Let's Talk About Synchrophasors, PMUs & Applications

Evangelos Farantatos, Ph.D.
Sr. Project Manager
Grid Operations and Planning R&D Group

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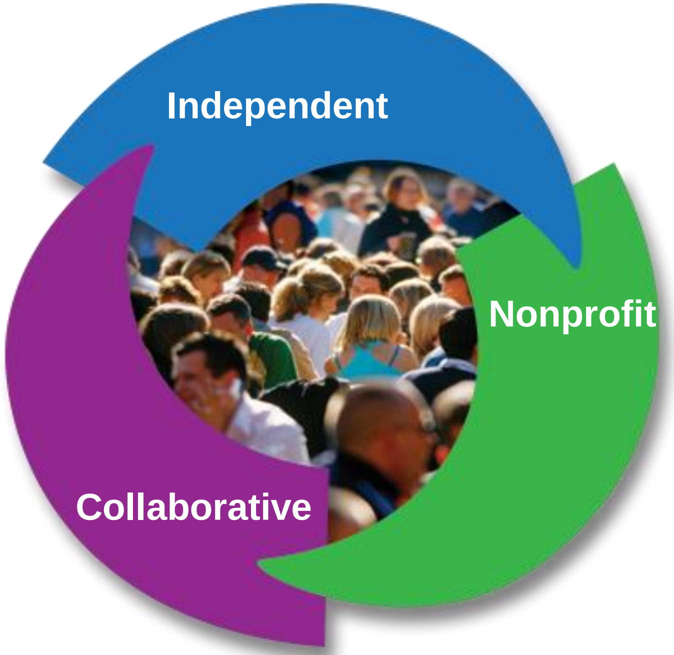
Outline

- Synchrophasor Technology Background
- State-of-the-Art PMU Applications & Use Cases
- Trending PMU Applications
- Synchrophasor/PMU Limitations - Towards Synchronized Sampled Value Measurements

Electric Power Research Institute (EPRI)

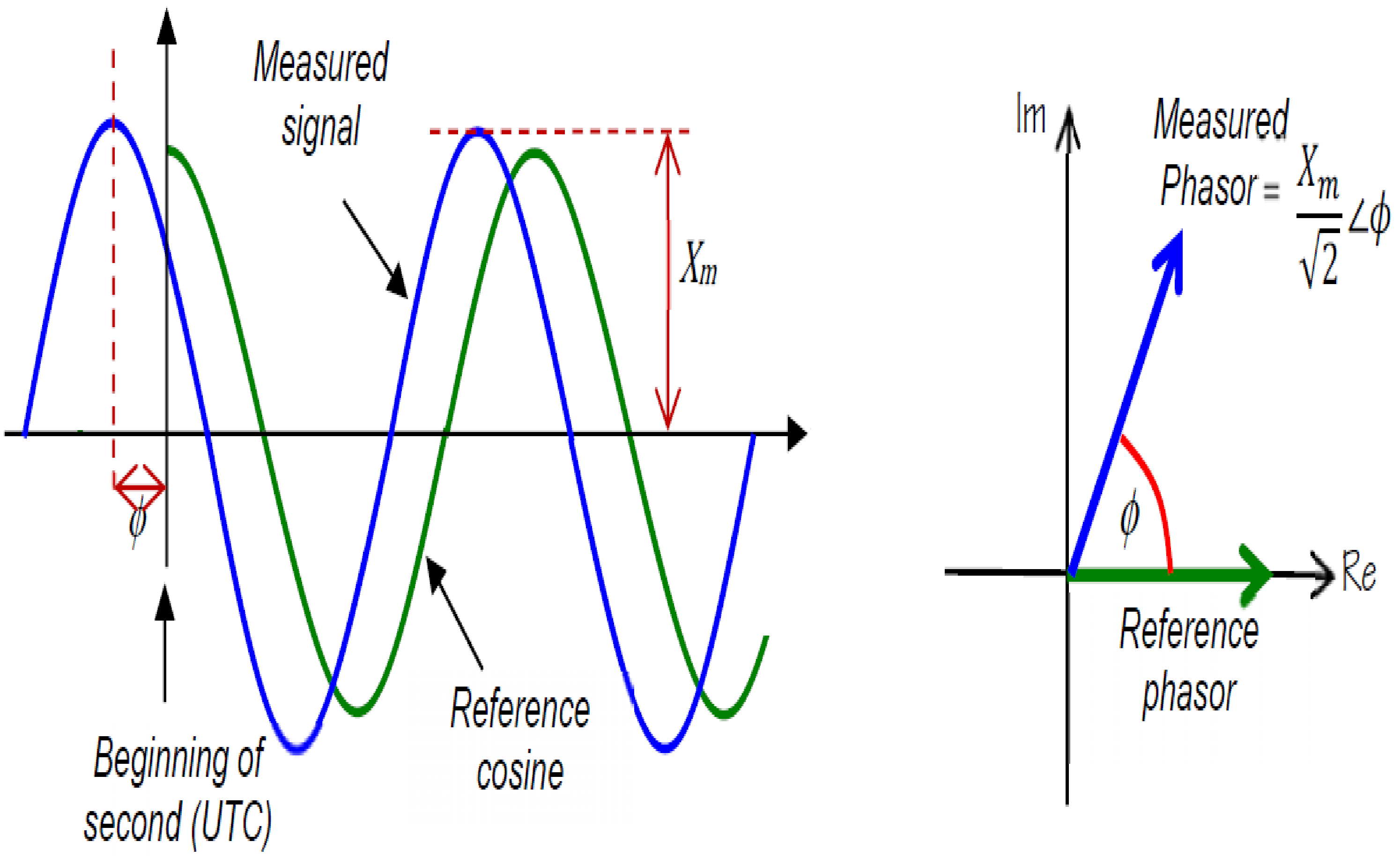
- **Mission**
  Advancing safe, reliable, affordable and environmentally responsible electricity for society through global collaboration, thought leadership and science & technology innovation
- **Independent**
  Objective, scientifically based results address reliability, efficiency, affordability, health, safety and the environment
- **Nonprofit**
  Chartered to serve the public benefit
- **Collaborative**
  Bring together scientists, engineers, academic researchers, industry experts



Disclaimer

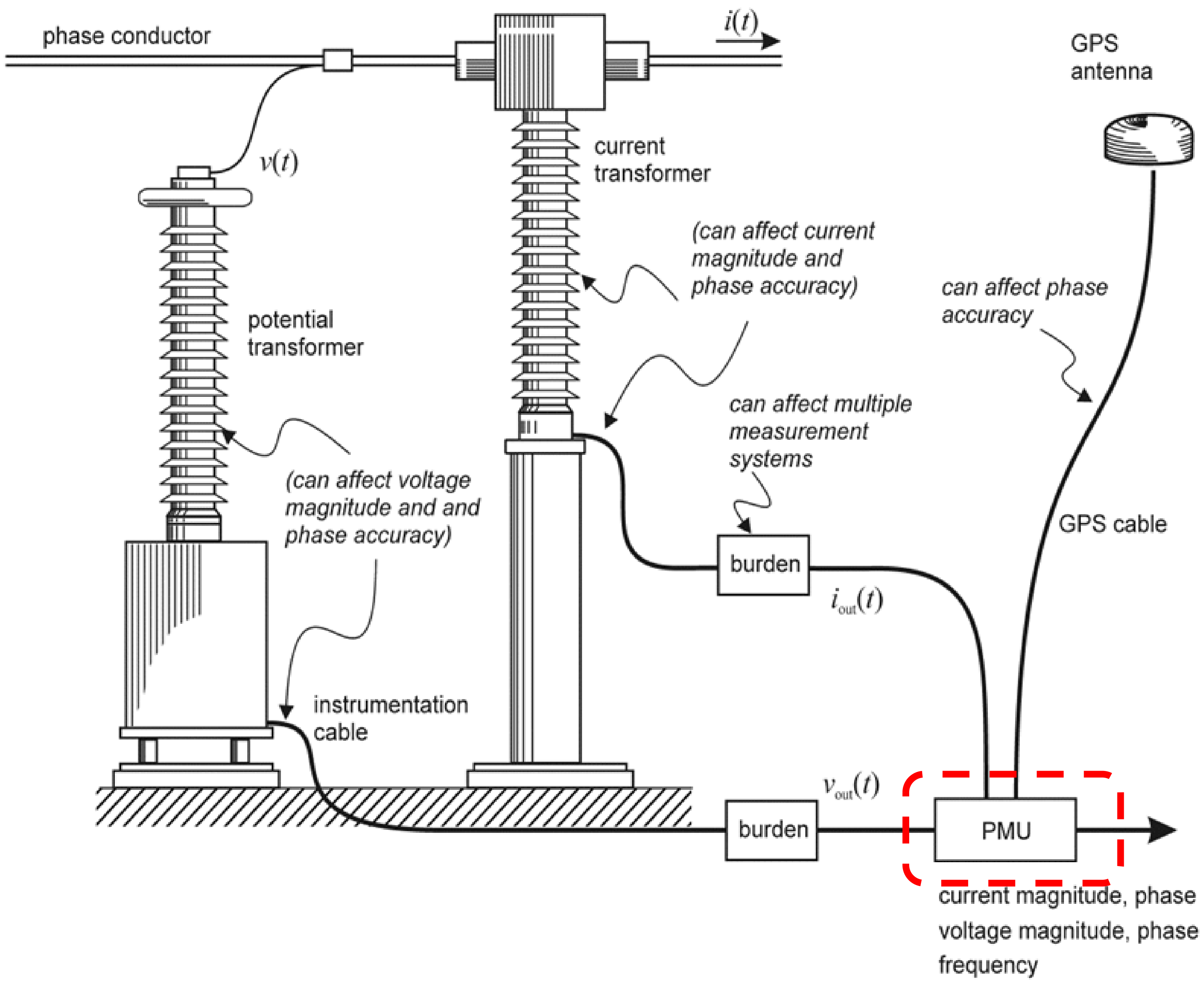
- The information in the next slides is from publicly available material
- EPRI is technology and vendor agnostic and does not recommend particular vendors or technologies over others
- The vendors are listed randomly. The list of vendors and tools is not exhaustive and it is based on the knowledge and experience of the presenter
- The example applications by utilities/ISOs are only representative and do not cover all the use cases presently in the industry

Synchrophasor Definition



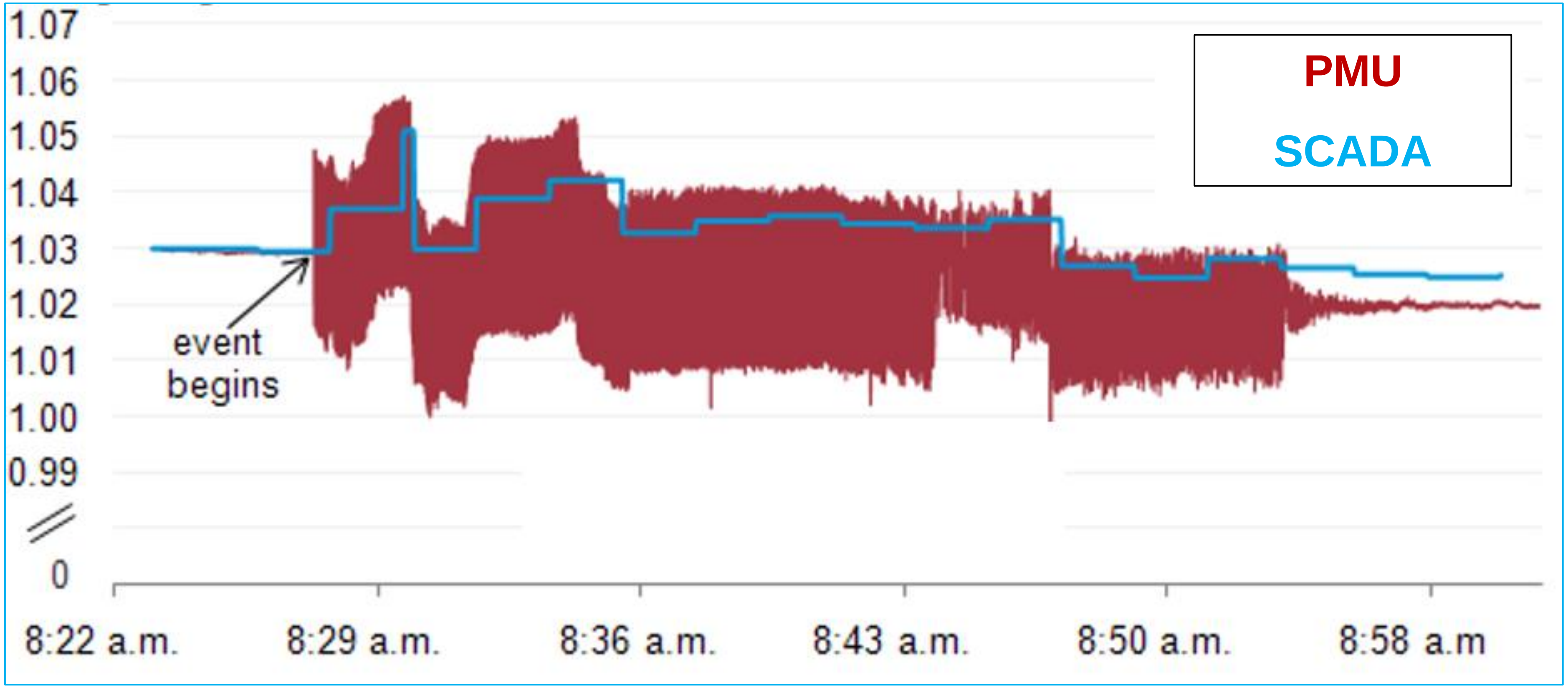
- Phasor is defined as a complex number which represents a sine (or cosine) wave's amplitude and phase angle
- Synchrophasor represents a phasor of which the phase angle is expressed relative to a reference phasor which is synchronized to the coordinated universal time (UTC)
- Typically Global Positioning System (GPS) is used for time synchronization

Phasor Measurement Unit (PMU)



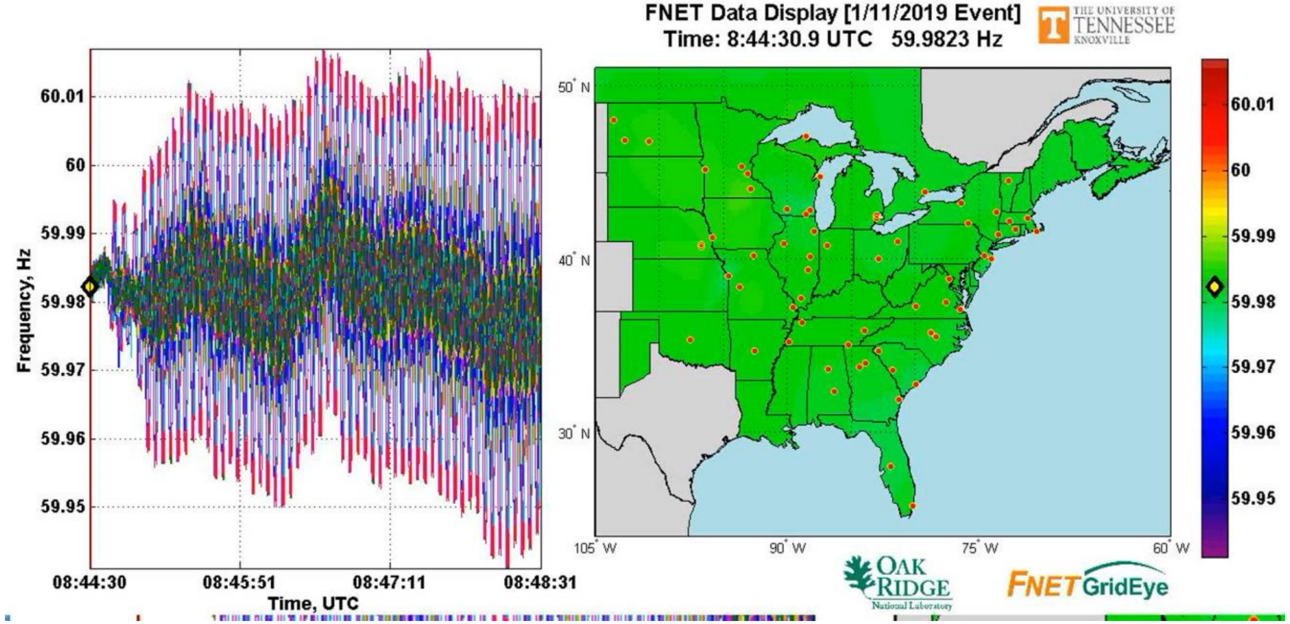
- PMU is a device which measures synchrophasors
- A PMU can measure voltage and current synchrophasors, frequency and ROCOF
- A PMU can be a stand-alone device or a functional unit within another physical unit
- Input voltage and current signals are from PTs and CTs

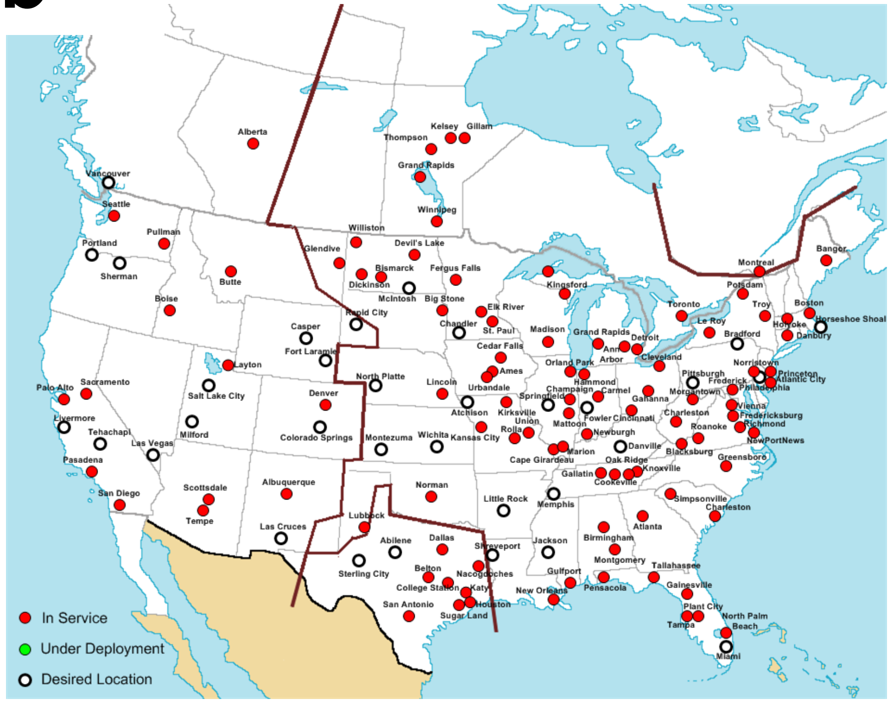
Synchrophasor Technology vs SCADA



- Synchrophasor data comprises current and voltage phasors, frequency and rate of change of frequency (ROCOF), whereas SCADA data is analog measurements of RMS voltages and currents, and real and reactive power.
- Synchrophasor data have high resolution, typically reported at 10 to 60 records per second, compared to 2 to 4 seconds per record in the case of SCADA data.
- Synchrophasor data have time synchronization and are time stamped using precise, standard specified times.

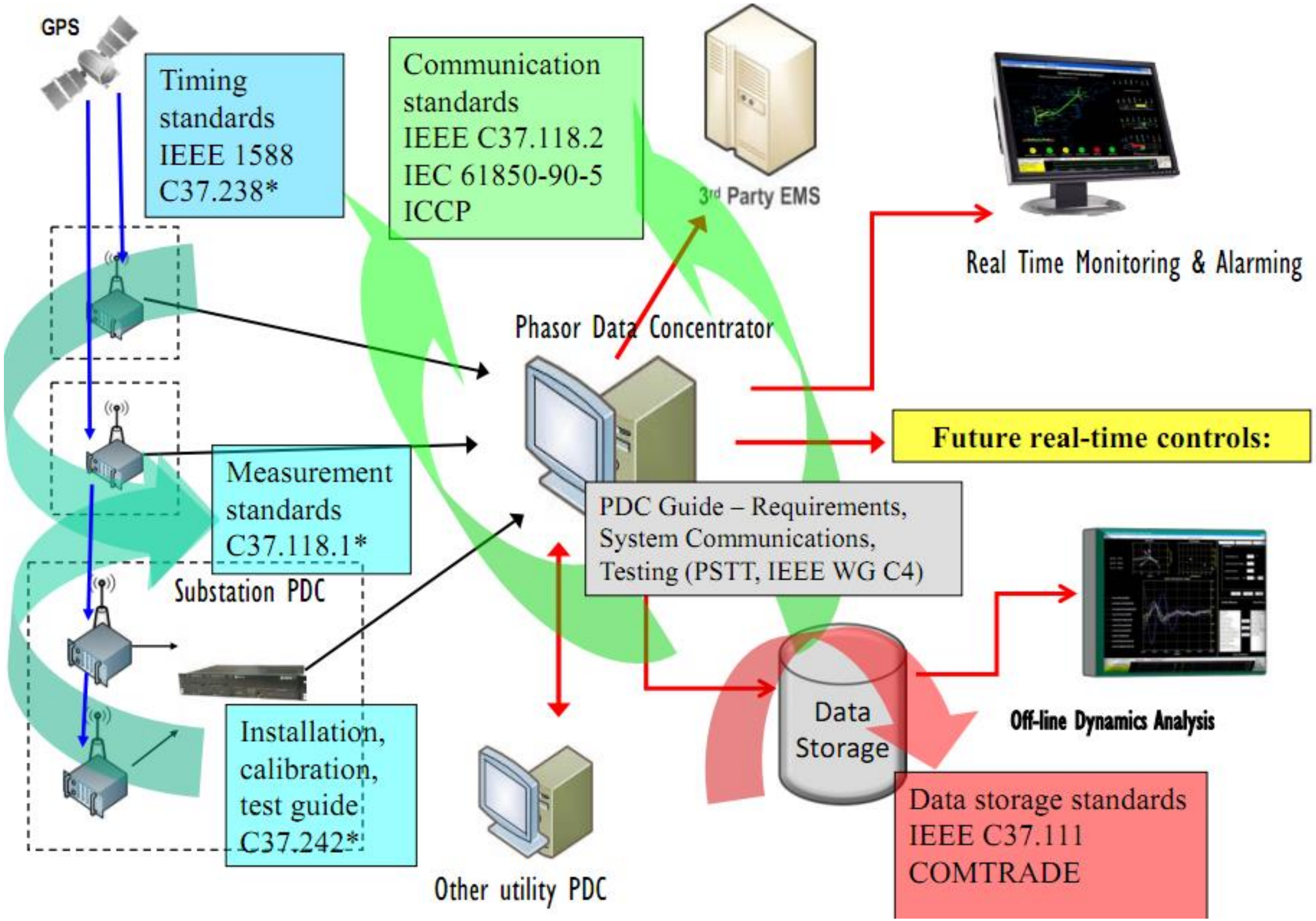
FNET/GridEye - UTK/Oak Ridge National Lab





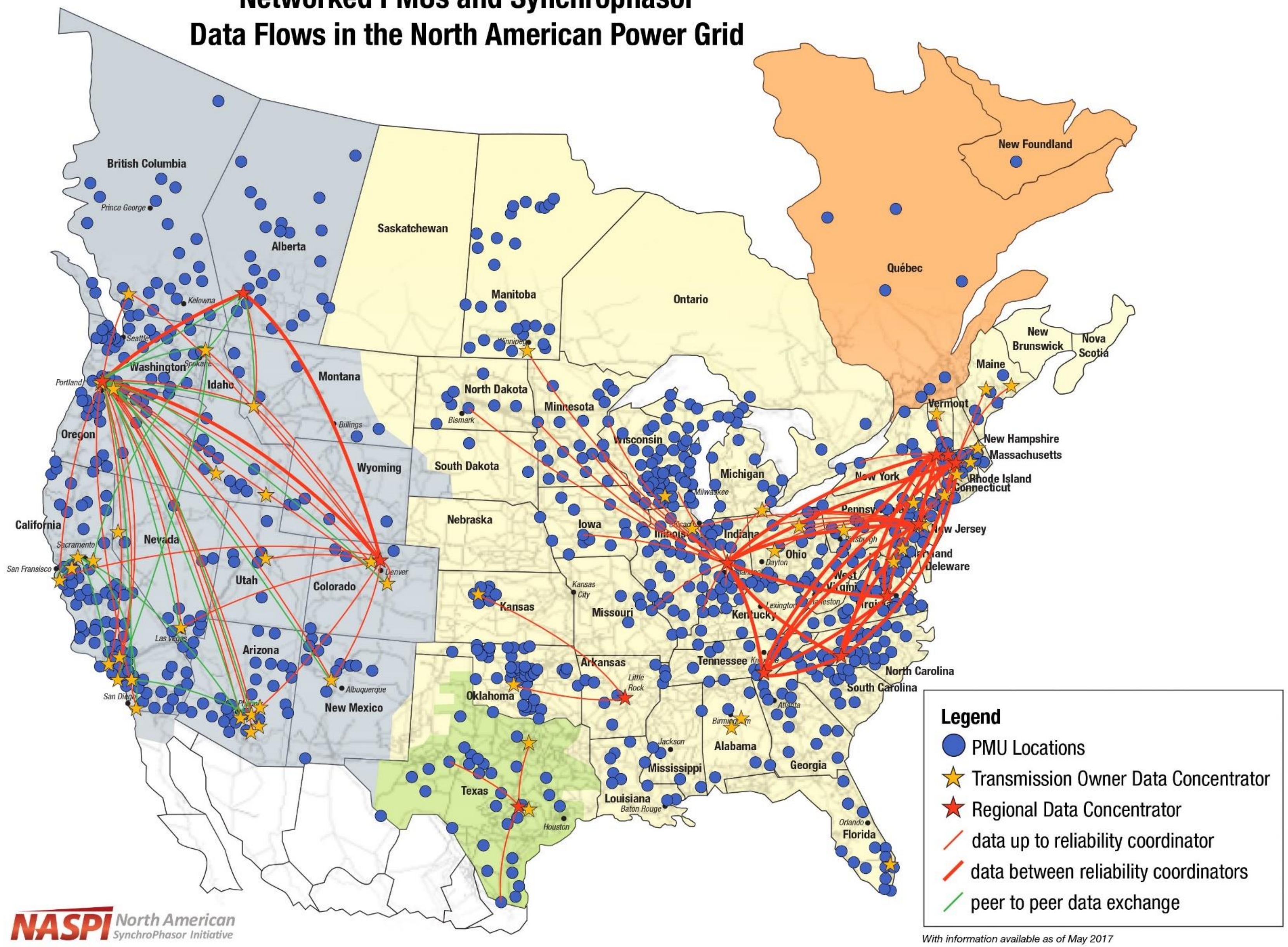
FNET GridEye

Synchrophasor Data Communication Protocol & Standards



NASPI PMU Map

Networked PMUs and Synchrophasor Data Flows in the North American Power Grid



With information available as of May 2017

Synchrophasor Applications & Use Cases

Synchrophasor Applications

Operations

- Wide Area Situational Awareness/Visualization
- State Estimation
- Event Detection
- Oscillation Detection
- Voltage Stability Monitoring
- Islanding Monitoring & Detection

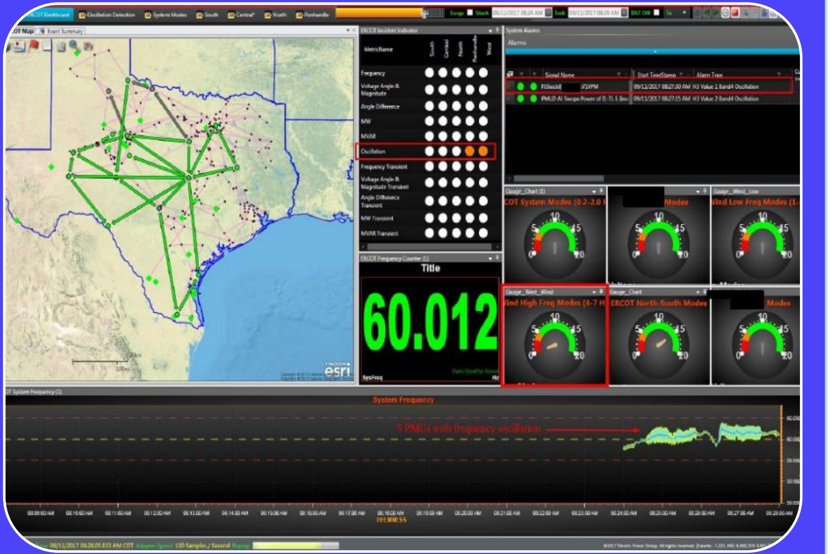
Planning

- Model Validation
- Event Analysis
- Operator Training
- Frequency Response Analysis

Wide Area Situational Awareness/Visualization

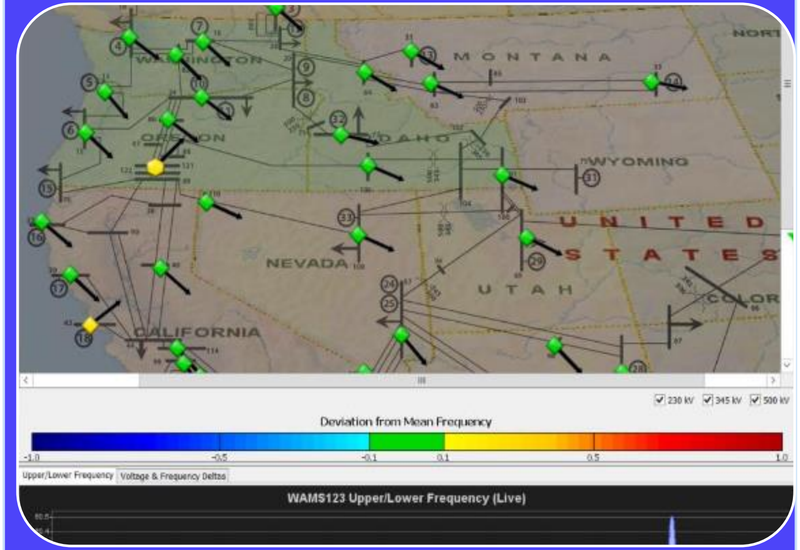
Wide Area Situational Awareness/Visualization – Vendor Tools & Use Cases

EPG RTDMS



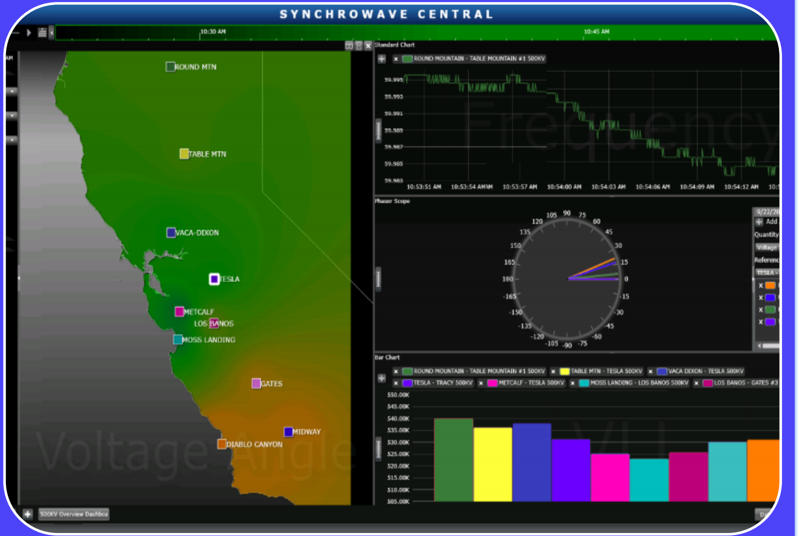
- **Example Use Cases:**
  - ERCOT
  - NYISO

GE PhasorPoint



- **Example Use Cases:**
  - ISO-NE
  - ATC

SEL SynchroWAVe Central

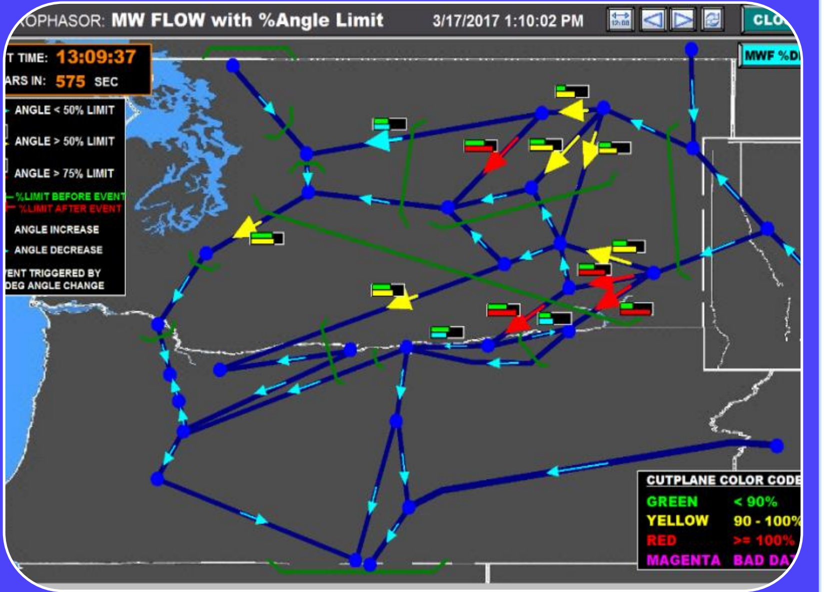


- **Example Use Cases:**
  - SDG&E
  - PG&E

- ➢ Geospatial displays
- ➢ Chart trends
- ➢ Phasor diagrams
- ➢ Line flows
- ➢ Voltage contours
- ➢ Phase angle differences
- ➢ Alerts/Alarms
- ➢ Color codes
- ➢ Arrows

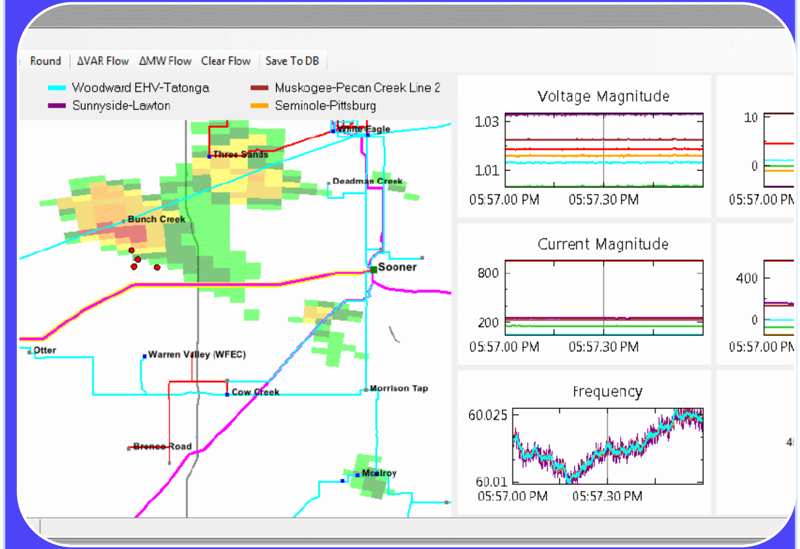
Wide Area Situational Awareness/Visualization – In-House Tools

BPA



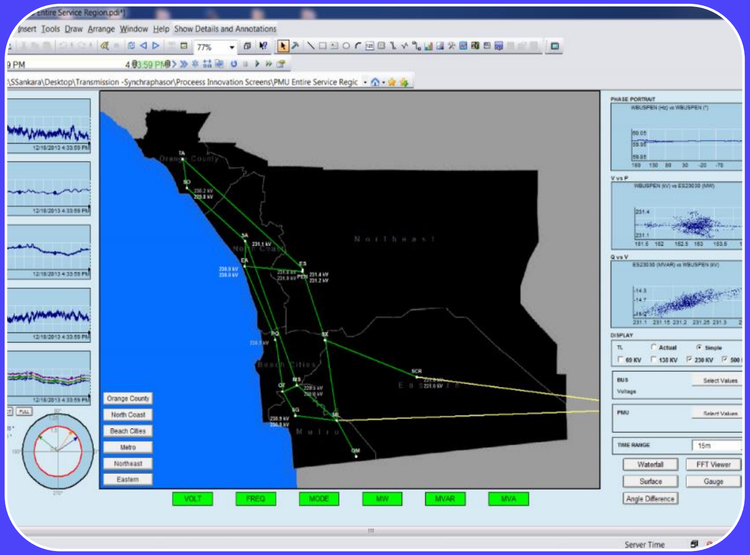
- Visualization displays using PI ProcessBook
- Over 18,000 synchrophasor measurements/second processed
- MW flows with % angle limit
- Phase angle monitoring
- Different colors and arrow sizes

OG&E



- PhasorView: In-house tool based on a Microsoft SQL database
- Synchrophasor data from 356 PMUs

SDG&E



- Based on PI ProcessBook
- Empowers users to graphically create displays and enrich them with layers of dynamic data.
- Helps users instantly access and visualize PI Server data through interactive, graphical displays

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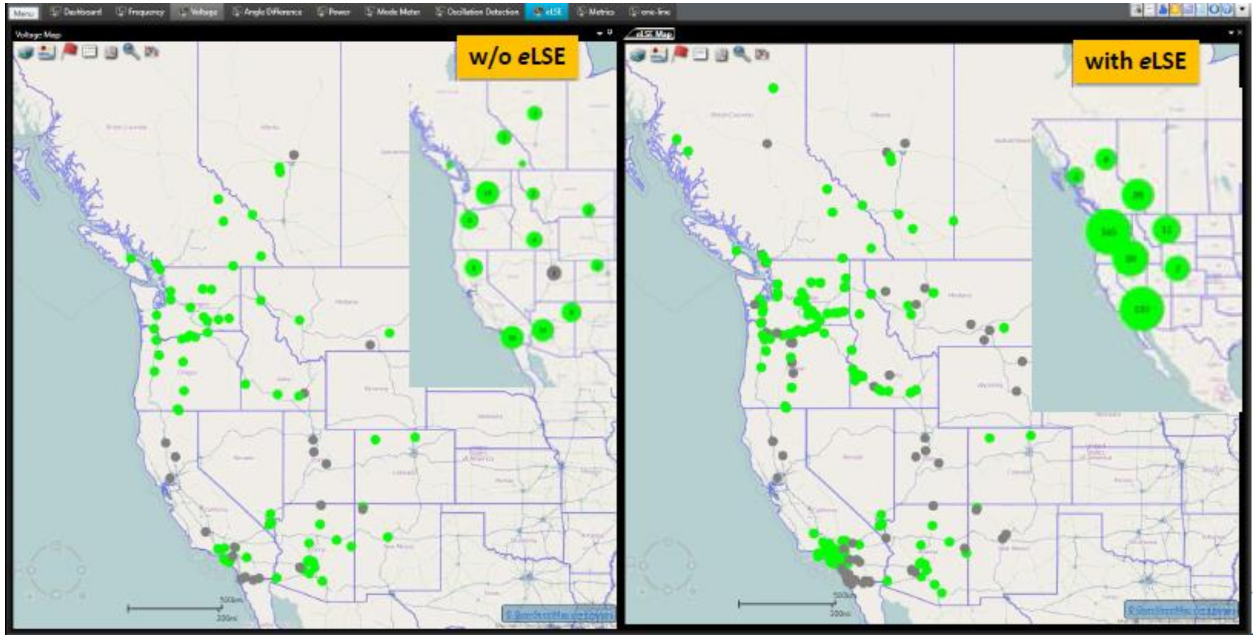
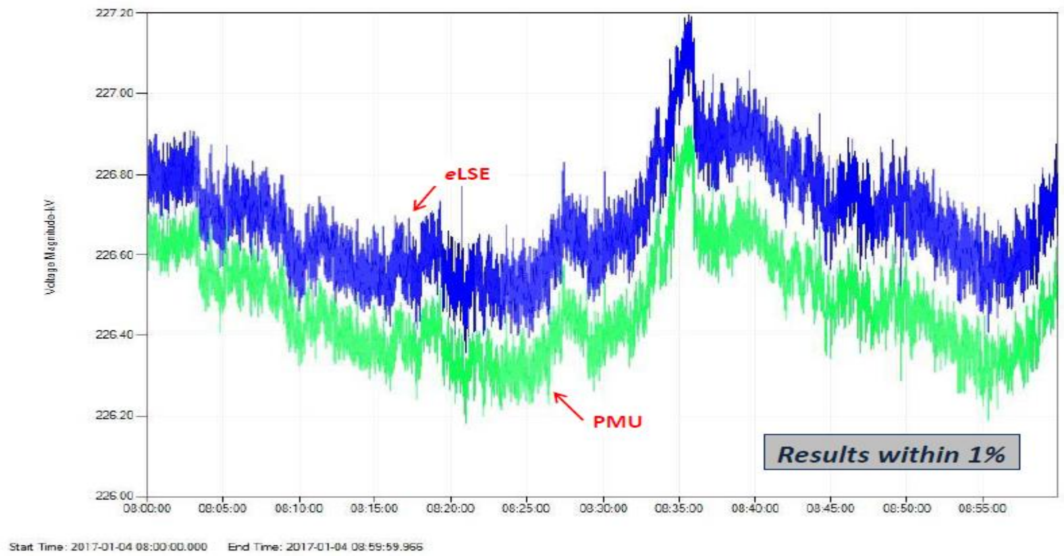
State Estimation

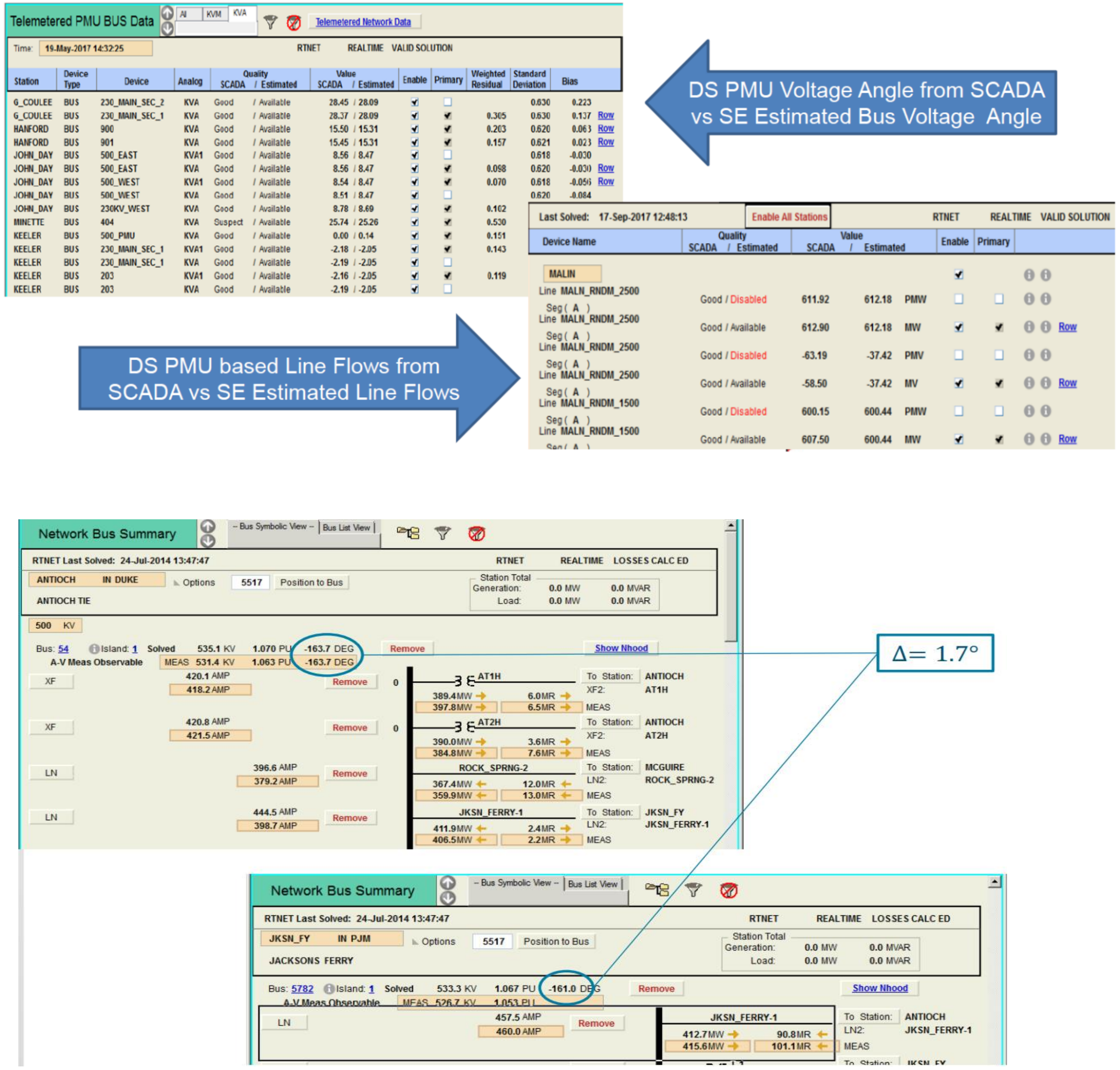
State Estimation – Linear State Estimation (LSE)





- Synchrophasor measurement only based state estimator
- Complementary to SCADA SE or backup
- Example Use Cases
  - DVP: In-house three-phase LSE for 500kV system
  - PJM – in-house
  - BPA & SCE – EPG's eLSE
  - Peak RC – V&R LSE

State Estimation – Hybrid State Estimation



- Incorporation of synchrophasor data into EMS State Estimator
  - Duke Energy – Alstom/GE EMS
  - Peak RC – Alstom/GE EMS
  - NYISO – ABB EMS
  - XM (Colombia)

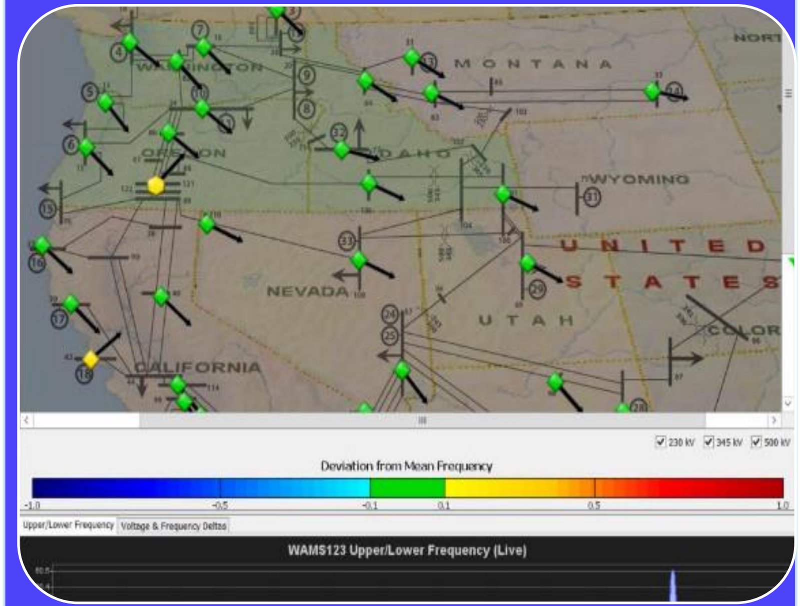
Oscillation Detection & Monitoring

Oscillation Detection – Vendor Tools & Use Cases

EPG RTDMS - ERCOT

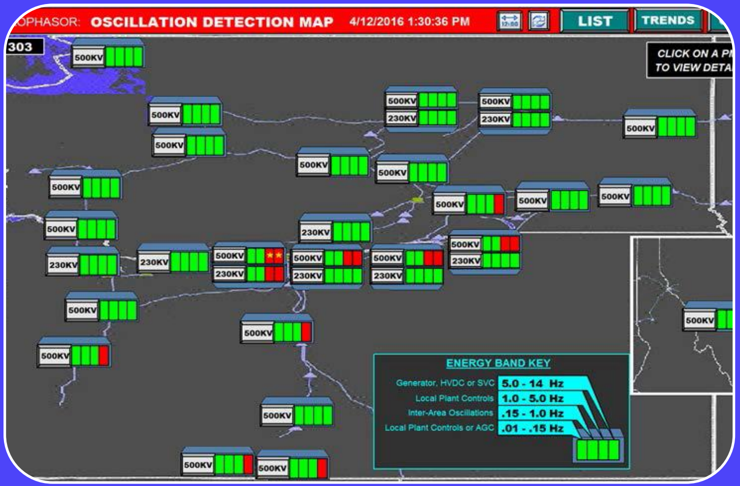
- 3 years of PMU data analyzed to identify ERCOT system modes
- Modes were analyzed to identify mode frequency, damping percentage, and energy level
- Mode meters in RTDMS were configured to track identified modes with the most common occurrence

GE PhasorPoint – ISONE



- Detection
- Characterization (Frequency, Damping, Mode shape)
- Alarming and Alerting
- Results are updated every 5 seconds

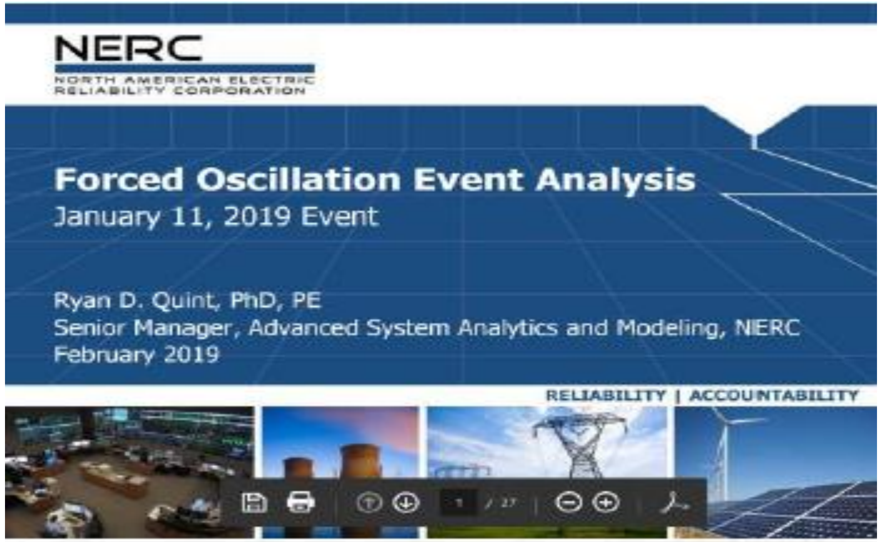
BPA - ODM



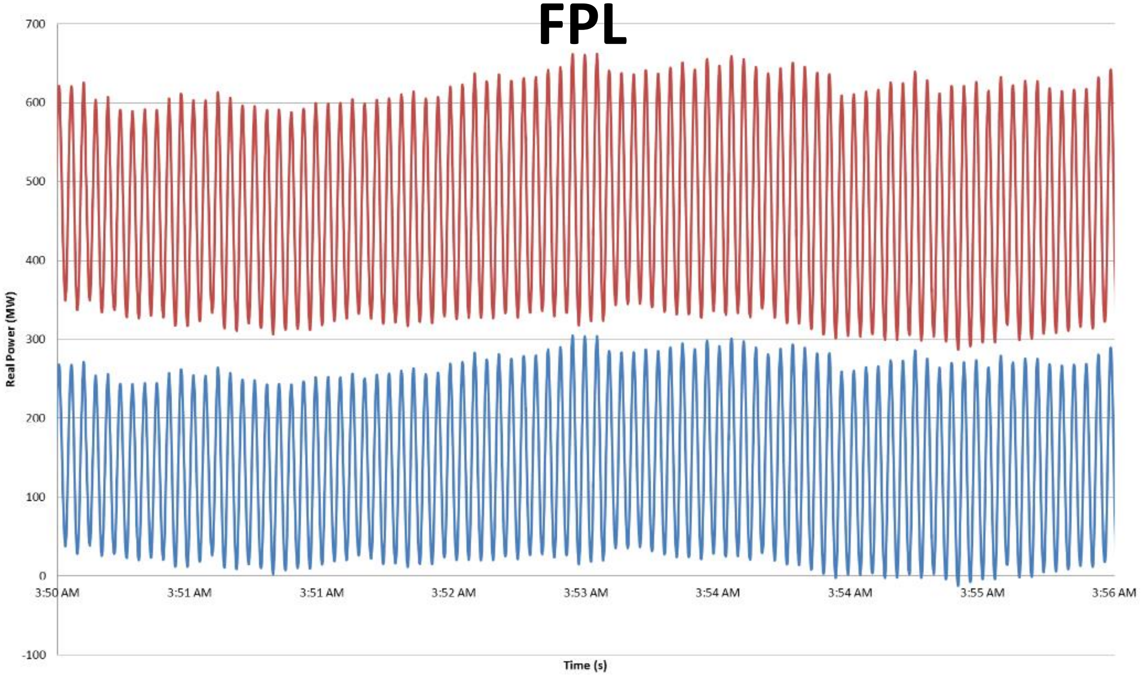
- Monitors oscillations using 150 measurements from 68 PMUs
- 4 frequency bands
  - 0.01-0.15 Hz
  - 0.15-1.0 Hz
  - 1.0-5.0 Hz
  - 5.0-14.0 Hz
- Tool is operational since 2016 and provides alarms to the operators

Forced Oscillations

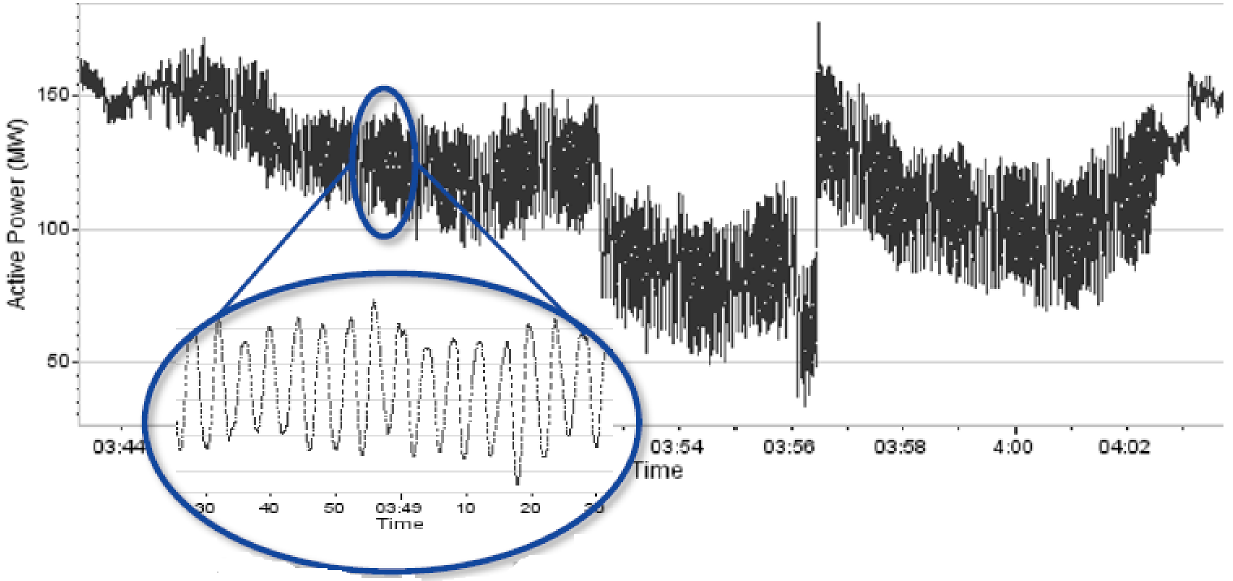
- Typically due to equipment failure/malfunction
- January 2019 event
  - 0.25 Hz oscillations propagated through entire Eastern Interconnection and lasted for 17 mins
  - Resonance with 0.25 Hz inter-area mode caused the propagation
  - Up to 200 MW peak-to-peak magnitude
  - The source of oscillations was a Florida generator



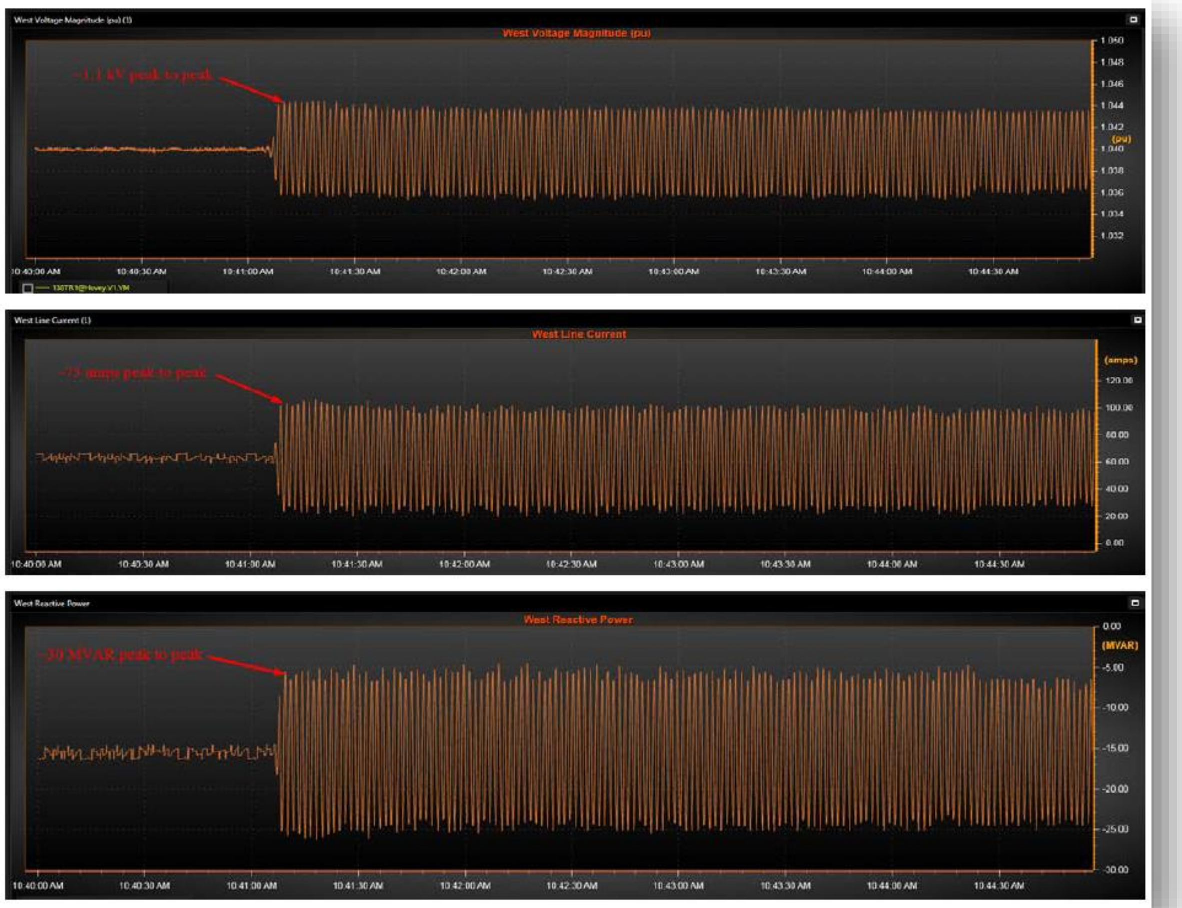
FPL



MW flow in 345 KV tie-line between NYISO and ISO-NE



Wind/Solar Inverter Caused Oscillations



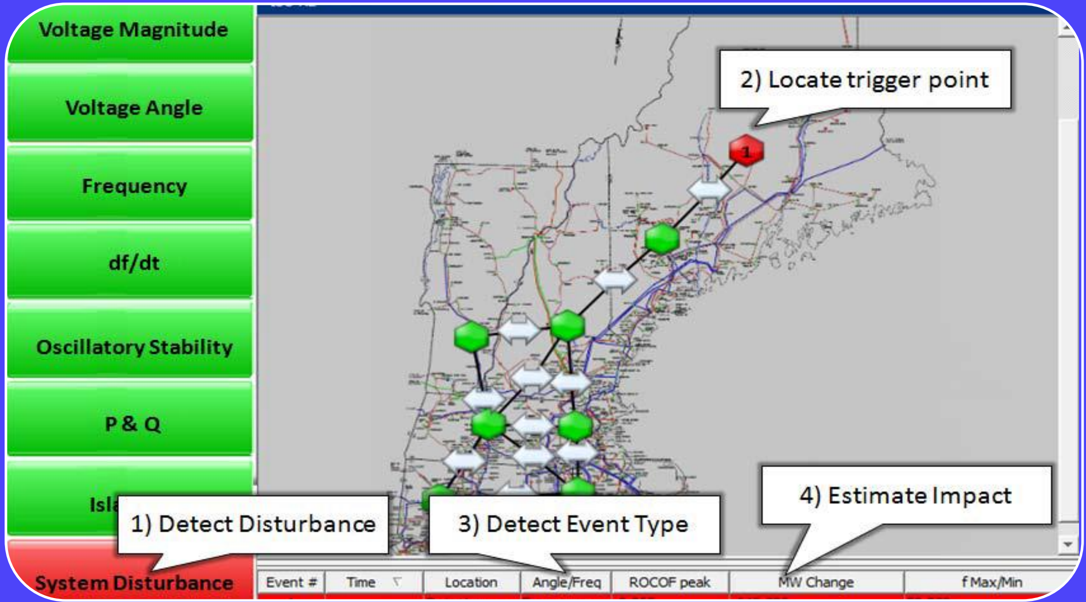
- Wind/solar plant inverter controls might create oscillations due to control interactions with neighboring equipment or due to resonance with the network

- Without use of synchrophasor data these oscillations cannot be observed

Event Detection

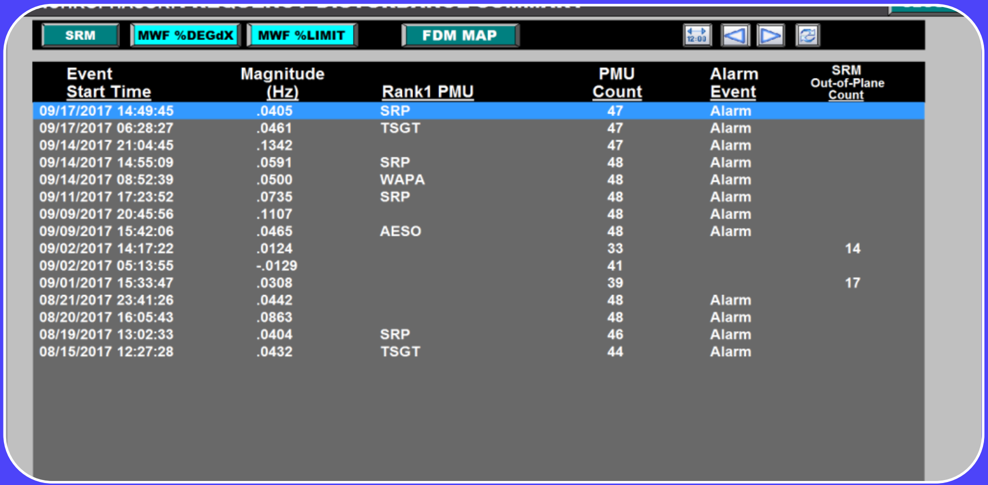
Event Detection – Vendor Tools & Use Cases

GE PhasorPoint – ISONE



- Event identification based on the rate of change of time-aligned voltage angle and frequency measurements
- Provides with
  - disturbance alarm
  - location
  - event type
  - estimated impact

BPA - FDM

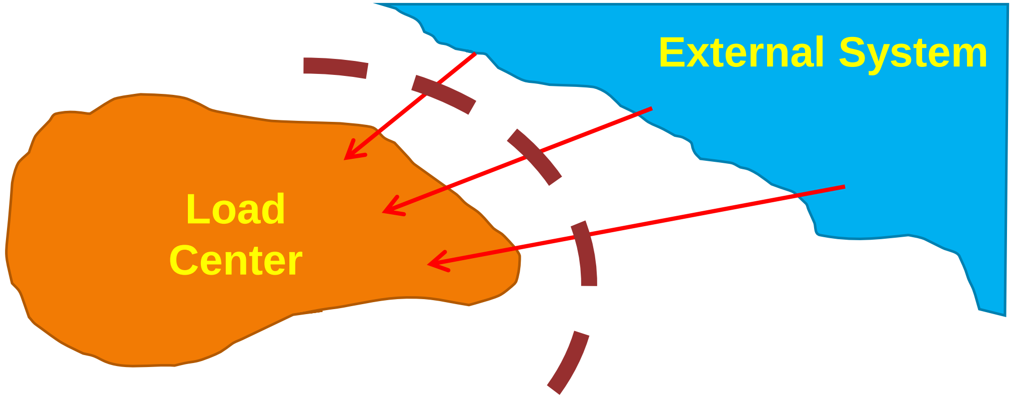


Event Start Time	Magnitude (Hz)	Rank1 PMU	PMU Count	Alarm Event	SRM Out-of-Plane Count
09/17/2017 14:49:45	.0405	SRP	47	Alarm	
09/17/2017 06:28:27	.0461	TSGT	47	Alarm	
09/14/2017 21:04:45	.1342		47	Alarm	
09/14/2017 14:55:09	.0591	SRP	48	Alarm	
09/14/2017 08:52:39	.0500	WAPA	48	Alarm	
09/11/2017 17:23:52	.0735	SRP	48	Alarm	
09/09/2017 20:45:56	.1107		48	Alarm	
09/09/2017 15:42:06	.0465	AESO	48	Alarm	
09/02/2017 14:17:22	.0124		33		14
09/02/2017 05:13:55	-.0129		41		
09/01/2017 15:33:47	.0308		39		17
08/21/2017 23:41:26	.0442		48	Alarm	
08/20/2017 16:05:43	.0863		48	Alarm	
08/19/2017 13:02:33	.0404	SRP	46	Alarm	
08/15/2017 12:27:28	.0432	TSGT	44	Alarm	

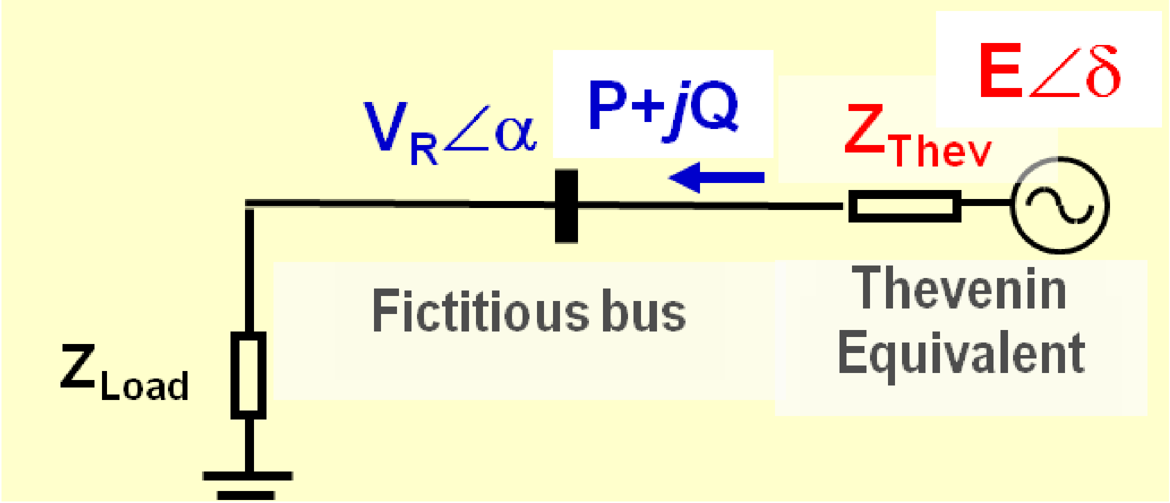
- Monitors 52 PMUs
- For an alarm to trigger:
  - 10 or more PMUs detect an event
  - there is an at least 0.04 Hz frequency drop
  - the 0.04 Hz deviation lasts for at least 10 secs

Voltage Stability

Voltage Stability Monitoring – Measurement Based Approach



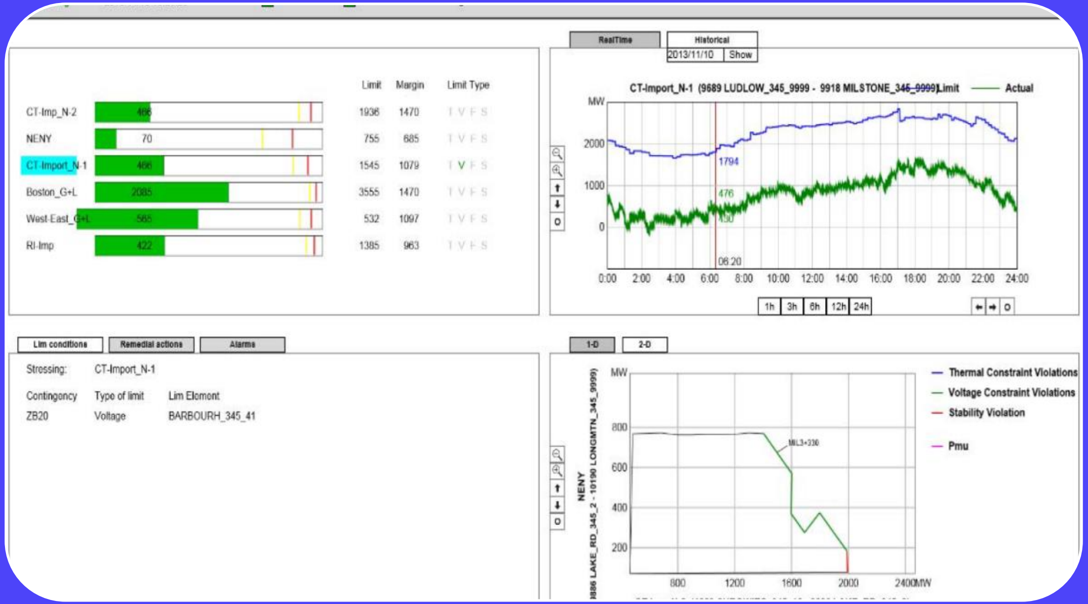
- Voltage stability analysis based on Thevenin Equivalent
- Disadvantage: Cannot predict N-x stability margins



Tool Name	Developed by	Applied By
Measurement-Based Voltage Stability Assessment (MBVSA)	EPRI	Entergy
Real Time Voltage Instability Indicator (RTVII)	Quanta Technology	PG&E, SCE
Measurement-Based Voltage Stability	In-house	BPA

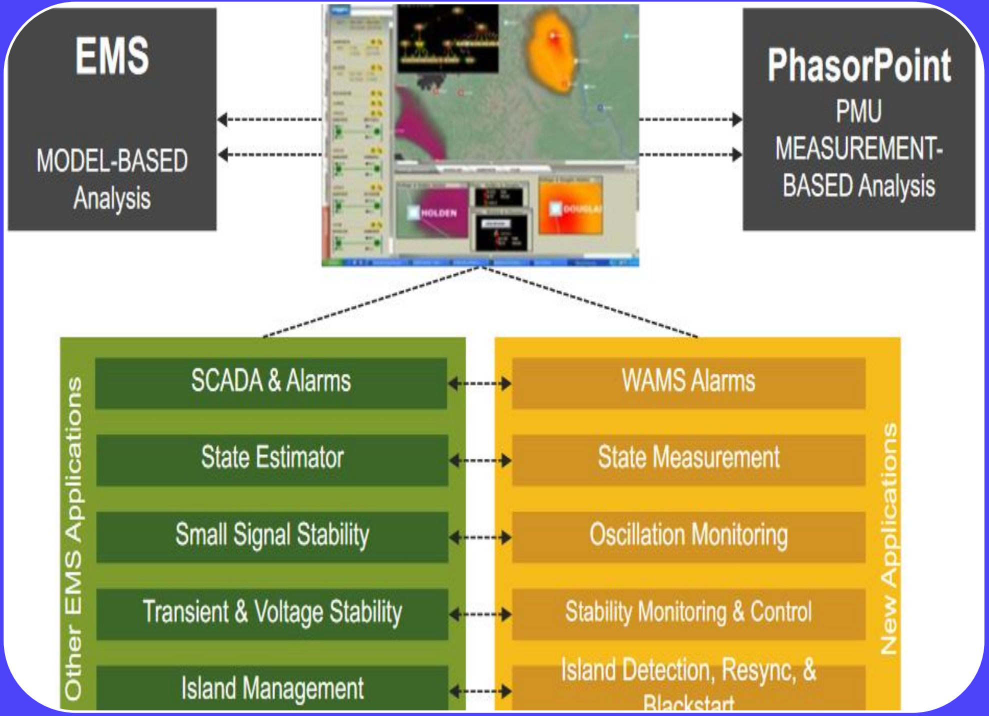
Voltage Stability Monitoring – Hybrid Approach

V&R Energy



- ROSE uses a “hybrid” approach in which SE model is used to compute voltage stability limits and synchrophasor data is used to determine where the current operation point is

GE

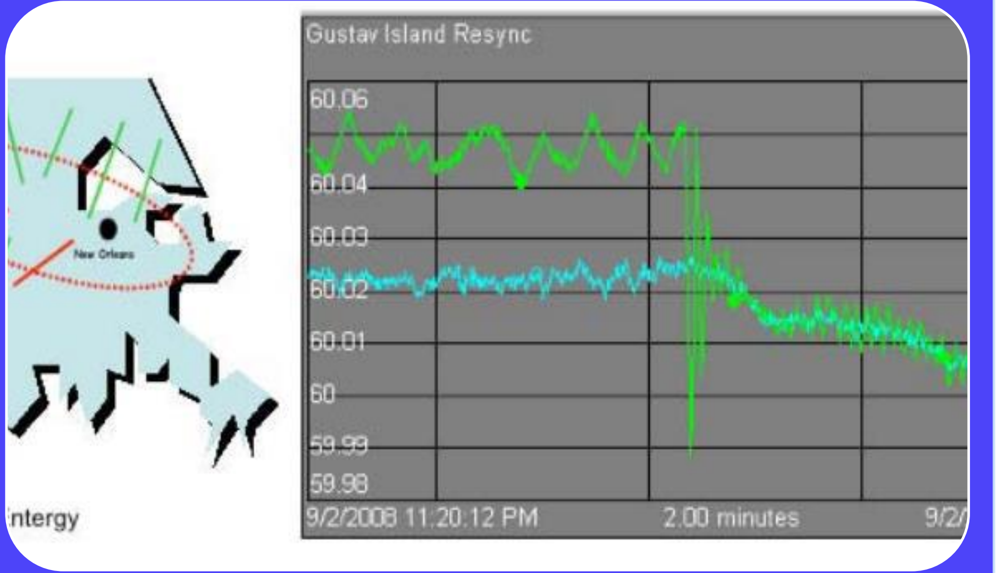


- Integration of WAMS with EMS
- EMS: Model Based Analysis
- WAMS: PMU Measurement Based Analysis

Islanding Detection & Restoration

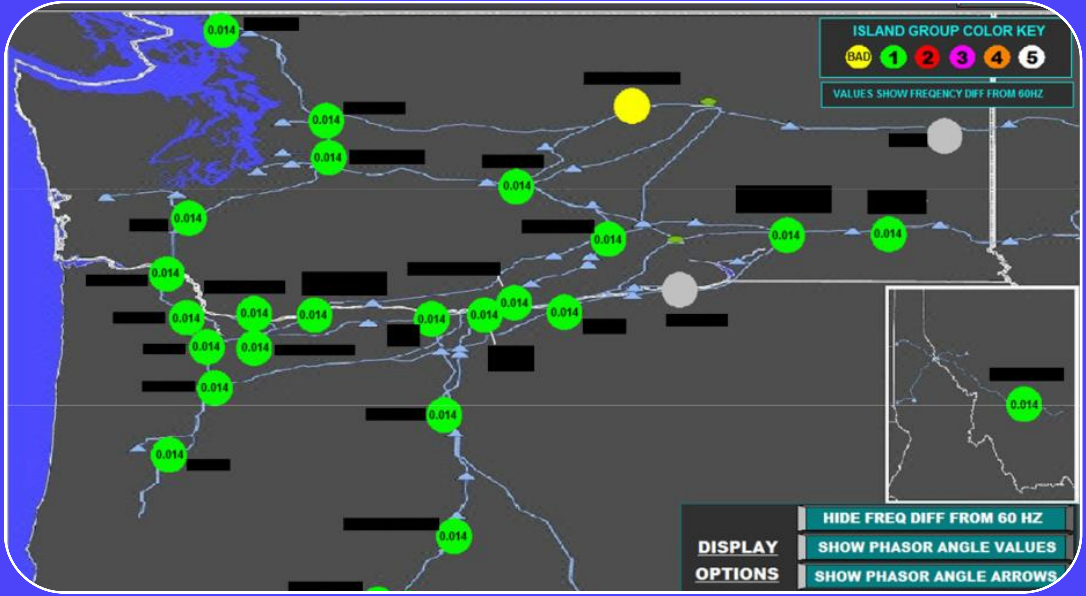
Islanding Monitoring Detection and Restoration

Entergy



- In 2008 the Gustav hurricane created an island and frequency separation was detected by PMU measurements
- Synchrophasor measurements in Entergy's system significantly increased the situational awareness of grid operators during the hurricane Gustav and its aftermath in 2008

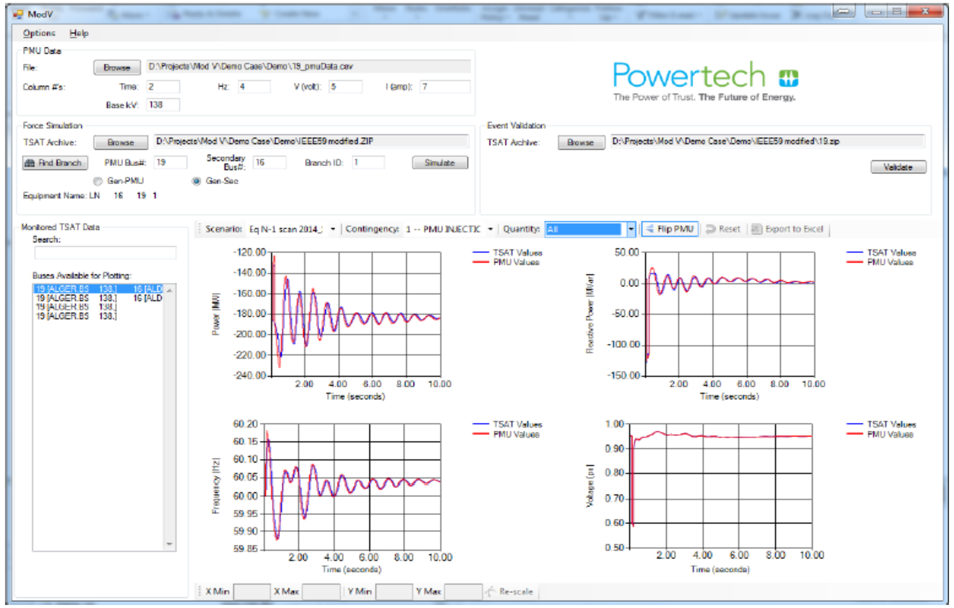
BPA

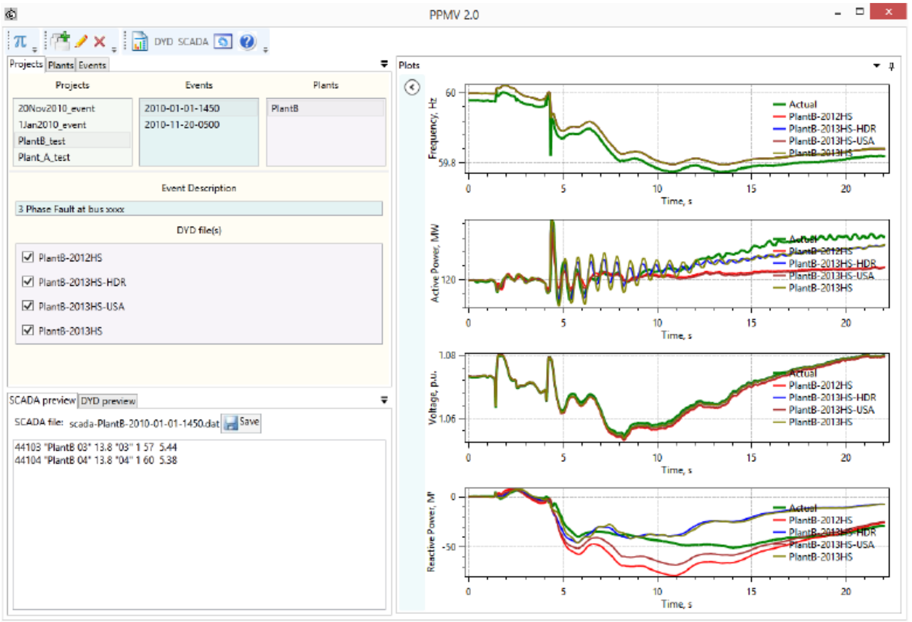


- Tool provides information on power system islands, their boundaries, frequency, and angular separation, information which dispatchers and technical operations staff can use during the system restoration process

Model Validation

Model Validation Tools

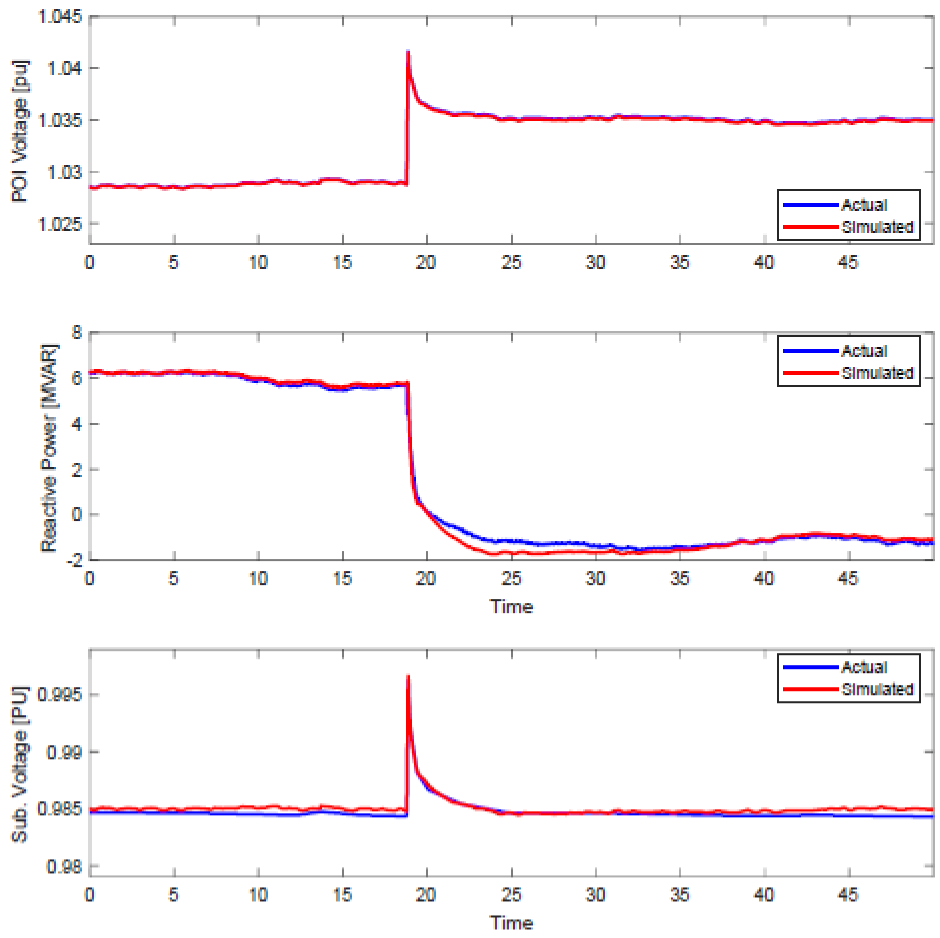




- Tools with playback feature
  - GE PSLF
  - Siemens PTI PSS/E
  - Powertech Labs TSAT & ModV
  - Powerworld
- Tools for automated model validation
  - PNNL-BPA Power Plant Model Validation (PPMV)
  - EPG's Generator Parameter Validation (GPV)
- Tools for model calibration (perform optimization to estimate model parameters)
  - EPRI PPPD (can be used to verify the models of shunt FACTS devices, wind and PV power plants, and synchronous generator based conventional power plants)
  - Matlab Simulink

Synchrophasor Applications for Renewable Energy - Model Validation for Wind Farms and Solar Plants

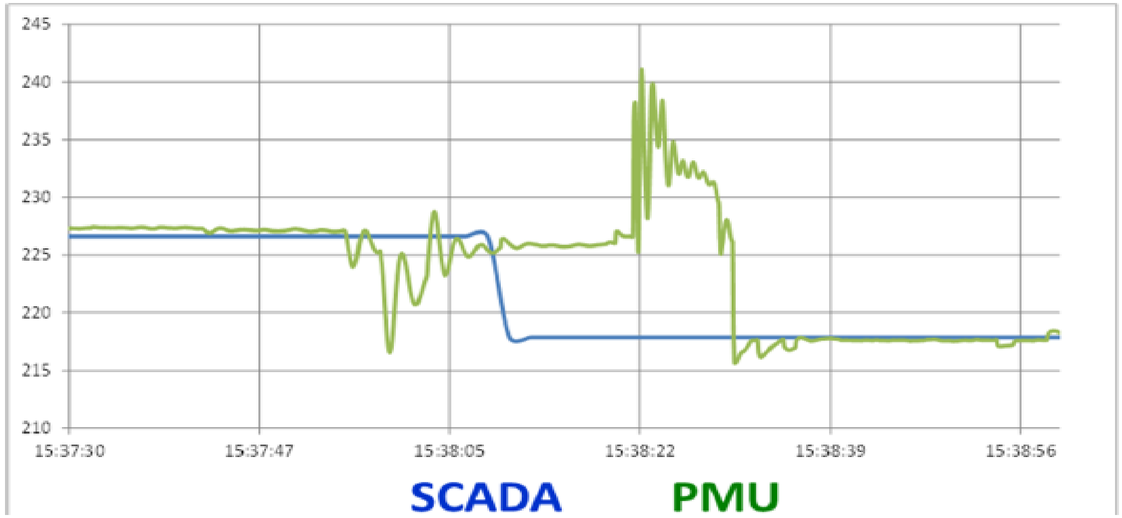
BPA Wind Plant

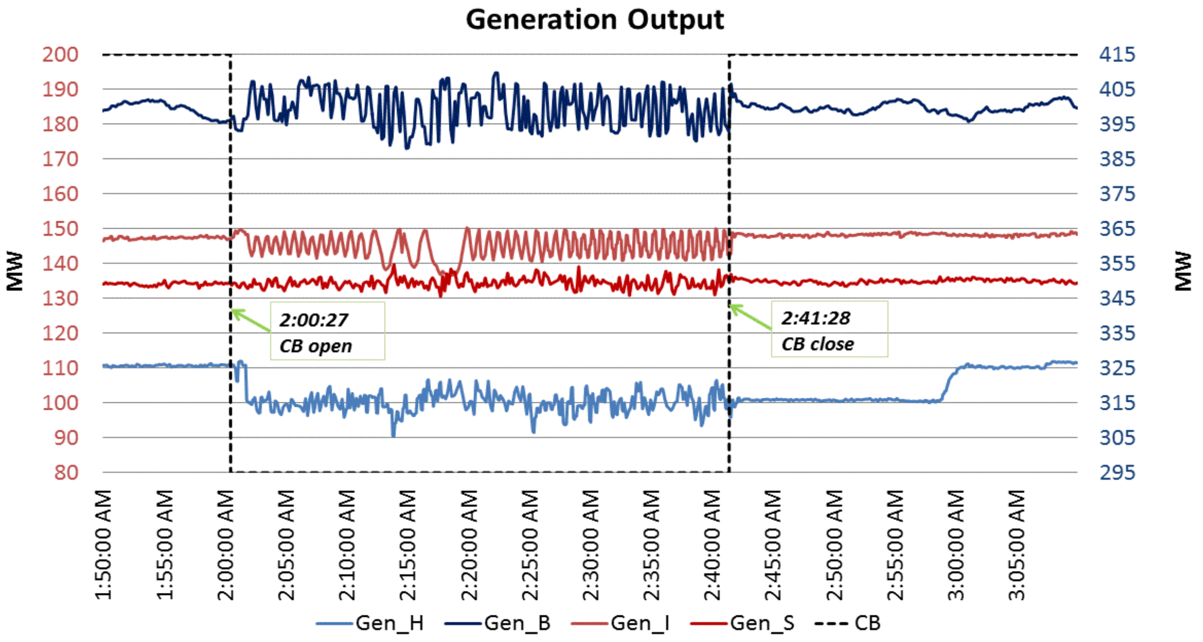


- Use of generic wind/solar plant dynamic models
- Several utilities have installed PMUs at wind/solar power plants
- Recorded synchrophasor data can be used to perform model validation and controller tuning of wind/solar plants

Event Analysis

Event Analysis Using Synchrophasor Data





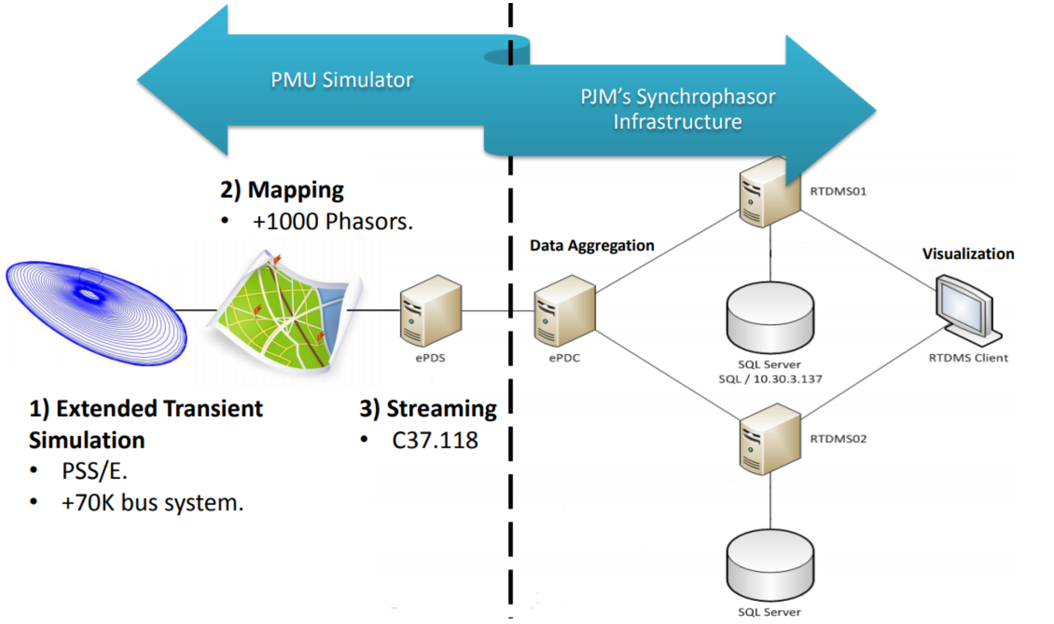
Benefits of Synchrophasor Data Based Event Analysis

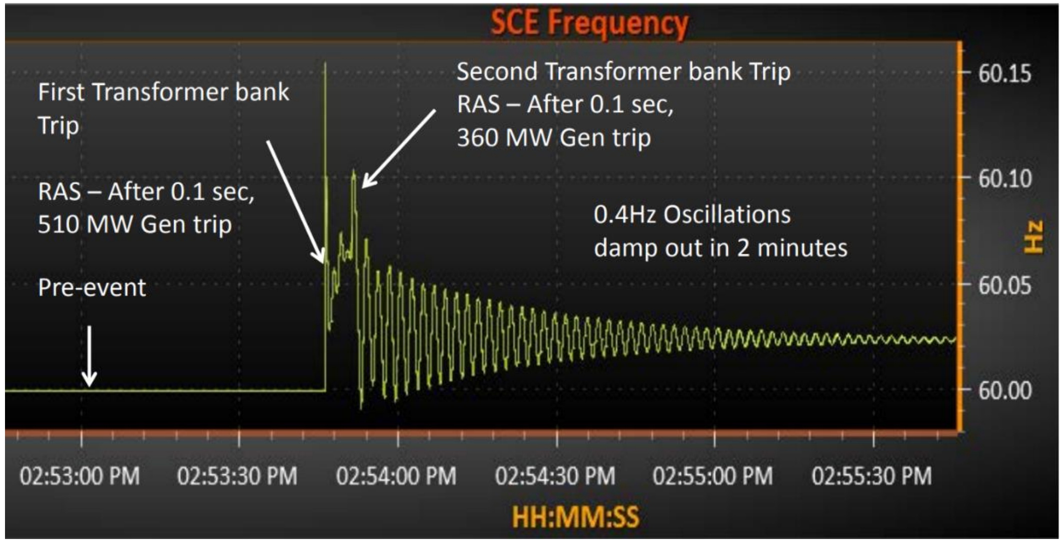
- High resolution, time-tagged synchrophasor data
- Reduced time for system events reporting and analysis
- Faster and easier communication with TO and ISO personnel on details of events
- In-depth system event analysis using specialized software features

Statement from BPA: “With SCADA, months would have been needed to analyze the event”

Operator Training

Operator Training on the Use of Synchrophasor Technology



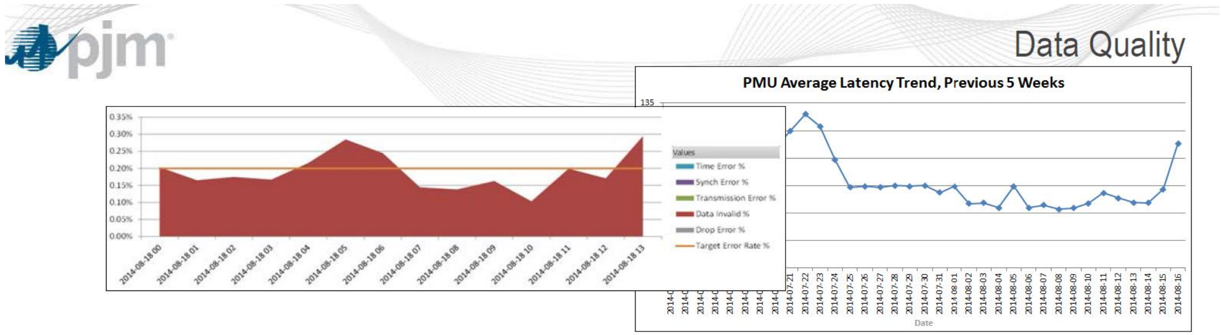


- Grid operators should respond effectively to an alert and/or an event in real time operations
- Train operators to:
  - use advanced synchrophasor technology metrics such as phase angles, sensitivities and oscillations/damping to monitor, diagnose, and take timely corrective actions in real-time
  - understand the early warning indicators and event pre-cursors for events over a wide-area such as the entire interconnection that have the potential to cascade, e.g., wide-area phase angle differences
  - manage what-if scenarios
  - test alternate corrective actions and observe consequences in a training environment

Synchrophasor Data Quality

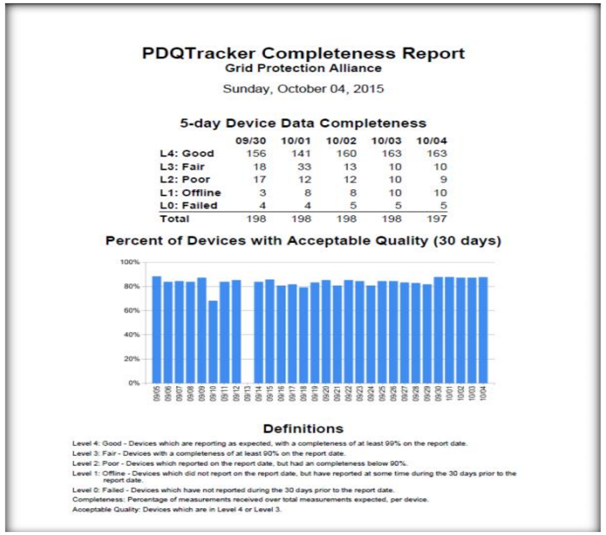
Synchrophasor Data Quality

TO	Total Error %	Drop Error %	Data Invalid %	Transmission Error %	Synch Error %	Time Error %	Average Latency	Min Latency	Max Latency
Apple	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	67	0	3861
Tomato	0.032%	0.001%	0.015%	0.000%	0.016%	0.000%	169	72	4065
Bean	0.046%	0.003%	0.044%	0.000%	0.000%	0.000%	210	99	4015
Garlic	0.214%	0.001%	0.177%	0.000%	0.035%	0.000%	149	121	4093
Brussel	0.415%	0.029%	0.385%	0.000%	0.001%	0.000%	210	59	2111
Pepper	0.505%	0.000%	0.000%	0.505%	0.000%	0.000%	141	75	3627
Lettuce	1.569%	1.512%	0.000%	0.000%	0.057%	0.000%	1243	682	4047
Parsley	1.731%	1.606%	0.000%	0.125%	0.000%	0.000%	1088	1045	4124
Daisy	6.323%	0.466%	5.837%	0.000%	0.018%	0.001%	1168	223	4125
Potato	9.364%	0.000%	9.363%	0.000%	0.000%	0.000%	310	137	4062
Basil	22.281%	0.000%	22.245%	0.000%	0.036%	0.000%	30	10	3981
Berry	33.338%	0.002%	33.335%	0.000%	0.000%	0.000%	3184	3013	4098
PJM Total	2.455%	0.757%	1.642%	0.033%	0.023%	0.000%	745	466	3750



- Data quality is a major factor for successful integration of synchrophasor technology in utility/ISO operations
- Data quality requirements depend on the application
- Data Availability - Missing Data
  - Data loss
  - Delivery delays
  - PMU hardware failure etc.
- Data Accuracy
  - Time accuracy (GPS)
  - Installation/Calibration (Instrumentation, CTs, PTs)
- Some ISOs are generating synchrophasor data quality reports
- Some ISOs are setting data quality targets with TOs

Synchrophasor Data Quality Tools



PDQTracker Completeness Report
Grid Protection Alliance
Sunday, October 04, 2015

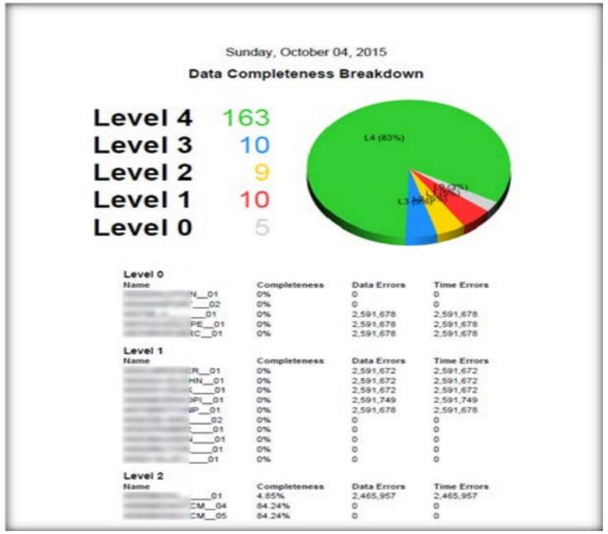
5-day Device Data Completeness

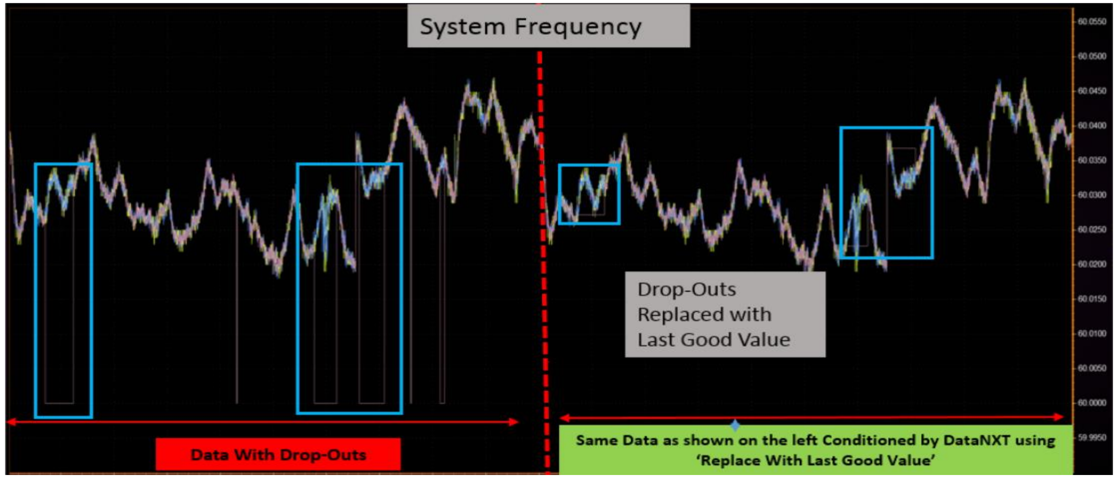
	09/30	10/01	10/02	10/03	10/04
L4: Good	156	141	160	163	163
L3: Fair	18	33	13	10	10
L2: Poor	17	12	12	10	9
L1: Offline	3	8	8	10	10
L0: Failed	4	4	5	5	5
Total	198	198	198	198	197

Percent of Devices with Acceptable Quality (30 days)

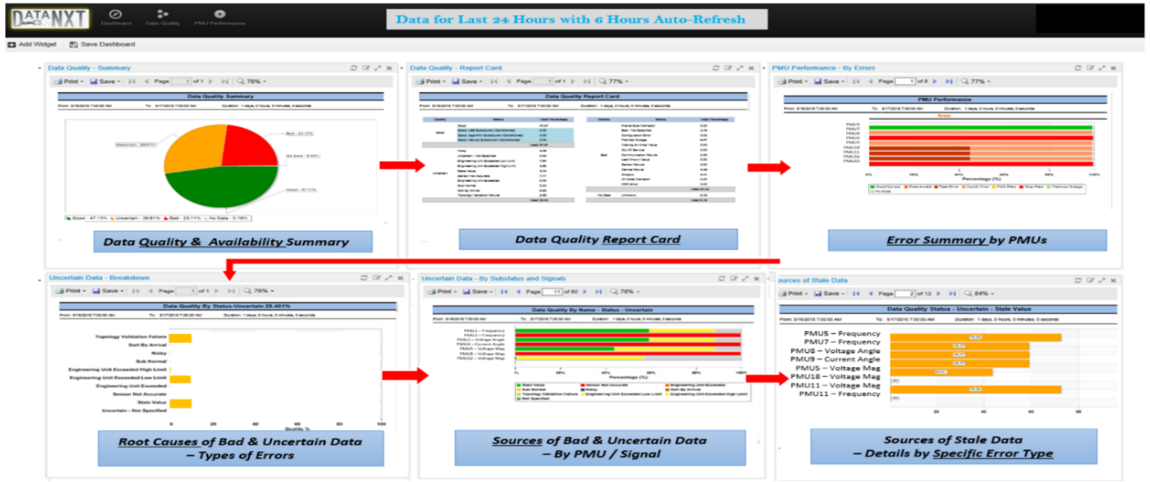
Definitions

Level 4: Good - Devices which are reporting as expected, with a completeness of at least 99% on the report date.
Level 3: Fair - Devices with a completeness of at least 90% on the report date.
Level 2: Poor - Devices which reported on the report date, but had an completeness below 90%.
Level 1: Offline - Devices which did not report on the report date, but have reported at some time during the 30 days prior to the report date.
Level 0: Failed - Devices which have not reported during the 30 days prior to the report date.
Completeness: Percentage of measurements received over total measurements expected, per device.
Acceptable Quality: Devices which are in Level 4 or Level 3.





- GPA's Phasor Data Quality Tracker (PDQTracker)
  - Open source
- EPG's DataNXT
  - Data corruption checks
  - Time related validations
  - Validations using data characteristics
  - Validations using LSE (model based)
- GE PhasorPoint
  - PDC level data handling
  - Application level handling



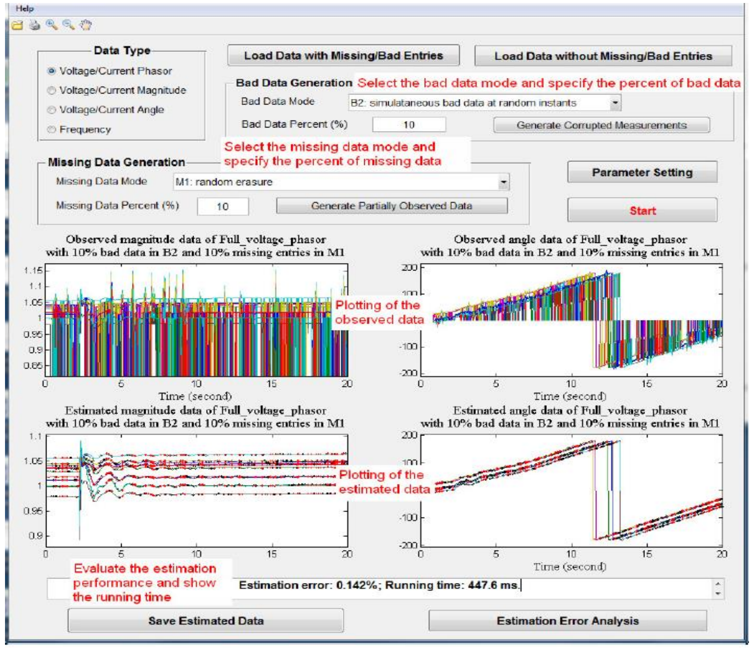
www.epri.com

ELECTRIC POWER RESEARCH INSTITUTE

EPRI - Data Quality Conditioning of Streaming Synchrophasor Data

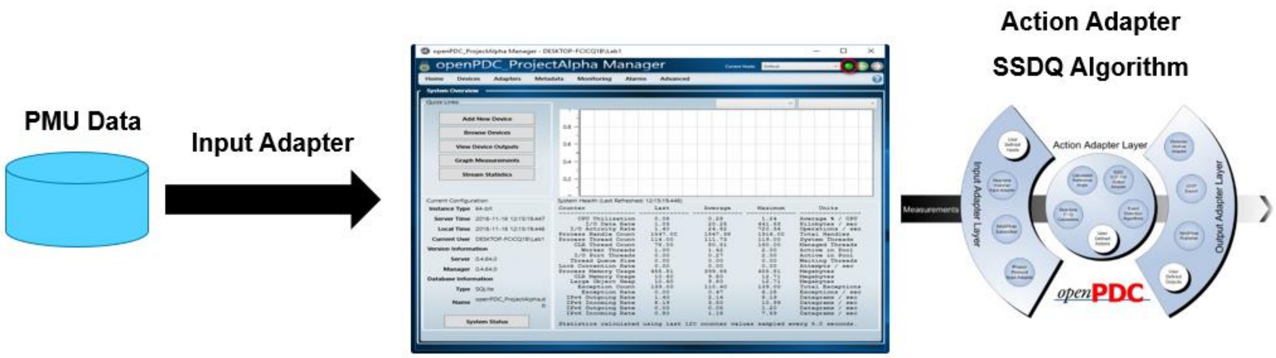
- Goal: Improve synchrophasor data quality by estimating missing data and replacing bad data in synchrophasor streams
- Model free technique, no need for topology information or system parameters
- Computationally efficient for real-time implementation
- Algorithms tested with recorded synchrophasor data provided by EPRI members
- Streaming Synchrophasor Data Quality (SSDQ) software – offline & online versions
- Ongoing: Demos with streaming synchrophasor data hosted by utilities/ISOs
- Next: Collaboration with vendors for implementation in commercial platforms

Offline SSDQ Tool



In collaboration with RPI

Online SSDQ Tool



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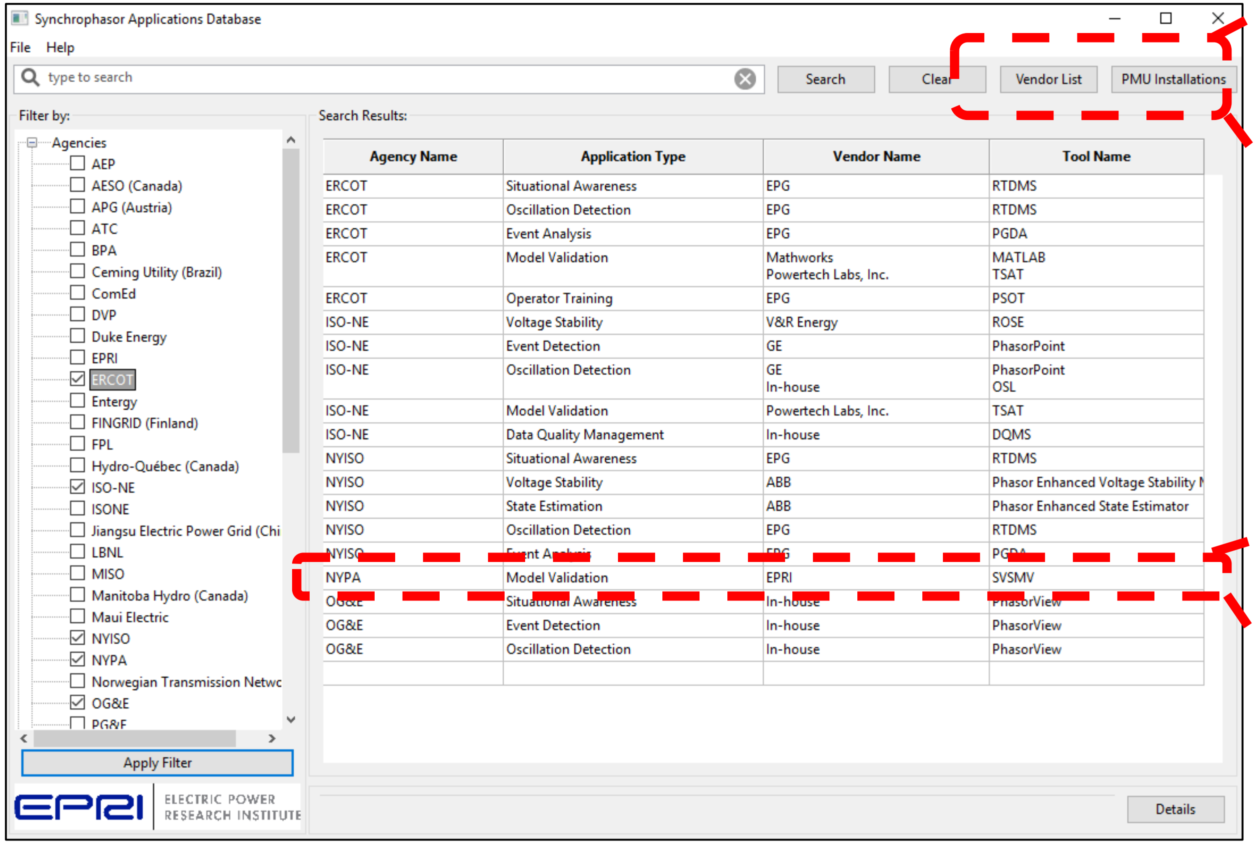
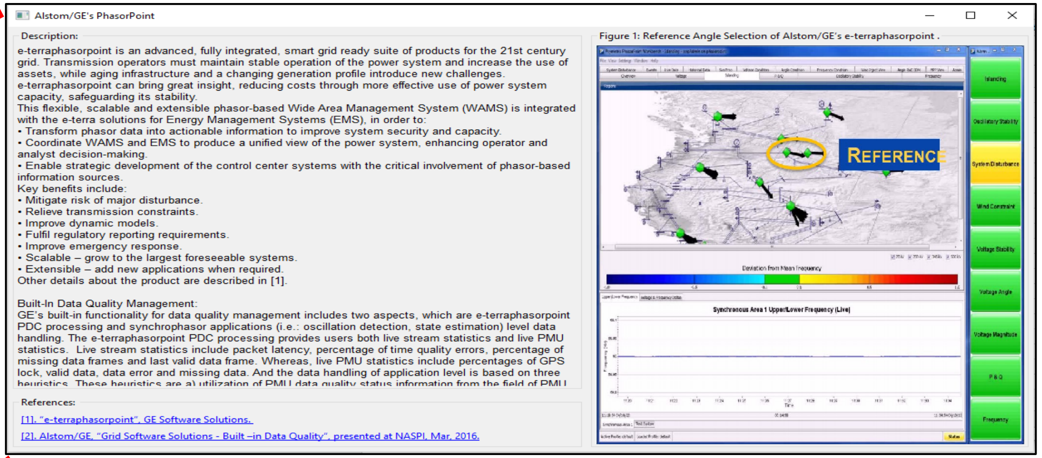
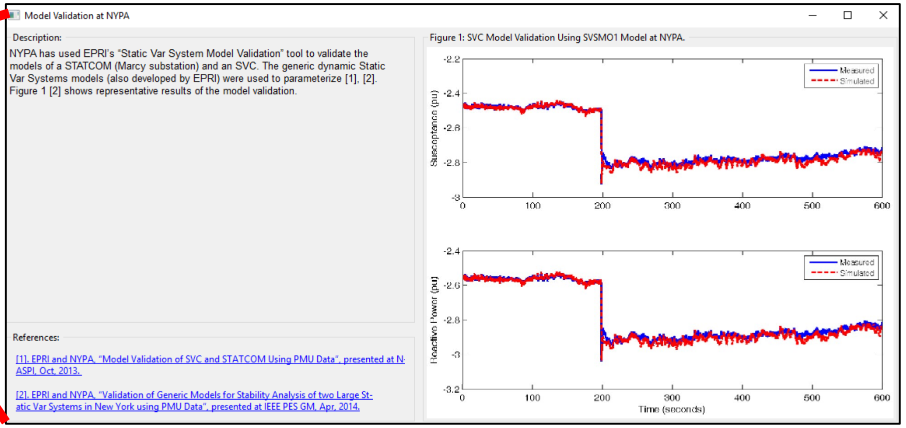
EPRI - Synchrophasor Applications Database



Agency Name	Application Type	Vendor Name	Tool Name
ERCOT	Situational Awareness	EPG	RTDMS
ERCOT	Oscillation Detection	EPG	RTDMS
ERCOT	Event Analysis	EPG	PGDA
ERCOT	Model Validation	Mathworks Powertech Labs, Inc.	MATLAB TSAT
ERCOT	Operator Training	EPG	PSOT
ISO-NE	Voltage Stability	V&R Energy	ROSE
ISO-NE	Event Detection	GE	PhasorPoint
ISO-NE	Oscillation Detection	GE In-house	PhasorPoint OSL
ISO-NE	Model Validation	Powertech Labs, Inc.	TSAT
ISO-NE	Data Quality Management	In-house	DQMS
NYISO	Situational Awareness	EPG	RTDMS
NYISO	Voltage Stability	ABB	Phasor Enhanced Voltage Stability M
NYISO	State Estimation	ABB	Phasor Enhanced State Estimator
NYISO	Oscillation Detection	EPG	RTDMS
NYISO	Event Analysis	EPG	PGDA
NYPA	Model Validation	EPRI	SVSMV
OG&E	Situational Awareness	In-house	PhasorView
OG&E	Event Detection	In-house	PhasorView
OG&E	Oscillation Detection	In-house	PhasorView





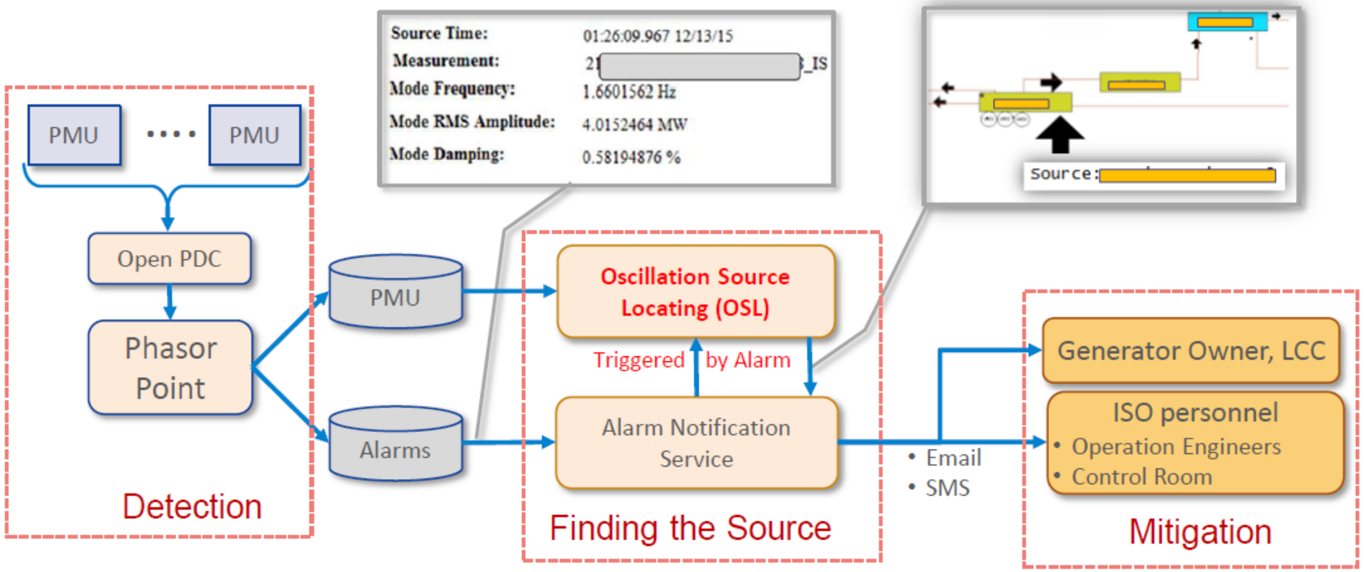
- Entries based on publicly available documents
- For each entry, summary description of application and related references

Value: Inform utility/ISO engineers and executive management about uses cases and derived value of synchrophasor technology

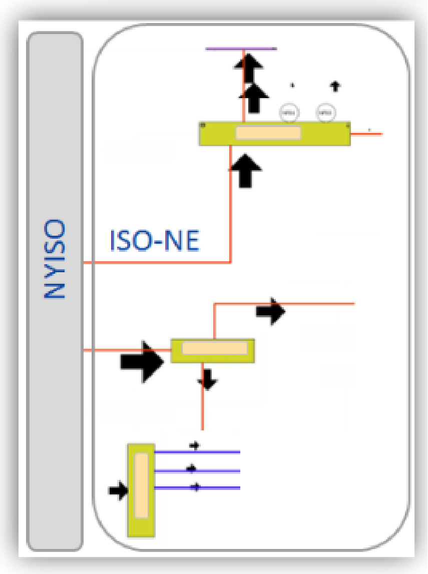
Trending PMU Applications

Oscillation Source Location

ISO-NE - Dissipating Energy Flow



Jan 2019 Event



IEEE PES PSDP TF: Oscillation Source Location

Cases #	Case name	Data of event	Power system - source of PMU	Type of oscillations	Frequency/Hz	Peak to peak magnitude	Source and location	Confidence level on the source location	Duration of sample set
1	ISO-NE case 1	Jun.17, 2016	ISO-NE	System-wide mode	0.27	Up to 27 MW	Generator outside of ISO-NE in Area 2.	100%	3 min
2	ISO-NE case 2	Oct.3, 2017	ISO-NE	Multi-frequency, wide-spread	Dominant modes: 0.08 0.15 0.31	Up to 130 MW	Generator outside of ISO-NE in Area 3.	100%	6 min
3	ISO-NE case 3	Jul.20, 2017	ISO-NE	Regional	1.13	Up to 115 MW	Generator located East from Sub:2. Lines Ln:2 and Ln:4 lead to the area, where the source generator resides.	100%	3 min

Artificial Intelligence (AI)/Machine Learning Using Synchrophasor Data

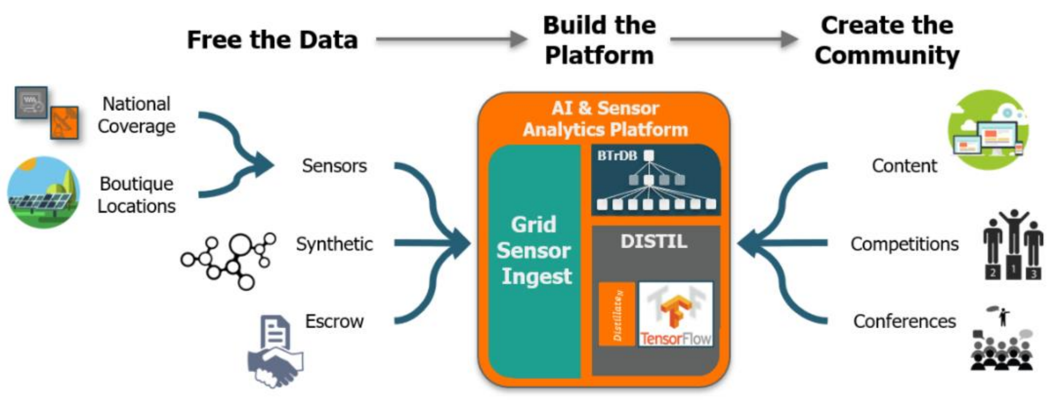
DOE FOA 1861

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

Department of Energy (DOE)
Office of Electricity (OE)

BIG DATA ANALYSIS OF SYNCHROPHASOR DATA
Funding Opportunity Announcement (FOA) Number: DE-FOA-0001861
FOA Type: Initial
CFDA Number: 81.122, Electricity Delivery and Energy Reliability, Research, Development and Analysis

ARPA-E PingThings



NASPI EATT

NASPI WHITE PAPER

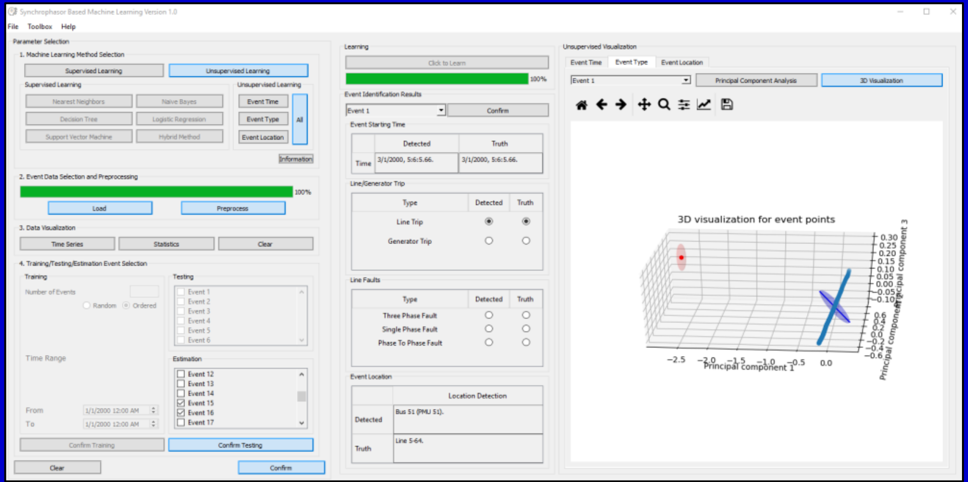
Data Mining Techniques and Tools for Synchrophasor Data

NASPI North American SynchroPhasor Initiative

Prepared by NASPI Engineering Analysis Task Team (EATT)

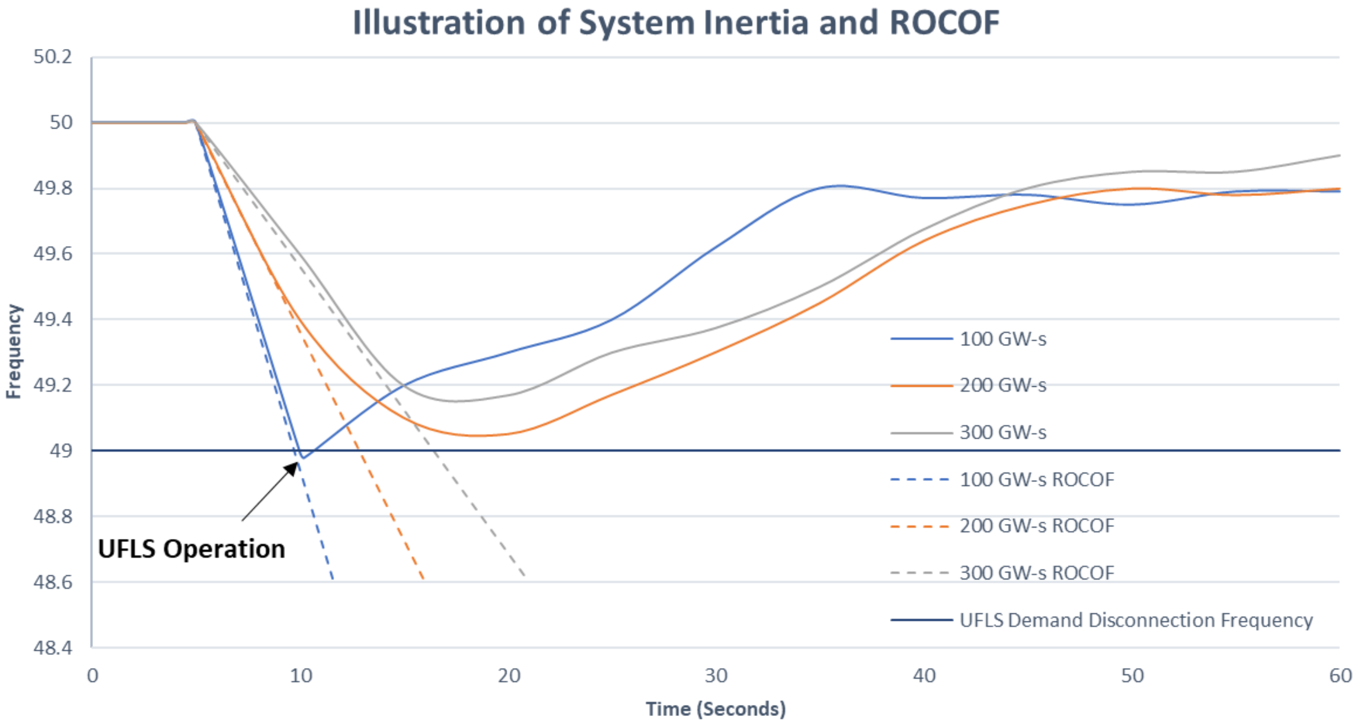
January 2019

EPRI



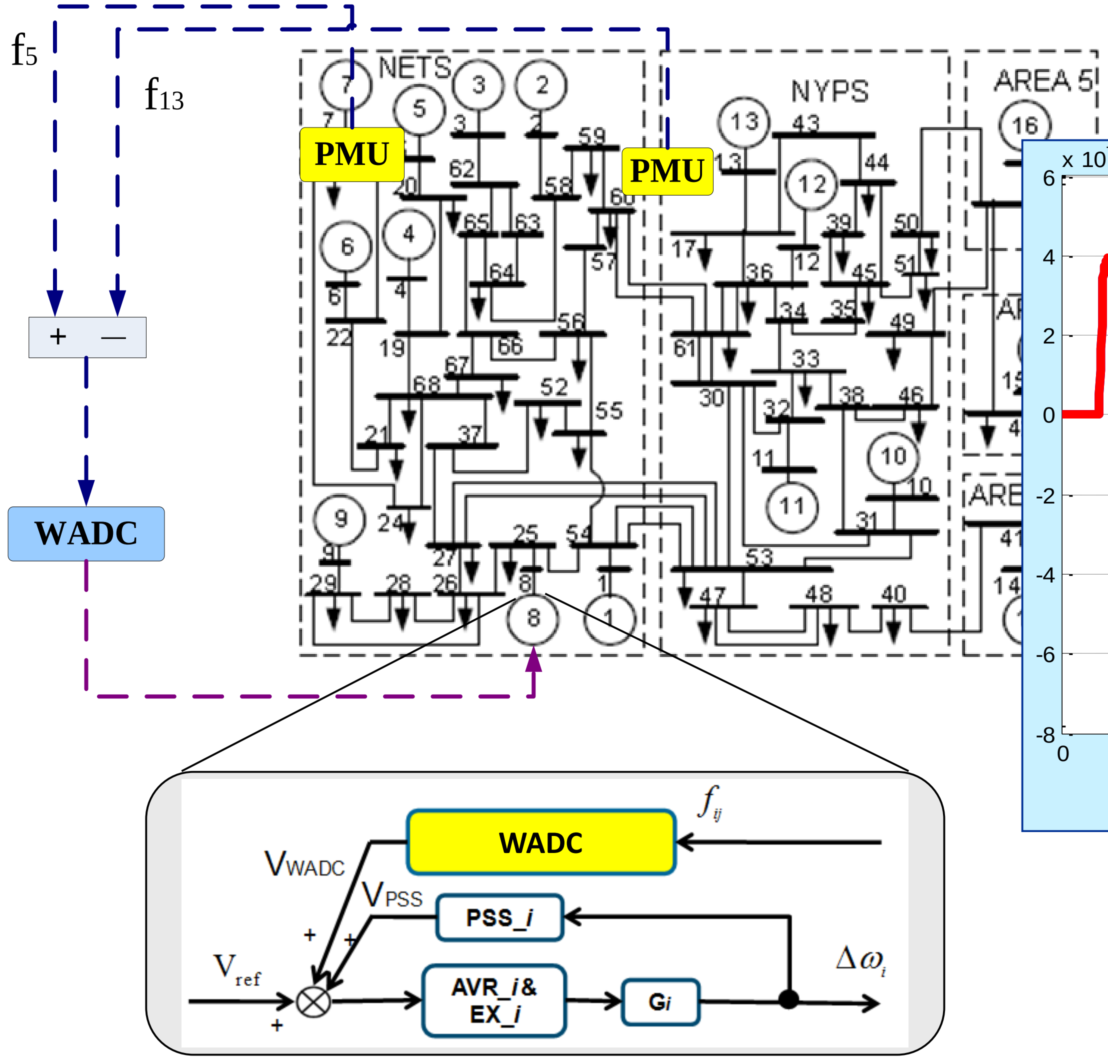
PMU Based Inertia Monitoring

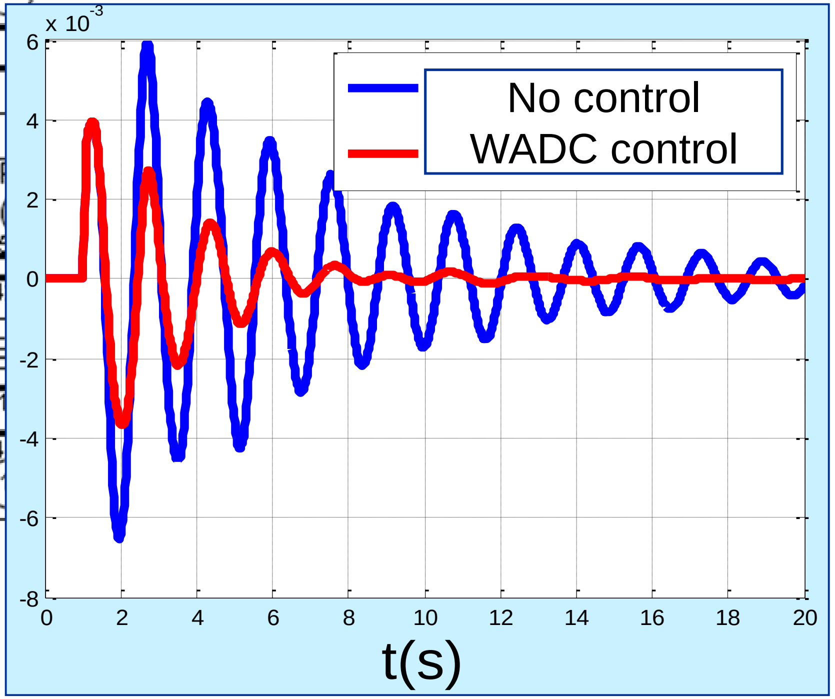
- With increasing levels of IBR, system inertia is decreasing
- RoCoF increase, less time for PFR to respond
- Growing interest and need for online inertia monitoring – inertia floor
- EPRI white paper "**Online Inertia Estimation & Monitoring - Industry Practices & Research Activities**"
  1. Present Industry Practices
  2. Research Activities and Proposed Technologies
     – Reactive Technologies
     – GE
     – EPG
     – UTK



PMU Control Applications

EPRI-Synchrophasor-Based Wide Area Oscillations Damping Controller



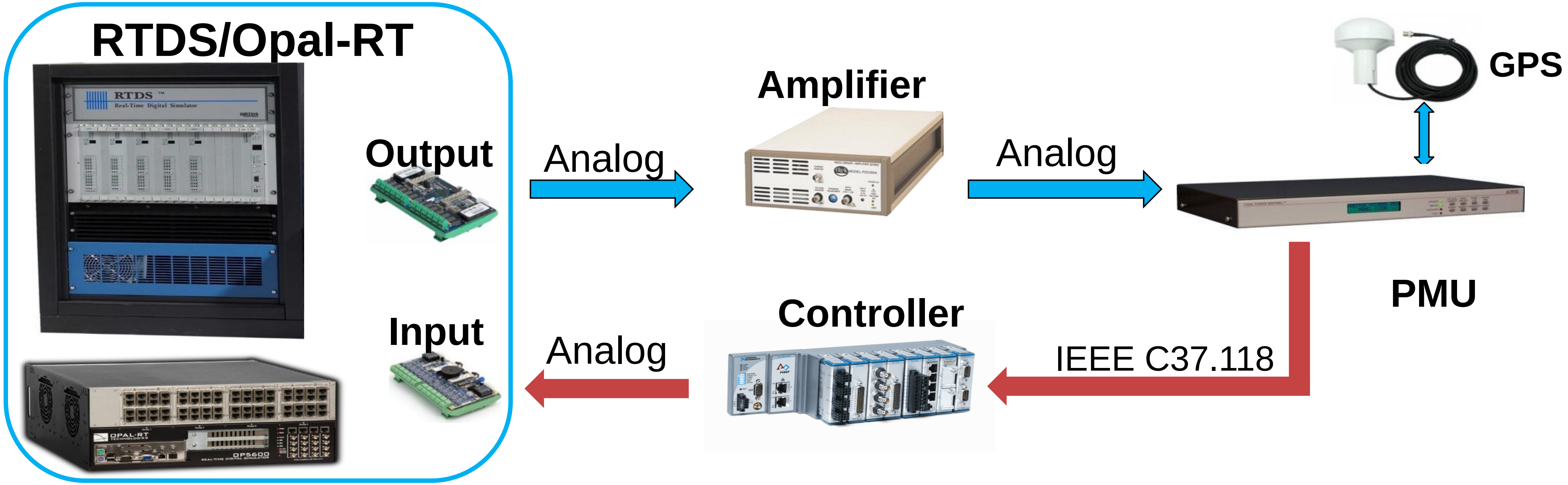


In collaboration with UTK

- **Improved Damping of Target Inter-area/Local Oscillations Mode**
- **Application of Synchrophasor Technology in Closed Loop Wide Area Control**

Synchrophasor-Based Closed-Loop Control Performance Requirements

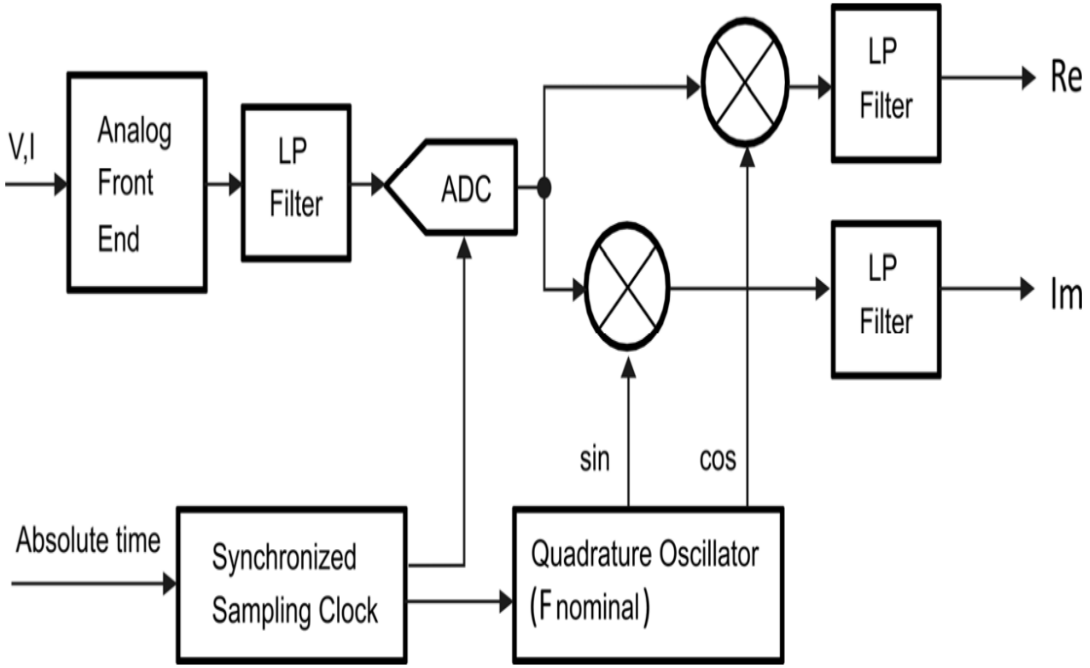
- Performance of synchrophasor-based control applications with respect to PMU filtering
- Functional and performance requirements for control applications
- Verification through Hardware-In-the-Loop experiments
- High-resolution sampled value synchronized measurements versus synchrophasors



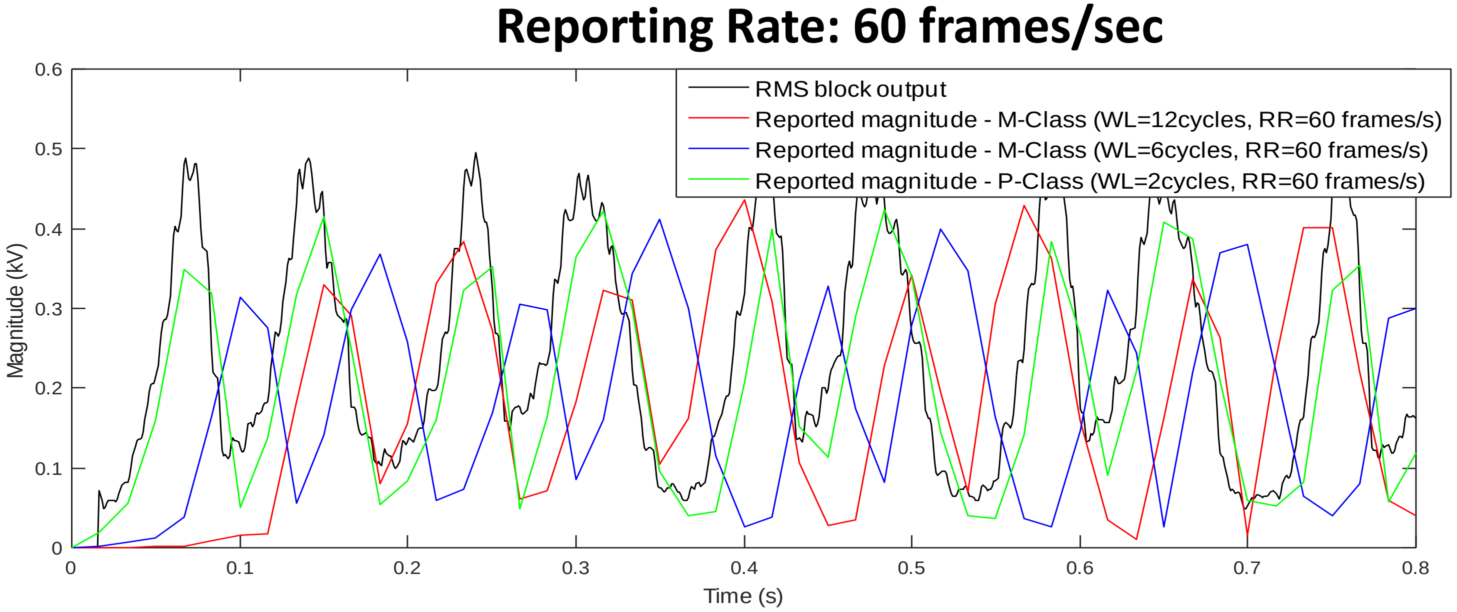
Towards Synchronized Sampled Value Measurements

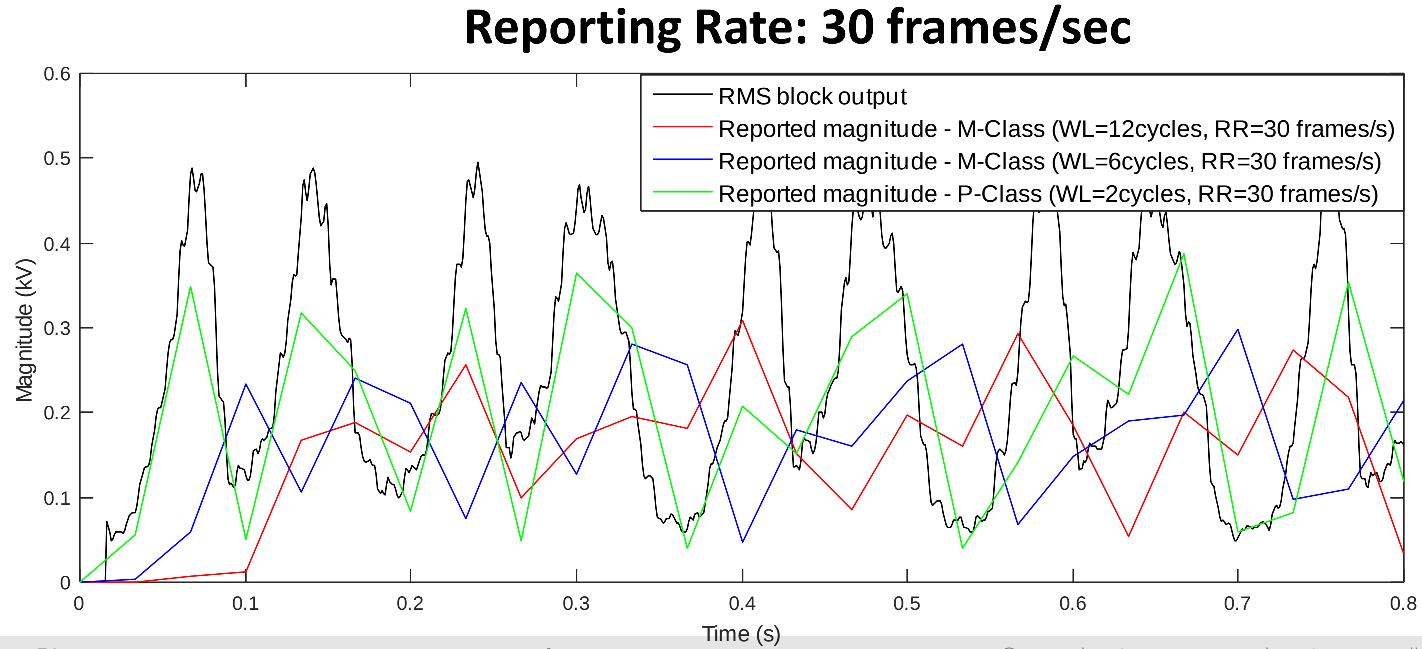
Impact of PMU Signal Processing on Synchrophasor Measurements, Monitoring and Control Applications

- Growing penetration of Inverter Based Resources (IBRs) → grid dynamics not common in the past
- Need for accurate and high-resolution monitoring of these dynamics/transients
- Emerging synchrophasor-based closed-loop control applications – Use of fast actuators (e.g. IBRs)
- Signal processing within a PMU might compromise the accuracy of the monitoring as well as the control action and effect



Inverter PLL Instability Example





- Original signal contains a wide range of frequency components
- Reported voltage magnitude different than true RMS due to attenuation of all frequency components above the Nyquist frequency as well as their overlapping and aliasing
- P-Class PMU report closer to true RMS compared to M-Class
- Filter window length affects the output delay → phase-shift

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Together…Shaping the Future of Electricity