PMU DEPLOYMENT FOR ENHANCED PROTECTION AND CONTROL

CAPER Workshop, August 7 & 8, 2017

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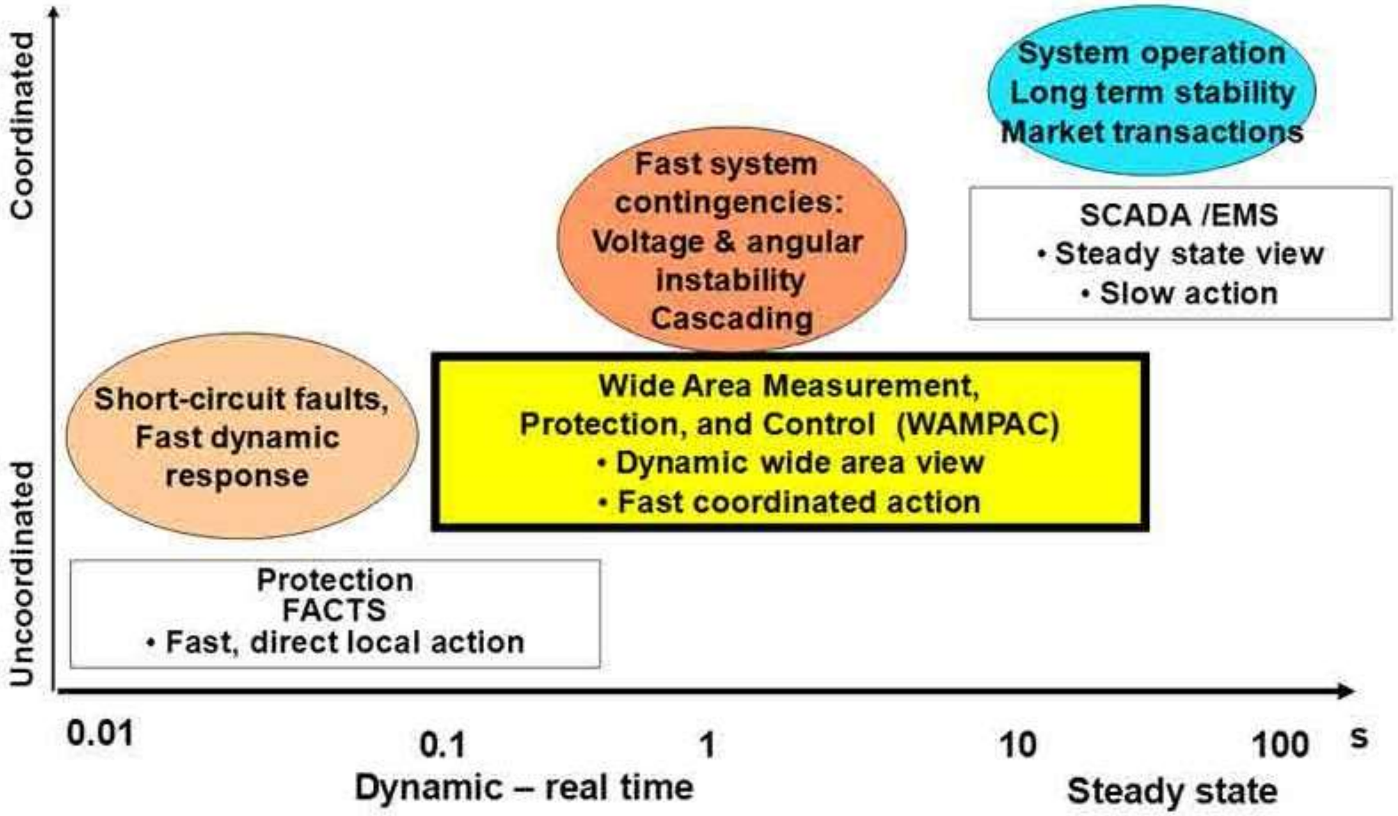
Bridging the Gap with Synchrophasors

1 μs precise grid measurements GPS signals

Dynamic wide-area network view at high speed (60 -120 observations/s) for better indication of grid stress

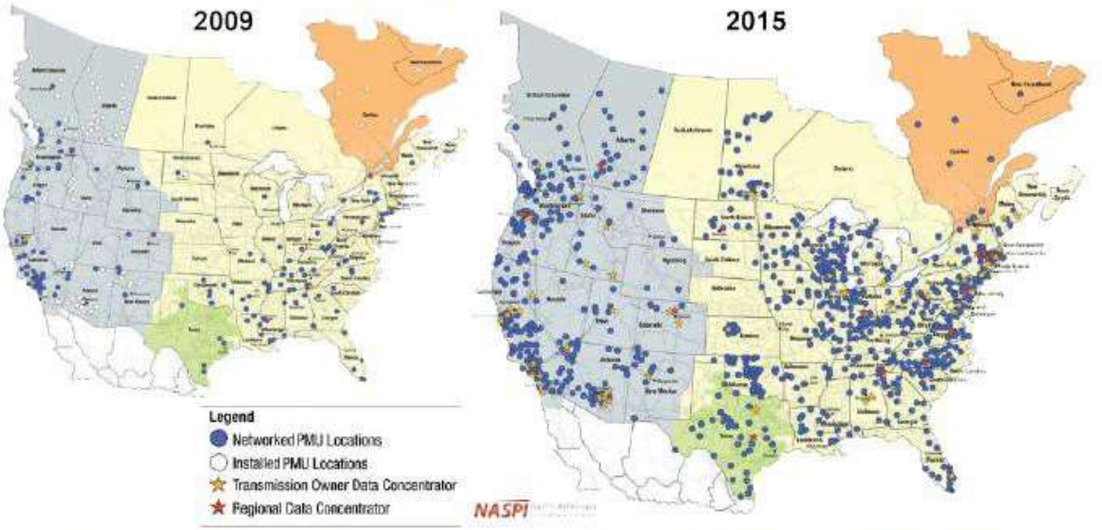
Timeframes of Grid Management using Wide Area Measurements, Protection, and Control



Technology Deployment Status

- Due to the American Recovery and Reinvestment Act of 2009, large number of Synchrophasor Technology projects funded ($620M) – mostly to address transmission needs – USA well covered with PMUs

Figure ES.1 Synchrophasor Advancements in North America

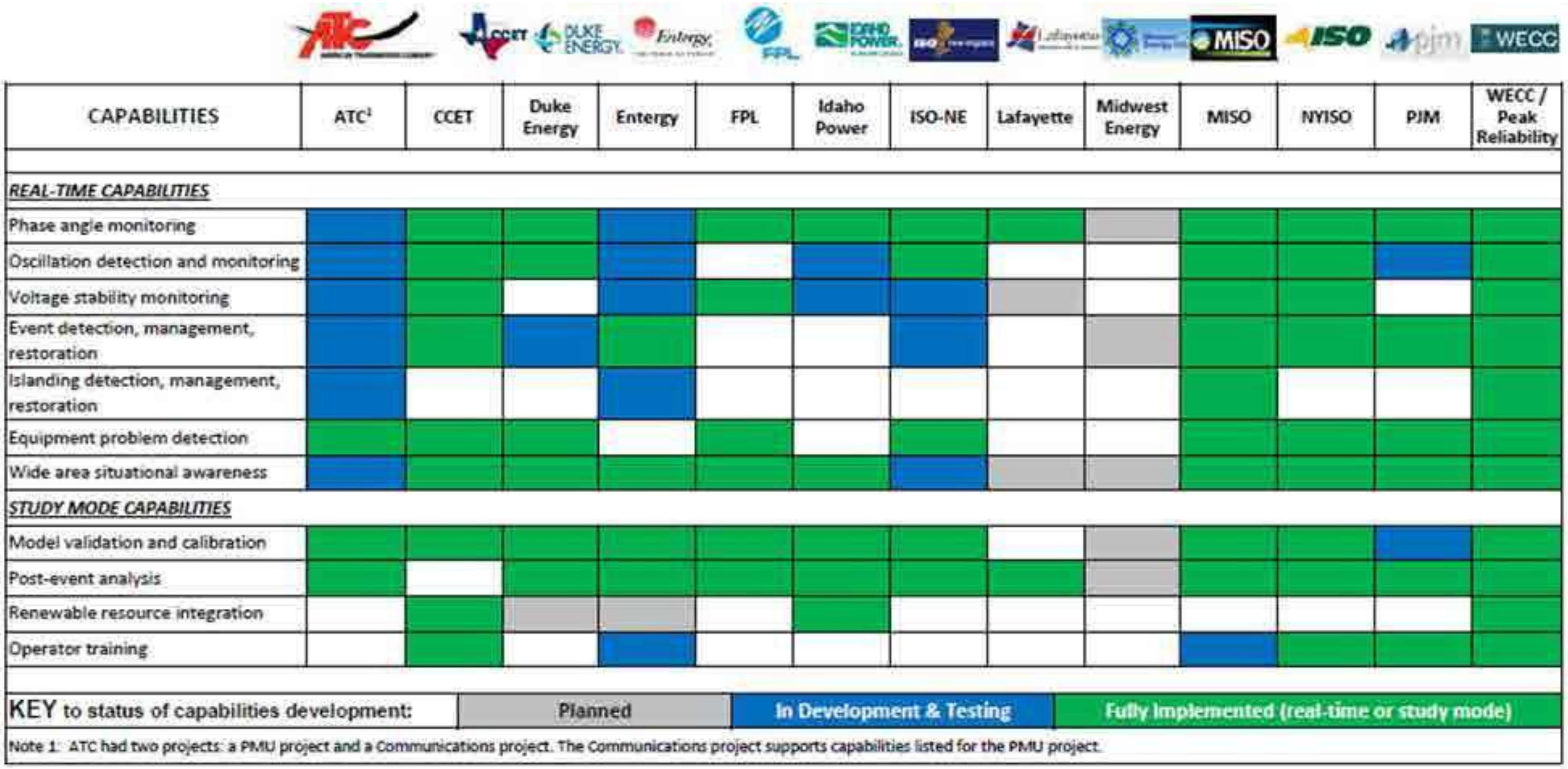


Networked PMUs in North America increased from about 166 in 2009 to over 1,700 in 2015

Source: DOE Report: “Advancement if Synchrophasor Technology in Projects Funded by the American Recovery and Reinvestment Act of 2009”, March 2016

Maturity Level of Synchrophasor System

Recovery Act Smart Grid Investment in Synchrophasor Capability



CAPABILITIES	ATC[1]	CCET	Duke Energy	Entergy	FPL	Idaho Power	ISO-NE	Lafayette	Midwest Energy	MISO	NYISO	PJM	WECC / Peak Reliability
REAL-TIME CAPABILITIES													
Phase angle monitoring	🟦	🟩	🟩	🟦	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩
Oscillation detection and monitoring	🟦	🟩	🟩	🟦		🟦	🟩			🟩	🟩	🟦	🟩
Voltage stability monitoring	🟦	🟩		🟦	🟩	🟦	🟦	▨		🟩	🟩		🟩
Event detection, management, restoration	🟦	🟩	🟦	🟩			🟦		▨	🟩	🟩	🟩	🟩
Islanding detection, management, restoration	🟦			🟦						🟩			🟩
Equipment problem detection	🟩	🟩	🟩		🟩		🟩			🟩	🟩	🟩	🟩
Wide area situational awareness	🟦	🟩	🟩	🟩	🟩	🟩	🟦	▨	▨	🟩	🟩	🟩	🟩
STUDY MODE CAPABILITIES													
Model validation and calibration	🟩	🟩	🟩	🟩	🟩	🟩	🟩		▨	🟩	🟩	🟦	🟩
Post-event analysis	🟩		🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩
Renewable resource integration		🟩	▨	▨		🟩							🟩
Operator training		🟩		🟦						🟦	🟩	🟩	🟩

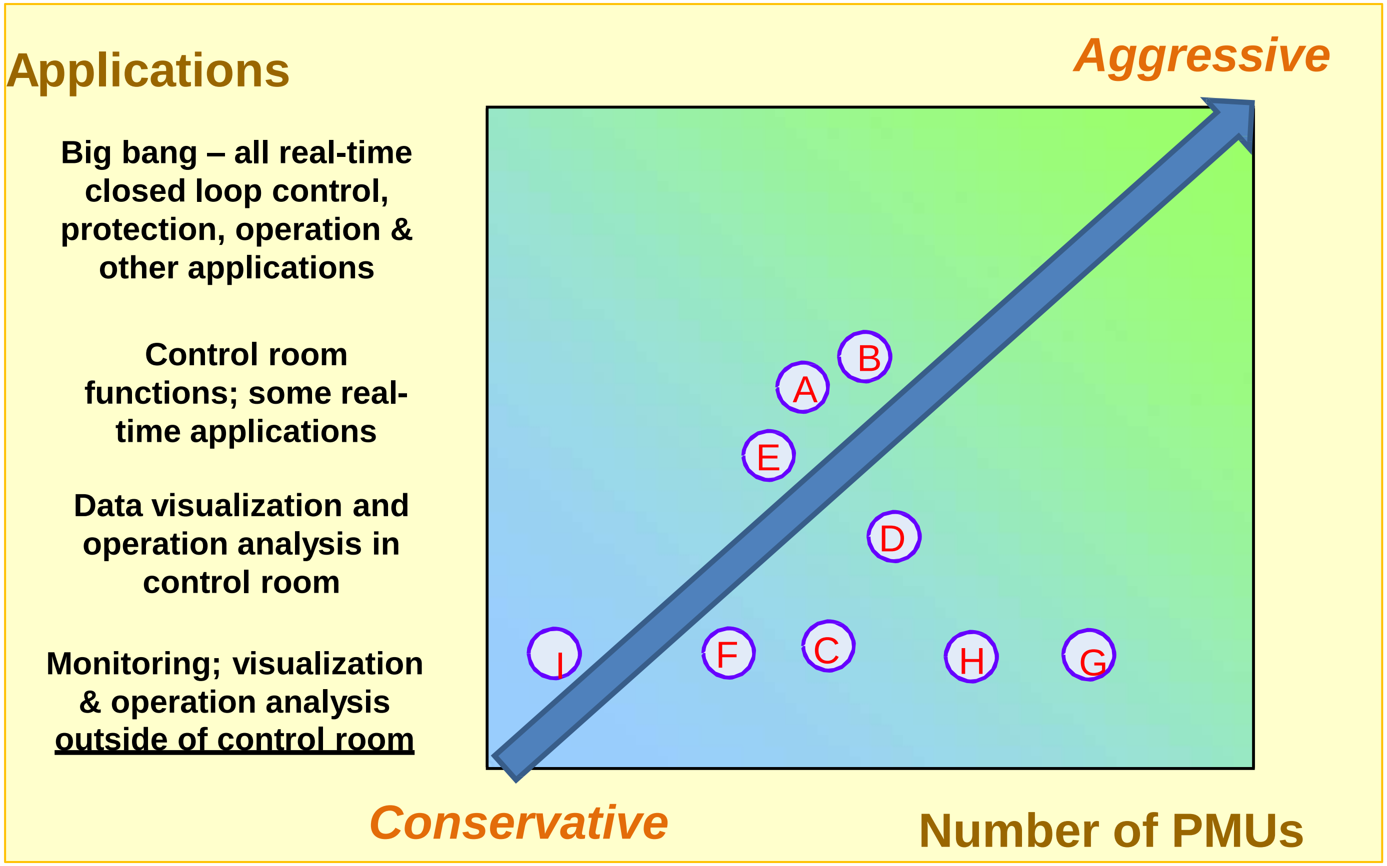
KEY to status of capabilities development: ▨ Planned | 🟦 In Development & Testing | 🟩 Fully Implemented (real-time or study mode)

Note 1: ATC had two projects: a PMU project and a Communications project. The Communications project supports capabilities listed for the PMU project.

Source: DOE Report: "Advancement if Synchrophasor Technology in Projects Funded by the American Recovery and Reinvestment Act of 2009", March 2016

DOE Projects Benchmark

Nine large SGIG Projects varied in focus



Applications

Big bang – all real-time closed loop control, protection, operation & other applications

Control room functions; some real-time applications

Data visualization and operation analysis in control room

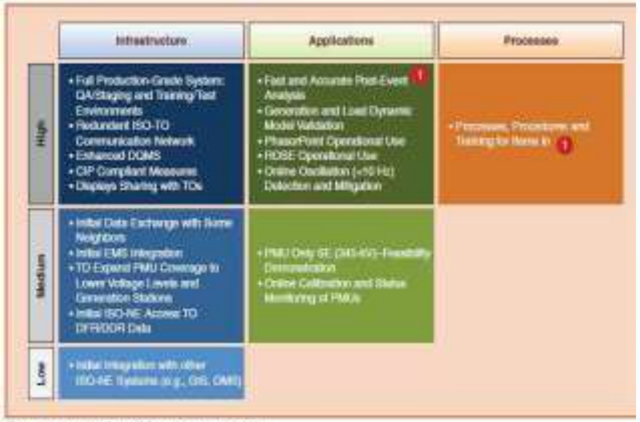
Monitoring; visualization & operation analysis <u>outside of control room</u>

Ⓧ ***US Synchrophasor Projects***

Technology Status

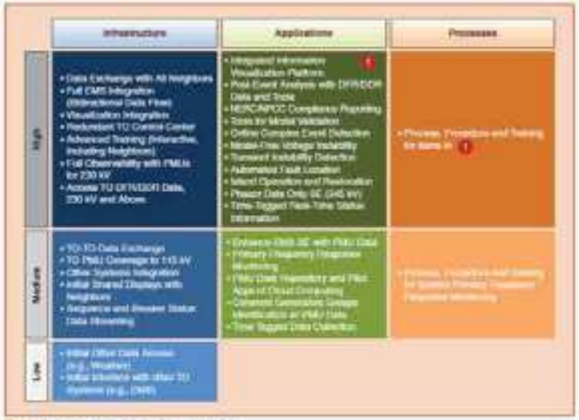
Transmission more mature, Distribution picking up

- Large number of utilities and ISOs implemented Synchrophasor projects, mainly with focus on Wide Area Monitoring Systems
- Decent number of applications implemented, even more envisioned
- After the wave of Smart Grid Investment Grant projects ended (2015), new project subdued
- Some utilities/ISOs preparing implementation roadmaps to assess next steps



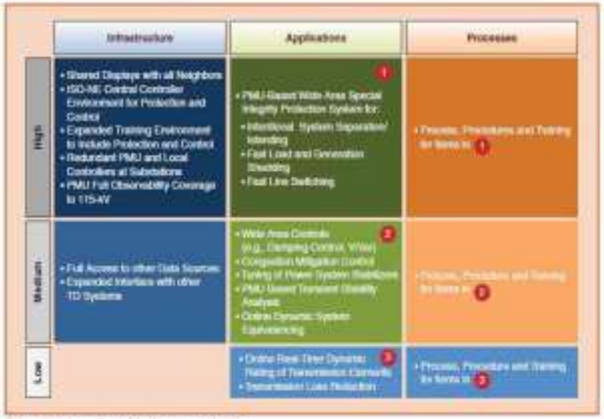
	Infrastructure	Applications	Processes
High	• Full Production-Grade System: QA/Staging and Training/Test Environments • Redundant ISO-TO Communication Network • Enhanced DQMS • CIP Compliant Measures • Displays Sharing with TOs	① • Fast and Accurate Post-Event Analysis • Generation and Load Dynamic Model Validation • PhasorPoint Operational Use • ROSE Operational Use • Online Oscillation (<10 Hz) Detection and Mitigation	• Processes, Procedures and Training for Items in ①
Medium	• Initial Data Exchange with Some Neighbors • Initial EMS Integration • TO Expand PMU Coverage to Lower Voltage Levels and Generation Stations • Initial ISO-NE Access TO DFR/DDR Data	• PMU Only SE (345 kV)–Feasibility Demonstration • Online Calibration and Status Monitoring of PMUs	
Low	• Initial Integration with other ISO-NE Systems (e.g., GIS, OMS)		

Figure 4. An overview of the near-term activities.



	Infrastructure	Applications	Processes
High	• Data Exchange with All Neighbors • Full EMS Integration (Bidirectional Data Flow) • Visualization Integration • Redundant TO Control Center • Advanced Training (Interactive, Including Neighbors) • Full Observability with PMUs for 230 kV • Access TO DFR/DDR Data, 230 kV and Above	① • Integrated Information Visualization Platform • Post-Event Analysis with DFR/DDR Data and Tools • NERC/NPCC Compliance Reporting • Tools for Model Validation • Online Complex Event Detection • Model-Free Voltage Instability • Transient Instability Detection • Automated Fault Location • Island Operation and Restoration • Phasor Data Only SE (345 kV) • Time-Tagged Real-Time Status Information	• Process, Procedure and Training for Items in ①
Medium	• TO-TO Data Exchange • TO PMU Coverage to 115 kV • Other Systems Integration • Initial Shared Displays with Neighbors • Sequence and Breaker Status Data Streaming	• Enhance Distr SE with PMU Data • Primary Frequency Response Monitoring • PMU Data Repository and Pilot Apps in Cloud Computing • Coherent Generation Groups Identification w/ PMU Data • Time Tagged Data Collection	• Process, Procedure and Training for System Primary Frequency Response Monitoring
Low	• Initial Other Data Access (e.g., Weather) • Initial Interface with other TO Systems (e.g., OMS)		

Figure 5. An overview of the mid-term activities.

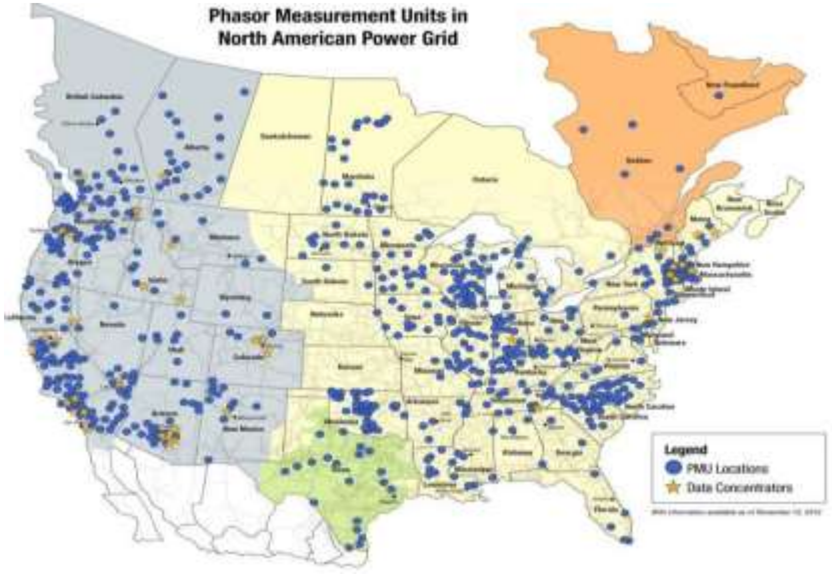


	Infrastructure	Applications	Processes
High	• Shared Displays with all Neighbors • ISO-NE Central Controller Environment for Protection and Control • Expanded Training Environment to Include Protection and Control • Redundant PMU and Local Controllers at Substations • PMU Full Observability Coverage to 115-kV	① • PMU-Based Wide Area Special Integrity Protection System for: • Intentional System Separation/Islanding • Fast Load and Generation Shedding • Fast Line Switching	• Process, Procedures and Training for Items in ①
Medium	• Full Access to other Data Sources • Expanded Interface with other TO Systems	② • Wide Area Controls (e.g., Damping Control, VVar) • Congestion Mitigation Control • Tuning of Power System Stabilizers • PMU Based Transient Stability Analysis • Online Dynamic System Equivalencing	• Process, Procedures and Training for Items in ②
Low		③ • Online Real-Time Dynamic Rating of Transmission Elements • Transmission Loss Reduction	• Process, Procedure and Training for Items in ③

Figure 6. An overview of the long-term activities.

Excerpt from ISO New England Synchrophasor Technology Roadmap (2014)

International Synchrophasor Deployment



Source: US DOE 2016 Advancement of Synchrophasor Technology Report

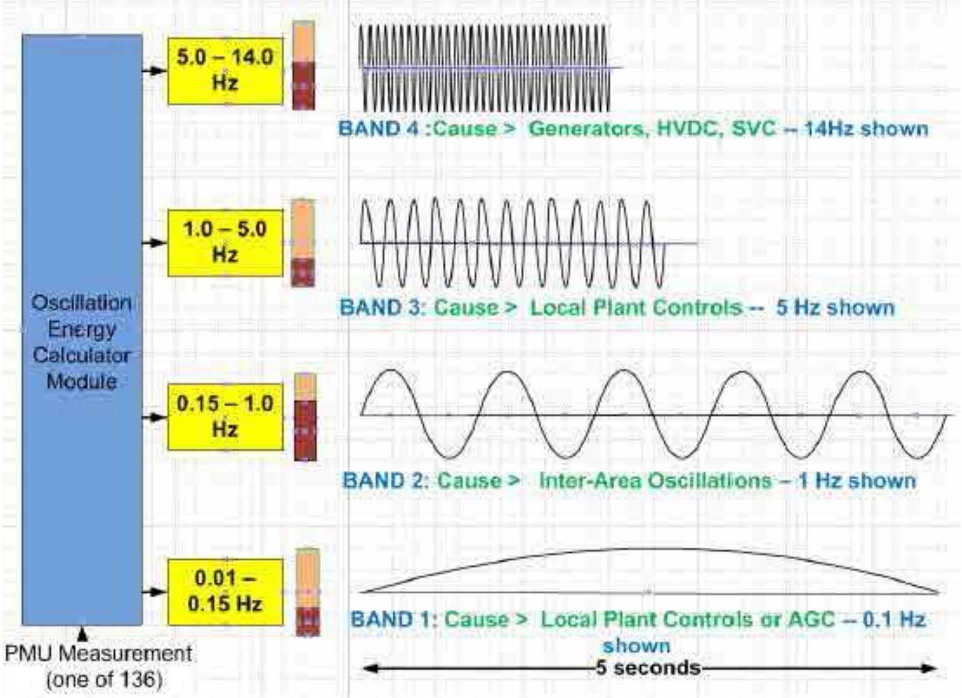
- In the US, over 1,000 substations with ~1,700 installed PMUs and the number continues to grow
- China has installed PMUs in over 1,700 750/500/330/230 kV substations by 2013 and the number is fast growing
- India installing 1,732 PMUs
- Latin America
  - Colombia – Deployed applications for improved grid observability and reliability
  - Ecuador – Deployed System Integrity Protection Scheme using PMUs
  - Brazil – ONS is procuring the PMU system
- Many European countries have installed PMUs

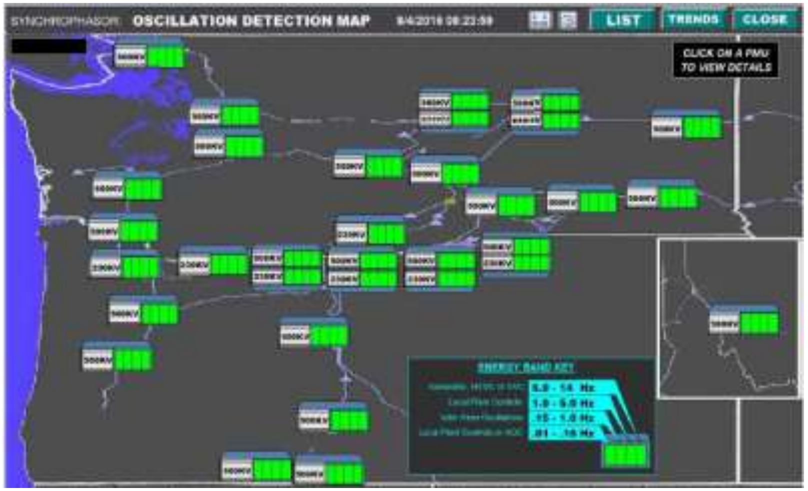
Variety of applications benefit from using the same infrastructure

Example: PMU in the control room NYISO

- Displays / dashboards organized by New York's electrical load zones, as well as by external neighboring electrical regions
- PMUs grouped by zones to reflect expected coherent generation response
- Visualization is part of NYISO control room video wall

Example: Oscillation Monitoring at BPA





[redacted]

BPA Oscillation Detection Monitor (ODM) (divided in 4 bands)

Implemented in Control Room in October 2013; Operating Procedures developed in 2016

- Monitoring 140 measurement points from 66 PMUs
- ODM Map display on video wall of Dispatch floor
- Full ODM application on all Dispatcher consoles
- Dispatcher training session performed
- Audible alarms SCADA; Operational Staff must respond to alarm
- Single PMU alarm: Sys Ops call field staff at alarmed measurement point; Multiple PMU alarm: Sys Ops take more proactive approach

Benchmark: Use Cases of Techn. Readiness

Ecuador – CENACE (ISO for Ecuadorean Power System)
- Implemented PMU-based SIPS
- Have ELPROS WAM – WAProtector with real-time functions: Voltage stab monitoring, LF oscill detection, Phase angle diff monit, Thermal monitoring, Over/Under value detection, Islanding detection. Oscill. Source detection

Colombia – XM
- Have WAMS info in the control center
- Executing Roadmap (prepared by Quanta T.)

INDIA – POSOCO, PowerGridIndia
- PMU based SPS
- Challenges with interoperability, data quality, comms, processing speed

CHINA
- Power oscillation detection, location detection
- Post event analysis
- Wide area protection
- Damping control system

BRASIL

EUROPE (Norway, Iceland,…)
- Norway, Moving from R&S to model validation, disturbance and fault analysis (by rid analysis team)

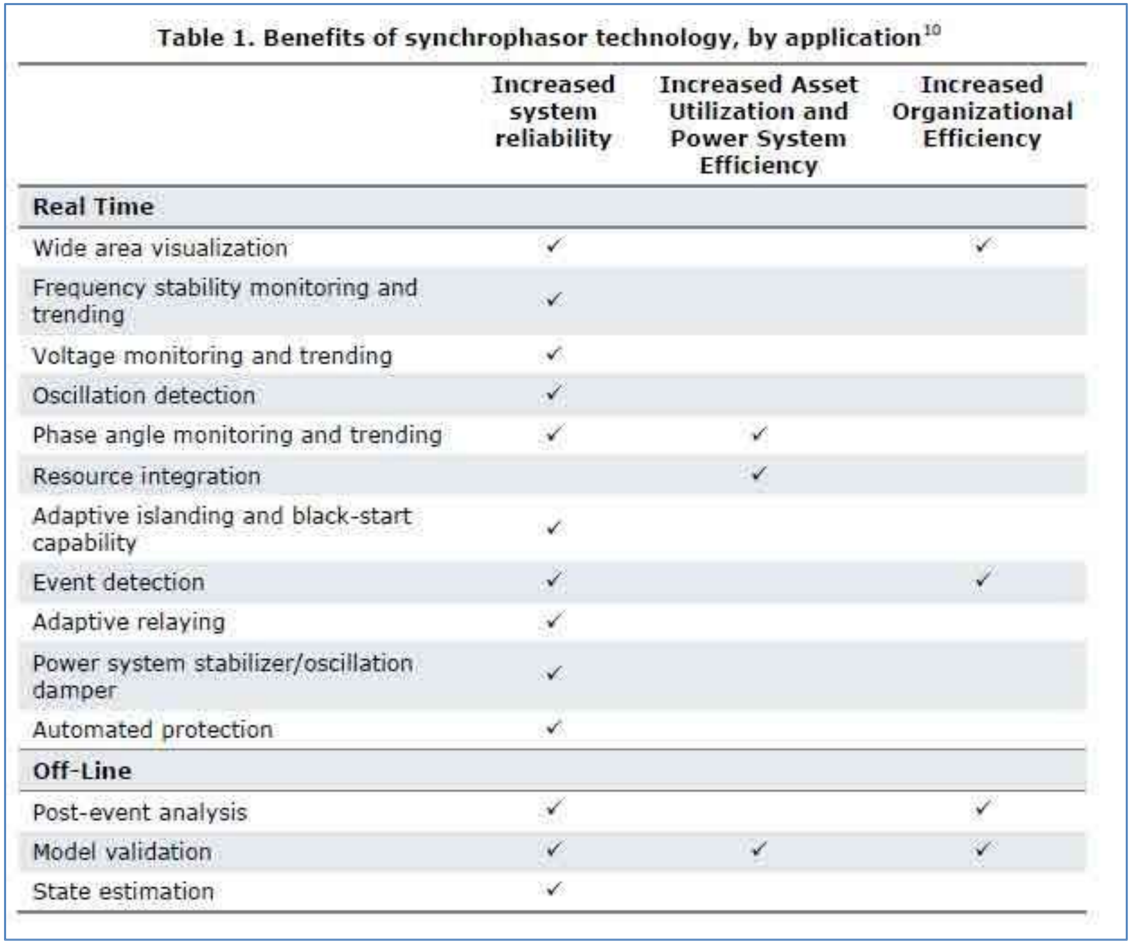
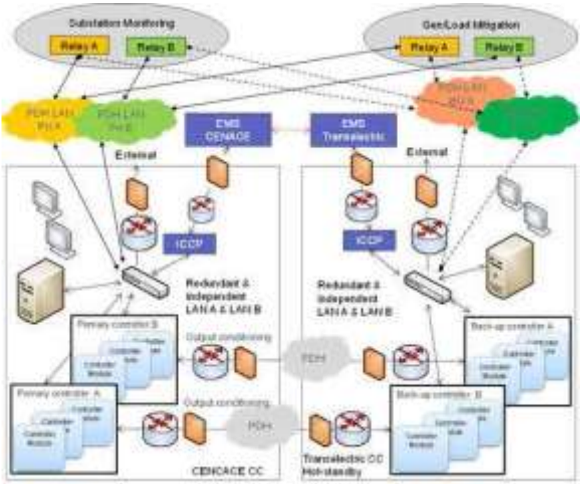


Table 1. Benefits of synchrophasor technology, by application[10]

	Increased system reliability	Increased Asset Utilization and Power System Efficiency	Increased Organizational Efficiency
Real Time			
Wide area visualization	✓		✓
Frequency stability monitoring and trending	✓		
Voltage monitoring and trending	✓		
Oscillation detection	✓		
Phase angle monitoring and trending	✓	✓	
Resource integration		✓	
Adaptive islanding and black-start capability	✓		
Event detection	✓		✓
Adaptive relaying	✓		
Power system stabilizer/oscillation damper	✓		
Automated protection	✓		
Off-Line			
Post-event analysis	✓		✓
Model validation	✓	✓	✓
State estimation	✓		

Source: P. Overholt, K. Uhlen, B. Marchionini, "Synchrophasor Applications for Wide Area Monitoring and Control, ISGAN Discussion Paper, 2016,

Ecuador: A Successful Deployment Experience



The need:

- Rapid generation expansion & demand growth lead to stressed grid operations - Double contingencies can cause a system collapse

The solution:

- PMU-based System Integrity Protection System - A fully redundant system involves 2 control centers, 12 monitoring and 11 mitigation substations, and a training system

The process (completed < 3 years):

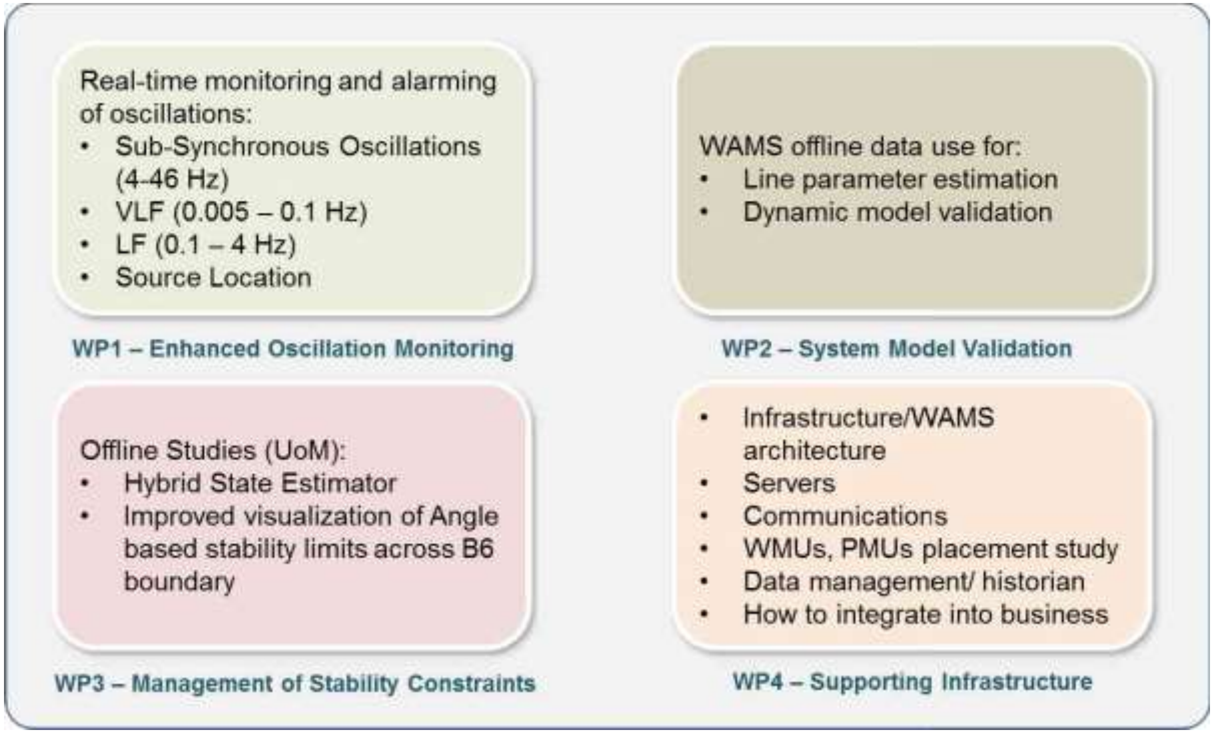
- System studies to identify problem areas and develop mitigation solutions
- Proceeded to system design and requirements specifications
- Deployed the SIPS through rigorous procurement, installation, testing and commissioning processes

The results:

- In operation since January 2015
- Correctly operated on May 6, 2015 – Realized USD $1.1M economic savings

Example: UK VISOR Project

- Pilot with GB SO and three TOs
- Trying to address challenges caused by fast changing power system infrastructure



Real-time monitoring and alarming of oscillations:
- Sub-Synchronous Oscillations (4-46 Hz)
- VLF (0.005 – 0.1 Hz)
- LF (0.1 – 4 Hz)
- Source Location

WP1 – Enhanced Oscillation Monitoring

WAMS offline data use for:
- Line parameter estimation
- Dynamic model validation

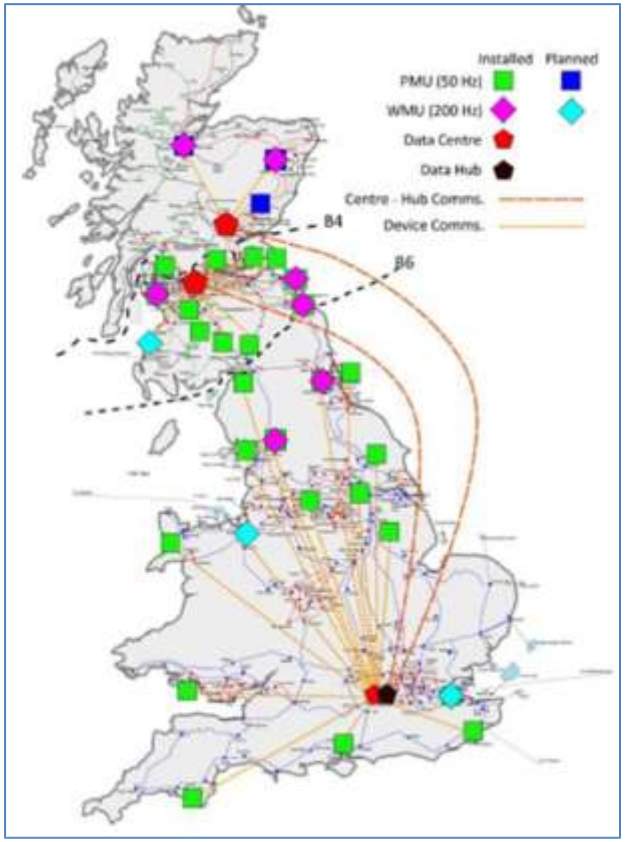
WP2 – System Model Validation

Offline Studies (UoM):
- Hybrid State Estimator
- Improved visualization of Angle based stability limits across B6 boundary

WP3 – Management of Stability Constraints

- Infrastructure/WAMS architecture
- Servers
- Communications
- WMUs, PMUs placement study
- Data management/ historian
- How to integrate into business

WP4 – Supporting Infrastructure



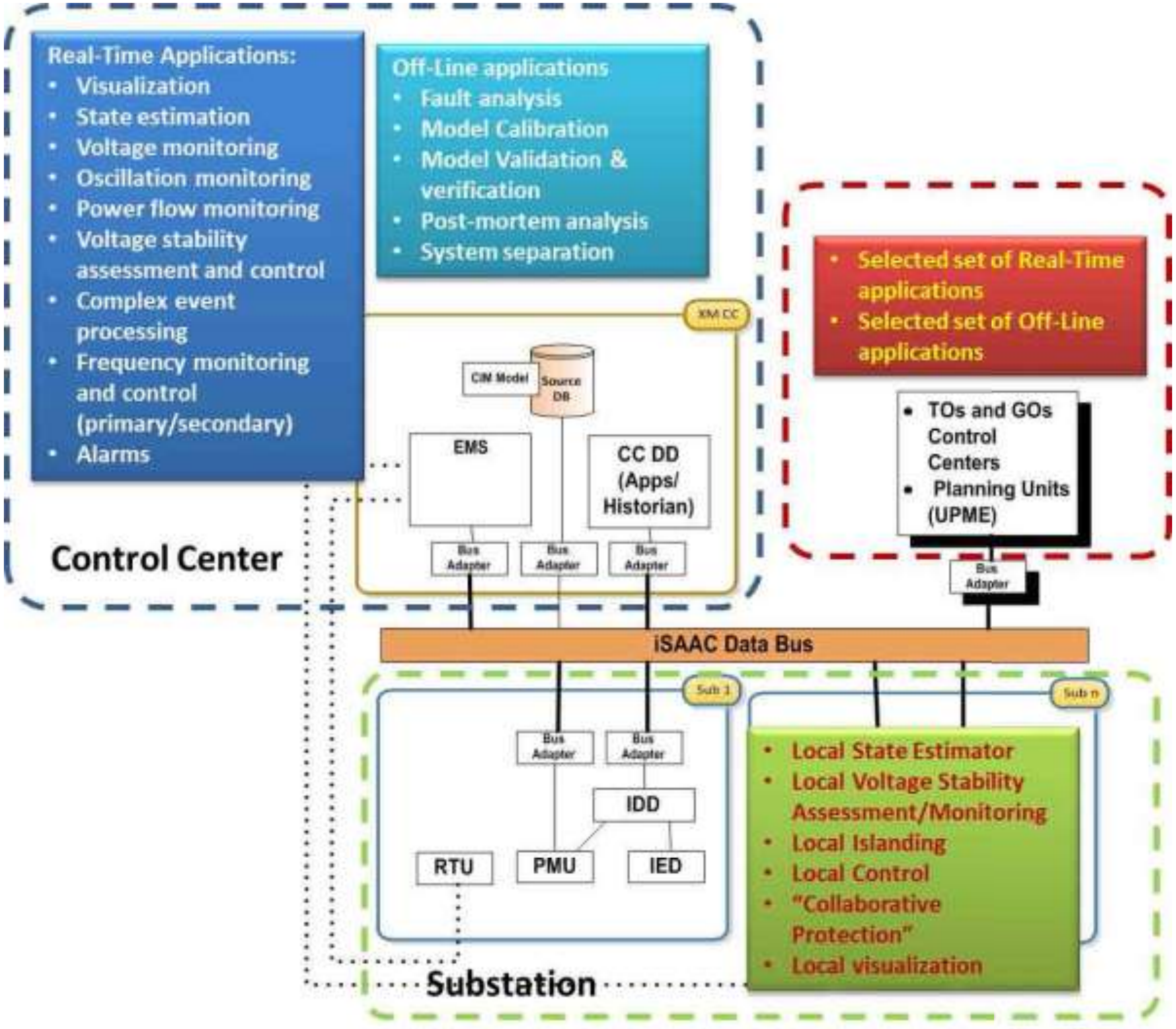
WAMS of Continental Europe

- Swissgrid is hosting a WAMS application where the power system frequencies and angle differences of grid operators from Austria (APG), Denmark (Energinet.dk), Portugal (REN), Slovenia (ELES), Croatia (HEP), Italy (TERNA) and Greece (IPTO) are monitored

Frequency	
Frequency set point	50.000 [Hz]
Current Frequency	49.996 [Hz]
Current Frequency Deviation	-0.004 [Hz]
Current grid time deviation	-14.098 [s]
Current Date/Time	**07.12.2016 17:20:07**
Sample Date/Time	**07.12.2016 17:19:46**

Source: https://www.swissgrid.ch/swissgrid/en/home/reliability/wam.html

XM Colombia: Applications Location Assignment



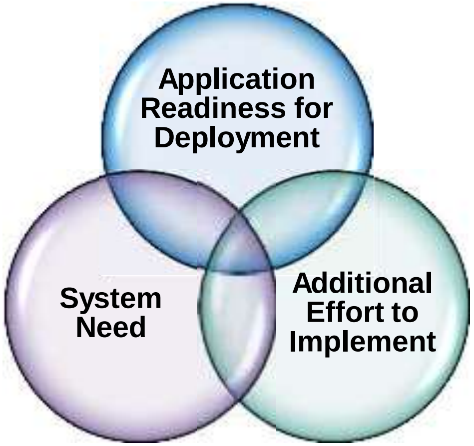
Real-Time Applications:
- Visualization
- State estimation
- Voltage monitoring
- Oscillation monitoring
- Power flow monitoring
- Voltage stability assessment and control
- Complex event processing
- Frequency monitoring and control (primary/secondary)
- Alarms

Off-Line applications
- Fault analysis
- Model Calibration
- Model Validation & verification
- Post-mortem analysis
- System separation

- Selected set of Real-Time applications
- Selected set of Off-Line applications

- TOs and GOs Control Centers
- Planning Units (UPME)

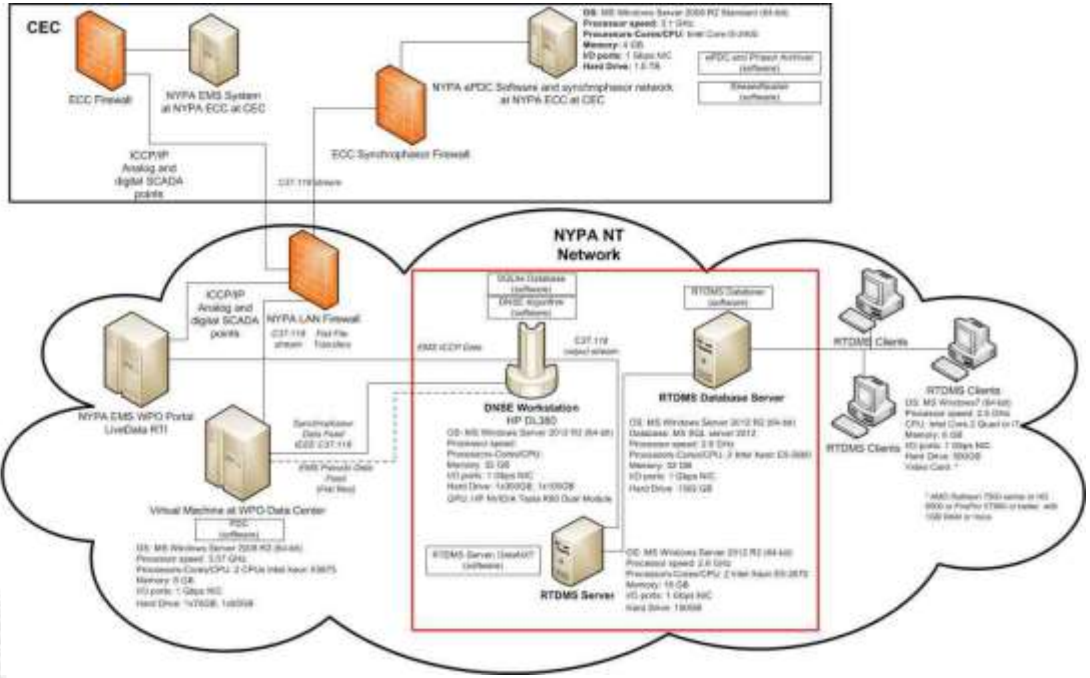
- Local State Estimator
- Local Voltage Stability Assessment/Monitoring
- Local Islanding
- Local Control
- "Collaborative Protection"
- Local visualization

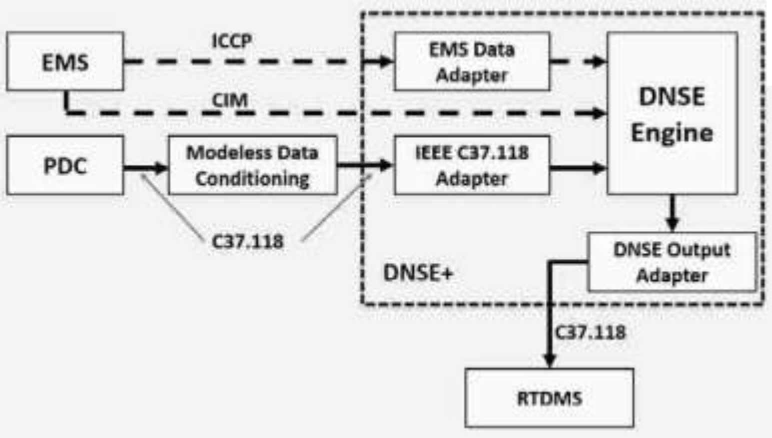


Three Criteria to identify and prioritize synchrophasor applications

Example: State Estimator - Quanta

- Integrated with EPG RTDMS system and NYPA EMS (Siemens)
- Using the IEEE C36.118 standard for PMU data and CIM/ICCP for SCADA EMS data
- Enhanced C37.118 to be able to accept large number of phasor measurements
- Runs up to 10 times/second
- Unknown if any other HSEs have been implemented in production environment
- 185 PMU measurements, 4419 SCADA measurements





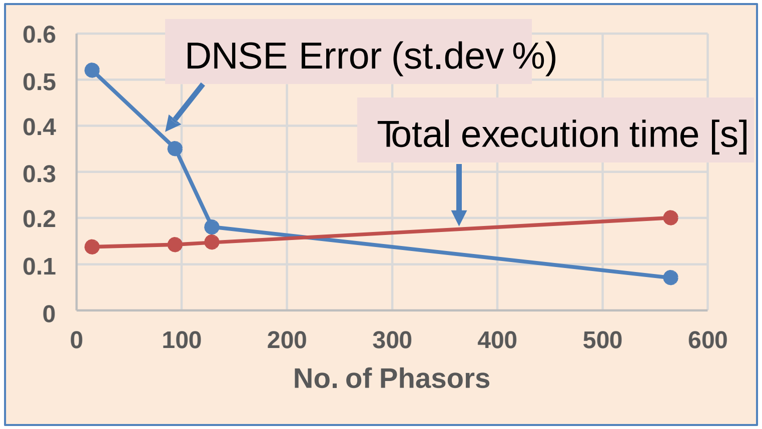
Why DNSE?

- combines both SCADA and PMU data to obtain the complete state of system; can provide synchrophasor output not available through PMUs
- mechanism to provide functionality to identify “bad” PMU data
- non-iterative;
- fast (executed at nearly phasor data rate); Challenge: huge systems of equations to be solved

DNSE Application – Test Results

Test: Add more PMUs in NY area and evaluate performance

	Base	>= 345 kV	>= 230 kV	>= 115 kV
Voltage phasors	15	94	129	565
Current phasors	47	397	520	2015
Observable buses	148	276	309	752
Error Mean at 1% noise	0.0048	0.0025	0.0012	0.0006
Error st.dev. at 1% noise	0.0052	0.0035	0.0018	0.0007
Preproc. time: observ. analysis	0.1100	0.1000	0.1000	0.0800
DNSE time (incremental)	0.0250	0.0400	0.0420	0.0700
Post.proc. time	0.0020	0.0020	0.0050	0.0500

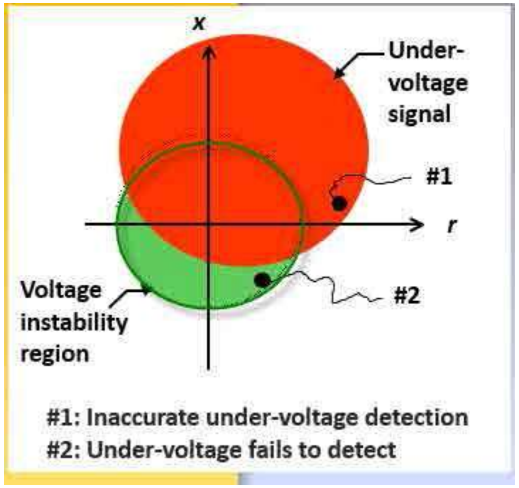


- Additional PMUs increase observability, and improve error rejection.
- DNSE observability analysis time decreases with more PMUs; DNSE solution time and post-processing time increases.

Example: Voltage Instability Indicator RVII

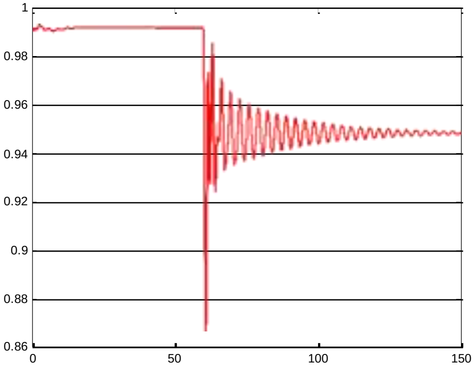
Fundamentally, local voltage instability detector

- Just like a relay, real time computation that uses only <u>local</u> information (no network model needed)
- Unlike a relay , able to <u>avoid</u> point #1 (see figure a & b), and <u>includes</u> point #2

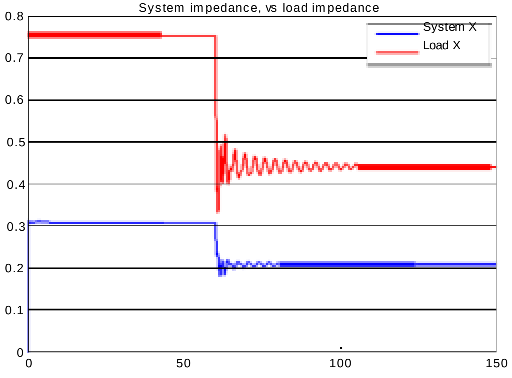


#1: Inaccurate under-voltage detection
#2: Under-voltage fails to detect

(a)



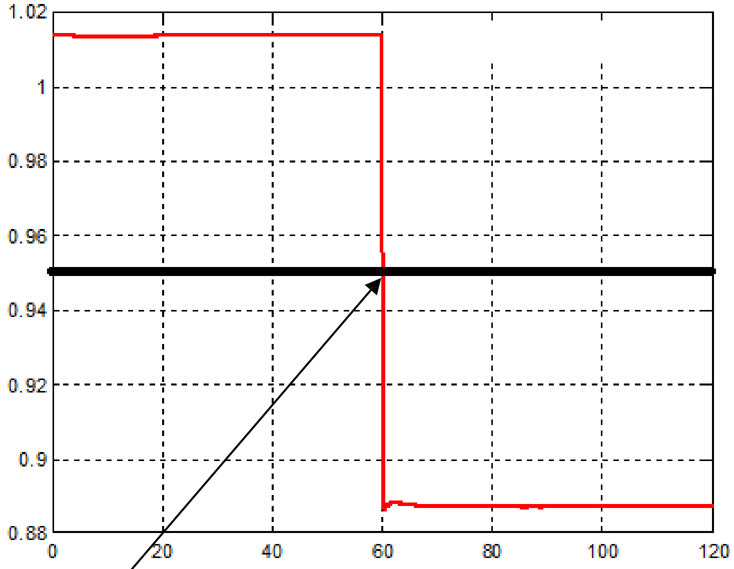
(b)



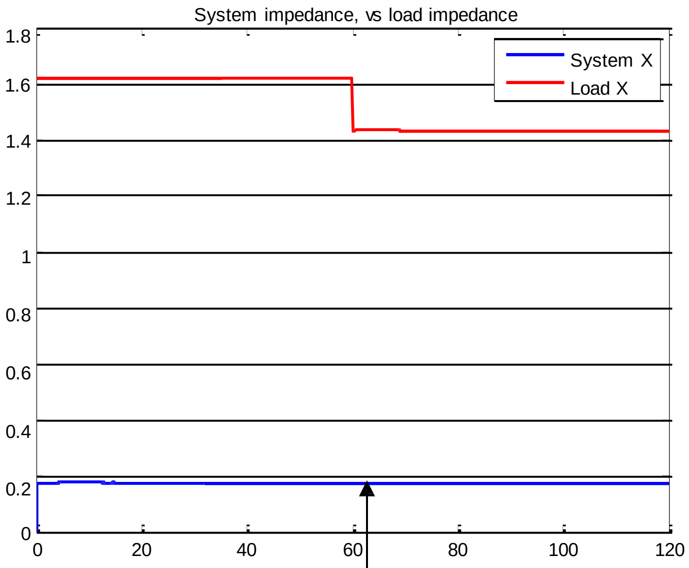
Under-voltage Relay Example

Double Contingency to Load Pocket

- Drastic action may be taken on voltages of 0.95 p.u to prevent instability.
- RVII would show, however, that system is far from collapse (verified by PSS/E time domain simulations).



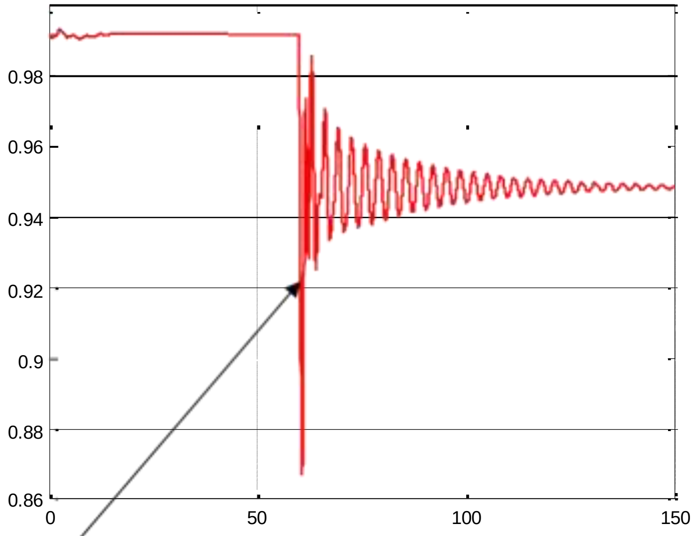
UVLS Triggers



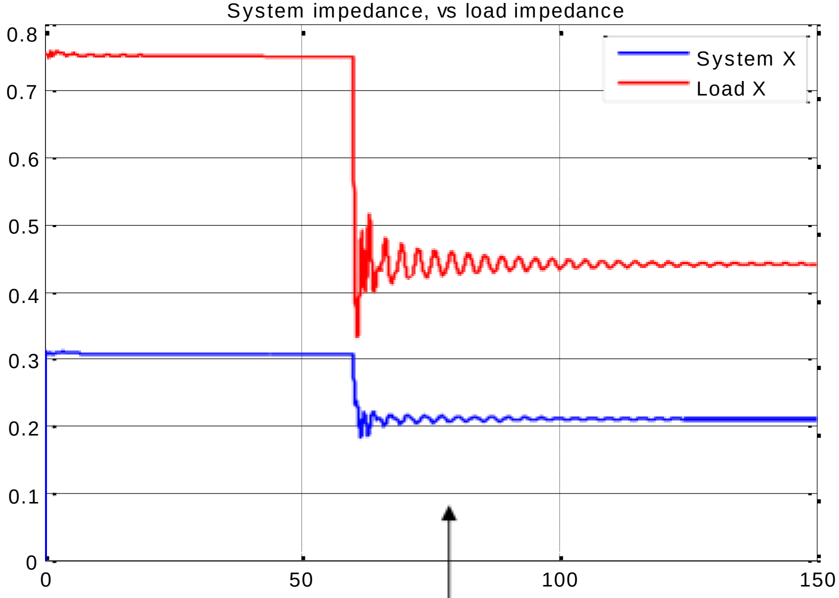
Very insignificant change in Thevenin Impedance

Stability Detection at Brink of UVLS Trigger

- RVII successfully identifies separation between system and load impedances, indicating a stable system condition.
- Absent RVII, drastic under-voltage action might be taken at voltages of 0.95 pu to prevent instability.



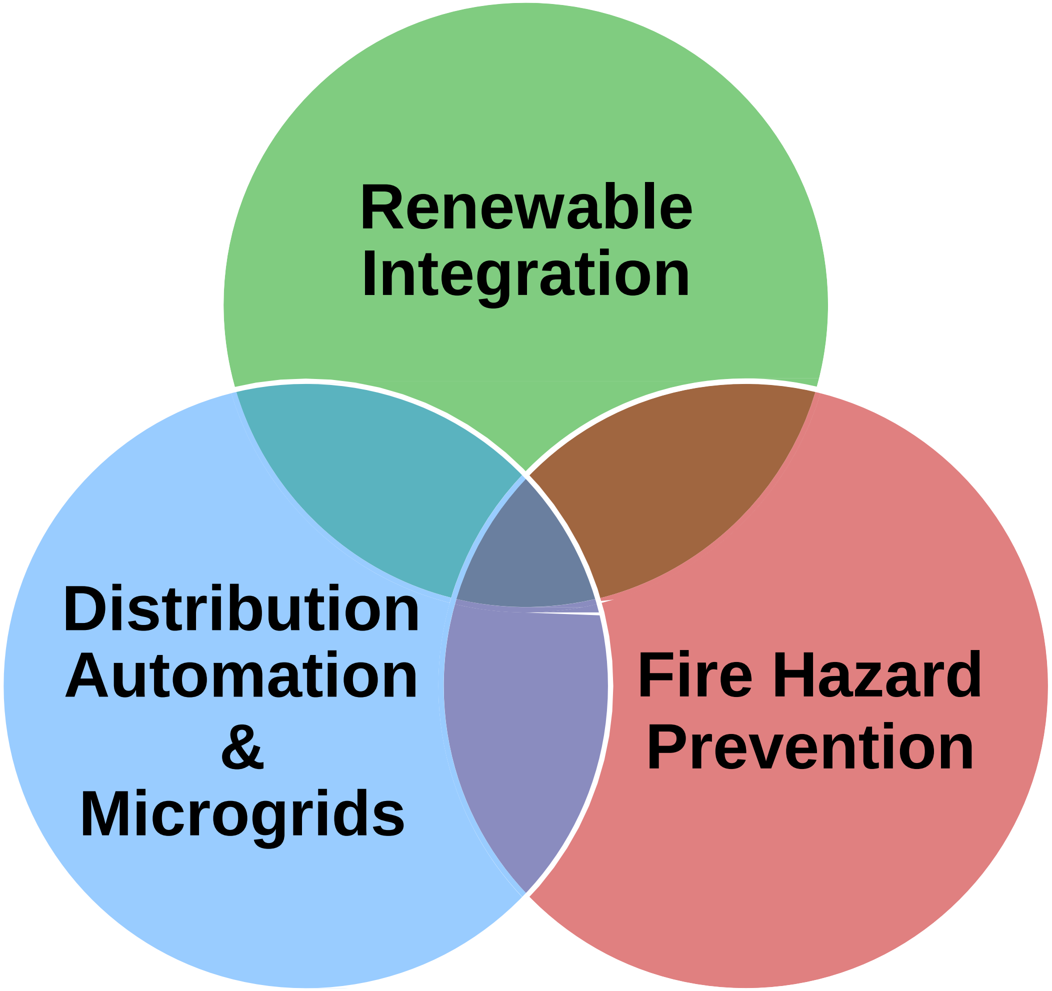
UVLS Triggers



Insignificant change in Thevenin Impedance

Applications in Distribution Systems

- Monitoring distributed Generation
- Distributed and closed-loop control
- Active/adaptive protection
- Common data format for reporting
- Synchronized measurement over entire system

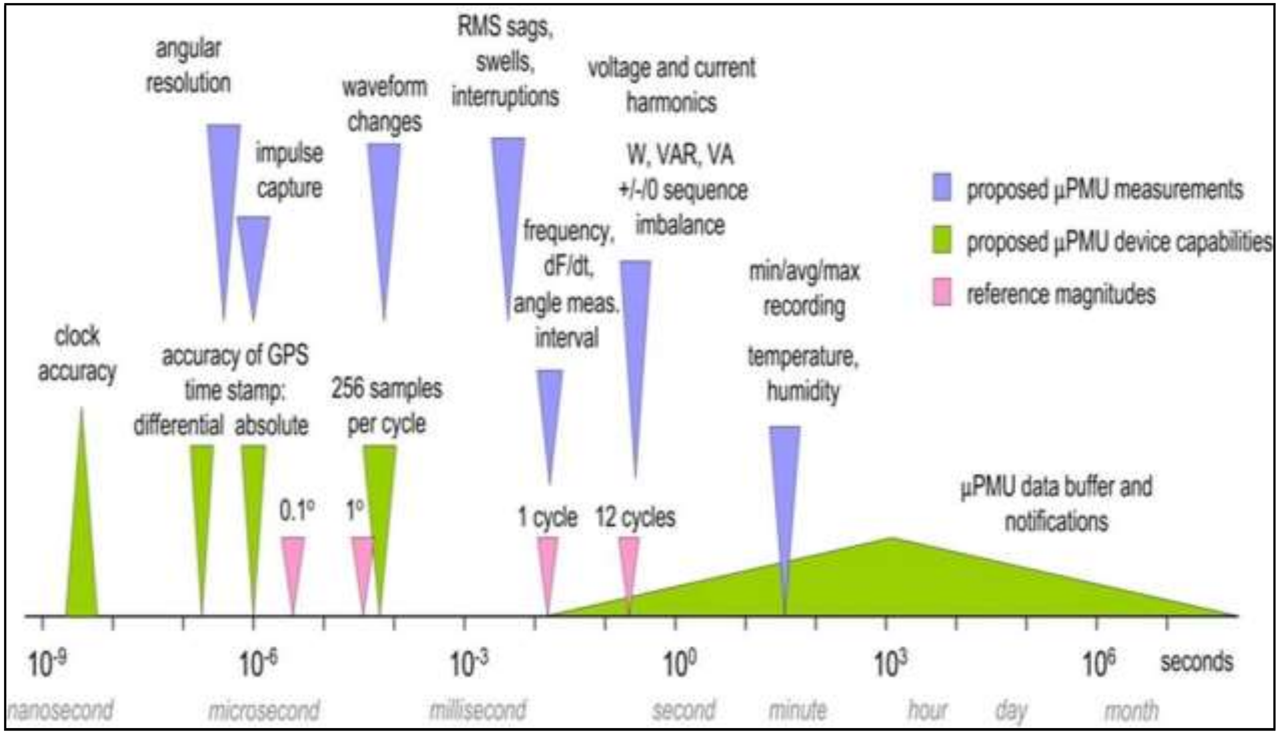


Renewable Integration

Distribution Automation & Microgrids

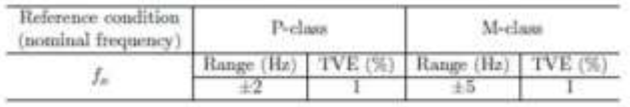
Fire Hazard Prevention

Smart Distribution Challenges



Source: E.M. Stewart, S. Kiliccote, C. M. Shand, A. W. McMorran, R. Arghndeh, A. von Meier, “Addressing the challenges for Integrating Micro-Synchrophasor Data with Operational System Applications”, Lawrence Berkeley National Laboratory Report, LBNL 6780E, July 2014

Requirements for Distribution PMUs

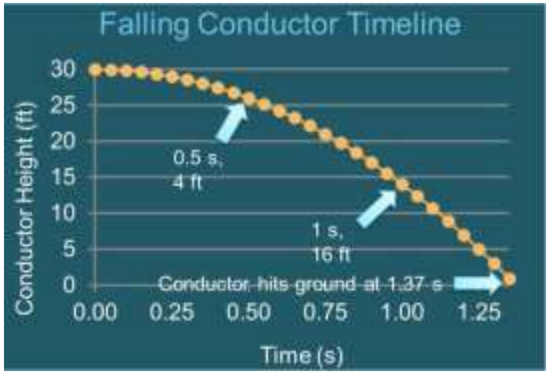
No	Category	Requirement	Comment
1	TVE 1%	Less than 0.1%	The shorter the feeder length, the higher the errors on the power flow regarding 1% TVE (this is especially disadvantageous for calculation of active and reactive power)
2	Freq. Dev.		This requirement is more stringent than USA allowed frequency thresholds of ±4Hz
3	Harmonic content	Very low TVE metric, adaptive in frequency, accurate estimation of harmonic components	This 'harmonic PMU' requirement does not exist in transmission grids
4	Measurement points	PMUs must be located in key points to improve system observability	This is performance vs. cost criterion
5	Cost-benefit ratio	To improve this criterion, it is important to develop a low-cost PMUs & PMU/IEDs that are interoperable and easy to install and maintain	µPMUs and FNET DFRs are good example of such devices

Reference condition (nominal frequency)	P-class		M-class	
	Range (Hz)	TVE (%)	Range (Hz)	TVE (%)
f_n	±2	1	±5	1

Source: M. Lelic, "Synchrophasor Applications for Transmission and Distribution Systems", Client Technical Report, Sep 2016

Application: Falling Conductor Protection: SDG&E

- Detect broken conductor and trip circuit before line hits the ground – Is it possible??



$$d = \frac{1}{2}gt^2 \rightarrow t = \sqrt{\frac{2d}{g}}$$

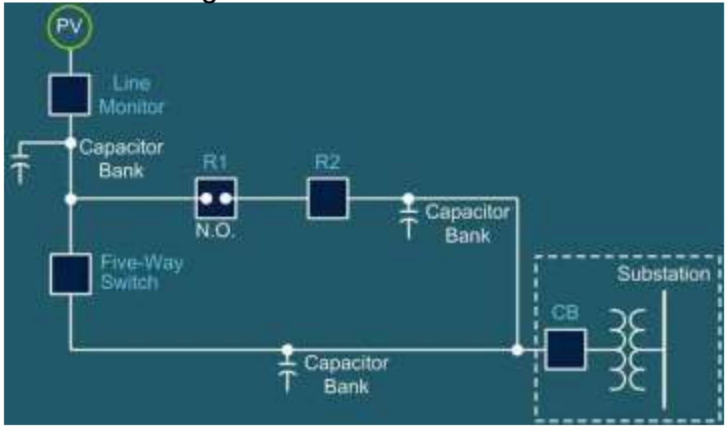
$$t = \sqrt{\frac{2(30)}{32.2}}$$

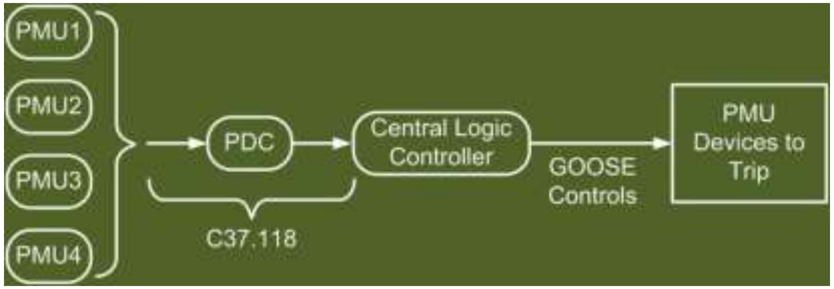
$$\text{time} \approx 1.37\,\text{s}$$

Detection Method

- dV/dt (change detection)
- V0 and V2 magnitude
- V0 and V2 angle

Falling Conductor PMU Locations





Source: W. O’Brien, E. A . Udren, “System for Detecting a Falling Electric Power Conductor and Related Methods”, US Patent 9,413,156, 2016

Thank You!

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