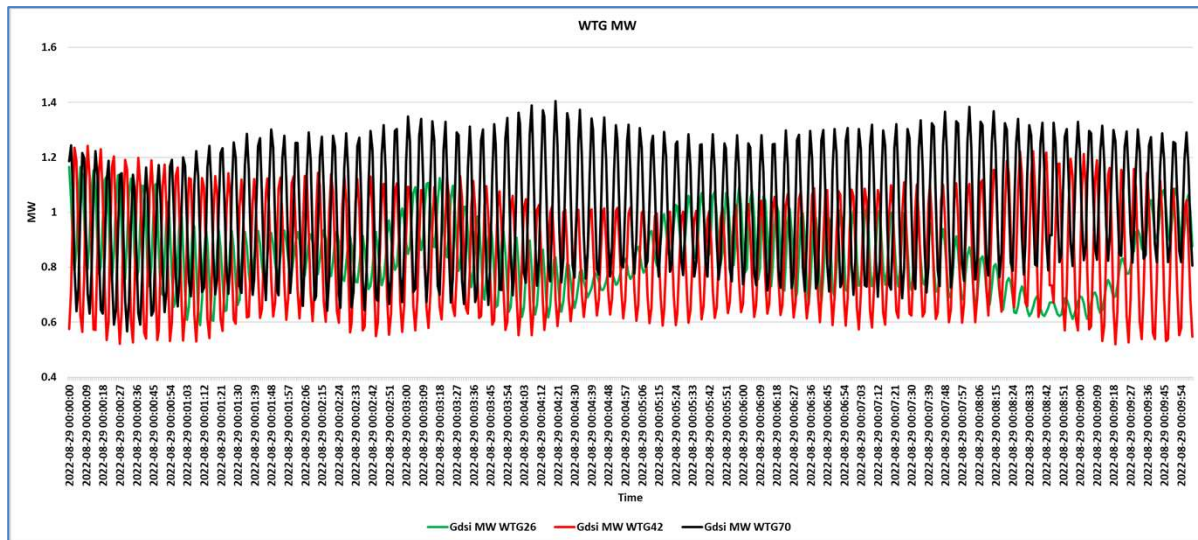
- RES-8 having an installed capacity of 555 MW,
- 3 types of IBRs, 2 MW, 2.1 MW & 2.2 MW
- Total 261 nos IBRs
- Multi plant controllers (Master-Slave)
- Voltage and reactive power were in phase
- One particular make slave PPC had issue of polling rate issue

Oscillations: Active Power

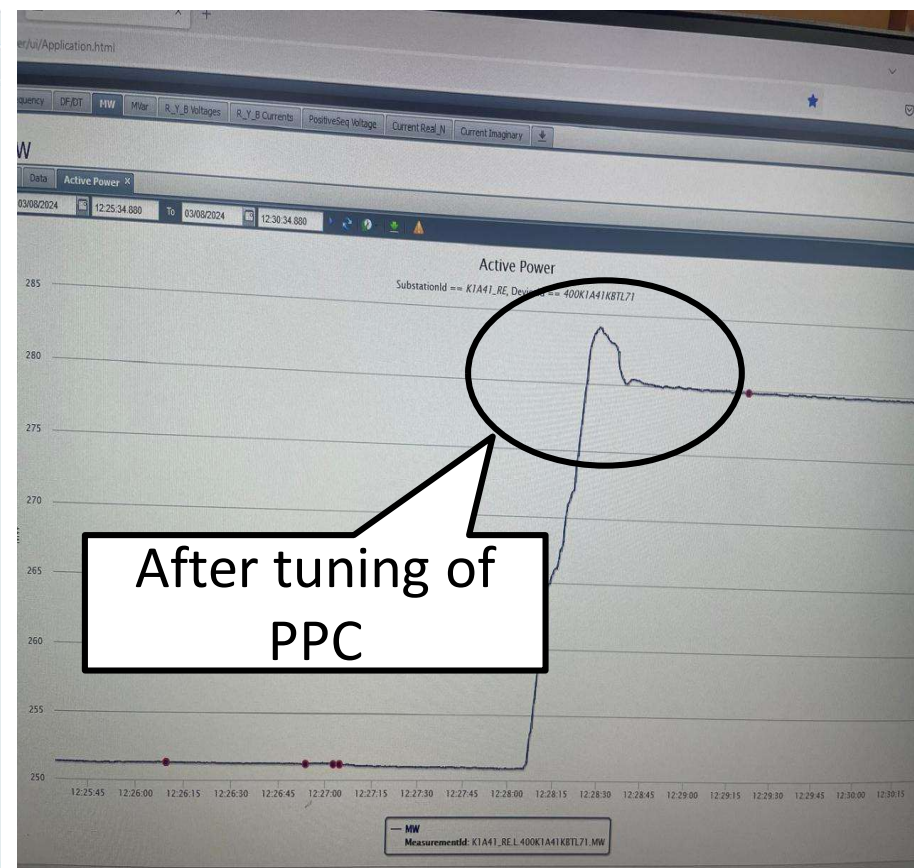
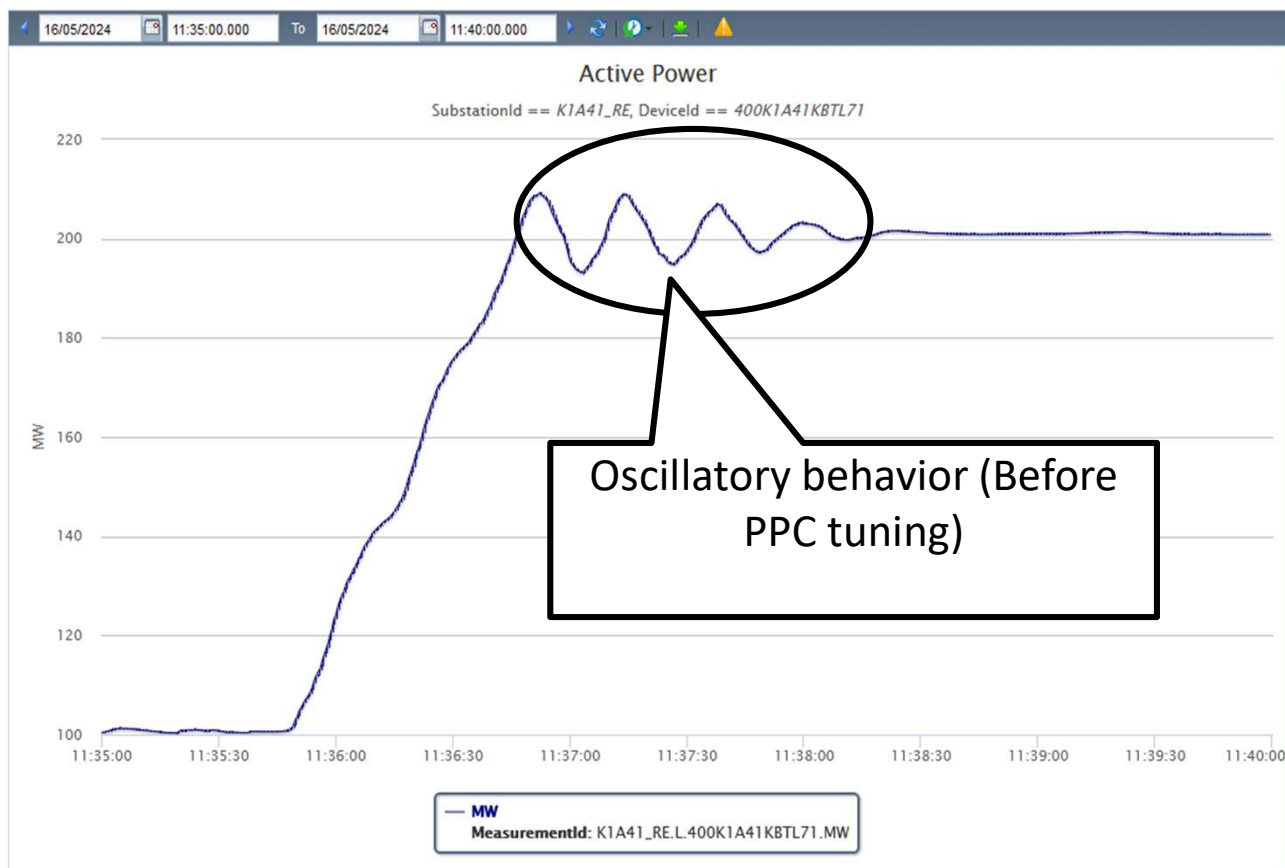


0.15Hz, ~0.6MW in WTGs

300 MW wind project
2.5 MW, 120 nos WTGs
Wind turbine blade mass imbalance



PPC Testing: Active Power Ramp Rate test



Typical WAMS Applications

- **Situational awareness**
 - Frequency, Voltage, Power flows, Angle Differences, Oscillation Detection
- Phase Angle and Grid Stress Monitoring
- Frequency Event Detection
- Islanding Detection
- Voltage and Angle Sensitivity Monitoring
- Frequency & Voltage Stability Monitoring
- Linear State Estimator
- Power Plant Model Validation
- Frequency Response Analysis
- Oscillation Event Analysis

Benefits of Synchrophasor : Reliability

- Reduction in **major outages**
- Faster **line reclosing/restoration**
- Smoother **generator synchronization**
- Faster **black start** restoration and synchronization
- Fewer **customers affected** by outages
- Fewer **equipment failures** and catastrophic emergencies
- Faster **forensic event analysis** and **validation** of protection systems
- Back-up system for situational awareness - loss of SCADA system

PMUs – A window to the Future

PMUs – A Window to the Future

- PMUs provide insight into what is coming¹:
 - Real-Time Capabilities
 - Situational awareness
 - Equipment problem detection
 - Study-Mode Capabilities
 - Model validation
 - Renewable resource integration



- Synchrophasor infrastructure must NOT be taken for granted:
 - Understand the information that is conveyed through the measurements
 - Perform periodic maintenance (calibration) of the associated equipment

1. U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, "Advancement of Synchrophasor Technology", Mar. 3 2016. [Online]. Available: https://www.smartgrid.gov/files/20160320_Synchrophasor_Report.pdf

Source: NASPI WG Meeting

