Meeting PMU Data Quality Requirements for Mission Critical Applications

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PSERC

PSERC Webinar
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Outline

- Synchrophasor based Mission Critical Applications
- PMU Data Quality Requirements
- PMU Performance Analyzer and Remote Testing
- Data Mining Approaches for Data Cleansing
- Impact of PMU Errors on Applications
- Summary

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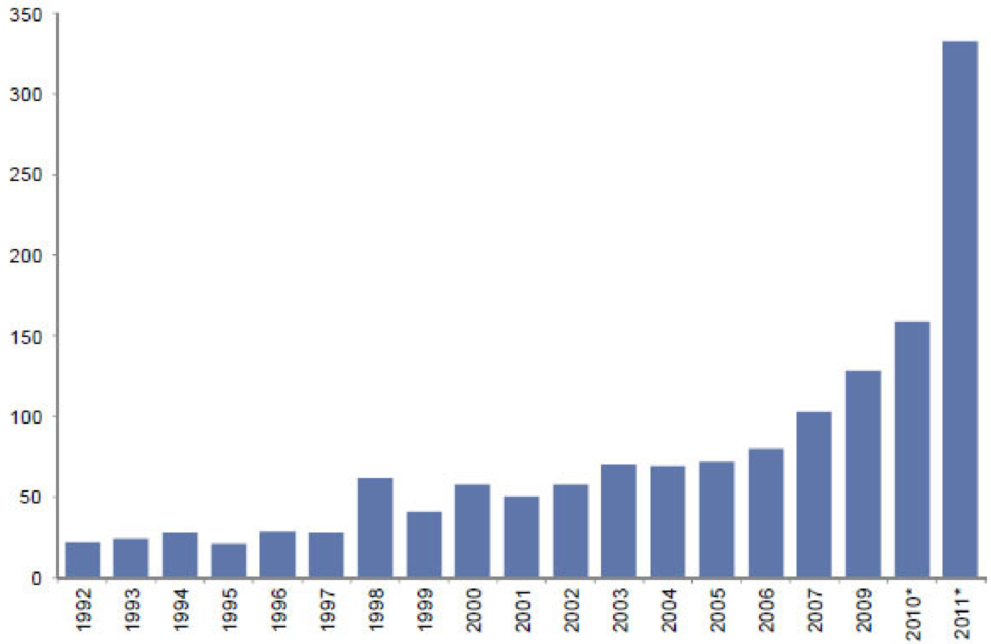
Motivation for Synchrophasors

- 2003 NE Power Blackout: Impacted 50 Million people, $6 Billion
- 2012 India Blackout: 670 People affected

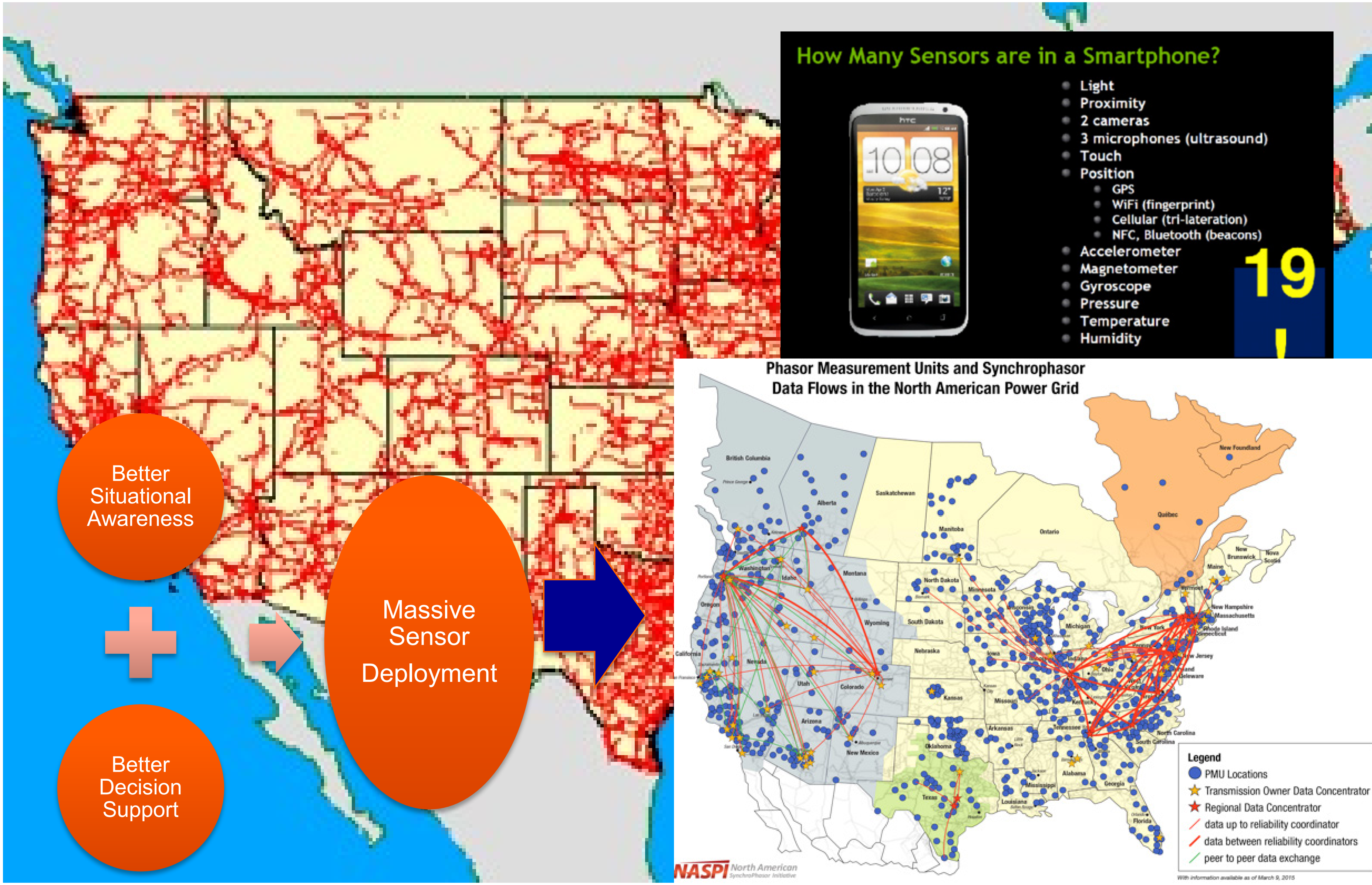
- Power outage cost $80 Billion every year
- Complexity of power grid is increasing
- Intermittency of renewable energy (wind, solar) and Increasing extreme weather events
- 2003 NE Blackout Investigation → Better situational Awareness and Decision Support

Power outages have risen sharply over the last decade
Major power disturbances in North America



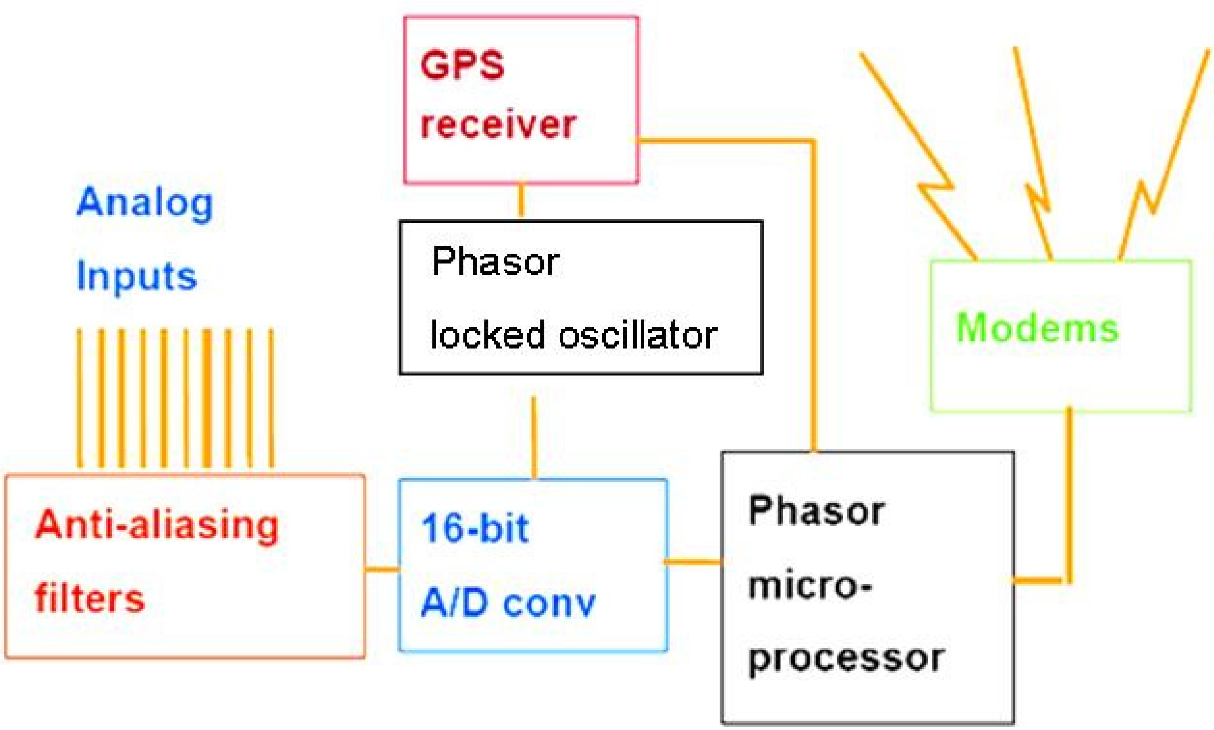
*Note: * NERC equivalent data estimated based on the trends seen in the Eaton Blackout tracker for number of outages affecting over 50,000 people.*
Source: NERC, Eaton Blackout Tracker, Goldman Sachs Research estimates.

Synchrophasor Unit Deployment



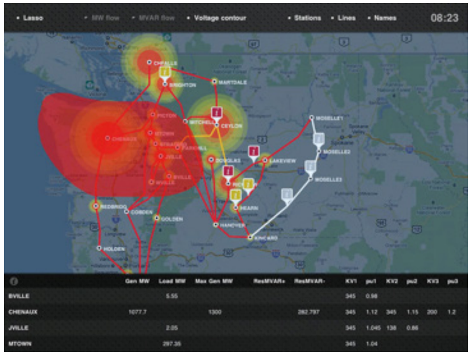
Phasor Measurement Units

- A Phasor Measurement Unit (PMU) is a device that provides as a minimum, synchrophasor and frequency measurements for one or more ‘three phase AC voltage and/or current’ waveforms.
- The device must provide a real-time data output which conforms to C37.118.1 requirements.



PMU Applications

- Angle/ Frequency Monitoring
- Post-Martem Analysis
- Voltage stability Monitoring
- Congestion Monitoring
- State Estimation
- Model Validation
- Managing Renewable Generation

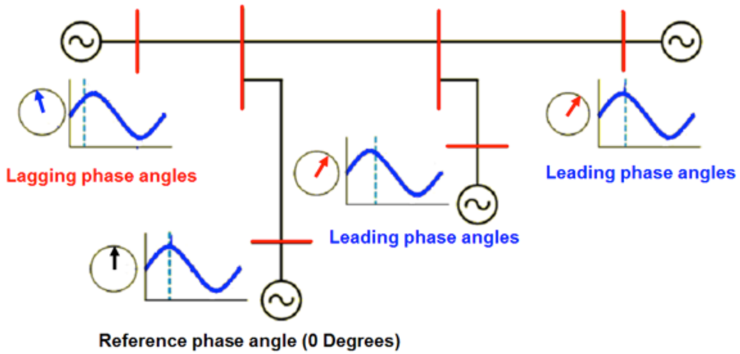


- Power System Restoration
- Controlled Islanding
- Adaptive Protection/ RAS
- Real Time Critical

Other PMU Applications

- Disturbance and equipment mis-operation (OG&E)
- Fault location using VAR flows (OG&E)
- Failing equipment mis-operation (Duke and OG&E)
- Calibrate Instrument transformers
- PMU data to verify load response to DR calls (ERCOT)
- Model validation for generator, line, SVC, STATCOM, wind plant, HVDC unit, load model, system model (BPA, WECC, CAISO, ERCOT, NYPA)
- Renewable integration

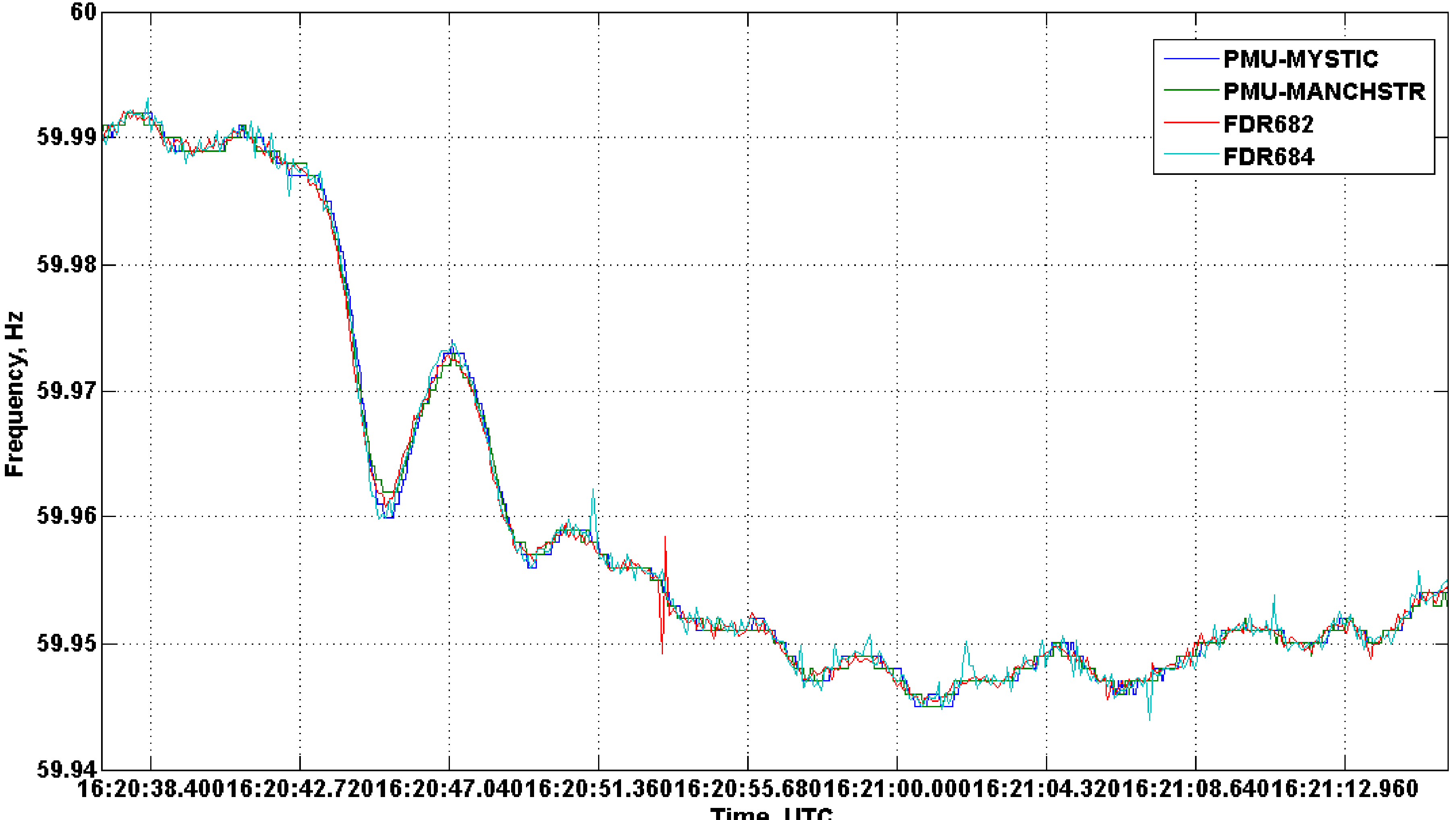
- Phasor data based GIC detection
- Automated control



Credit: NASPI

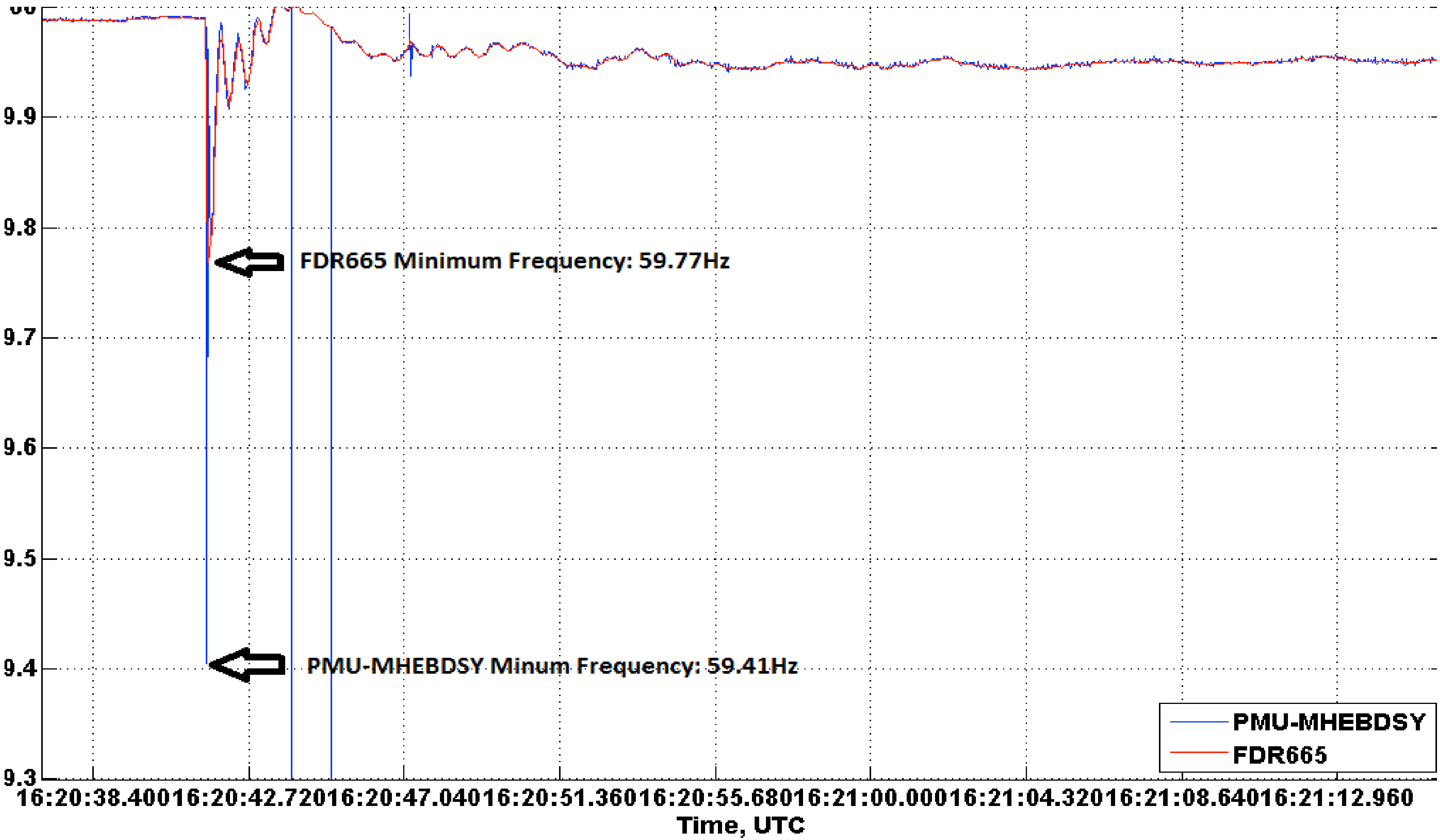
Outline

Frequency - New England PMU & DFR



Credit: Dave Bertagnolli

Frequency - Manitoba PMU and DFR



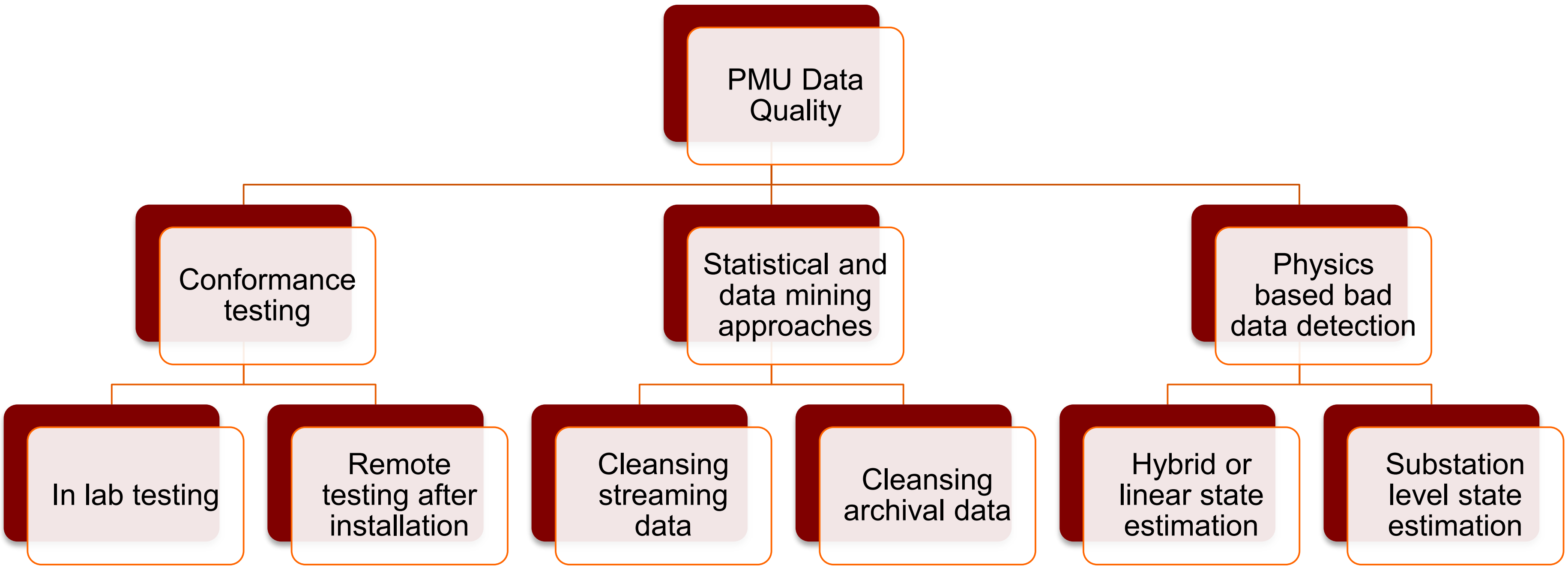
Credit: Tony Weekes

Accuracy Requirements

Data quality Issues may develop from:

- Dropouts/packet loss
- Latency
- Repeated values
- Measurement bias
- Bad/missing timestamps
- Loss of GPS synchronization
- Incorrect signal meta data
- Planned/Unplanned outage
- Poor server performance
- Improper device configurations

PMU Data Quality



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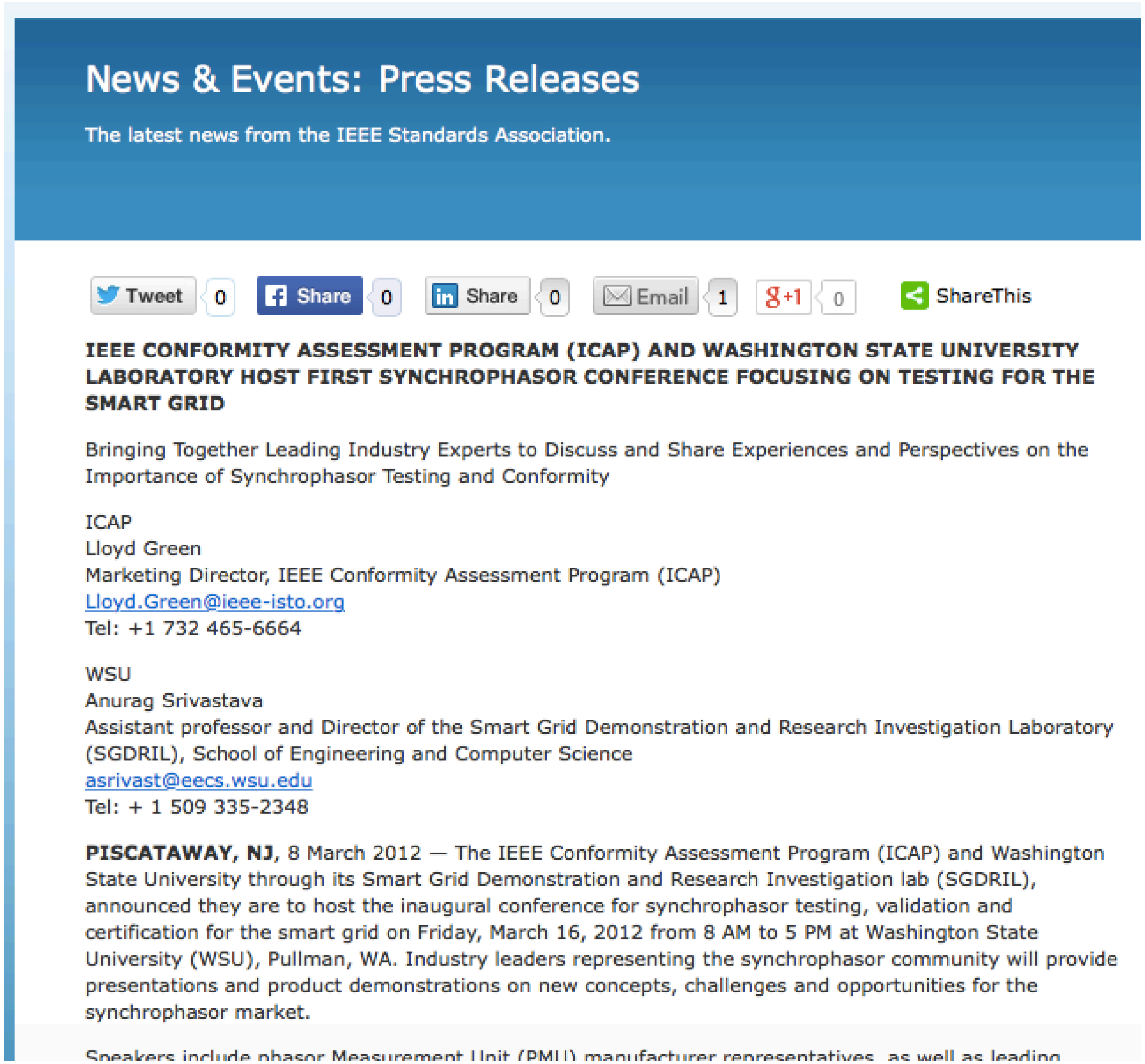
Conformance Testing

IEEE ICAP TSS

- ☑ Workshop at WSU and NASPI efforts led to IEEE ICAP TSS
- ☑ None of the PMU passed initially based on NIST testing
- ☑ Some of the PMU were able to pass after modification in firmware/hardware
- ☑ IEEE Test suite specification provides ways to test PMU and requirements



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IEEE CONFORMITY ASSESSMENT PROGRAM (ICAP) AND WASHINGTON STATE UNIVERSITY LABORATORY HOST FIRST SYNCHROPHASOR CONFERENCE FOCUSING ON TESTING FOR THE SMART GRID

Bringing Together Leading Industry Experts to Discuss and Share Experiences and Perspectives on the Importance of Synchrophasor Testing and Conformity

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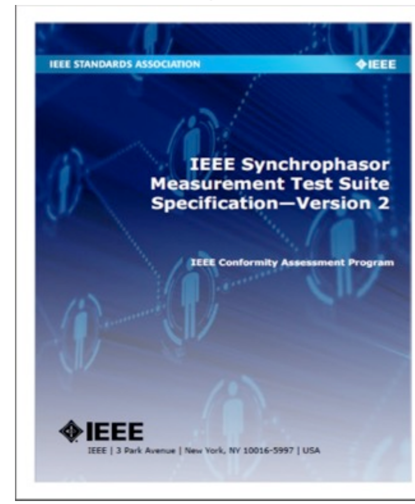
PISCATAWAY, NJ, 8 March 2012 — The IEEE Conformity Assessment Program (ICAP) and Washington State University through its Smart Grid Demonstration and Research Investigation lab (SGDRIL), announced they are to host the inaugural conference for synchrophasor testing, validation and certification for the smart grid on Friday, March 16, 2012 from 8 AM to 5 PM at Washington State University (WSU), Pullman, WA. Industry leaders representing the synchrophasor community will provide presentations and product demonstrations on new concepts, challenges and opportunities for the synchrophasor market.

Speakers include phasor Measurement Unit (PMU) manufacturer representatives, as well as leading

IEEE Test Suite Specification (TSS)

- The certification program is developed to ensure PMUs are tested for compliance to the standards:
  - Developed by IEEE Synchrophasor Conformity Assessment Steering Committee (SCASC)
  - Unambiguous, systematic way of testing PMUs according to IEEE C37.118.1a-2014
  - Version 2 published on September 2015
    - Modified due to findings during pilot tests
  - Available on IEEE Xplore and Techstreet
    - Search for “Synchrophasor TSS”

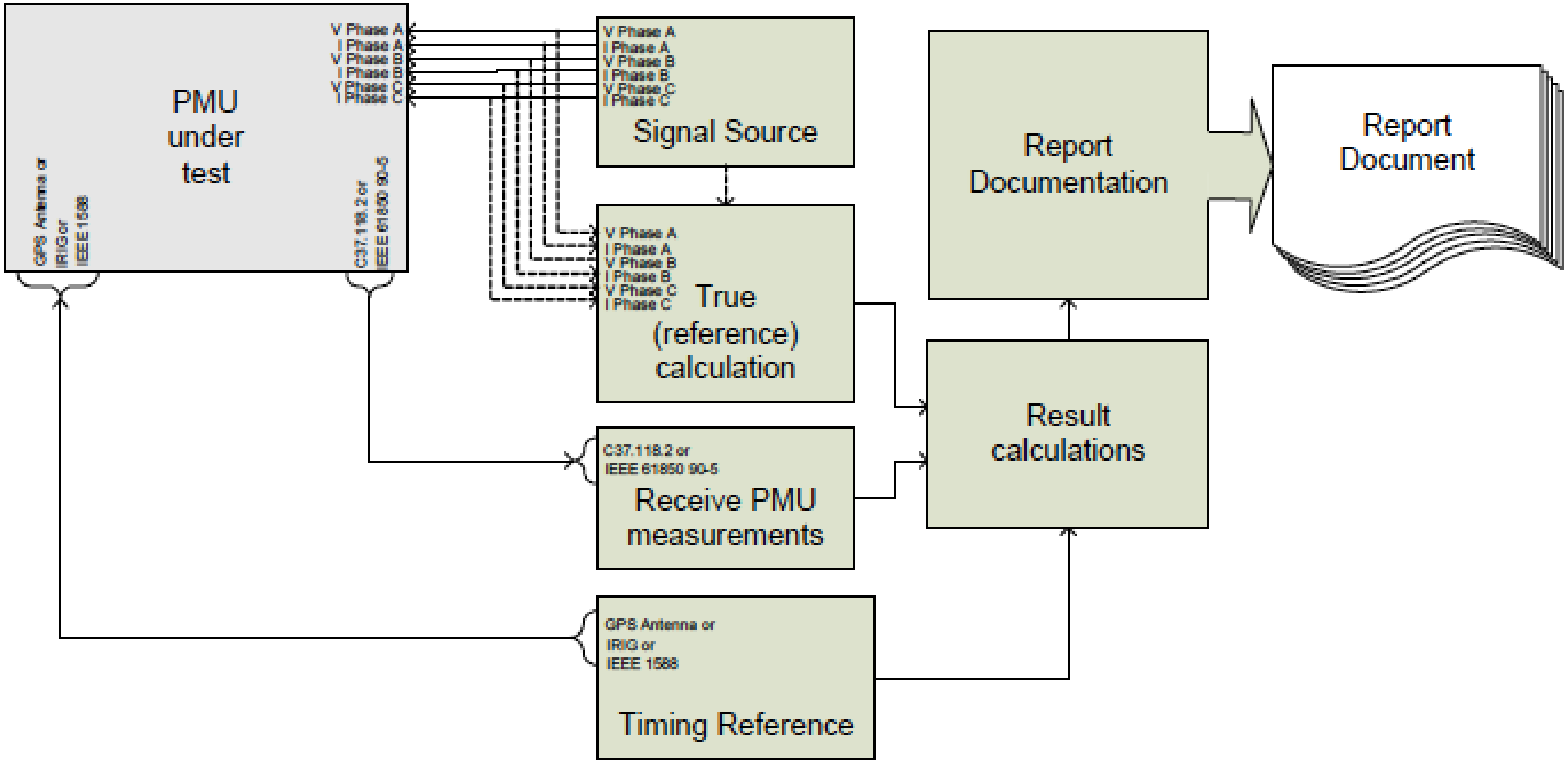


- PMUs are to be **certified**
  - Utilities and end-users to require certified devices – high level of assurance the PMUs will work in a larger system

IEEE Certified™ C37.118.1a-2014 Synchrophasors

Credit: Ravi Subramaniam, IEEE ICAP

PMU Testing Procedure



PMU Testing and Analysis Using PPA

(1) Needs complex test bed setup

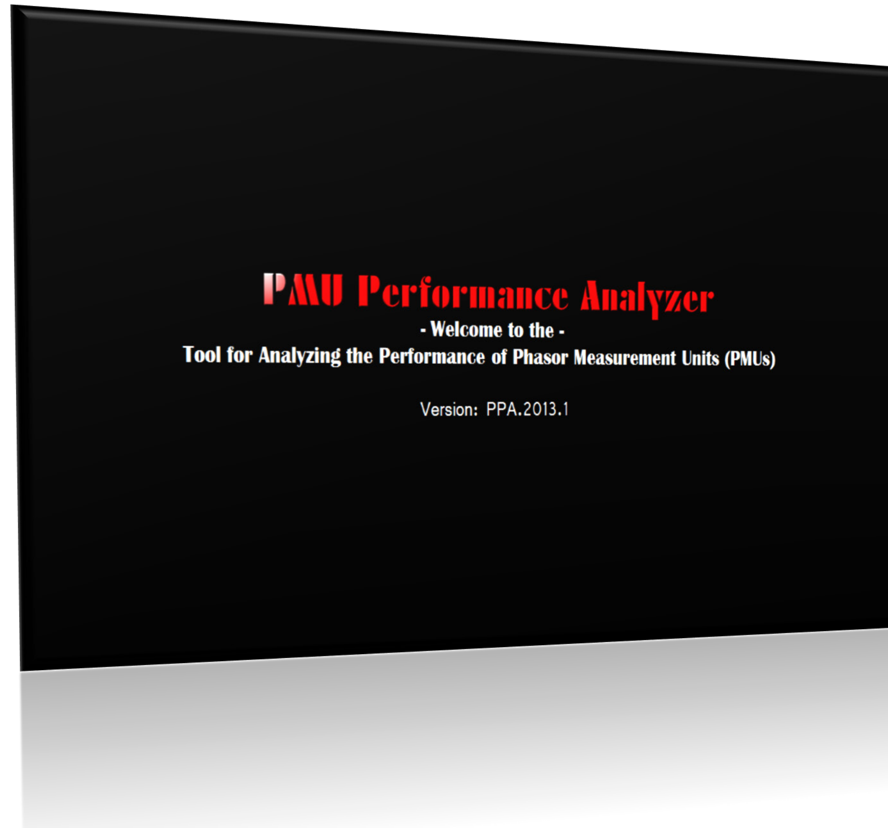
(2) Requires specially trained person

(3) Very labor intensive

(4) Highly time taking

(5) Very costly

There is need of an automated / semi-automated method for testing and analyzing PMUs



PMU Performance Analyzer: A software application for analyzing the performance of PMUs under different system conditions

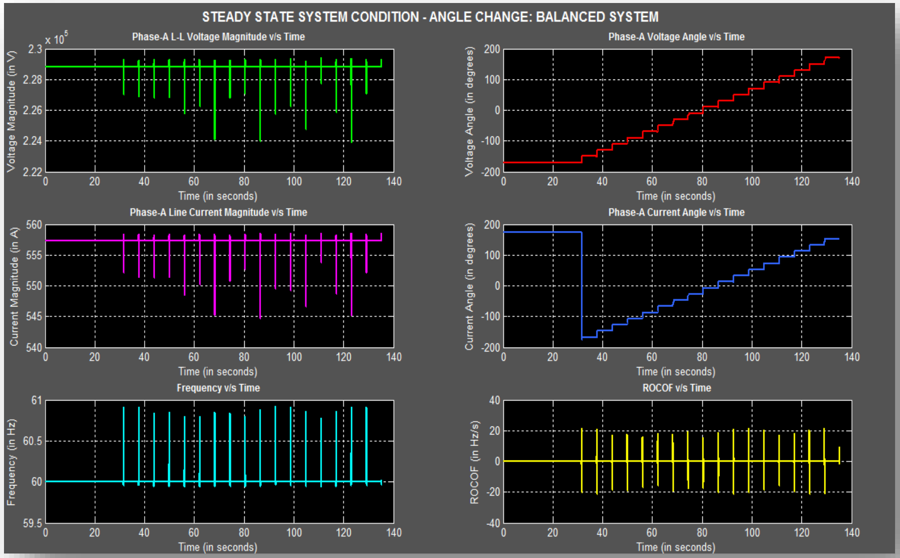
PMU Performance Analyzer

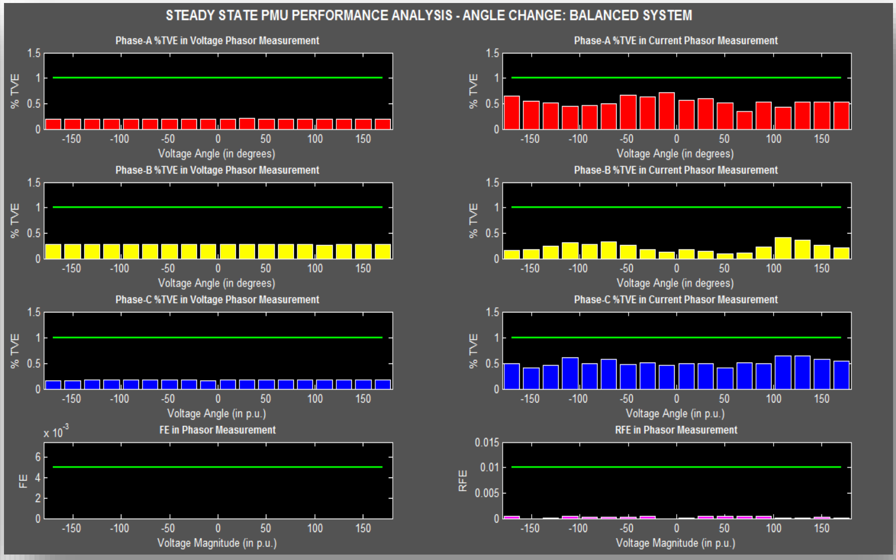
(1) It is an automated analysis tool to test the performance of the PMU under different test conditions specified in IEEE TSS

(2) It works with a Phasor Data Concentrator (PDC) and the Real Time Digital Simulator (RTDS)

Note – Substitute for the RTDS:

(i) High quality analog signal generator with GPS input





PMU Performance Analyzer

(1) Time aligns the synchrophasor data of the test PMU with the ideal PMU

(2) Calibrate the test PMU to offset steady state magnitude error and phase angle error

(3) Analyzes performance of test PMUs under different steady state and dynamic conditions as mentioned in the IEEE Standard for Synchrophasors C37.118.1-2011

(4) Analyzes performance of test PMUs under other realistic conditions outside the IEEE Standard

(5) Allows the user to choose required tests from the suite of test configurations

(6) Provides visualization of test conditions and corresponding results in the form of figures while carrying out the analysis

(7) Automatically generates a detailed PDF test report for the PMU instantly after the completion of test analysis

PMU Performance Analyzer

Parameters	PMU Performance Analyzer (Version – PPA.2015.1)
No. of Tests	44*
Reporting Rates supported by tool	30, 60
Type of PMU supported	Both P and M type
Supported Base Voltage	Any voltage given by user
Total Time Required to Test	90 Minutes (for one reporting rate and base voltage)

*Each test may involve number of subtest for changing quantitties like frequency ramp test, amplitude modulation etc. and number depends on the step size

Test Suites for PMU Performance Analysis

Test Name/C37.118.1 section	Parameter	Settings	Reporting rates, (# of tests)	Input Frequency	Reported Quantities
Preliminary Tests					
1. Reporting rates w/ frequency range / 5.4.1 and 5.5.5	Reporting rate	45 Hz to 55 Hz in 0.5 Hz increments. 5 second duration.	10,(9 tests) 12,(11 tests) 15,(13 tests) 20,(17 tests)	f0±2.0 Hz for Fs ≤ 10 f0±Fs/5 for 10≤Fs20	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
		45 Hz to 55 Hz in 0.5 Hz increments. 5 second duration.	10,(9 tests) 25,(21 tests) 50,(21 tests)	*f*0±2.0Hz for *Fs* ≤10 *f*0±*Fs*/5 for 10≤*Fs*25 *f*0±5.0Hz for *Fs*≥25	
Steady-State performance					
1. Signal frequency range/ 5.5.5	Frequency	55 Hz to 65 Hz in 0.2 Hz increments, 5 second duration, 23°C±1°C	30,(51 tests) 60,(51 tests)	55 Hz to 65 Hz in 0.2Hz increments	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
2. Signal magnitude / 5.5.5	Magnitude	V: 10 % to 120 % nominal I: 10 % to 200 % nominal	30,(V:13 tests), (I:21 tests) 60,(V:13 tests), (I:21 tests)	60 Hz	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
3. Harmonic distortion / 5.5.5	10 % Harmonic	Each from 2nd to 50th. 5 second duration.	30,(49 tests) 60,(49 tests)	60 Hz	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
4. Out-of-band interference / 5.5.5	10 % of nominal amplitude out-of-band interfering signal	Fundamental freq at nominal and nominal ± 10 % of Nyquist Interharmonic: 10 Hz to 120 Hz in 1 Hz increments	30,(144 tests)	58.5 ,60, 61.5 Hz fundamental plus: • 10Hz to 20Hz • 22 Hz to 30 Hz • 31 Hz to 45 Hz • 75Hz to 89 Hz • 90 Hz to 100 Hz • 105 Hz to 120 Hz	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
			60,(93 tests)	57, 60, 63 Hz fundamental plus: • 10Hz to 20 Hz , • 21 Hz to 30Hz • 90Hz to 100 Hz • 102 Hz to 110Hz • 115 Hz to 120 Hz	

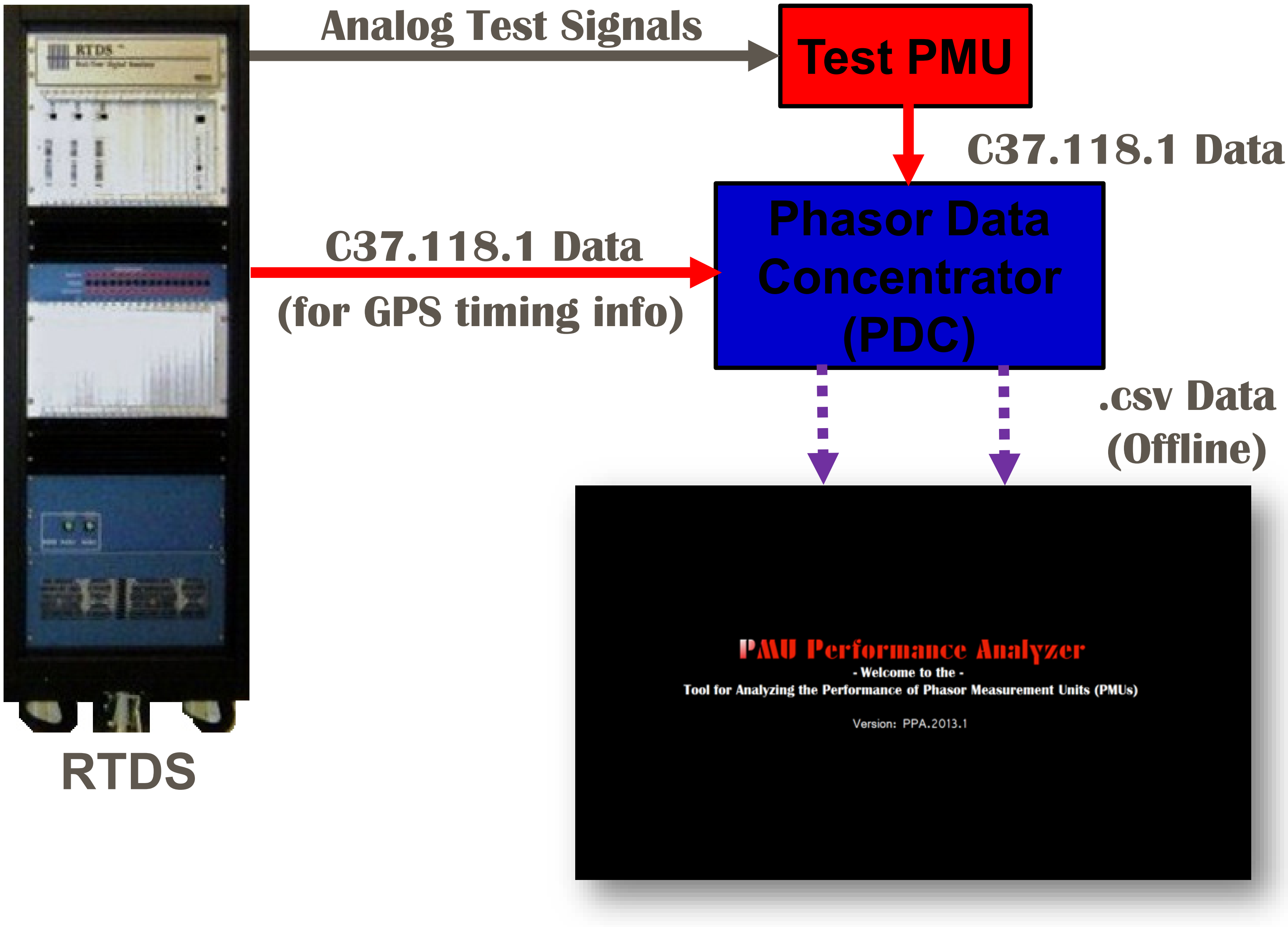
Test Suites for PMU Performance Analysis

Test Name/C37.118.1 section	Parameter	Settings	Reporting rates, (# of tests)	Input Frequency	Reported Quantities
Dynamic performance					
1. Measurement bandwidth (amplitude modulation) / amended 5.5.6	0.1 amplitude mod. Index and 0.0 phase mod. index	Modulation frequencies: • 0.1Hz to 2.1 Hz, in 0.5 Hz increments. • 2.4 Hz to 3.9 Hz in 0.3 Hz increments • 4.1 to 10.1 Hz in 0.2 Hz increments.	30,(41 tests) 60,(41 Tests)	60 Hz	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
2.Measurement bandwidth (phase modulation) / 5.5.6	0.1 phase mod. Index and 0.0 amplitude mod. index	Modulation frequencies: • 0.1Hz to 2.1 Hz, in 0.5 Hz increments. • 2.4 Hz to 3.9 Hz in 0.3 Hz increments • 4.1 to 10.1 Hz in 0.2 Hz increments.	30,(41 tests) 60,(41 Tests)	60 Hz plus phase modulation	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
3. Frequency ramp / amended 5.5.7	Frequency	Linear ramp at +1 Hz/s from 55 Hz to 65 Hz, and then -1 Hz/s down to 55 Hz	30,(2 tests) 60,(2 tests)	Ramp from 55 Hz to 65 Hz and Ramp from 65 Hz to 55 Hz.	FE, RFE, VTVE, ITVE, and phasor magnitude & phase errors
4. Magnitude step / 5.5.8	Magnitude	+10% step and −10% step from 100% using equivalent time sampling technique over 10 iterations	30,(2 tests of 10 iterations each) 60,(2 test of 10 iterations each)	60 Hz	Response Times of voltage and current phasors, FE & RFE. Delay Time of voltage and current phasors, FE & RFE. Overshoot/undershoot of voltage and current phasors.
5. Phase step / 5.5.8	Phase	+10° step and −10° step using equivalent time sampling technique over 10 iterations.	30,(2 tests of 10 iterations each) 60,(2 test of 10 iterations each)	60 Hz	Mean, standard deviation, max & min of each of the following: Response Times of VTVE, ITVE, FE & RFE, Delay Time, Overshoot/undershoot
6. PMU latency / 5.5.9	Latency	Nominal frequency for 1000 report duration	30 (1 test), 60 (1 test)	60 Hz	Mean, standard deviation, max & min of Latency over 1000 reports

PPA and Conventional Methods

Factors for Comparison	Conventional Methods	*PMU Performance Analyzer*
Simplicity of Test Setup	Complex	Simple
Mode of Test Execution & Analysis	Mostly Manual	Mostly Automated
Requirement of Trained Person	Yes	No
Auto-generation of PMU Test Report	No	Yes
Time Required for Entire Process	Very High	Very Low (For 1 PMU: 90 minutes for all tests [in the test suite] conducted once for one reporting rate)
Cost of the Entire Process	Very High	Very Low

Architecture for Using the *PPA*

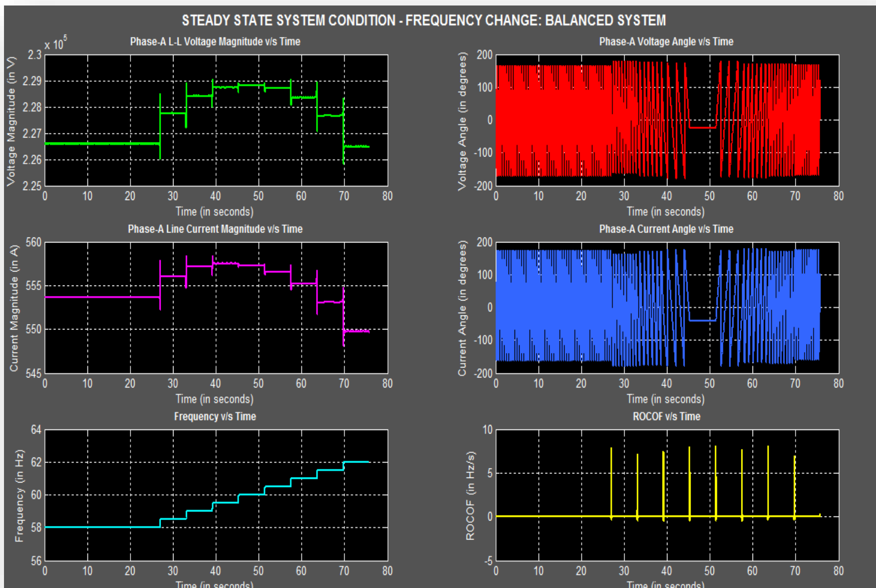


An Example of Steady State Test and Result

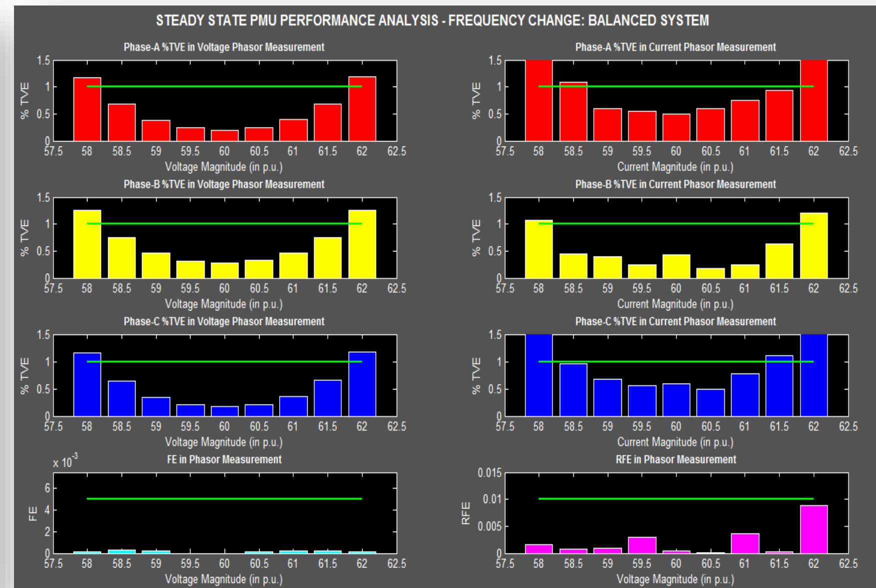
→ Quantity changed: Frequency

→ System condition during the change: Balanced System, No Harmonics

Test Condition



Test Results

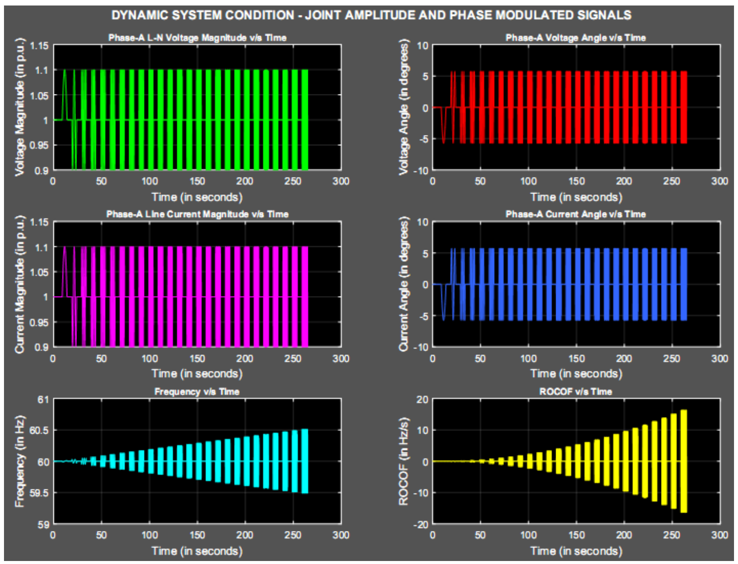


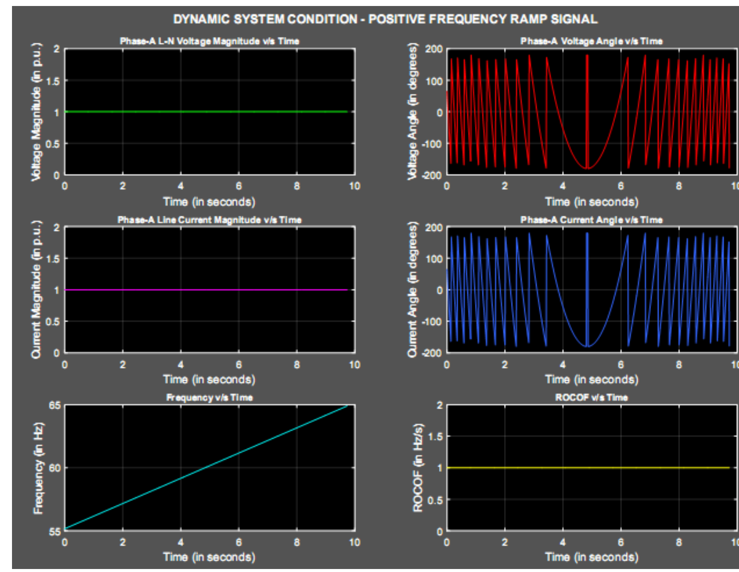
→ Detailed analysis of the test is available in the test report

An Example of a Dynamic Test and Result

→ Quantity changed: Frequency

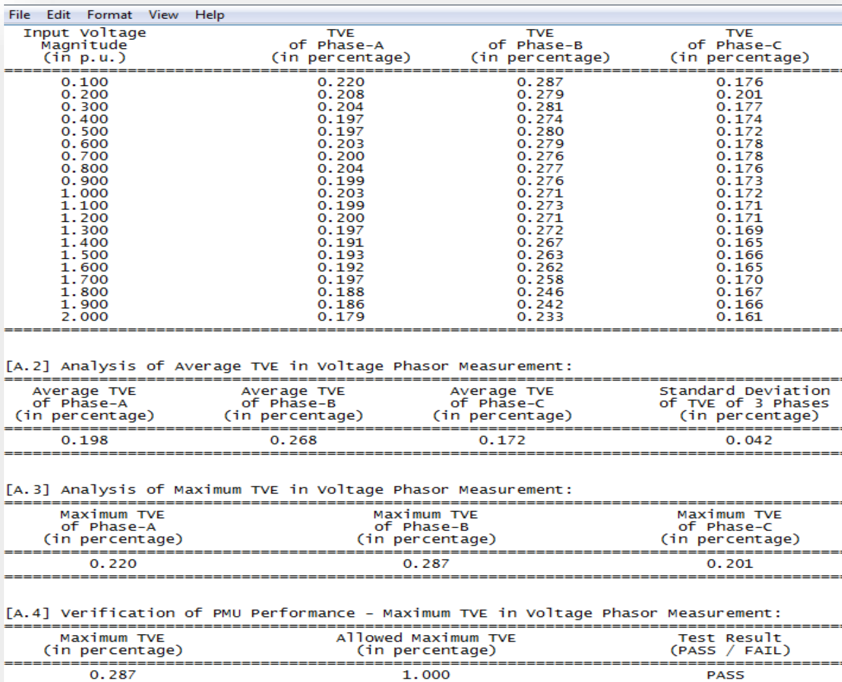
Joint Amplitude and phase modulation **Ramp Change in Frequency**





→ Detailed analysis of the test is available in the test report

An Example of an Auto-generated PMU Test Report



File Edit Format View Help

Input Voltage Magnitude (in p.u.)	TVE of Phase-A (in percentage)	TVE of Phase-B (in percentage)	TVE of Phase-C (in percentage)
0.100	0.220	0.287	0.176
0.200	0.208	0.279	0.201
0.300	0.204	0.281	0.177
0.400	0.197	0.274	0.174
0.500	0.197	0.280	0.172
0.600	0.203	0.279	0.178
0.700	0.200	0.276	0.178
0.800	0.204	0.277	0.176
0.900	0.199	0.276	0.173
1.000	0.203	0.271	0.172
1.100	0.199	0.273	0.171
1.200	0.200	0.271	0.171
1.300	0.197	0.272	0.169
1.400	0.191	0.267	0.165
1.500	0.193	0.263	0.166
1.600	0.192	0.262	0.165
1.700	0.197	0.258	0.170
1.800	0.188	0.246	0.167
1.900	0.186	0.242	0.166
2.000	0.179	0.233	0.161

[A.2] Analysis of Average TVE in Voltage Phasor Measurement:

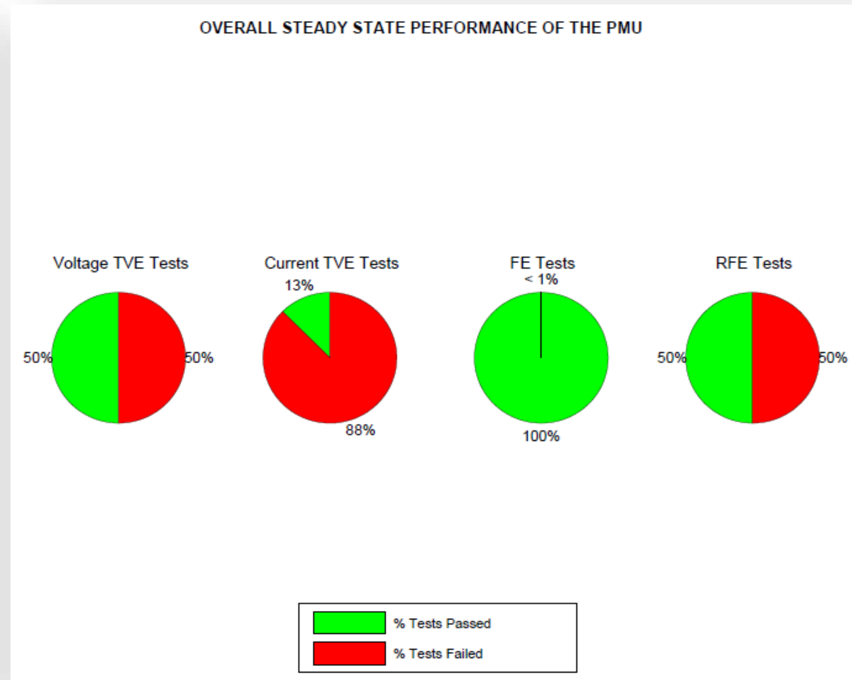
Average TVE of Phase-A (in percentage)	Average TVE of Phase-B (in percentage)	Average TVE of Phase-C (in percentage)	Standard Deviation of TVE of 3 Phases (in percentage)
0.198	0.268	0.172	0.042

[A.3] Analysis of Maximum TVE in Voltage Phasor Measurement:

Maximum TVE of Phase-A (in percentage)	Maximum TVE of Phase-B (in percentage)	Maximum TVE of Phase-C (in percentage)
0.220	0.287	0.201

[A.4] Verification of PMU Performance - Maximum TVE in Voltage Phasor Measurement:

Maximum TVE (in percentage)	Allowed Maximum TVE (in percentage)	Test Result (PASS / FAIL)
0.287	1.000	PASS



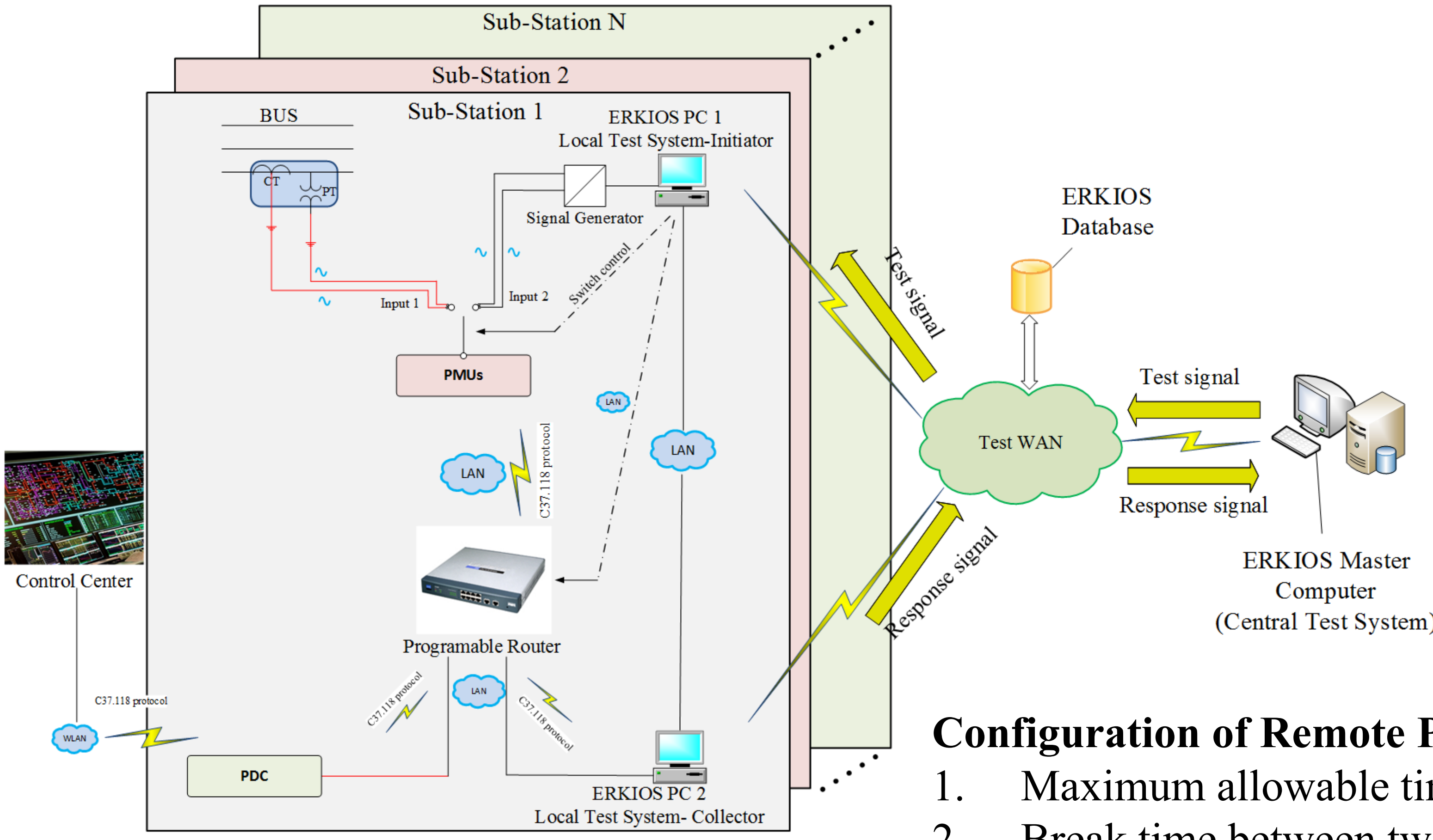
→ The PMU test report consists of:

(a) Detailed analysis of all the tests performed on the PMU in the form of text and corresponding figures

(b) Results in conformance with IEEE Standard C37.118.1

→ The PMU test report is very easy to interpret

Remote PMU Testing



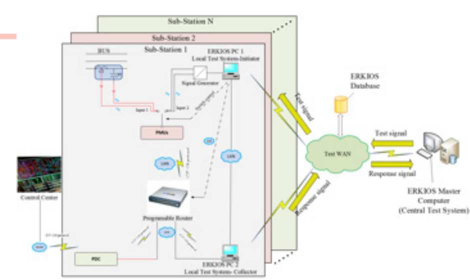
Configuration of Remote PMU Testing

1. Maximum allowable time
2. Break time between two tests
3. Authentication

With Dave Bakken, WSU

Remote PMU Testing Requirements

Central Test System	Initiate remote PMU testing by generating test signal and transmit to LTI
Local Test System Initiator	Disable CT/PT input to PMU, connects PMU input to Signal Generator. Unpacks the test signal data received from Central Test System and transmits them to Signal Generator. Controls Programmable Router to transmit C37.118 data to LTC
Signal Generator	Generates voltage and current signal for the test signal received from LTI
Programmable Router	Transmits the C37.118 phasor data to the LTC during testing and switch back to substation PDC during normal operation
Local Test System Collector	Receives the C37.118 phasor data during test and transmits to Central Test System for reporting, analysis and archiving



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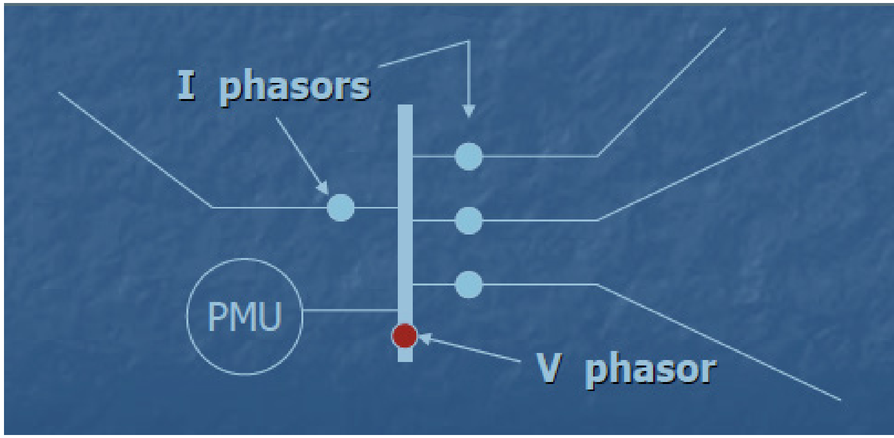
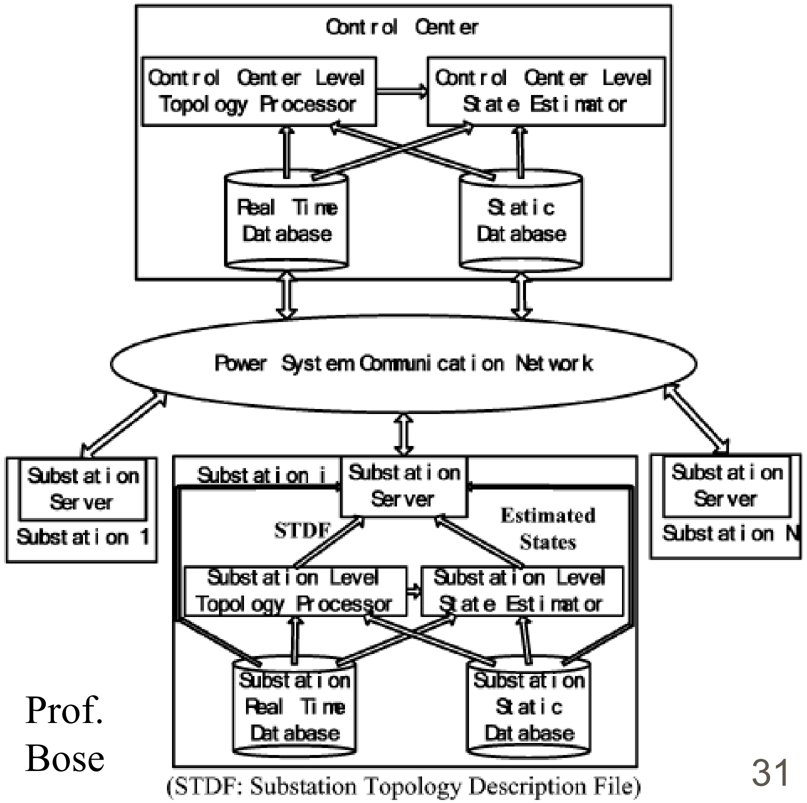
State Estimation Based Bad Data Detection

- Linear State Estimation: With less number of PMUs, bad data in critical PMU can not be detected
- Two Level Linear State Estimation: Bad data can be detected at substation level (e.g. at one level voltage SS, all voltage should be similar, KCL)
- Decentralized State Estimation: Multiple DSE can be solved using residue for bad data
- Distributed State Estimation (Super Calibrator): Bad data detection at multiple level





Prof. Bose

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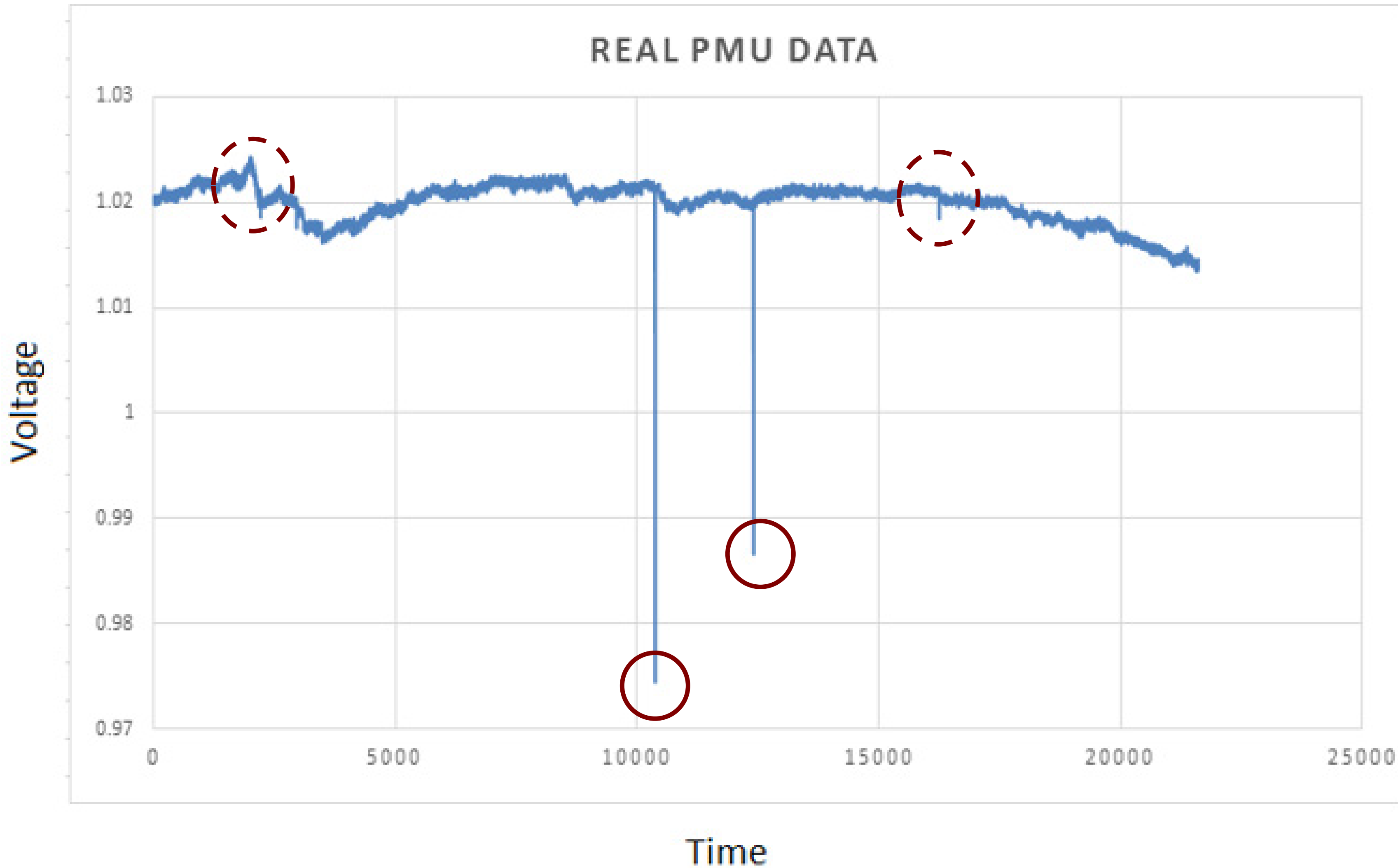
PMU Data from Field



Biggest challenge: Differentiate between event vs bad data

Credit: EPRI

Statistical/ Data Mining Approaches

1. Median Absolute Deviation Method

- $Median\ Absolute\ Deviation\ (MAD) = \ median_i|x_i - \overline{x}|$
- $Ratio_i = \frac{x_i}{(MAD)}$ > C ➔ Outlier is detected

2. Linear Regression Method with Standard Deviation

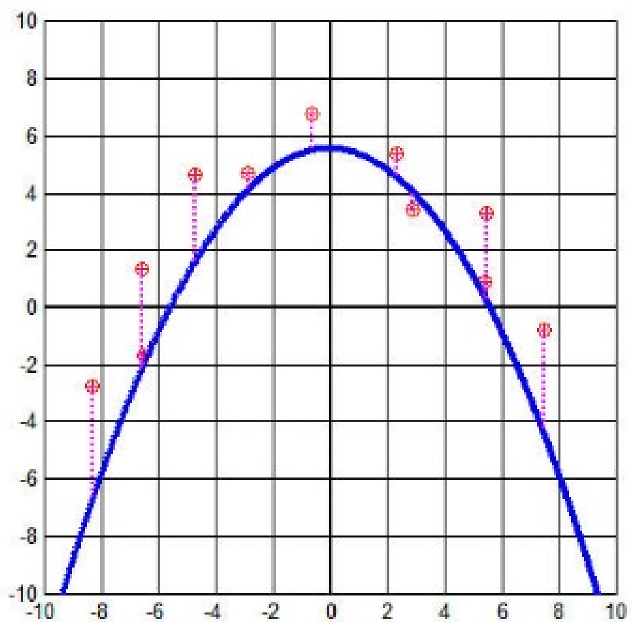
- Outlier is detected if value > mx + b ± Cσ
- Upper and lower limits are calculated based on historic data of power system measurements

Alternative Estimators

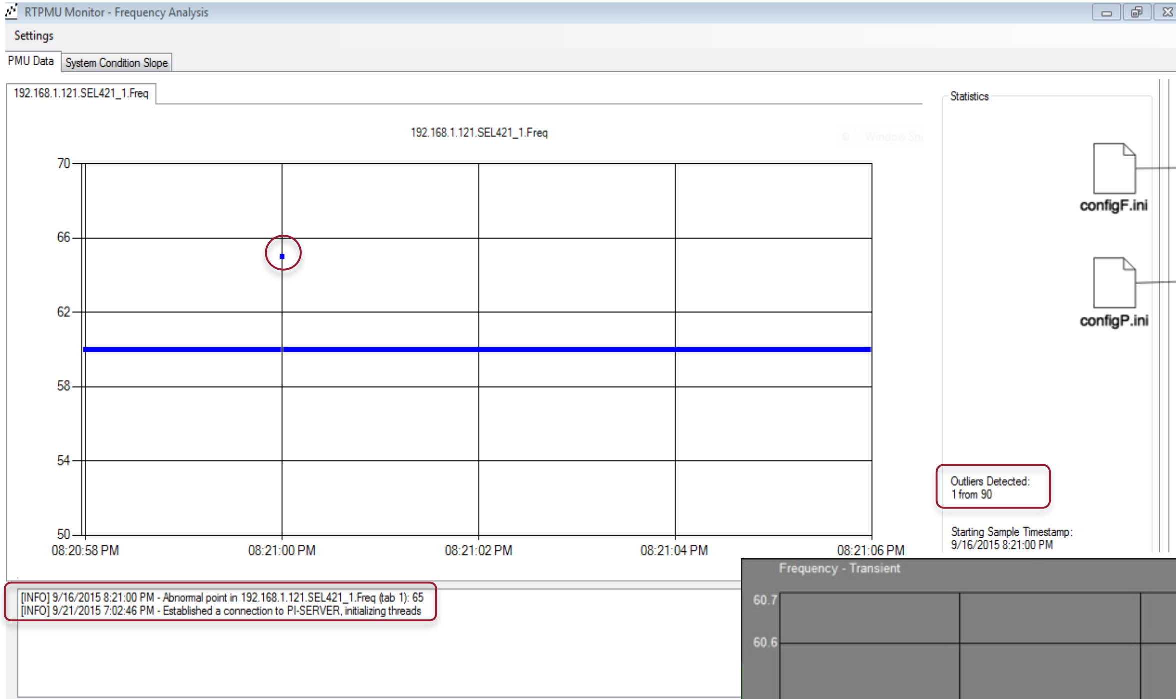
Nonlinear measures: Quadratic regression method to PMU outlier detection

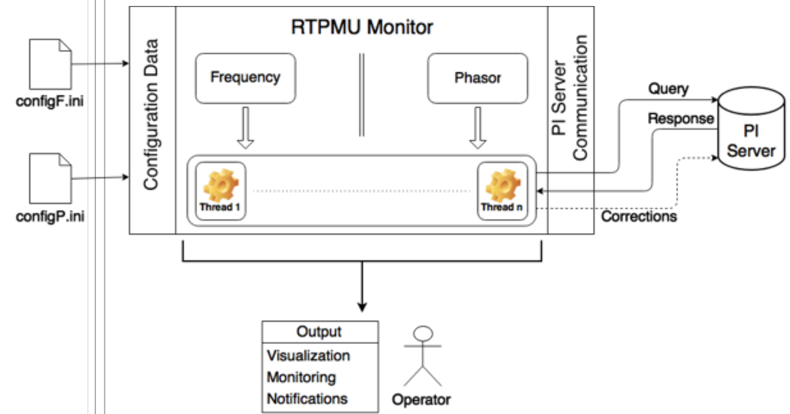
- Determine a quadratic equation model that approximates the PMU data

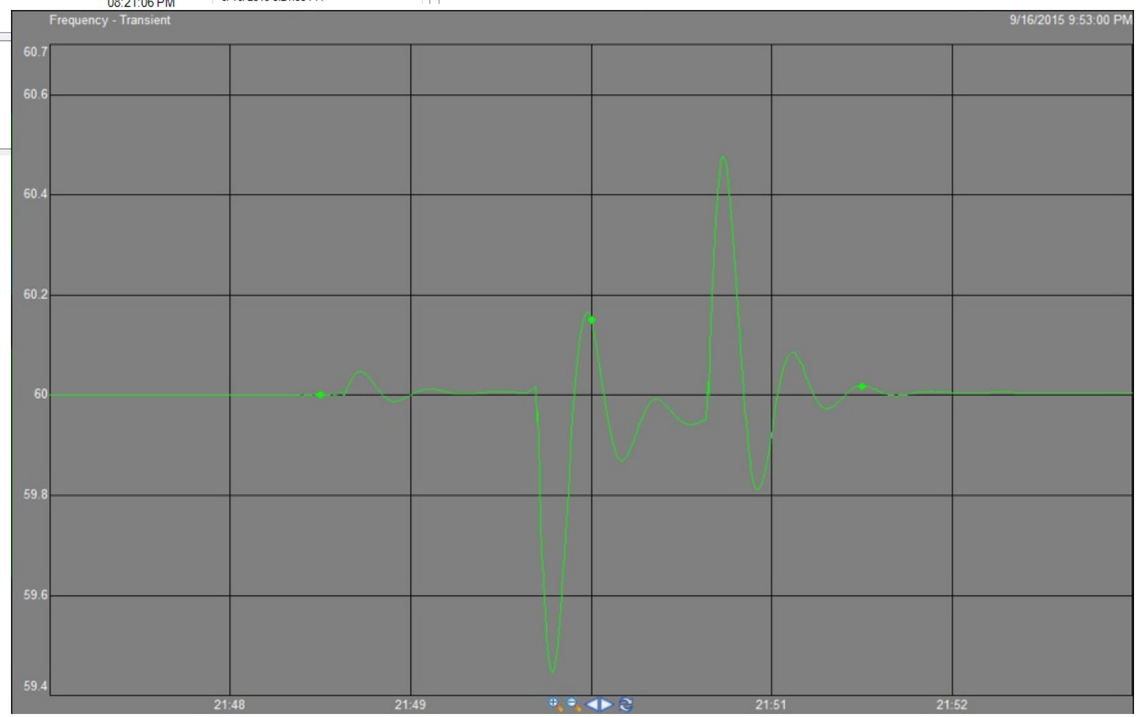
- Outlier detected if value > $f(x) = ax^2 + bx + c \pm C\sigma$



RT-PMU Monitor



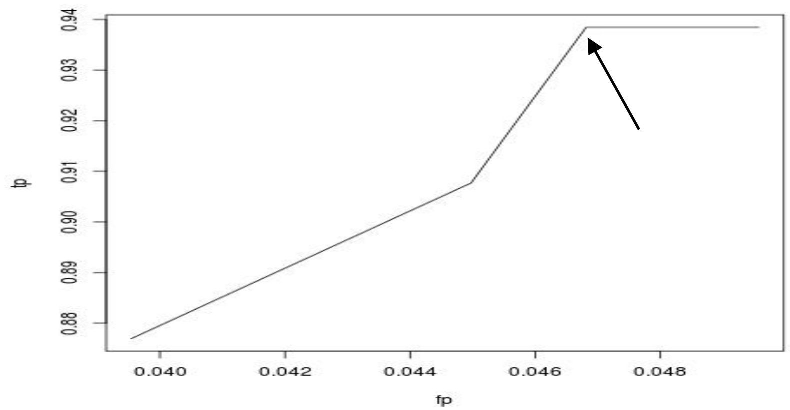




Outlier and Transient
Event Detection

Wavelet Based Approach

- Slide step, window size, algorithms, levels in wavelet, and basis were chosen based on the plots of True Positive v/s False Positive
- True Positive is also known as "Recall"



TRUE Positive vs False Positive with changing window size

- Recall = $\dfrac{Detected\ Bad\ Data \cap Actual\ Bad\ Data}{Actual\ Bad\ Data}$

- Precision= $\dfrac{Detected\ Bad\ Data \cap Actual\ Bad\ Data}{Detected\ Bad\ Data}$

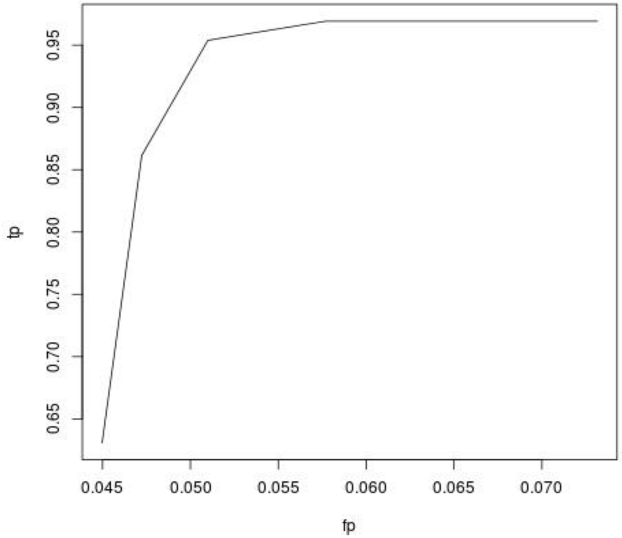
- False Positive = 1- $\dfrac{Detected\ Bad\ Data \cap Actual\ Bad\ Data}{Detected\ Bad\ Data}$

With Dr. Y. Wu, WSU

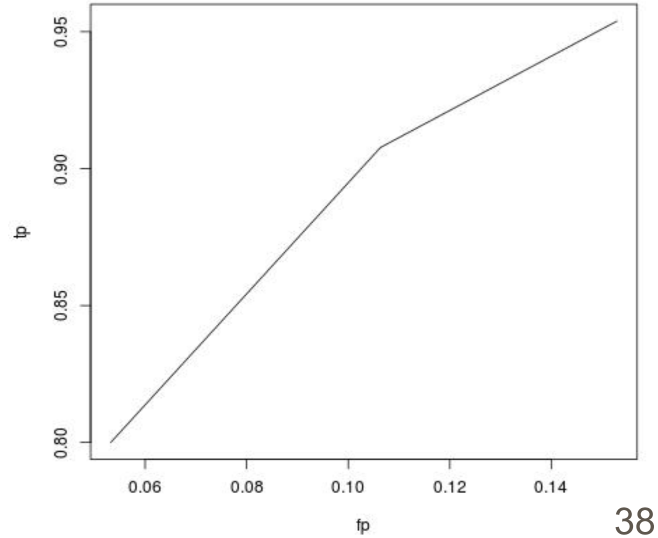
Wavelet Based Approach

- Five different basis Haar, Daubechies, coiflet4, symlet8 and LA8 wavelets were used for each method to cleanse the data and the results were then compared.
- Two different tolerance methods have been used for bad data and event detection.
- Method 1: $Max\left(abs\left(M_i(t)\right)\right) > beta$
- Method 2: $\log(M_i(t+1)) - \log(M_i(t)) > alpha$

Plot to choose the threshold values (α &β)

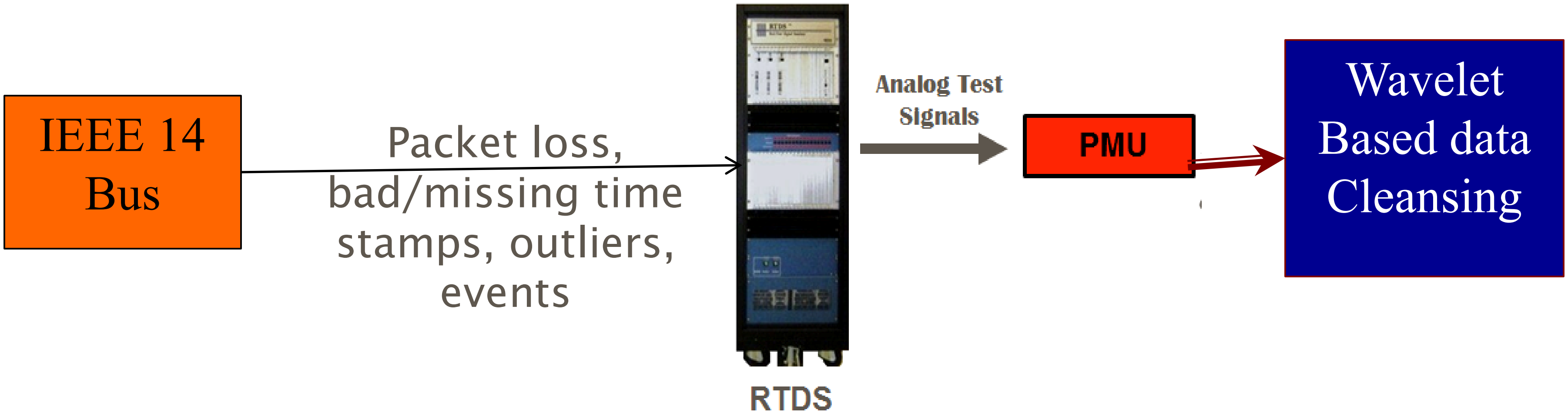


Plot to choose the wavelet “level”



Test Data Generated Using Hardware PMU

- IEEE 14 bus system was modeled using RTDS.
- The hardware PMU data of 14th Bus was obtained.
- Script containing different events were used to get the PMU data.
- Bad data were introduced such as dropouts/ packet loss, Bad/missing time stamps, outliers, etc.



Performance of Wavelet Based Data Cleansing

Index	Tolerance Method 1					Tolerance Method 2				
	LAB	Haar	BL14	C30	D4	LAB	Haar	BL14	C30	D4
True Positive	0.6538	0.8462	0.0385	0.5769	0.8077	0.6923	0.6923	0.3846	0.5769	0.2308
False Positive	0.5152	0.3529	0.0323	0.4688	0.6364	0.7826	0.6667	0.5263	0.8333	0.1935
Precision	0.4848	0.6471	0.9677	0.5313	0.3636	0.2174	0.3333	0.4737	0.1667	0.8065
Recall	0.6538	0.8462	0.0385	0.5769	0.8077	0.6923	0.6923	0.3846	0.5769	0.2308

Online Regression for Data Streams

- We may leverage efficient regression algorithms over data streams
- PMU anomaly detection follows the turnstile model
  - Input: A sequence of updates to an object (vector, matrix, database, etc.)
  - Output: An approximation of some statistics of the object
  - Space: significantly sublinear in input size
  - Overall time: near-linear in input size
- Efficient streaming algorithm in the turnstile model for linear regression

Outline

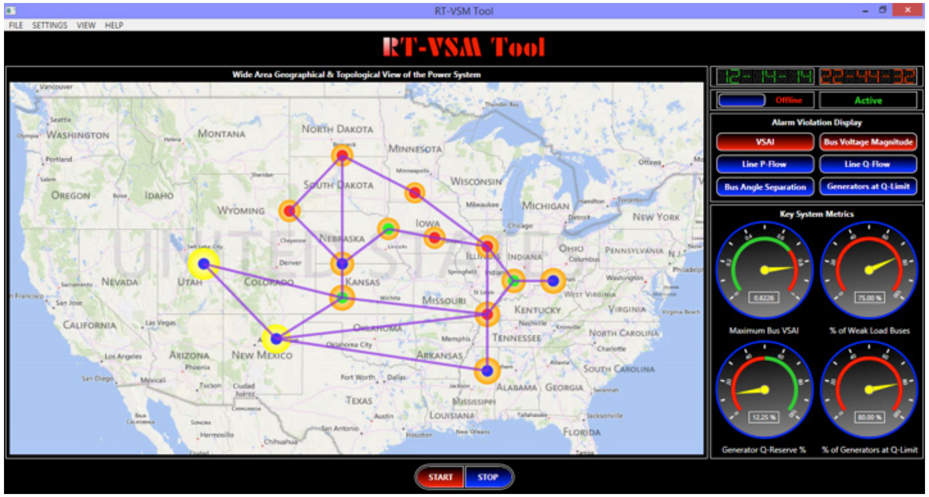
- Synchrophasor based Mission Critical Applications
- PMU Data Quality Requirements
- PMU Performance Analyzer and Remote Testing
- Data Mining Approaches for Data Cleansing
- **Impact of PMU Errors on Applications**
- Summary

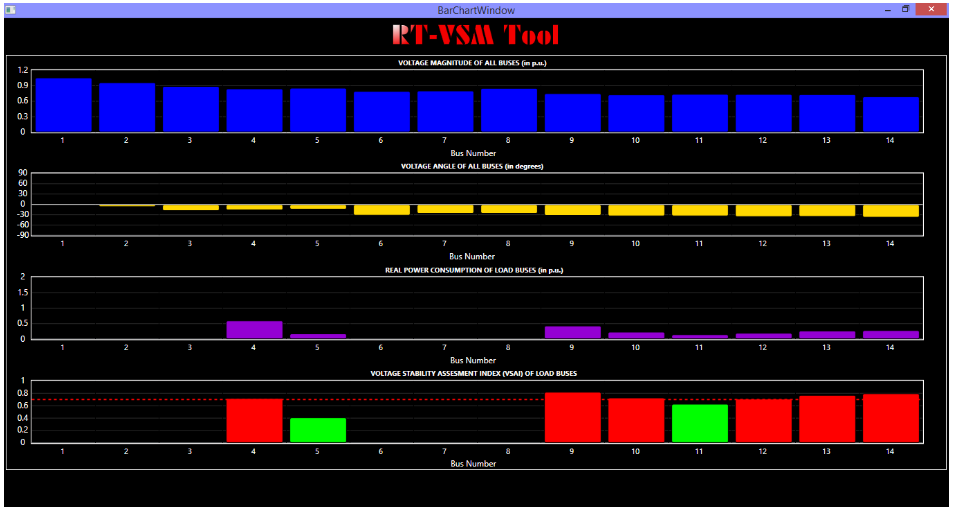
Application Example: RT-VSMAC

(1) It is a new tool for monitoring and controlling the voltage stability of a power system from a central control center

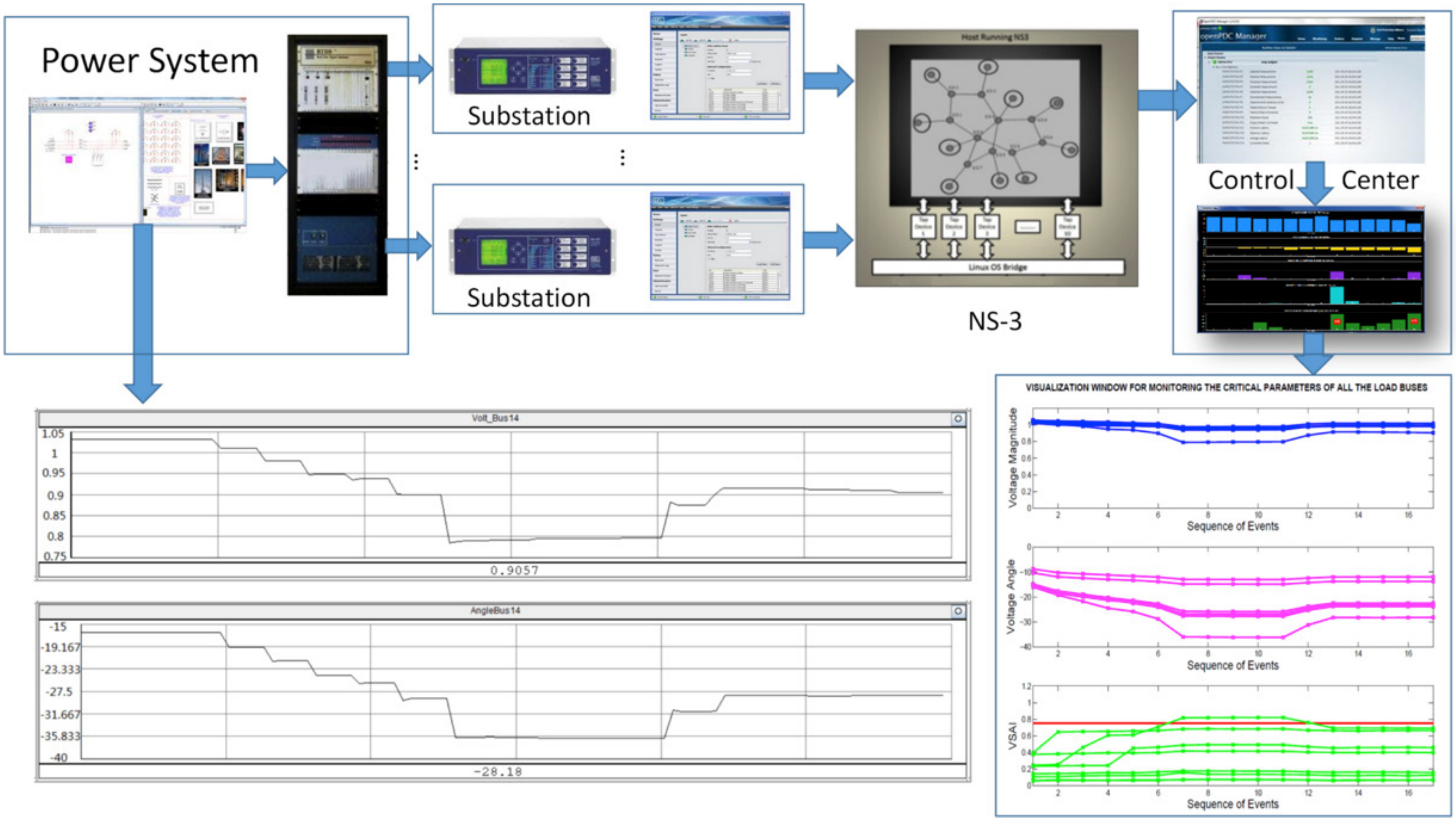
(2) ‘Monitoring Module’ uses a non-iterative mathematical analysis to compute Voltage Stability Assessment Index (VSAI) between 0 and 1 and other critical metrics to indicate voltage stability status of the system

(3) ‘Control Module’ is dual mode (i.e. normal mode & emergency mode) and adapts to either mode based on user preference and system voltage stability severity situation





Voltage Stability Application Using SGDRIL Testbed



Integrate RTVSMAC into SGDRIL Testbed

The testbed setup consists of a modified IEEE 14-bus system that is made completely observable using PMUs, and automated closed-loop control is used with the RT-VSMAC tool as the control application.

Impact of PMU Missing Data

- Data flood was simulated for the PMU on bus 14. During the simulation, RT-VSMAC detects that one of the phasor data streams is missing, which could indicate either a communication failure, a power system failure, or some data failure. In order to prevent making wrong control actions based on the bad data, RTVSM keeps using previous VSAI data until all phasor data streams recover back to the normal condition.
- From the Figure 1, it is notable that RT-VSM does not give any control action back to the system, since it always keeps using the previous data which is still under the threshold. However, during the PMU data failure, load is still increasing and the voltage angle keeps dropping shown in the Figure 2.

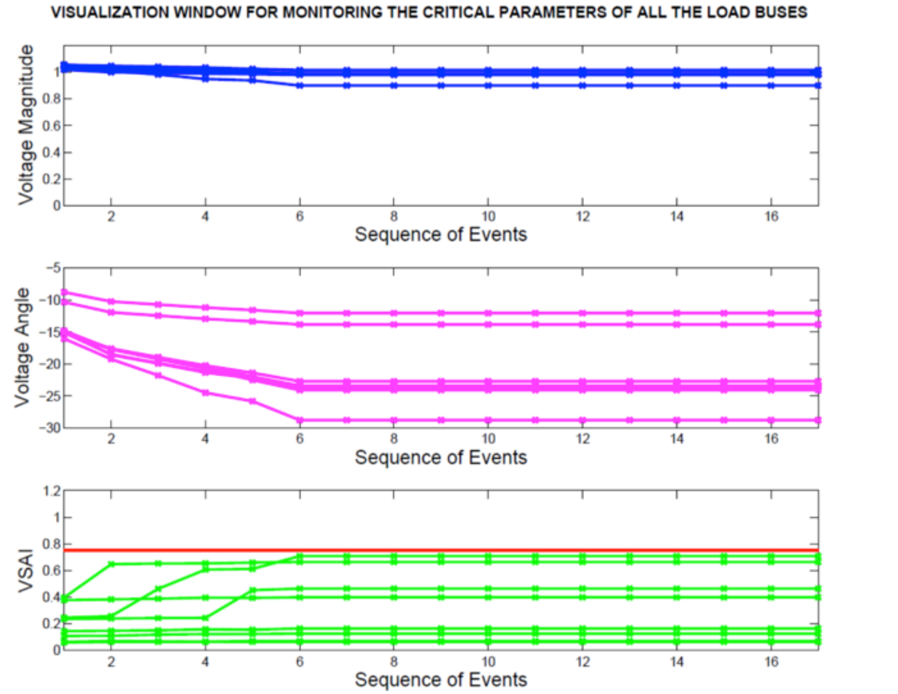


Figure 1. Wide-Area VSAI and Voltage Phasor Data for PMU failure

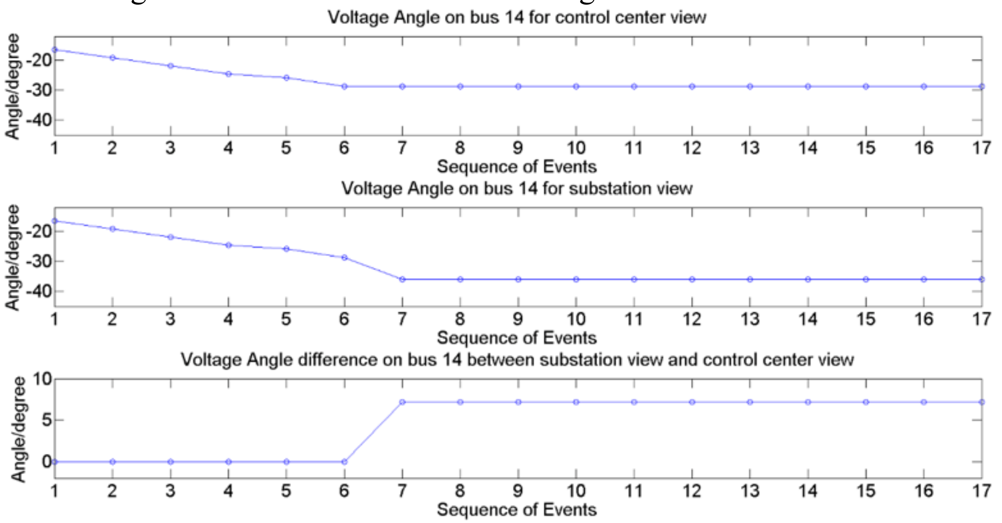
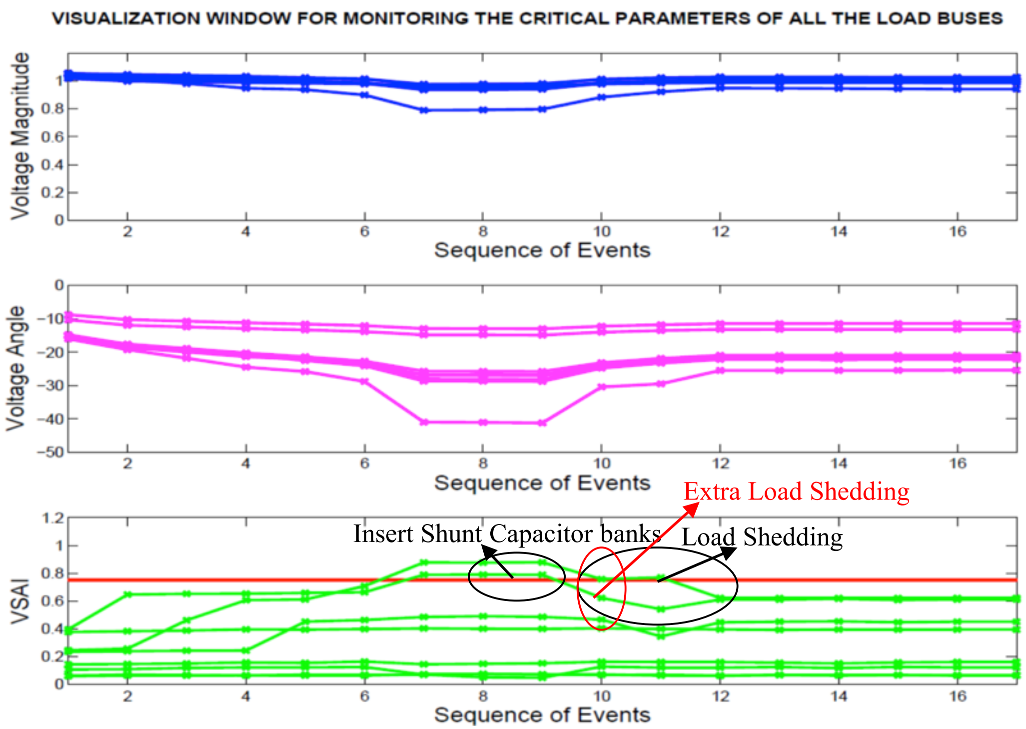


Figure 2. Voltage Angle Value at bus 14 for PMU failure

Impact of PMU Data Error

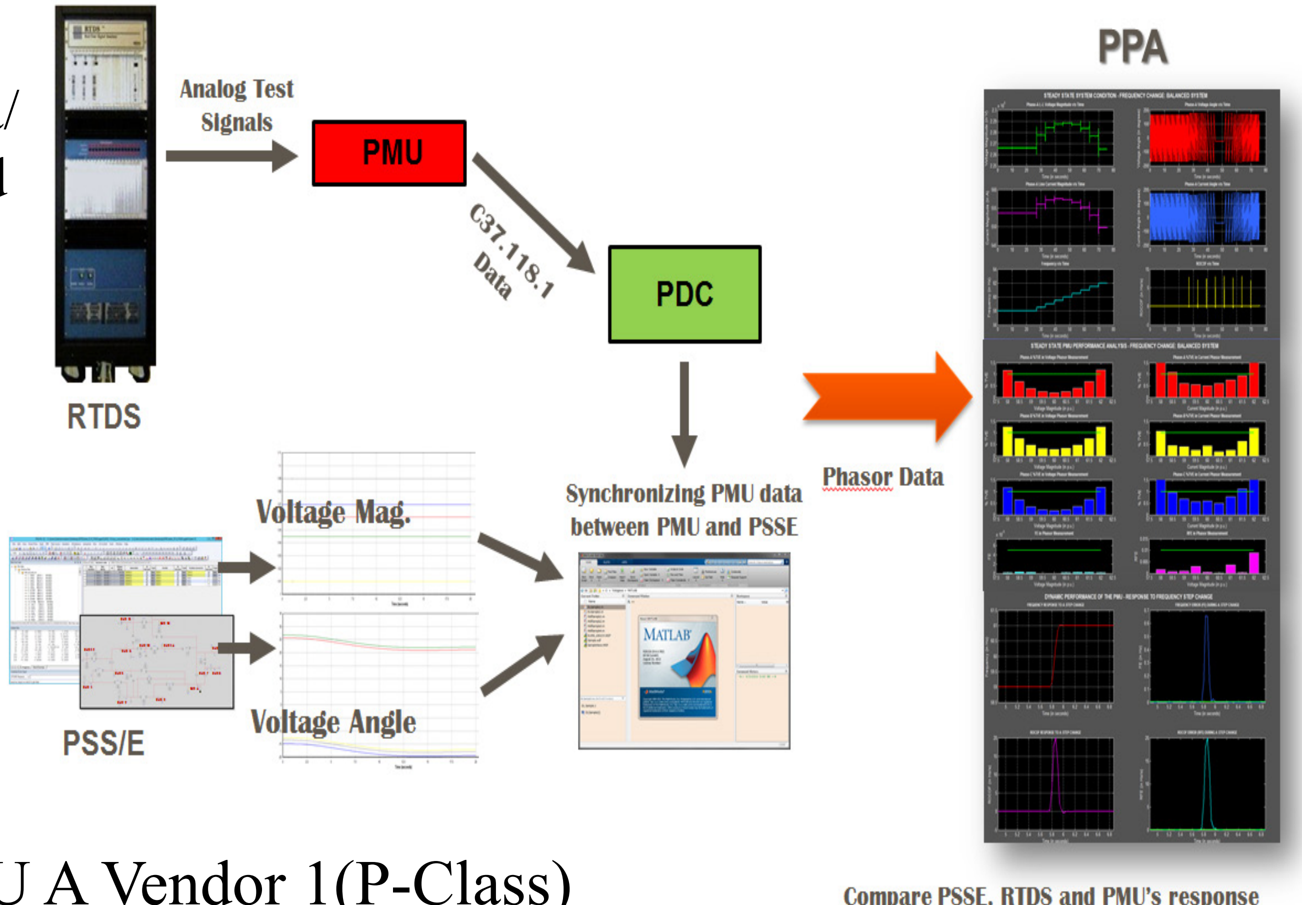
In the PMU error simulation, the error are added through man-in-the-middle attack into the measurements from bus 9, bus 13 and bus 14. Based on the error data, control center considers the power system as more stressed than its true status. The first control action is remote load shedding at bus 9 and the second control action is local load shedding at bus 14. With these two extra control actions, there are 36% additional load shedding at bus 14 and additional load shedding at bus 9 compared to the normal condition. Under this condition, the PMU error mislead the application to generate inaccurate output signals.



Wide-Area VSAI and Voltage Phasor Data for PMU Error Condition

Model Validation

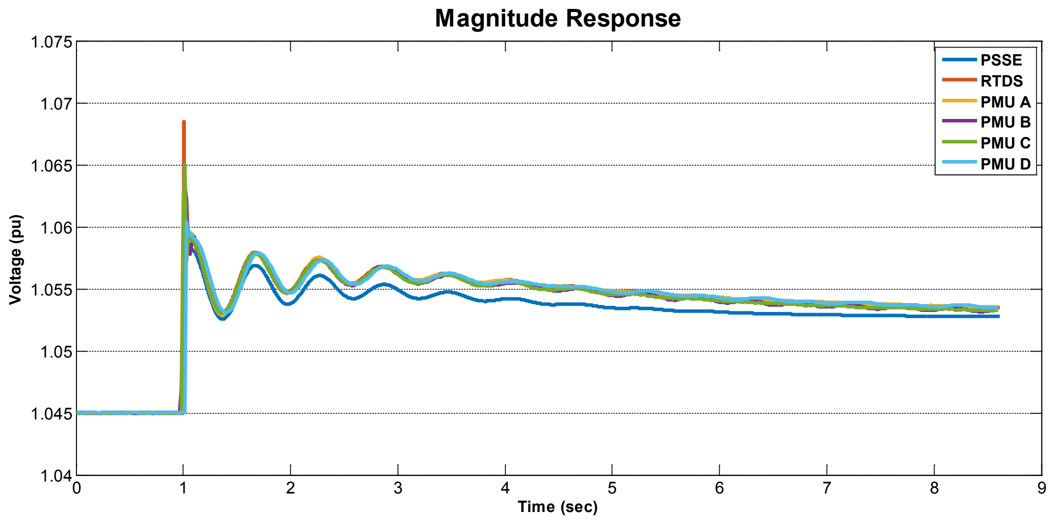
Field Data/ Simulated Data



PMU A Vendor 1(P-Class)
PMU B Vendor 2 (M-Class)
PMU C Vendor 2 (P-Class)
PMU D Vendor 3 (DFR)

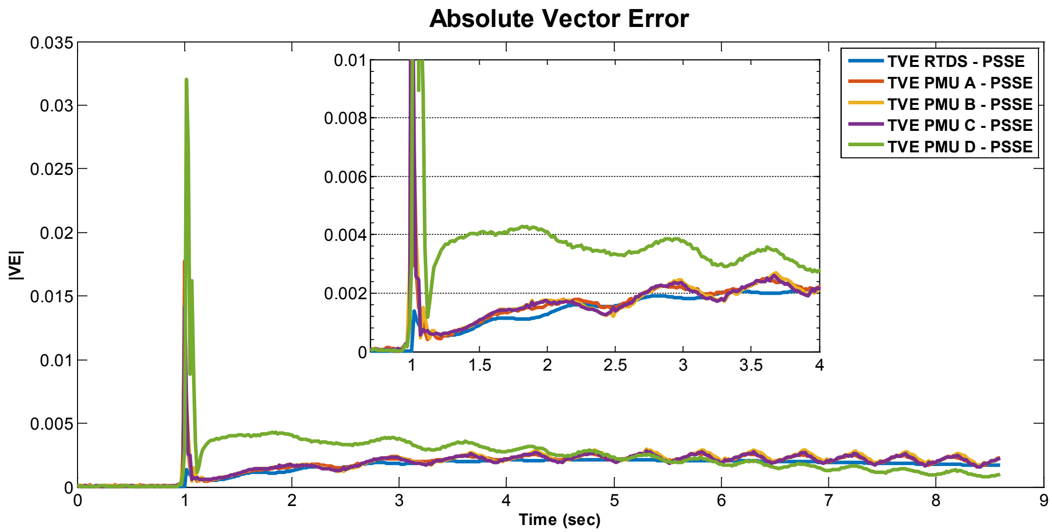
With EPRI

Test Scenarios 1: Load Shedding at Bus 3



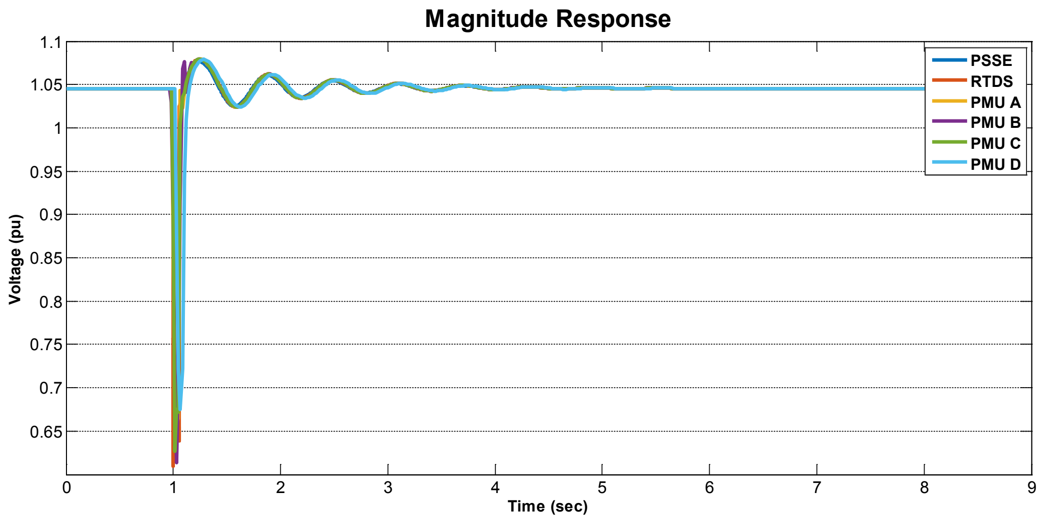
$$AVE_{RTDS\_PSSE} = |\bar{V}_{PSSE} - \bar{V}_{RTDS}|$$

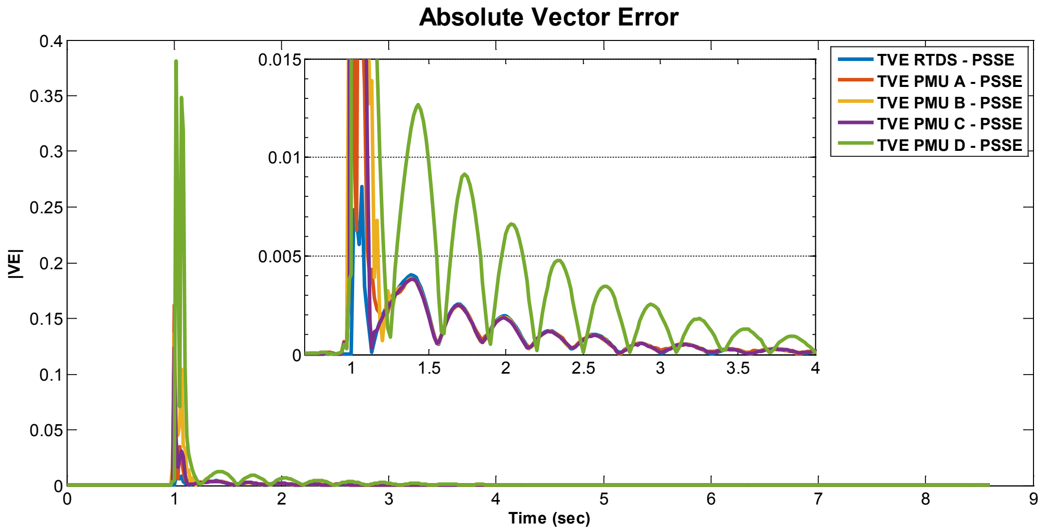
$$AVE_{PMUx\_PSSE} = |\bar{V}_{PSSE} - \bar{V}_{PMUx}|$$



PMUs installed at Bus 2

Test Scenarios 2: Bus Fault at Bus 3

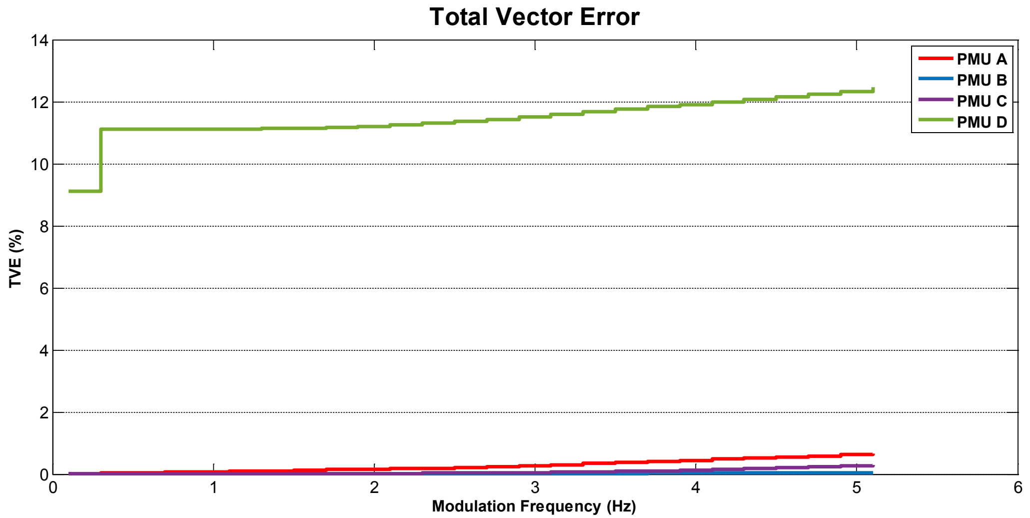




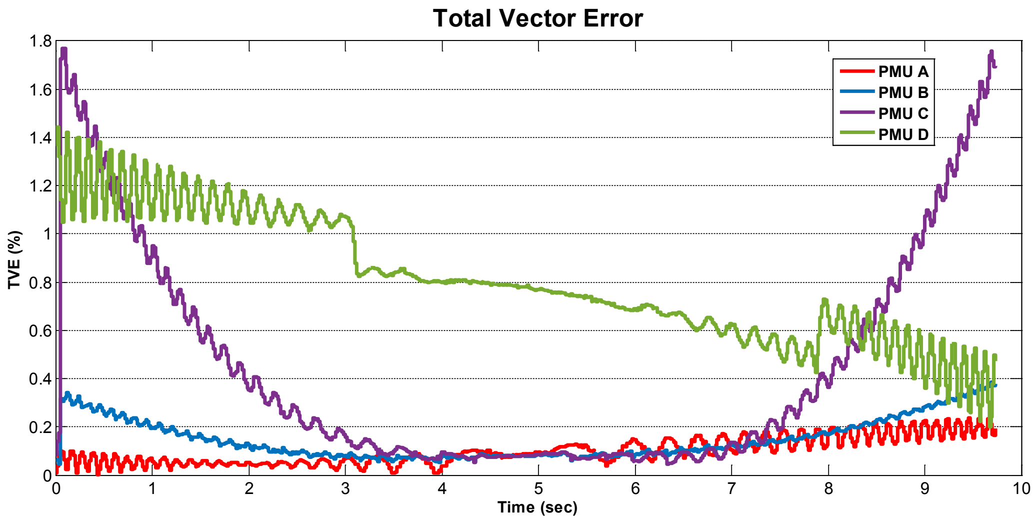
No consideration of PMU error

PMUs installed at Bus 2

Test Scenarios 3: Dynamic Compliance Validation of PMUs



Joint Amplitude and Phase modulation with modulation index 0.1 and modulation frequency 0.1Hz to 5.1Hz in steps of 0.2Hz



Positive Frequency Ramp

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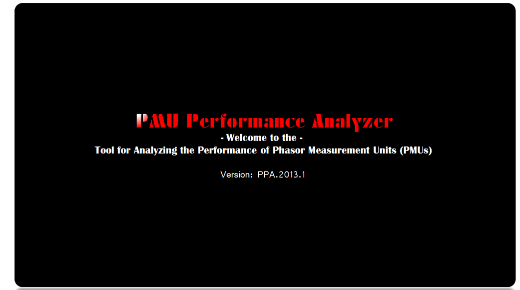
Summary



- ☑ Data quality of synchrophasor device is important for mission critical application
- ☑ A new PMU performance testing tool has been developed and being improved. PPA can perform testing and reporting in very short time
- ☑ Remote testing platform is being integrated with real time monitoring and control test bed
- ☑ Data mining techniques has been discussed for PMU data cleansing
- ☑ Impact of PMU error on PMU applications have been discussed

Acknowledgements

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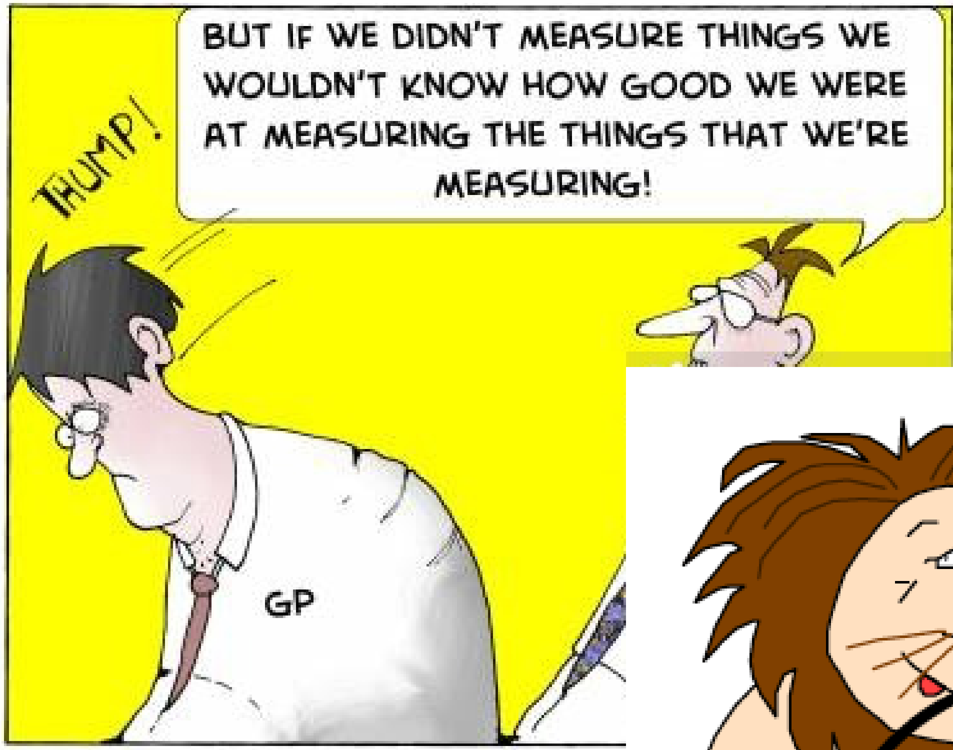
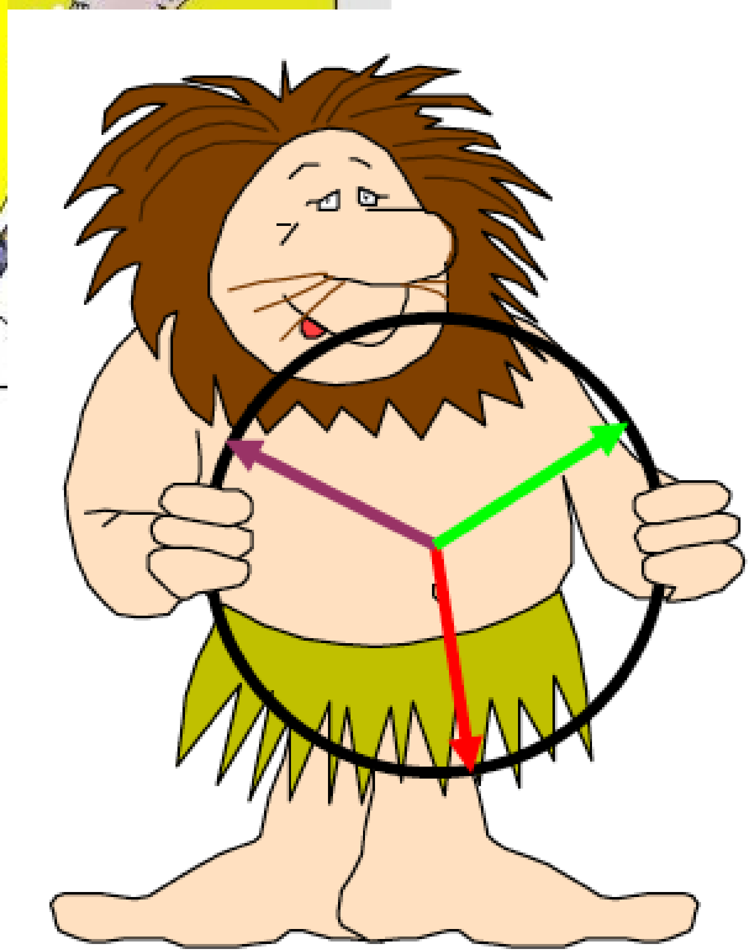
- Industry advisory members for PSERC projects S45, S57, T57-HI





Questions and Thank You