Testing and Validation of Synchrophasor Devices and Applications

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PSERC Webinar

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Outline

- Synchrophasor Applications for the Smart Electric Grid
- Real Time Monitoring and Control Test Bed
- PMU Performance Analyzer (PPA)
- Real time Voltage Stability Monitoring and Control (RT-VSMAC)
- Summary

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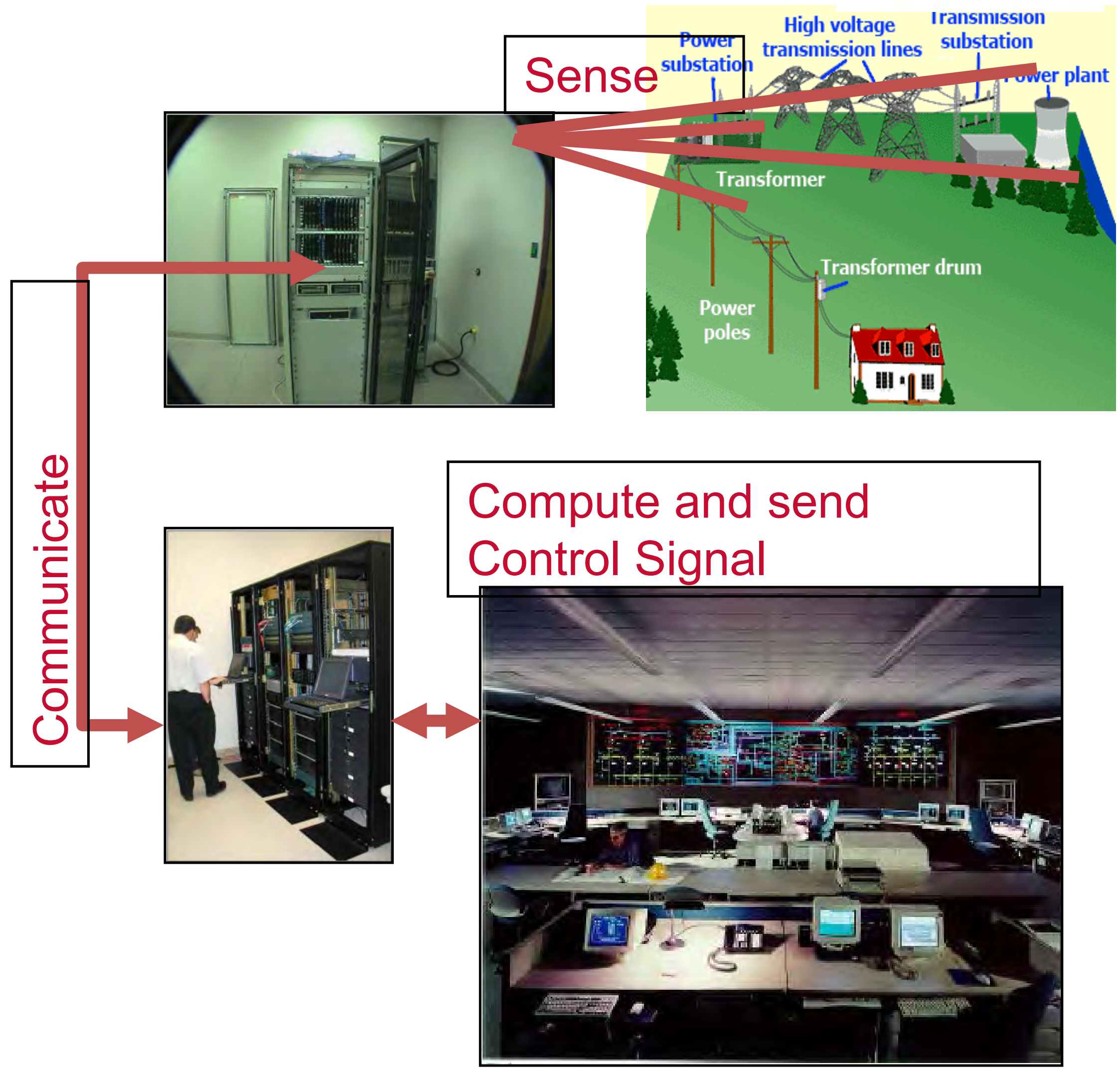
Synchrophasor Applications

- ☑ Synchrophasor applications are one of the important smart grid activities for transmission system
- ☑ Enables real time monitoring and control
- ☑ These devices and new applications need to be tested with system modeling
- ☑ Interoperability test with several different devices
- ☑ Real time control need to be specially designed carefully

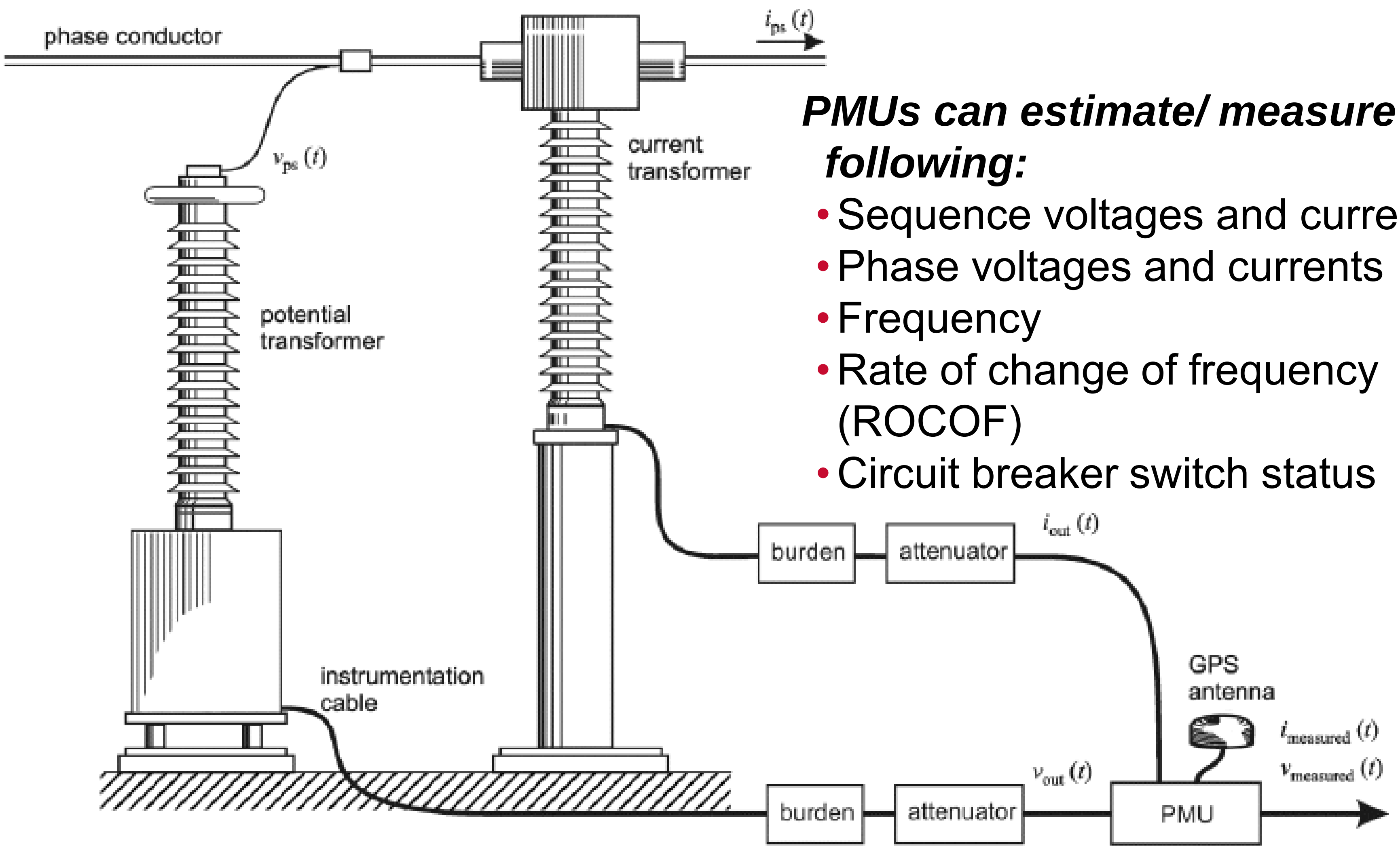


Phasor Measurement Units

- 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 synchrophasor and frequency values must meet the general definition and minimum accuracy required in the IEEE Synchrophasor Standard, C37.118-2005 or 2011 version.
- The device must provide a real-time data output which conforms to C37.118(.2) requirements.

"It's like going from an X-ray to a MRI of the grid."
Terry Boston, CEO PJM Interconnection

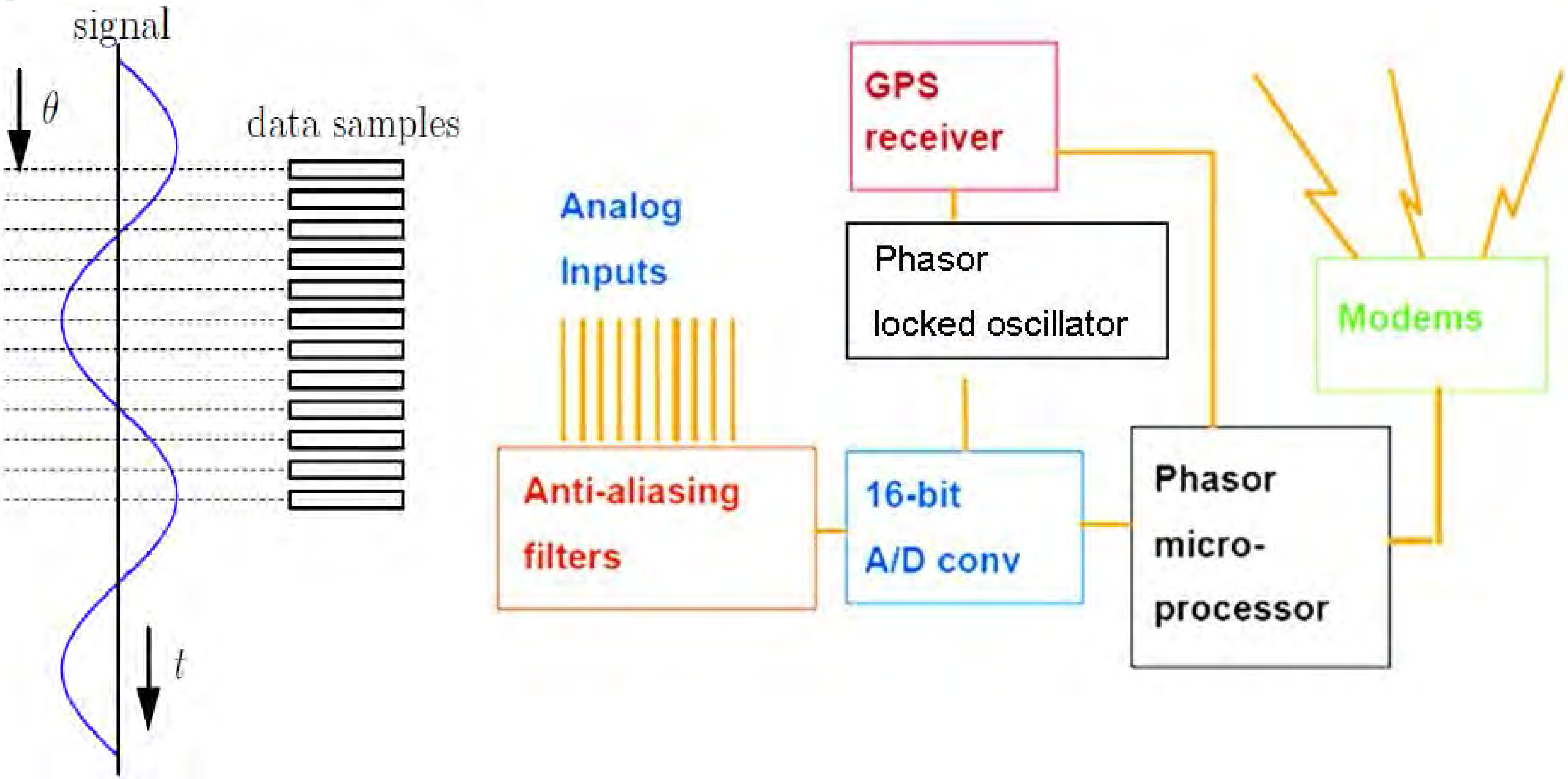
Instrumentation Including a PMU



PMUs can estimate/ measure the following:

- Sequence voltages and currents
- Phase voltages and currents
- Frequency
- Rate of change of frequency (ROCOF)
- Circuit breaker switch status

Synchrophasor Estimation

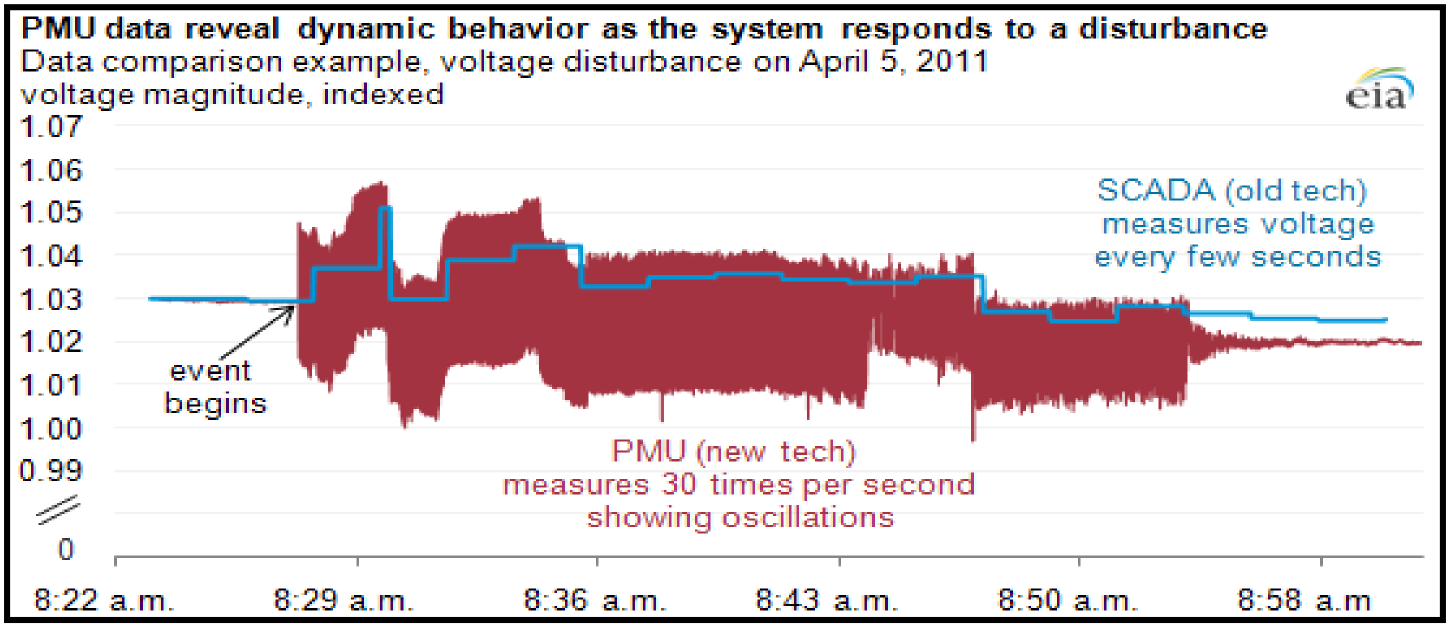


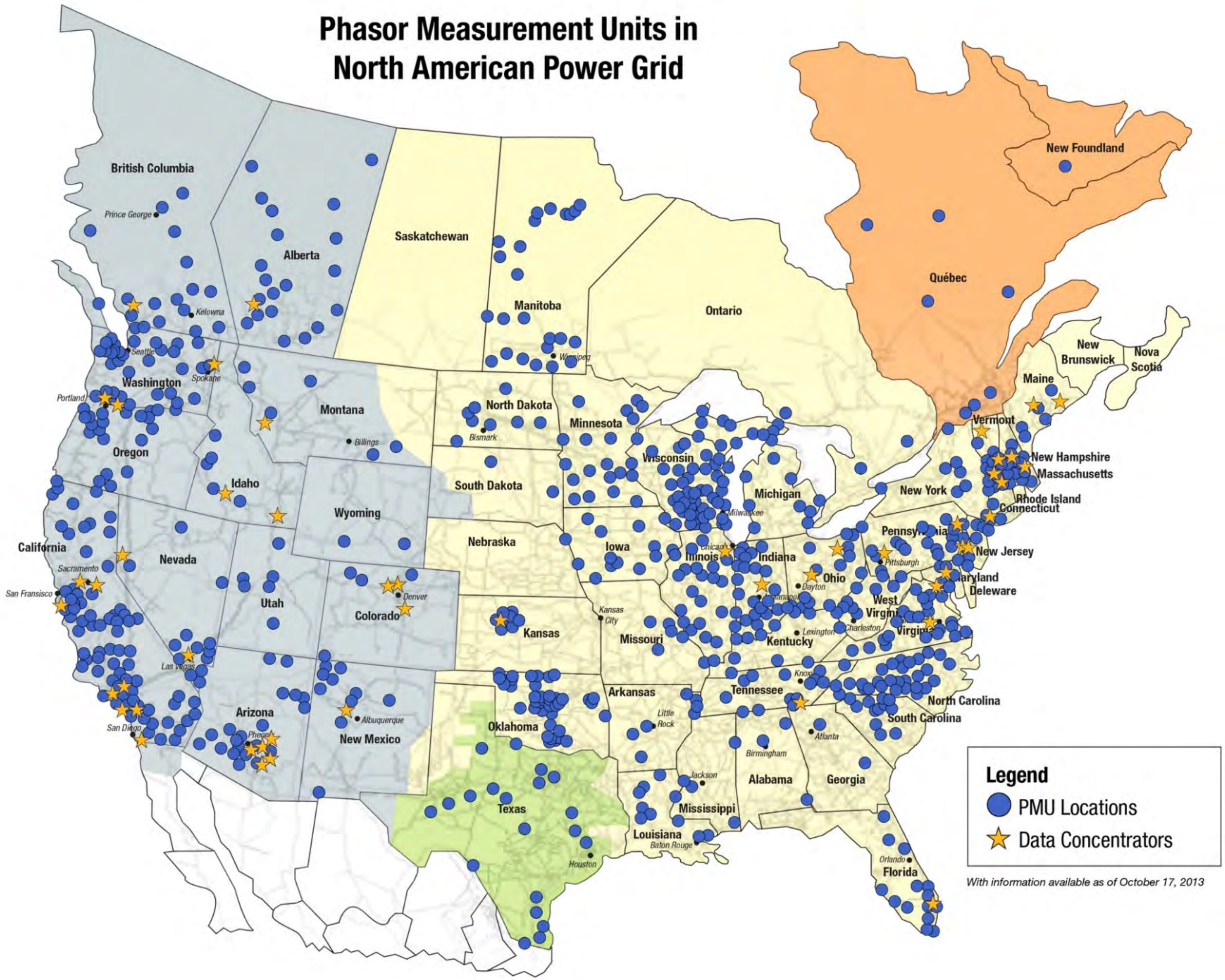
- Most phasor calculation in commercial PMUs uses a 1-cycle window, (sometimes, 2 or maybe 4 to reduce the impact of noise)
- There is latency in the PMU itself –number of cycles and processing time

** R.F. Nuqui, “State Estimation and Voltage Security Monitoring Using Synchronized Phasor Measurements”, Doctorate Dissertation, Virginia Polytechnic Institute, Blacksburg, VA, July 2, 2001*

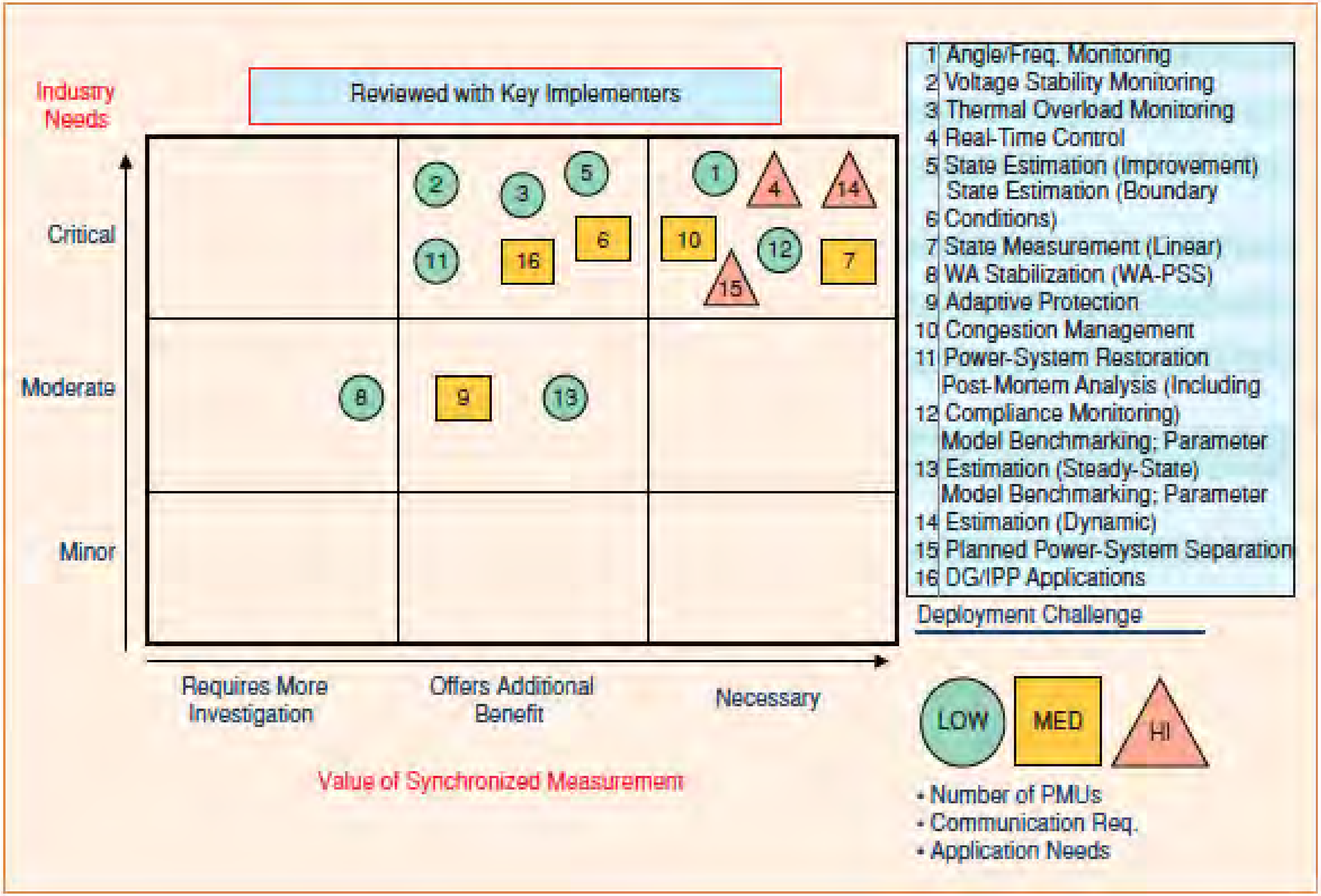
PMU Measurements

- High resolution data
- Synchronized data (angle measurements)
- Estimation may help with data accuracy (unless better quality CT and PT)
- System monitoring is more critical during disturbance and transients. Faster synchronized data is needed to capture the dynamics




Phasor Measurement Units in North American Power Grid
British Columbia
Alberta
Saskatchewan
Manitoba
Ontario
Québec
New Foundland
New Brunswick
Nova Scotia
Washington
Oregon
California
Nevada
Idaho
Montana
Wyoming
Utah
Colorado
Arizona
New Mexico
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Texas
Minnesota
Iowa
Missouri
Arkansas
Louisiana
Wisconsin
Illinois
Michigan
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
West Virginia
New York
Pennsylvania
New Jersey
Maryland
Deleware
Maine
Vermont
New Hampshire
Massachusetts
Rhode Island
Connecticut
Legend
PMU Locations
Data Concentrators
With information available as of October 17, 2013

Synchrophasor Technology Applications



Source: Novosel, 2008

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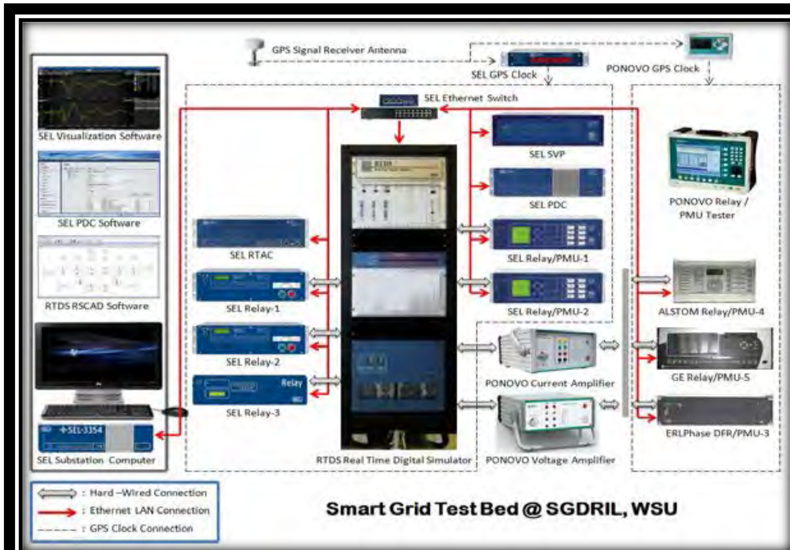
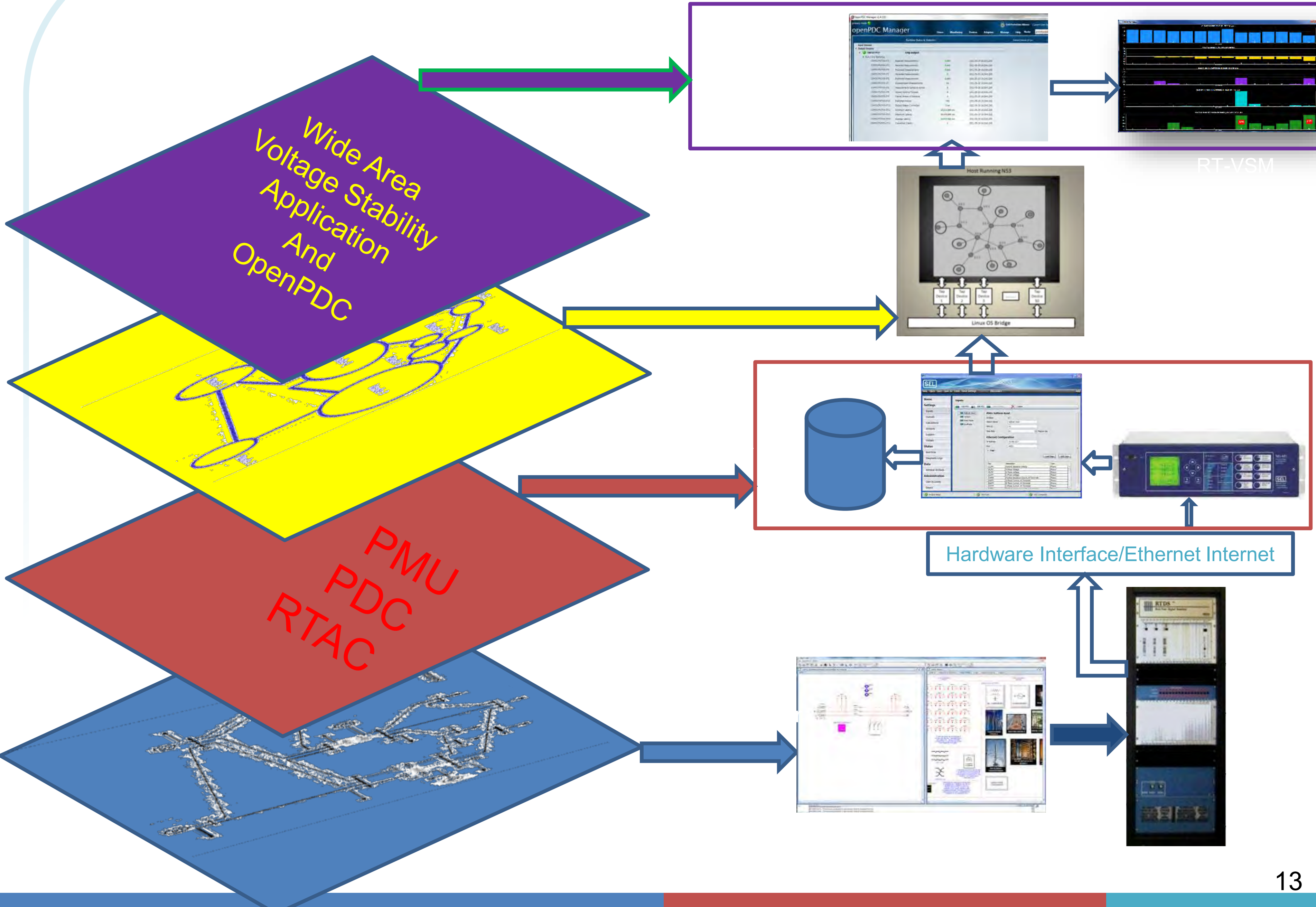
Real Time Test Bed

a) Real Time Digital Simulator
b) Master Computer
c) Hardware and software PMUs
d) Software & Hardware PDCs
e) Synchrophasor Vector Processor (SVP)
f) Real Time Automation Controller (RTAC)
g) GPS Clocks
h) Ethernet Hub
i) Amplifiers
j) Communication modeling tools
k) Different Software Tools

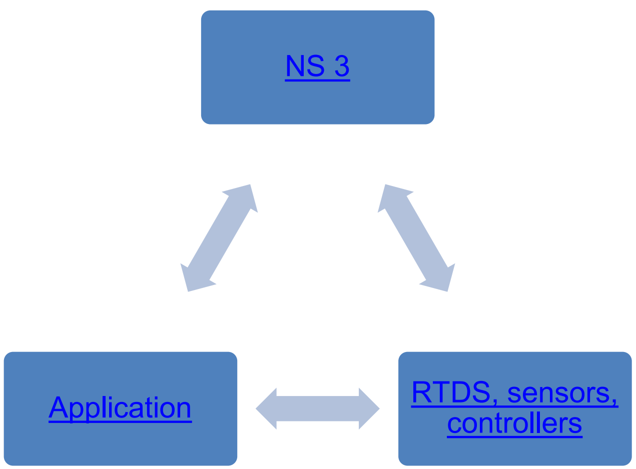


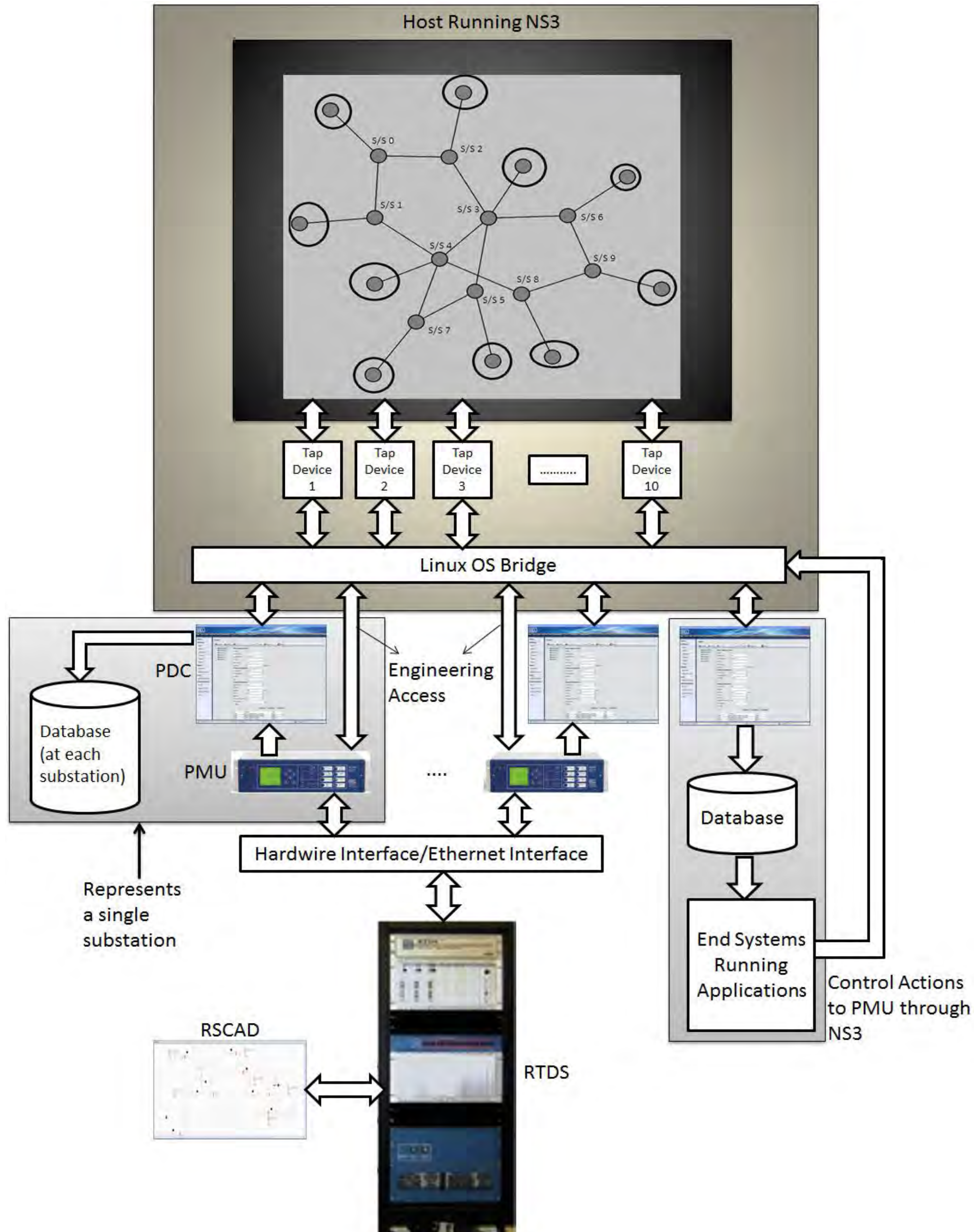
Cyber-Physical Test Bed



Architecture of Test Bed

Real time end to end modeling and simulation





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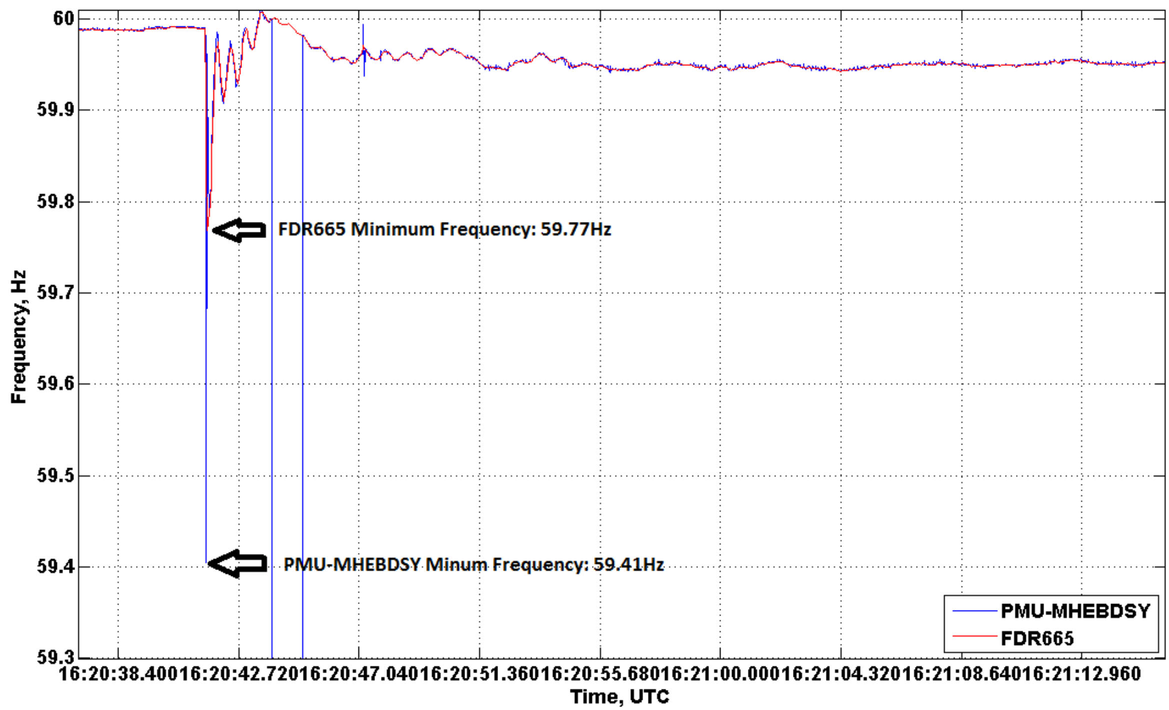
Synchrophasor Device Testing

☑ Testing of PMU is required before putting in the field

☑ PMU testing is required to compare between options and design next generation PMU

☑ PMU testing require accuracy testing following IEEE standard C37.118.1 under different conditions



Frequency Estimation at Manitoba by PMU & FDR

PMU Testing and Analysis

(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

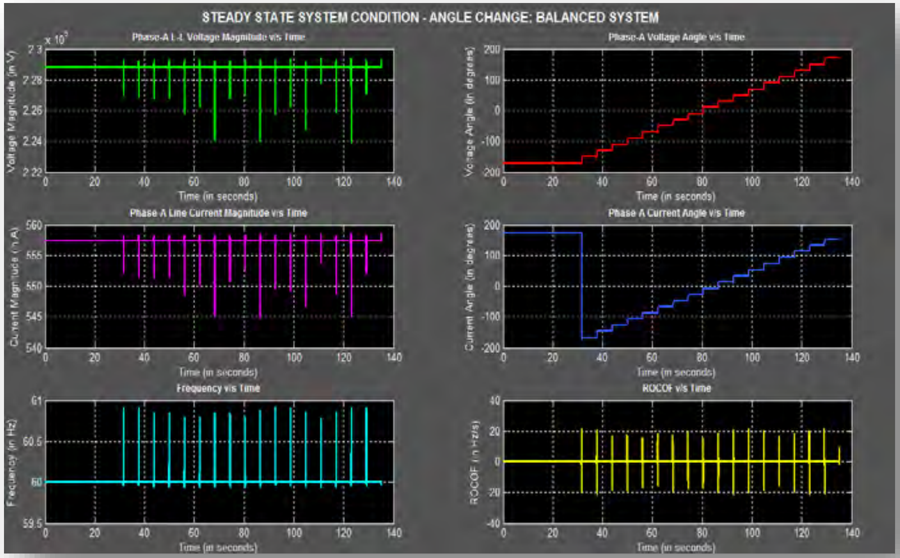
(1) It is an automated analysis tool for analyzing the performance of the test PMU under different test conditions

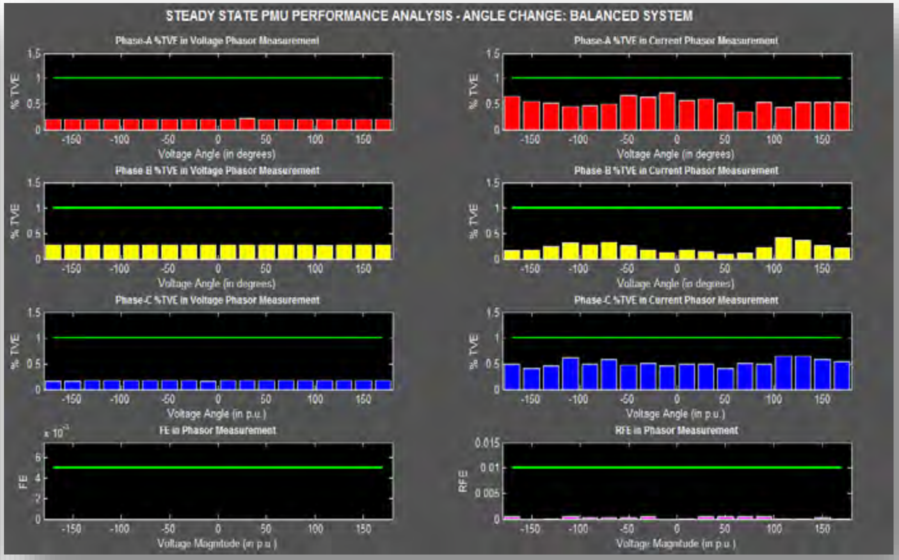
(2) It works with a Phasor Data Concentrator (PDC) and the Real Time Digital Simulator (RTDS)

Note – Substitute for the RTDS:

(i) High quality analog signal generator

(ii) High quality PMU (simulated / hardware)





PMU Performance Analyzer

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

(2) Automatically tracks the changes in the test conditions and finds the suitable data for test analysis

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

(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 printer-friendly test report for the PMU instantly after the completion of test analysis

PMU Performance Analyzer

Parameters	PMU Performance Analyzer (Version – PPA.2014.1)
No. of Tests	760
Reporting Rates supported by tool	10, 12, 15, 20, 25, 30, 50, 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)

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	

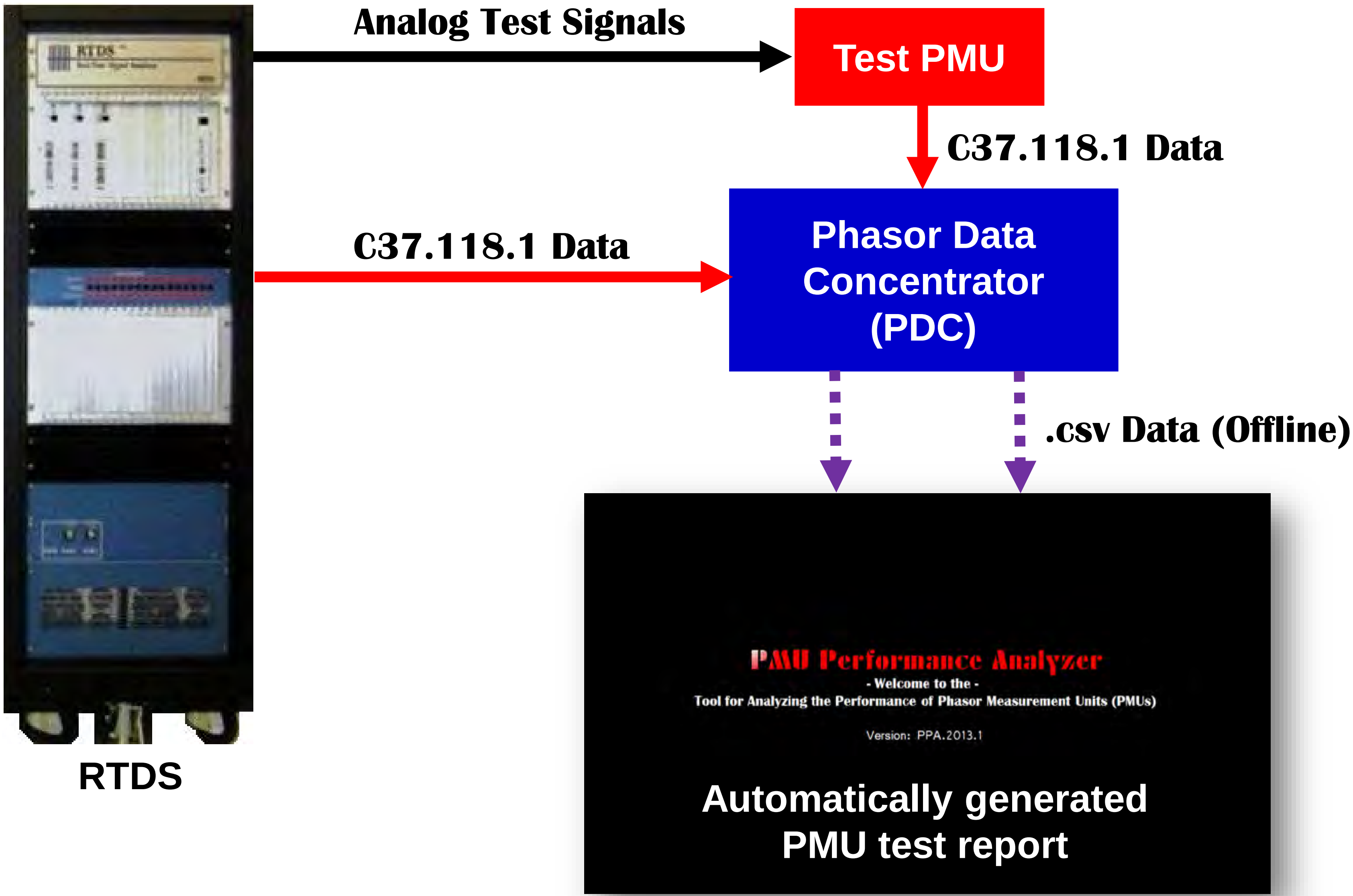
Test Suites for PMU Performance Analysis

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	Method using *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*

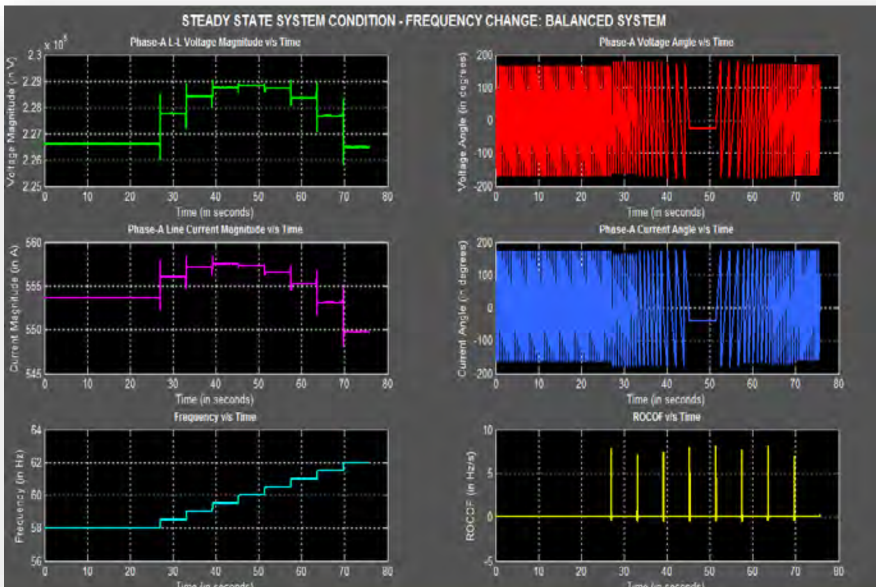


An Example of Steady State Test and Result

→ Quantity changed: Frequency

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

Test Condition



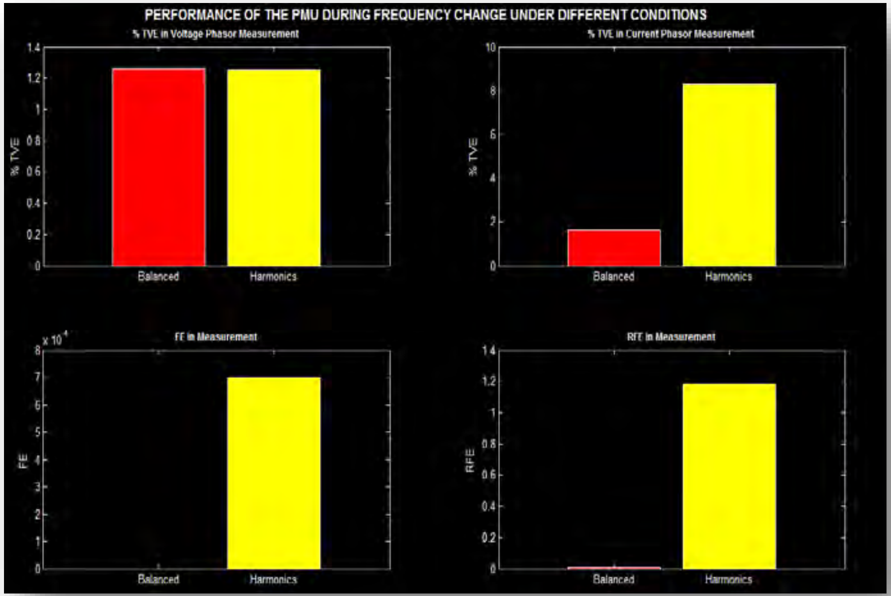
Test Results

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

An Example of Change in System Condition

→ Quantity changed: Frequency

→ System condition during the change: With & Without Harmonics



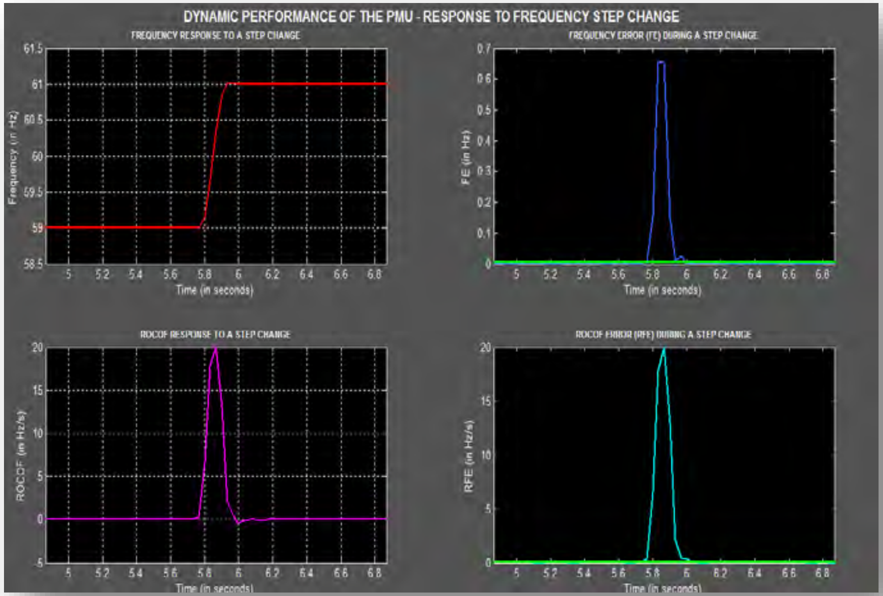
→ PMU performance varies drastically with system conditions for the same variation in the changing quantity

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

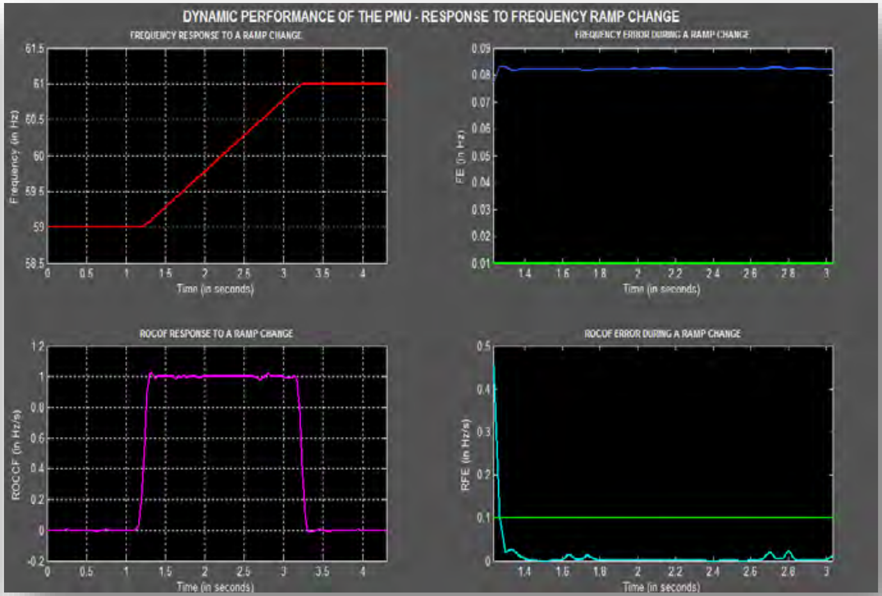
An Example of a Dynamic Test and Result

→ Quantity changed: Frequency

Step Change in Frequency



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:

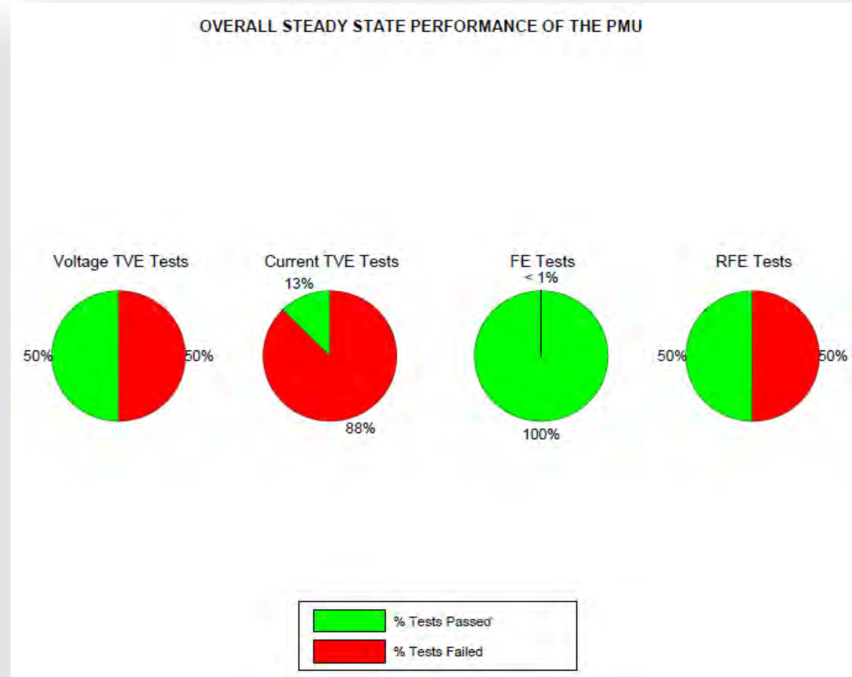
Average TVE of Phase-A (in percentage)	Average TVE of Phase-B (in percentage)	Average TVE of Phase-C (in percentage)	Standard Deviation of TVE of 3 Phases (in percentage)
0.198	0.268	0.172	0.042

[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

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Testing of Synchrophasor Applications

- ☑ Testing of applications is required before putting in the field
- ☑ Application testing allow choosing right algorithms for specific application
- ☑ Application testing requires cyber-physical model for synchrophasors
- ☑ Real hardware PMU or modeling of phasor estimation is required
- ☑ Voltage stability tool is used as an example application for testing

Real Time 'Monitoring Module' of RT-VSMAC

Common Approaches for Online Static Analysis of Voltage Stability

Multiple Power-flow based Approach

Measurement Window based Approach

(1) Limitation of 'Multiple Power-flow' based approaches –

- (a) Computationally burdensome
- (b) Not fast enough for real time applications

(2) Limitations of 'Measurement Window' based approaches –

- (a) Not accurate with the changing system states
- (b) Following assumption may not be valid during the window period –
    - (i) Need the load side parameters to change, and
    - (ii) System side to remain constant

Real Time 'Control Module' of RT-VSMAC

Common Approaches for Steady State Control of Voltage Stability

Centralized Control Approach

Decentralized Control Approach

(1) Limitations of 'Centralized' approaches –

(a) Not fast enough for real time applications

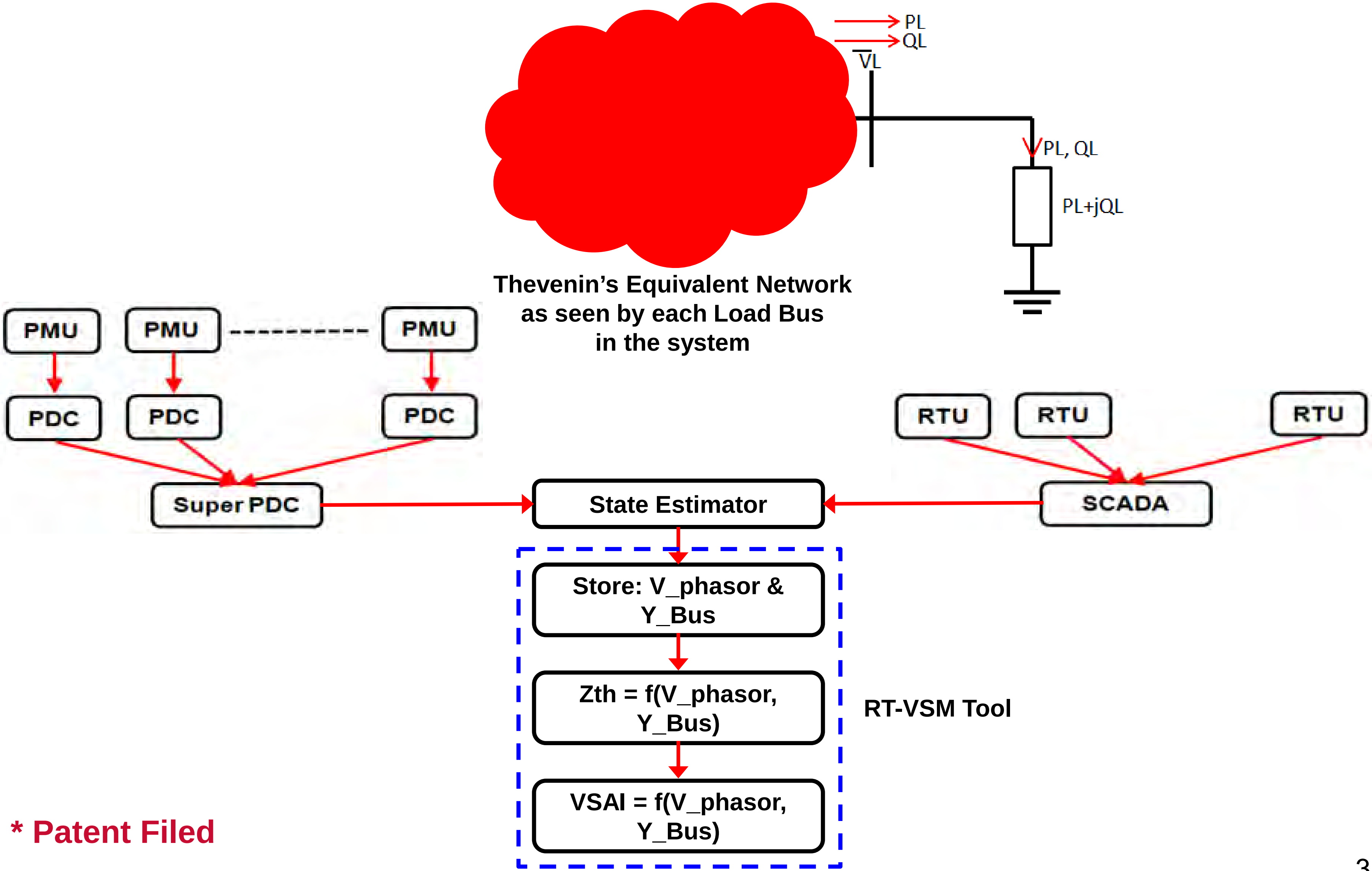
(b) Control actions are highly dependent on mathematical models, which may lead to inaccuracy

(2) Limitations of 'Decentralized or Local' approaches –

(a) May not be accurate as they are based on local measurements only

(b) Wide area coordination of control devices not easy

Voltage Stability Monitoring Algorithm based on 'System-Centric Thevenin's Equivalent'



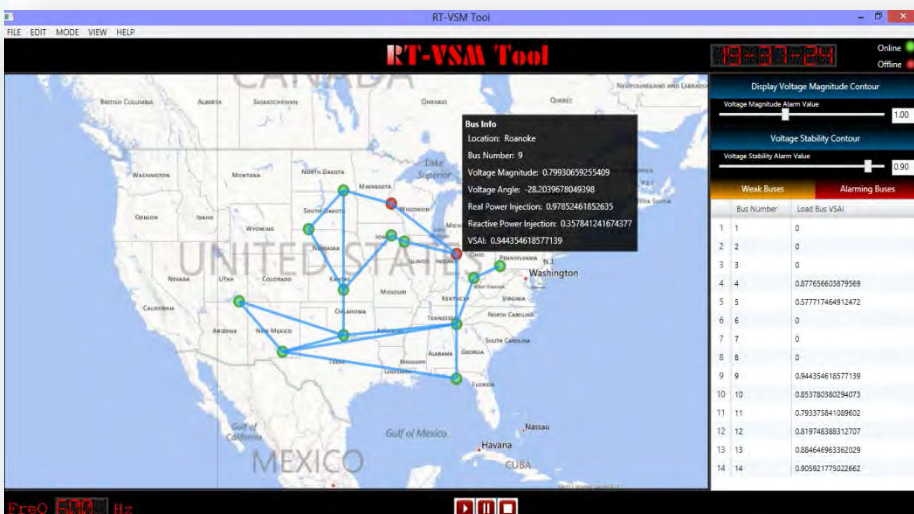
*** Patent Filed**

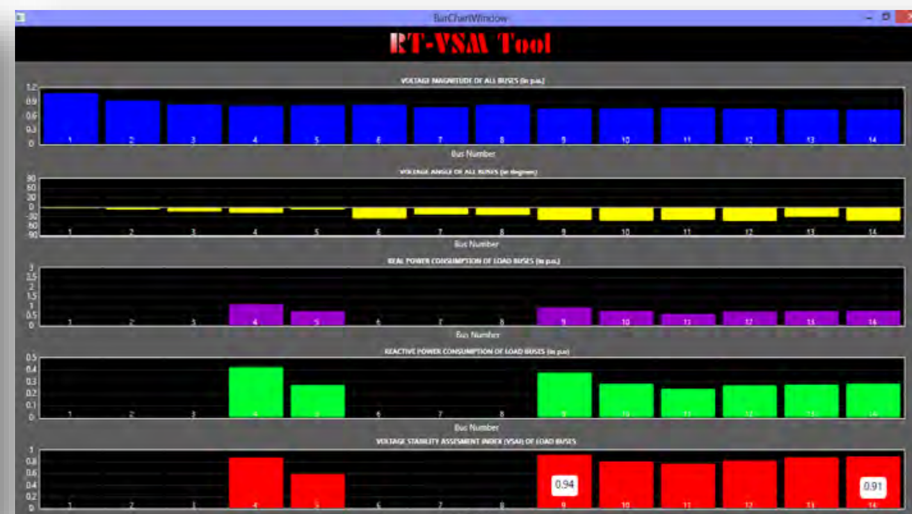
RT-VSMAC

(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) 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





RT-VSMAC Monitoring Module

(1) Computes the following –

→ "Easy-to-interpret" index for voltage stability status of the load buses.

VSAI near "0" indicates: Highly voltage stable

VSAI near "1" indicates: On the verge of voltage collapse

→ Voltage angle separation

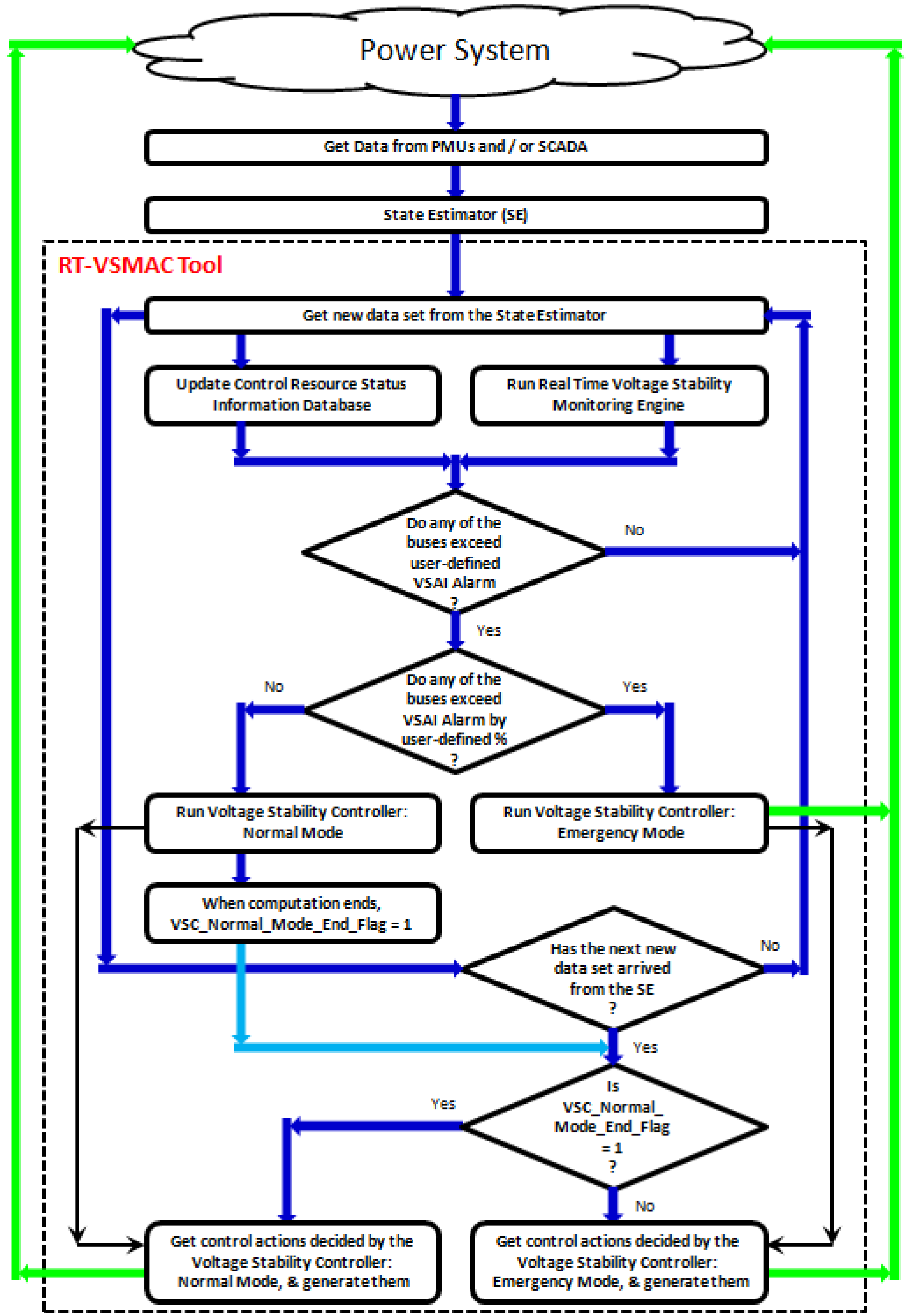
→ Real and reactive power injections at all the buses

→ Real and reactive power flows in all the lines

(2) Provides a simple and yet comprehensive visualization of key metrics to the system operators

(3) Provides multiple dynamic alarm setting features to the system operators

RT-VSMAC Control Module



RT-VSMAC Control Module

(1) Voltage Stability Controller: Normal Mode – to control voltage stability of a system with minimum number of control actions

(2) Voltage Stability Controller: Emergency Mode – to control voltage stability of a system in minimum time, and hence this mode is 'non-iterative' in nature

(3) Both the modes in the control module can strategize the coordination of the assets according to their availability and real time status –

→ Transformer automatic load tap changer blocking at the selected buses

→ Local & Remote shunt reactive power compensation at the selected buses

→ Generator reactive power compensation at selected buses

→ Series reactive power compensation at selected lines

→ Local & Remote Line Switching between selected buses

→ Local & Remote load-shedding at selected buses

RT-VSMAC Control Module

The control module has 2 sub-modules for the control action

→ Control Action Activation Sub-module (CAAS) – Activates the previously strategized coordinated control actions in steps based on real time feedback from actual system measurements

→ Control Action Deactivation Sub-module (CADS) – Once, the CAAS has acted in steps to successfully enhance the voltage stability status at the targeted weak buses, the CADS deactivates the previously activated control actions in steps based on real time feedback from actual system measurements

→ Automatic Hunting Detection Sub-module (AHDS) – To detect if there is any hunting between CAAS & CADS

Provides a simple visualization of the real time status of all the control devices for voltage stability control to the operators

Data Requirements for RT-VSMAC

(1) Data requirements for ‘monitoring module’ –

→ Voltage phasors at the buses in the system

→ Topological information of the system, i.e. branch data

(2) Data requirements for ‘control module’ –

→ Status of the control devices (for voltage stability control) available in the system that include:

(a) Transformer automatic load tap changer blocking

(b) Shunt reactive power compensation devices

(c) Series reactive power compensation devices

(d) Generator reactive power and their limits

(e) Load priority for application of the load-shedding scheme

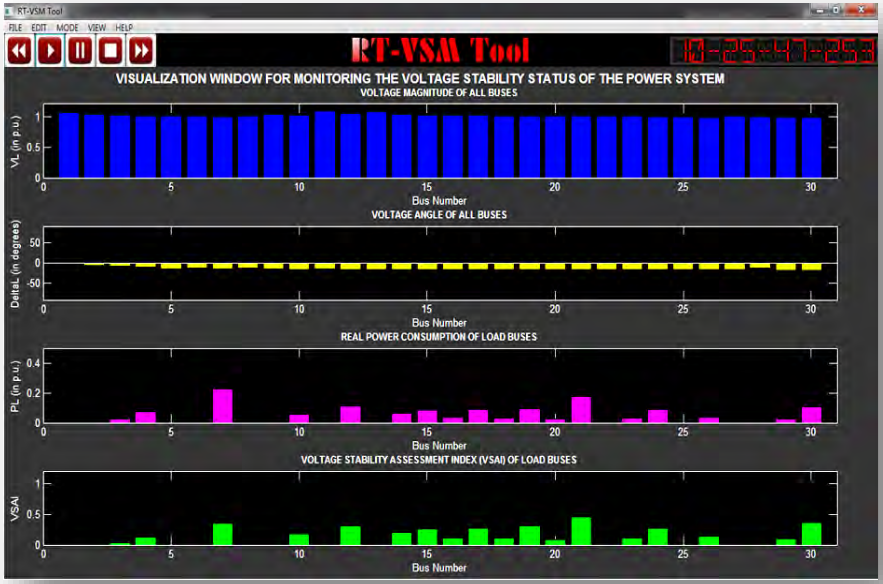
(f) Availability of line switching of extra lines

Simulation Results for Monitoring Module

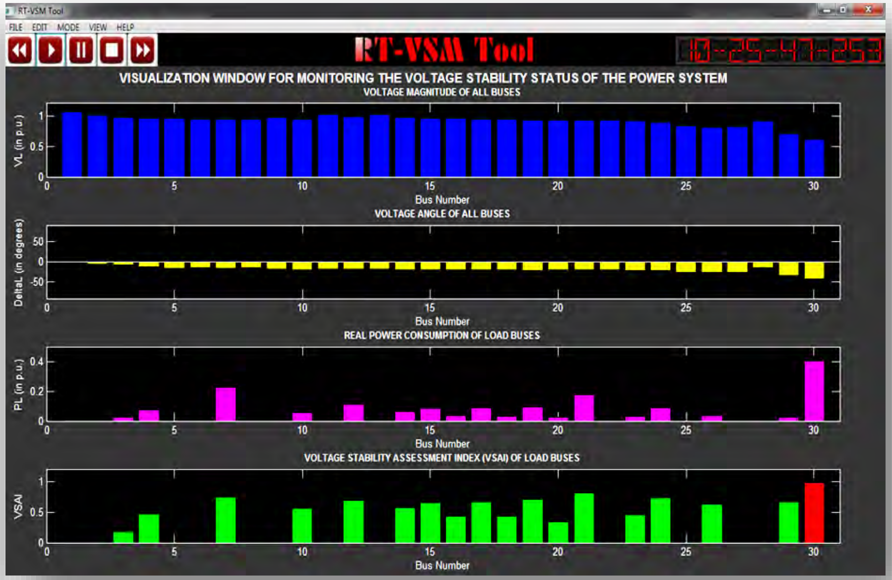
Decrease in voltage stability due to increase in load (i.e. a type of small disturbance voltage stability issue) –

→ Increase in load at Bus-30 in the IEEE-30 Bus test case:

Base Case Loading



Stressed Case Loading



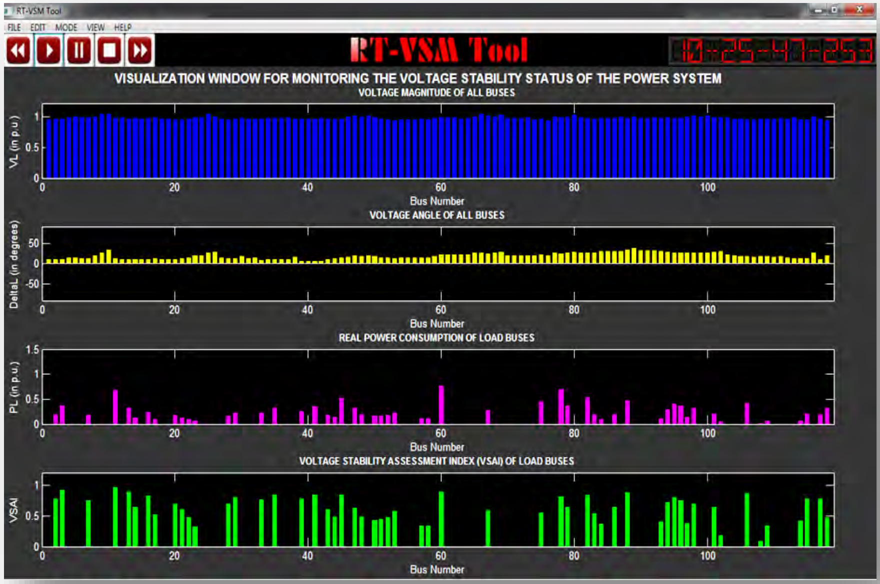
→ Increase in VSAI at the load buses indicate decrease in voltage stability

→ Power-flow fails to converge when the highest VSAI in the system is 0.985 (@ Bus-30)

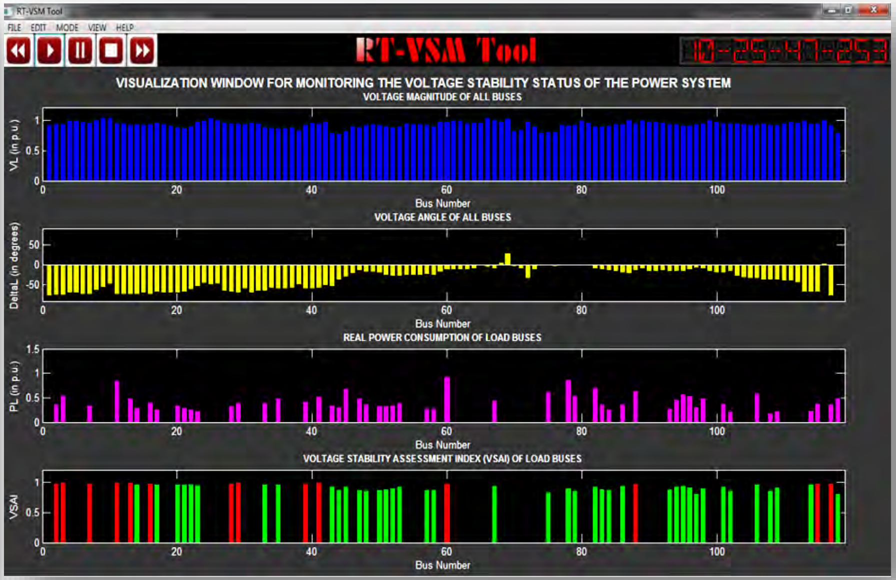
Simulation Results for Monitoring Module

→ Increase in load at all the load buses in the IEEE-118 Bus test case:

Base Case Loading



Stressed Case Loading



→ Increase in VSAI at the load buses indicate decrease in voltage stability

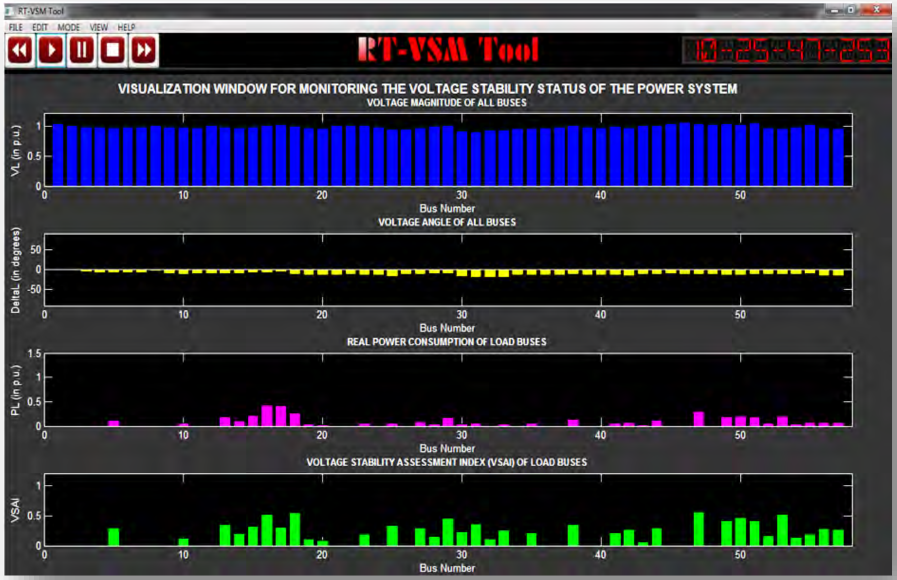
→ Power-flow fails to converge when the highest VSAI in the system is 0.995 (@ Bus-11)

Simulation Results for Monitoring Module

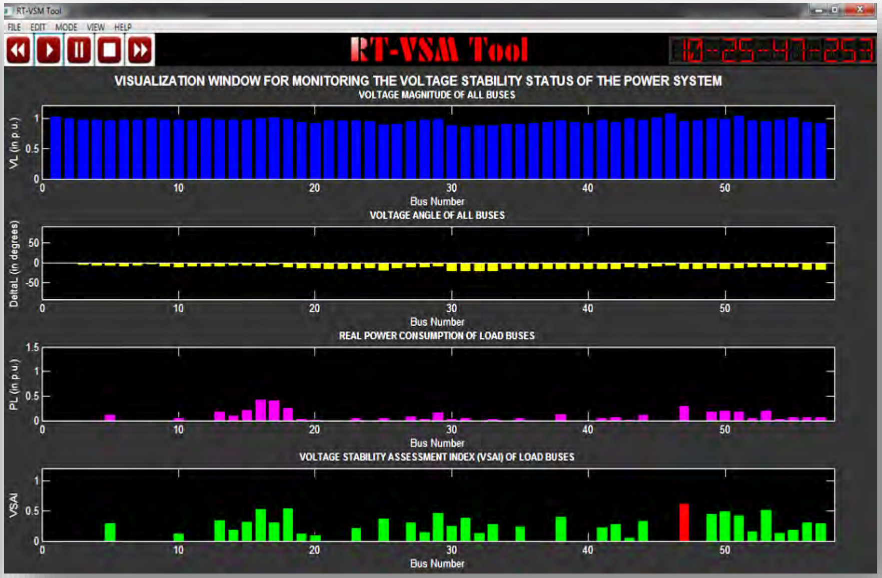
Decrease in voltage stability due to contingency (i.e. a type of large disturbance voltage stability issue) –

→ Tripping of Line 46-47 in the IEEE-57 Bus test case:

Before Contingency



After Contingency



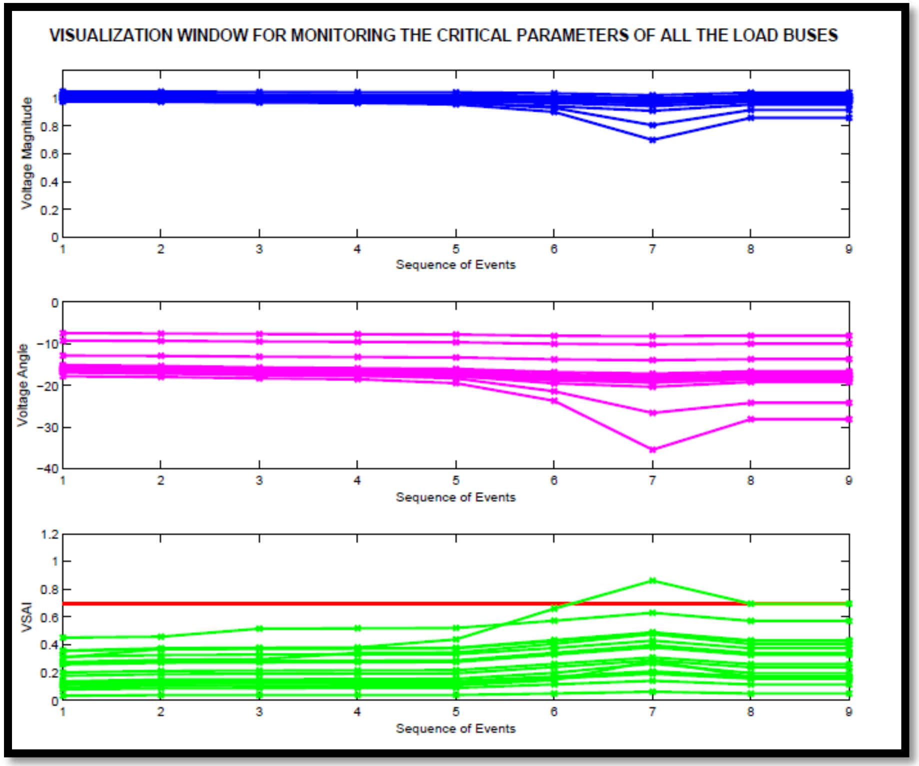
→ Increase in VSAI at the load bus 47 (from 0.57 to 0.62) indicate a slight decrease in voltage stability

→ Continuation Power-flow also shows a slight reduction in distance to point of collapse after the contingency

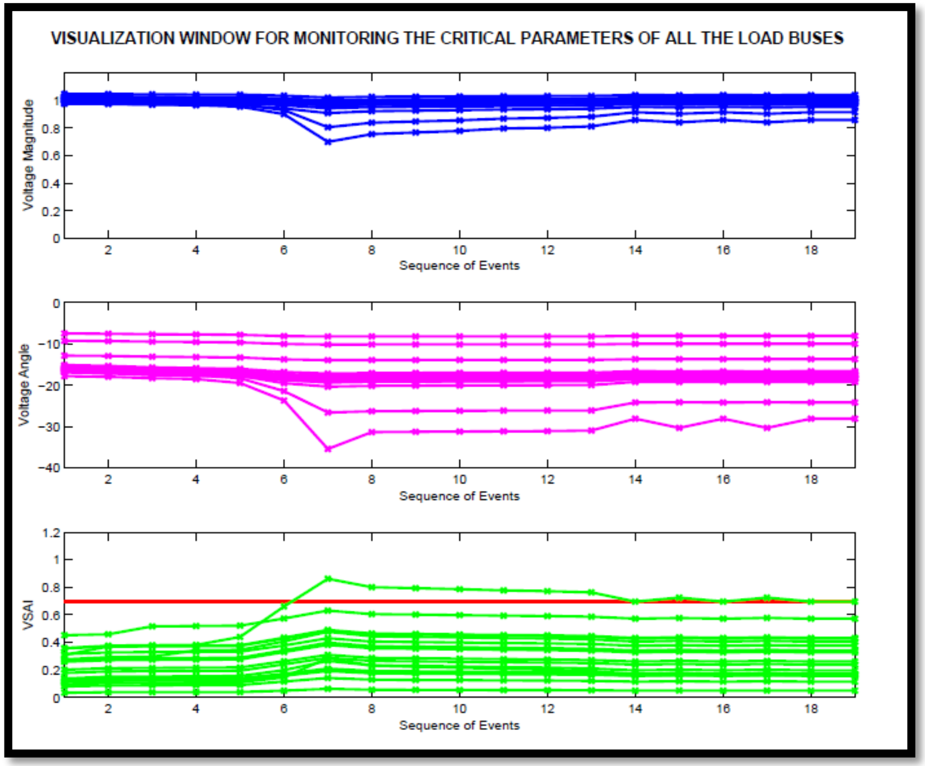
Simulation Results for Control Module

→ Voltage stability problem caused by gradual increase in load at buses in an area followed by line tripping (IEEE-30 Bus, VSAI limit = 0.70)

Control by: Normal Mode



Control by: Emergency Mode



→ Load Buses violating VSAI limit before control: Bus-30

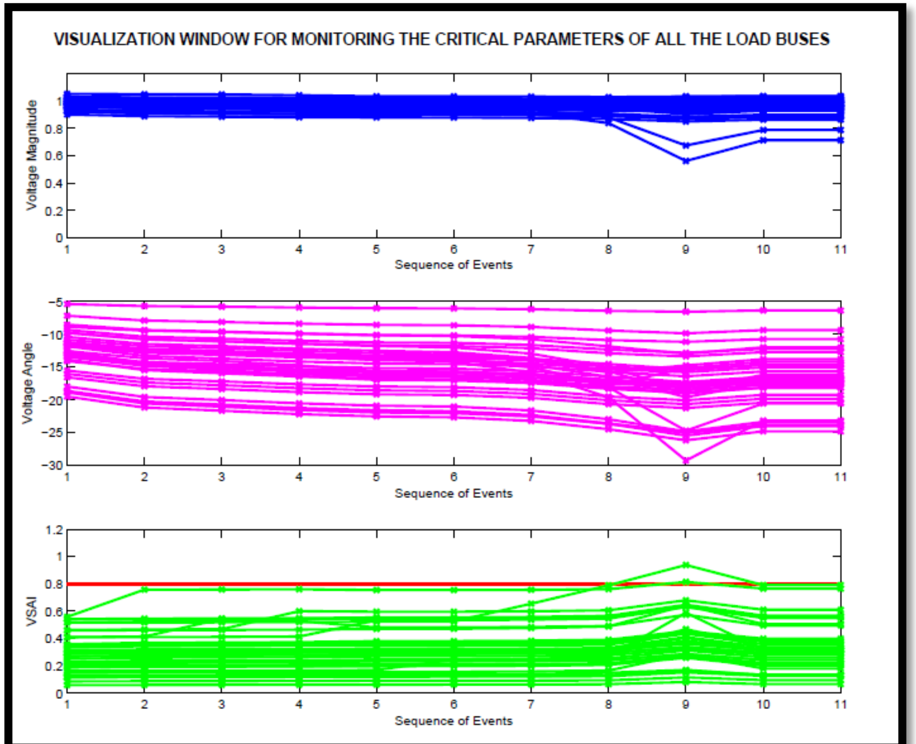
→ Weakest load bus VSAI before control: 0.8614

→ Weakest load bus VSAI after control: 0.6959

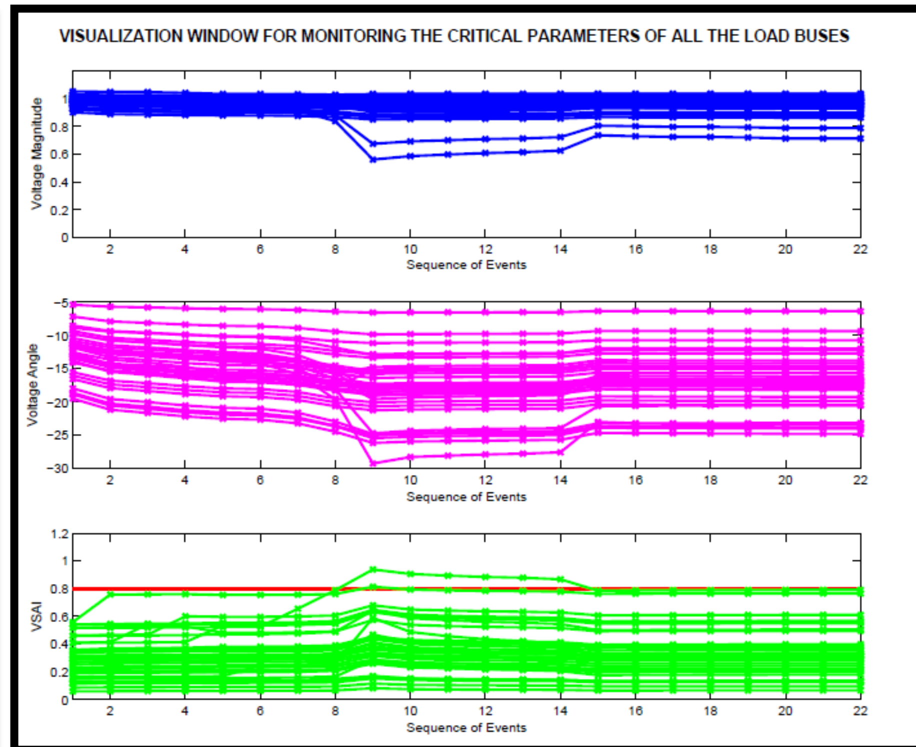
Simulation Results for Control Module

→ Voltage stability problem caused by gradual increase in load at buses in an area followed by line tripping (IEEE 57, VSAI limit=0.80)

Control by: Normal Mode



Control by: Emergency Mode



→ Load Buses violating VSAI limit before control: Bus-53 & Bus-47

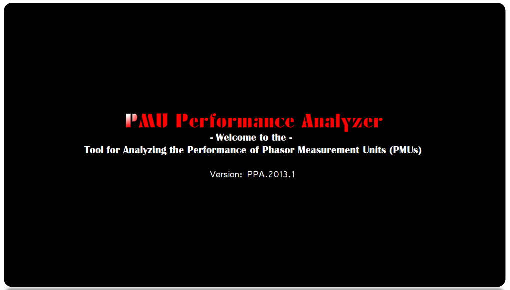
→ Weakest load bus VSAI before control: 0.9379

→ Weakest load bus VSAI after control: 0.7906

Outline

- Synchrophasor Applications for the Smart Electric Grid
- Real Time Monitoring and Control Test Bed
- PMU Performance Analyzer (PPA)
- Real time Voltage Stability Monitoring and Control (RT-VSMAC)
- Summary

Summary



- ☑ Synchrophasor device and application testing is critical
- ☑ Real time monitoring and control test bed has been developed to perform the testing
- ☑ A new PMU performance testing tool has been developed. PPA can perform testing and reporting in very short time
- ☑ A new real time voltage stability monitoring and control tool ‘RT-VSMAC Tool’ has been developed. The developed algorithm is non-iterative for monitoring as well as control
- ☑ Results of testing RT-VSMAC for different IEEE test cases have been discussed

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