Energy Systems Innovation Center

Making Dynamic Simulations Output Comparable to Synchrophasor Measurements of PMUs

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Washington State University World Class. Face to Face.

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EPRI Electric Power Research Institute

Outline

- **Introduction to PMU based model validation**
- **Motivation and goals for this study**
- **Test system benchmarking in RTDS and Dynamic Simulators**
  - Test system model
  - Steady state response
  - Dynamic response
- **Hardware in the loop benchmarking and PMU filtering effect**
  - Disturbance test scenarios and results
  - Dynamic compliance validation and results
- **Summary**

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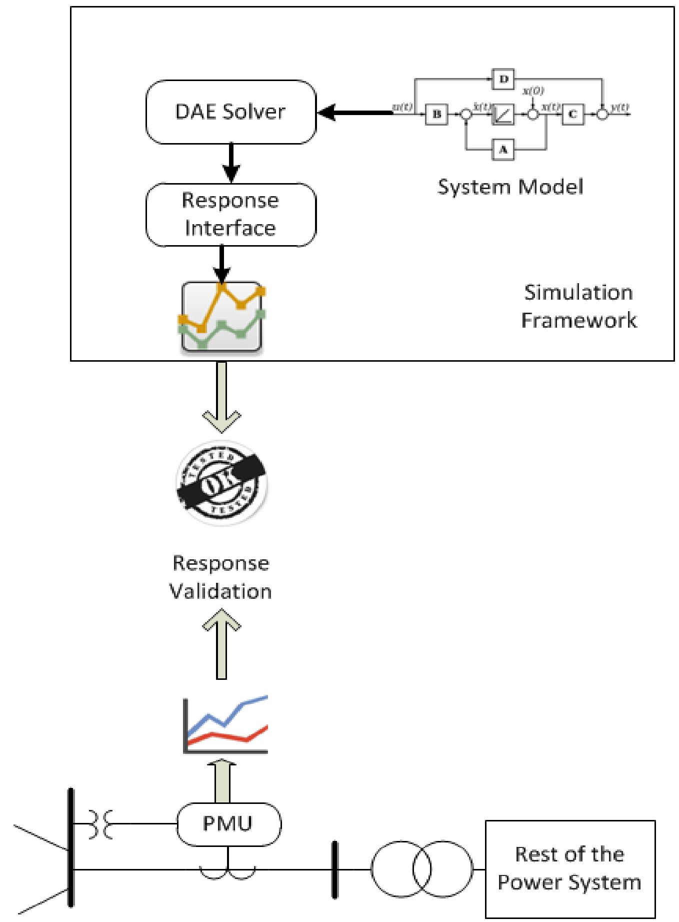
Introduction to PMU Based Model Validation

Number of applications for PMU based model validation:

- Validation of Power Plant Models (PPPD), Renewable Energy Models (REMV), Static Var System Models (SVSMV) - (EPRI)
- Validating Generator model using PPMV (BPA)
- Model validation of HVDC and Nuclear Unit (ISO-NE)
- Tuning Wind Turbine model (ERCOT)
- Load Model validation (WECC)

Better model leads to better analysis, Understanding interaction of components, Improve situational awareness and Higher resource utilization

Typical Schematic for PMU based model Validation



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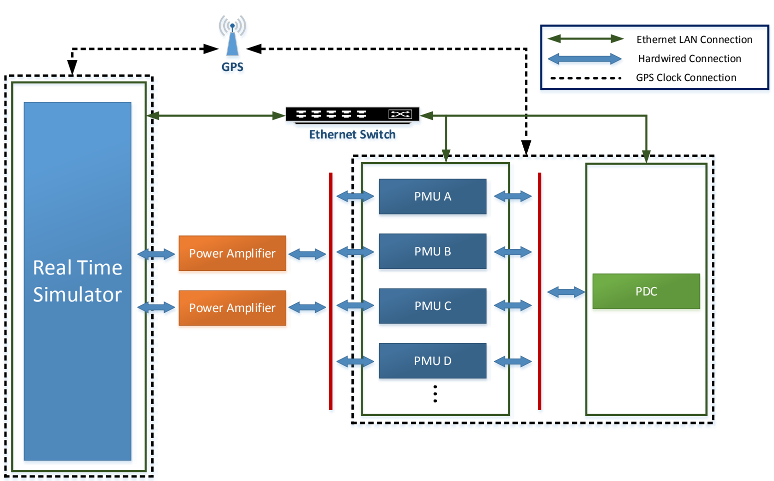
Motivation for this study

The phasor values obtained from dynamic simulation tools and PMUs in the field may differ due to:

- The filters used in the PMU may introduce magnitude attenuation and phase offset
- The results from phasor domain simulations do not result from estimation algorithm from a point of wave signal
- PMU may use several cycle data to obtain the phasor at any instant. Hence, estimated phasor by PMU is representative of several preceding cycles.

Goals for This Study

- Test system benchmarking by matching response from RTDS and Electromechanical Dynamics Simulation Platform
- Analyzing effect of PMU filtering and estimation by comparing RTDS+PMU with Dynamics simulation platform



Test Bed @ Washington State University

PMU Performance Analyzer

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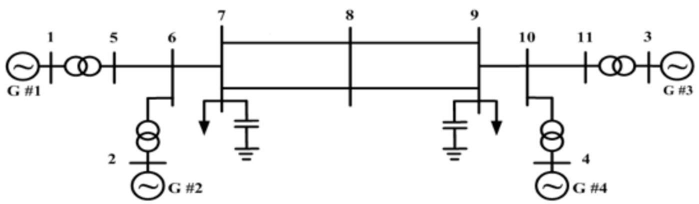
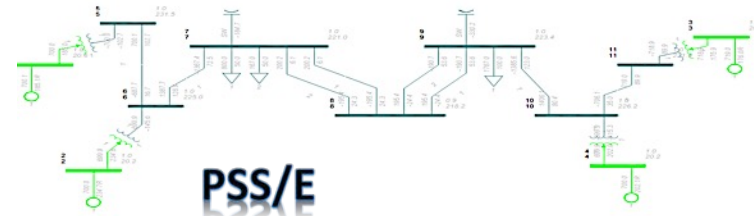
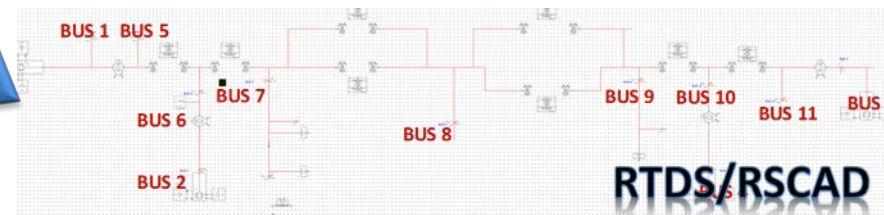
Test System Benchmarking in RTDS and Dynamic Simulators

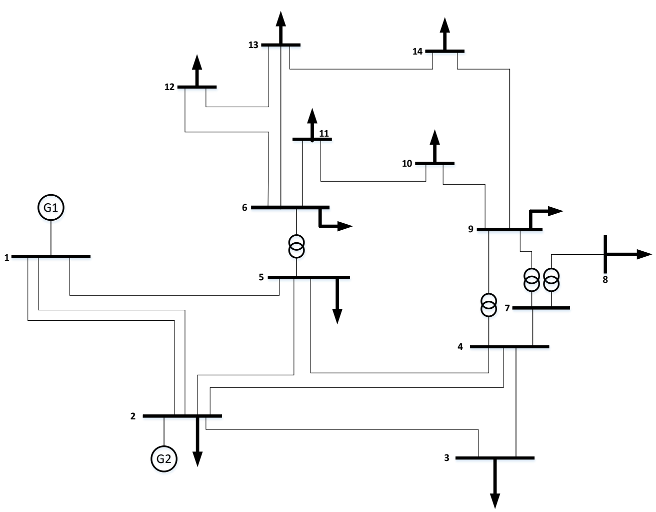
Test System Model: Kundur System

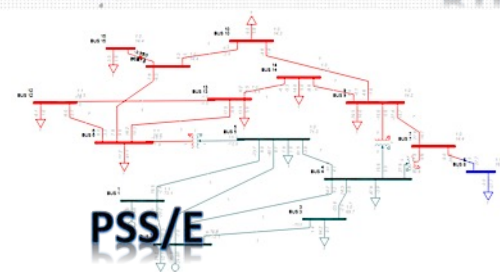


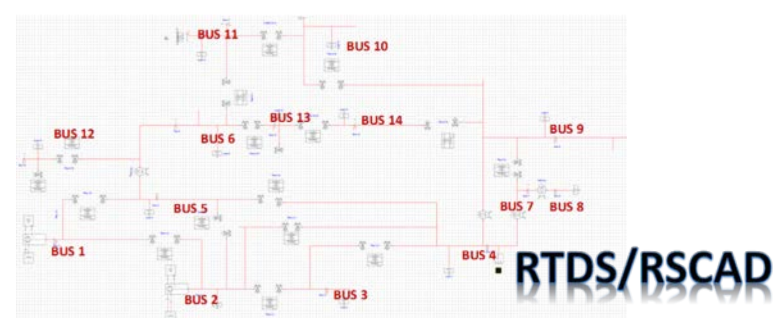




Test System Model: IEEE 14 System



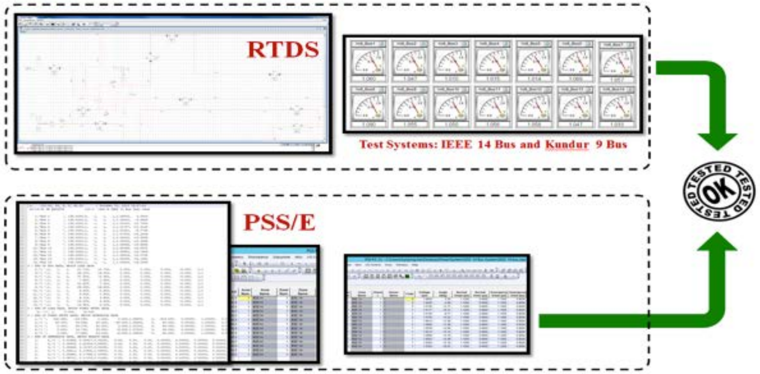




Test System Benchmarking in RTDS and Dynamic Simulators

- The voltage magnitude and angle at each bus are obtained from the power flow solution of the test systems in both PSS/E and RTDS.
- Total Vector Error (TVE) gives a measure of the mismatch between the voltage phasors obtained from the RTDS and PSS/E, by considering the phasors generated from RTDS as the true value.

$$TVE_{PF} = \frac{\left|\overline{V}_{PSSE\_PF} - \overline{V}_{RTDS\_PF}\right|}{\left|\overline{V}_{RTDS\_PF}\right|}$$



Comparison between RTDS and PSS/E

where,

$\overline{V}_{PSSE\_PF}$: denotes the voltage phasors obtained from PSS/E power flow solution

$\overline{V}_{RTDS\_PF}$: denotes the voltage phasors obtained from RTDS power flow solution

Test System Benchmarking in RTDS and Dynamic Simulators

- According to the IEEE ICAP Synchrophasor Measurement Test Suite Specifications [1], the following two criteria are used as metrics to compare the response between the two platforms:
  - **Error at the Peak Point**
  - **Error at Settling Point**

$$\text{Magnitude Error} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_{RTDS} - P_{PSSE})^2}}{\sum_{i=1}^{N}(P_{RTDS})^2} + e$$

where,

N = Number of peak points and valley points

P_{RTDS}, P_{PSSE}=values at peak points and valley points

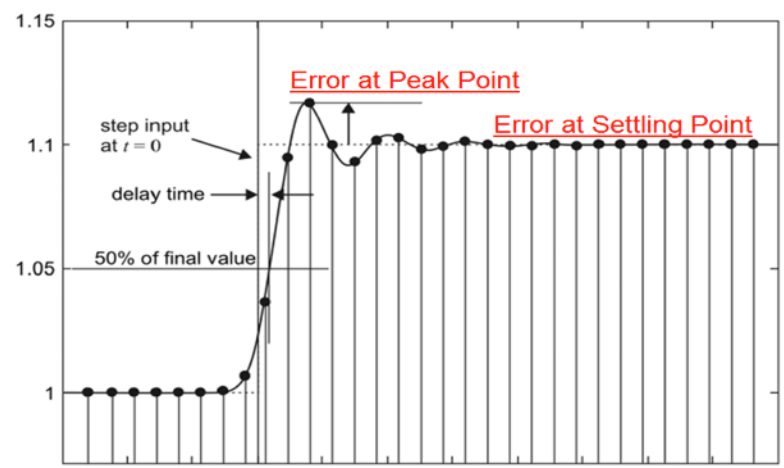
e = mismatch at settling point

$$\text{Time Error} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_{RTDS} - T_{PSSE})^2}$$

where,

N= Number of peak points and valley points

T_{RTDS}, T_{PSSE}=time at peak points and valley points



[1] “IEEE Synchrophasor Measurement Test Suite Specification," in *IEEE Synchrophasor Measurement Test Suite Specification”*, vol., no., 2014

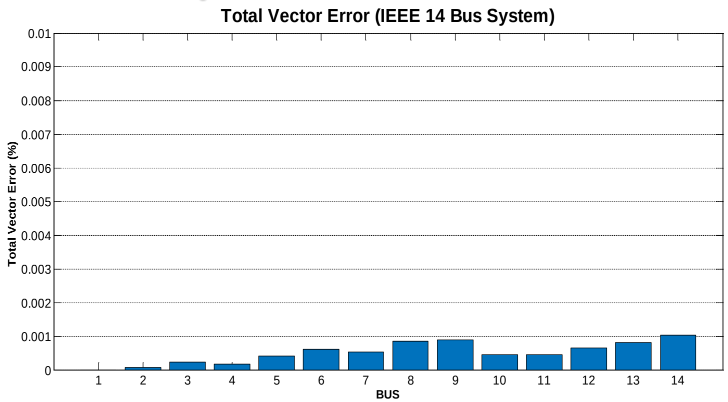
Test System Benchmarking in RTDS and Dynamic Simulators

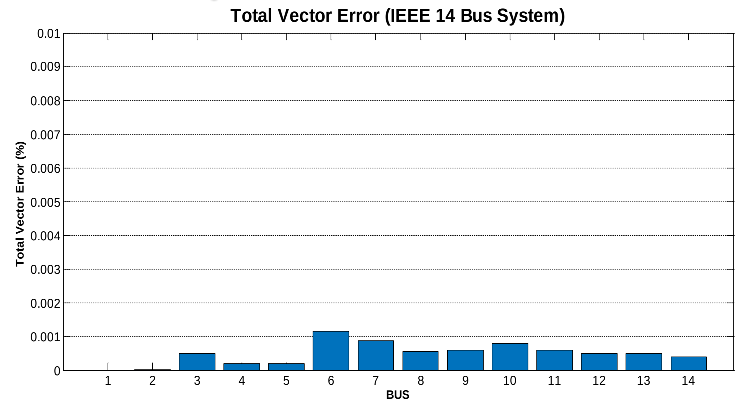
Steady State Response Results and Benchmarking

Operation Condition A

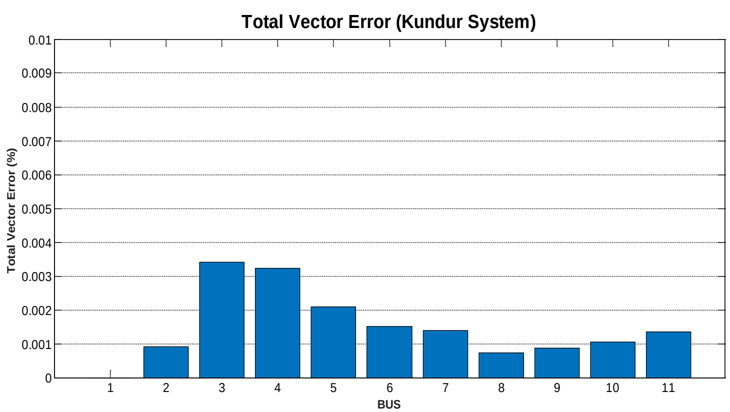
Operation Condition B

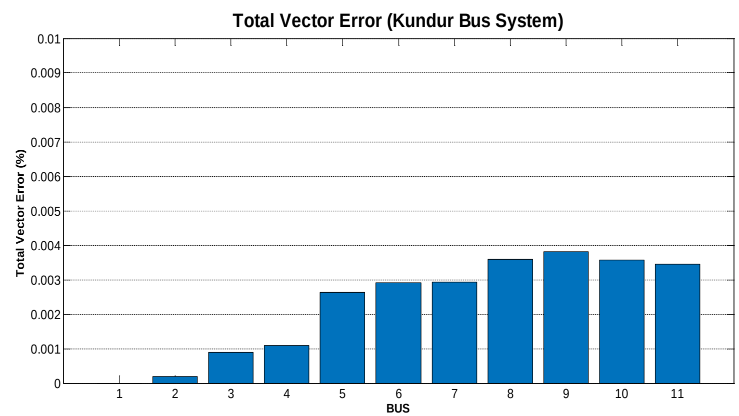
%TVE (IEEE 14)





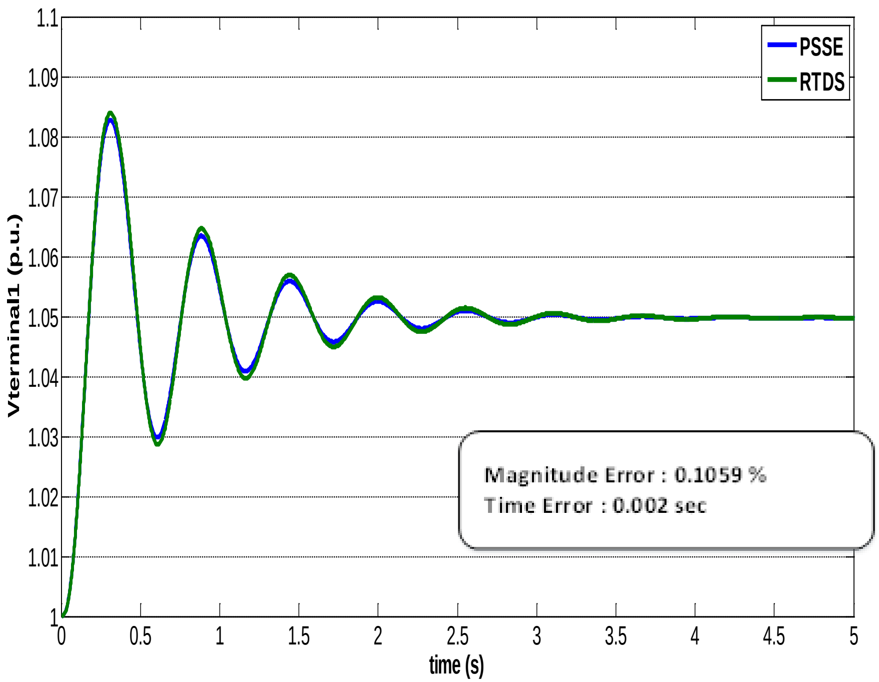
%TVE (Kundur)



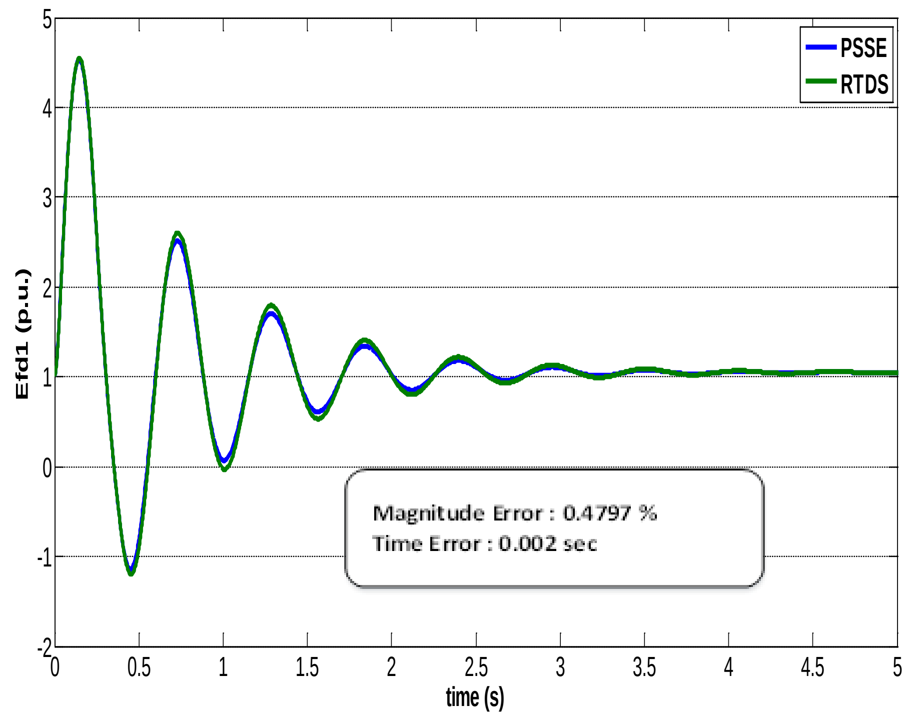


Test System Benchmarking in RTDS and Dynamic Simulators

Exciter Step Change Response of Generator 1



Terminal Voltage Magnitude of Generator 1

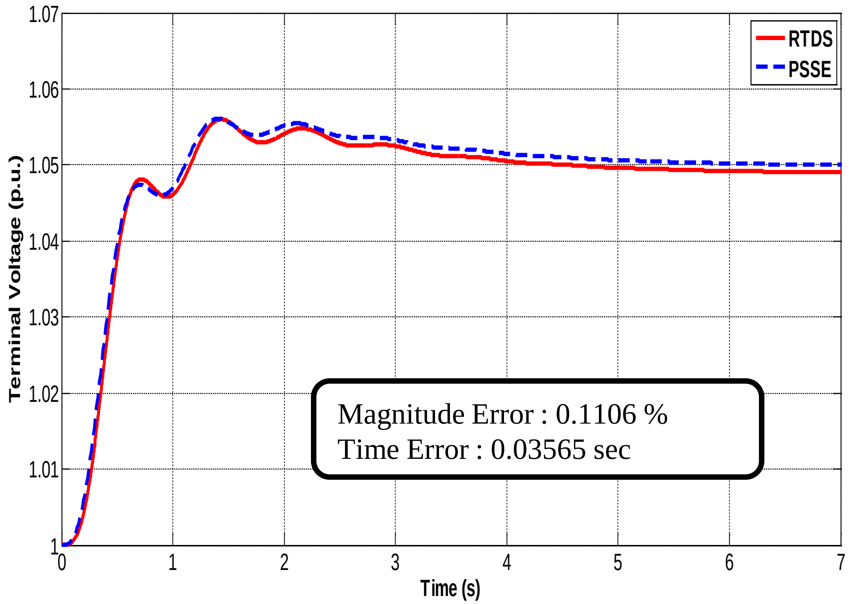


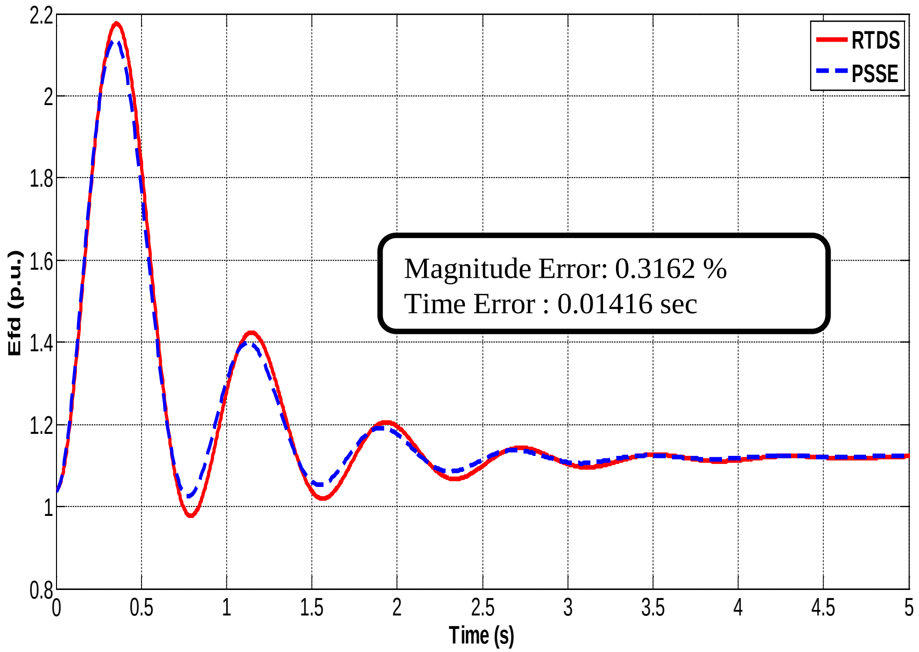
Field Voltage Magnitude of Generator 1

(IEEE 14)

Test System Benchmarking in RTDS and Dynamic Simulators

Exciter Step Change Response of Generator 1





Terminal Voltage Magnitude of Generator 1

Field Voltage Magnitude of Generator 1

(Kundur)

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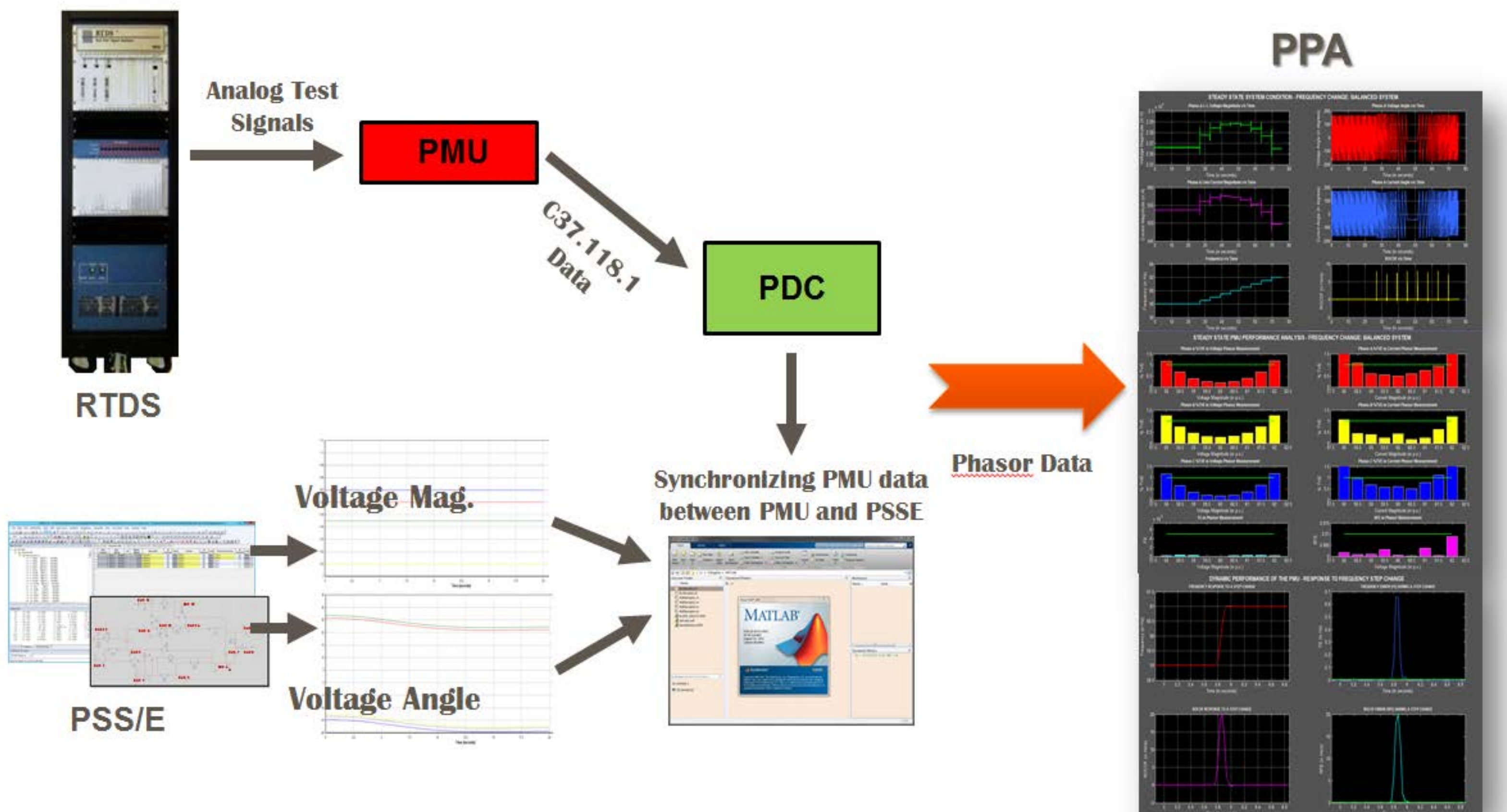
Hardware in the Loop Benchmarking and PMU Filtering Effect



Compare PSSE, RTDS and PMU's response

Hardware in the Loop Benchmarking and PMU Filtering Effect

- The Absolute Vector Error (AVE) was used as a metric to quantify the comparison between the PSS/E and RTDS simulation results and between the PSS/E simulation results and the measured responses from the PMUs.

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

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

- The Total Vector Error comparing PMU ‘x’ with PSS/E and RTDS with PSSE is also evaluated for the best and the worst PMU during the initial 0.2sec of the transient for the PMUs located at the generator bus for both the test system.

$$TVE_{PMUx\_PSSE} = \frac{\left|\bar{V}_{PSSE} - \bar{V}_{PMUx}\right|}{\left|\bar{V}_{PSSE}\right|} \times 100$$

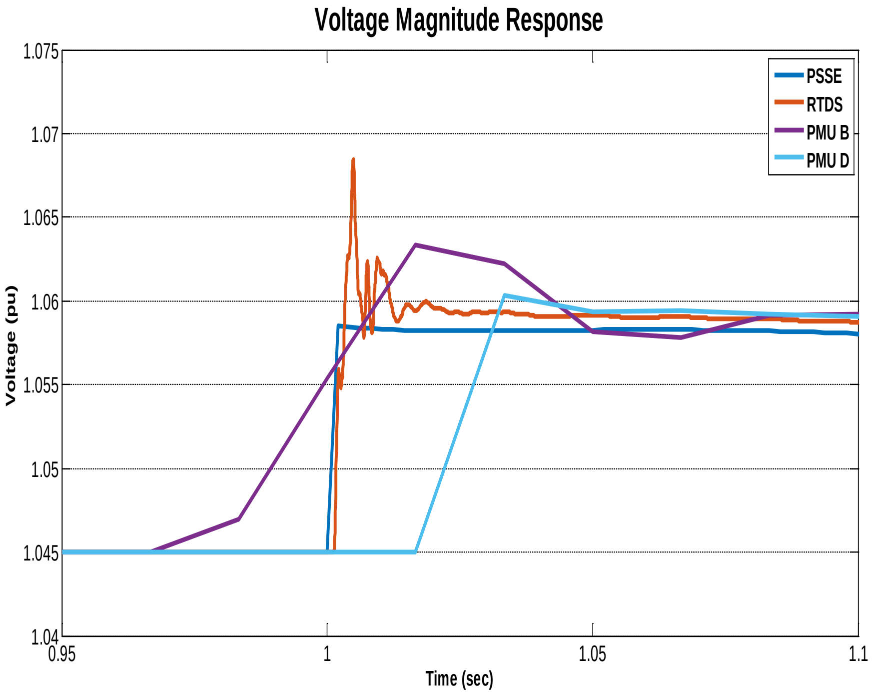
$$TVE_{RTDS\_PSSE} = \frac{\left|\bar{V}_{PSSE} - \bar{V}_{RTDS}\right|}{\left|\bar{V}_{PSSE}\right|} \times 100$$

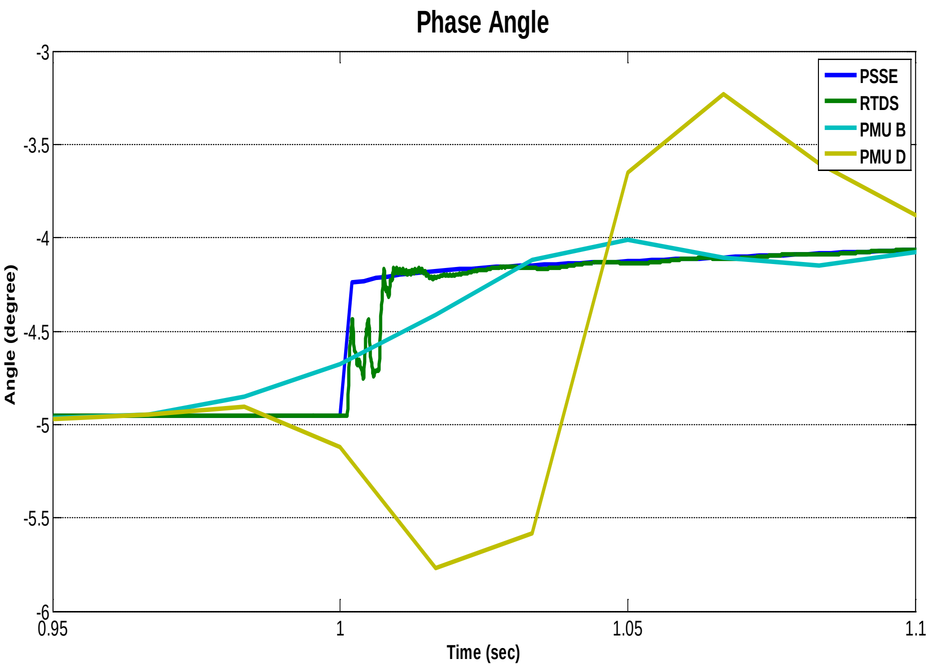
Four PMUs have been used in the experiments:

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

Hardware in the Loop Benchmarking and PMU Filtering Effect

IEEE 14 Bus system: Load Shedding at Bus 3



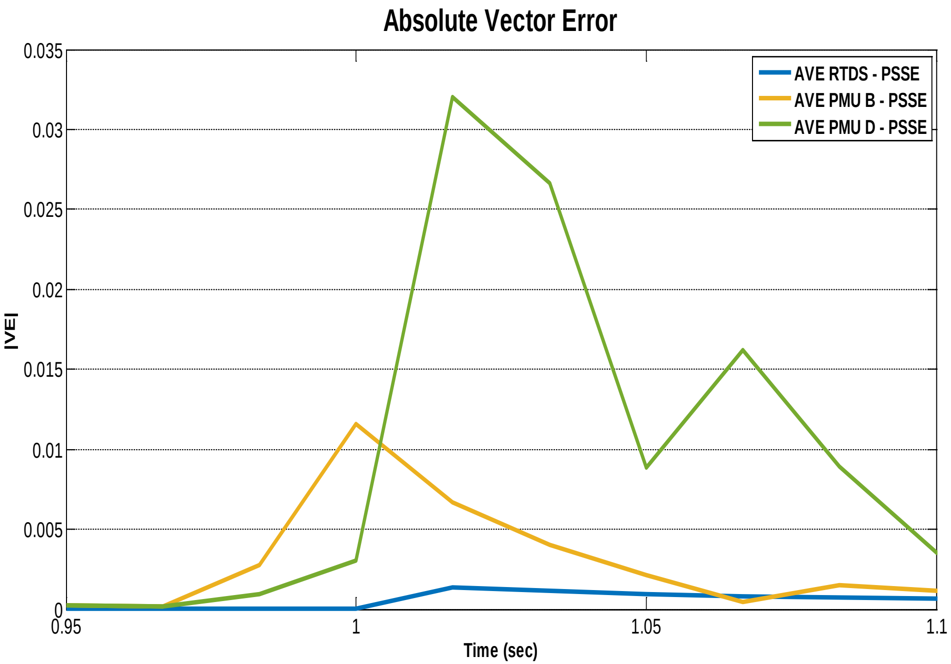


Voltage Magnitude Response from 0.95sec to 1.1sec
– Load Shed – PMU installed at Bus 2

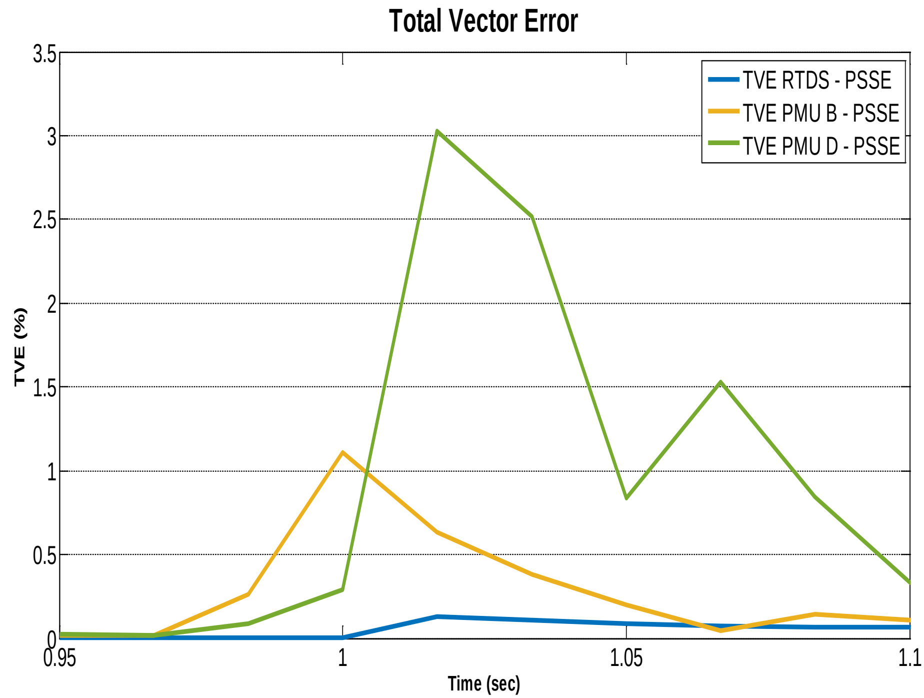
Phase Angle Response from 0.95sec to 1.1sec
– Load Shed – PMU installed at Bus 2

Hardware in the Loop Benchmarking and PMU Filtering Effect

IEEE 14 Bus system: Load Shedding at Bus 3



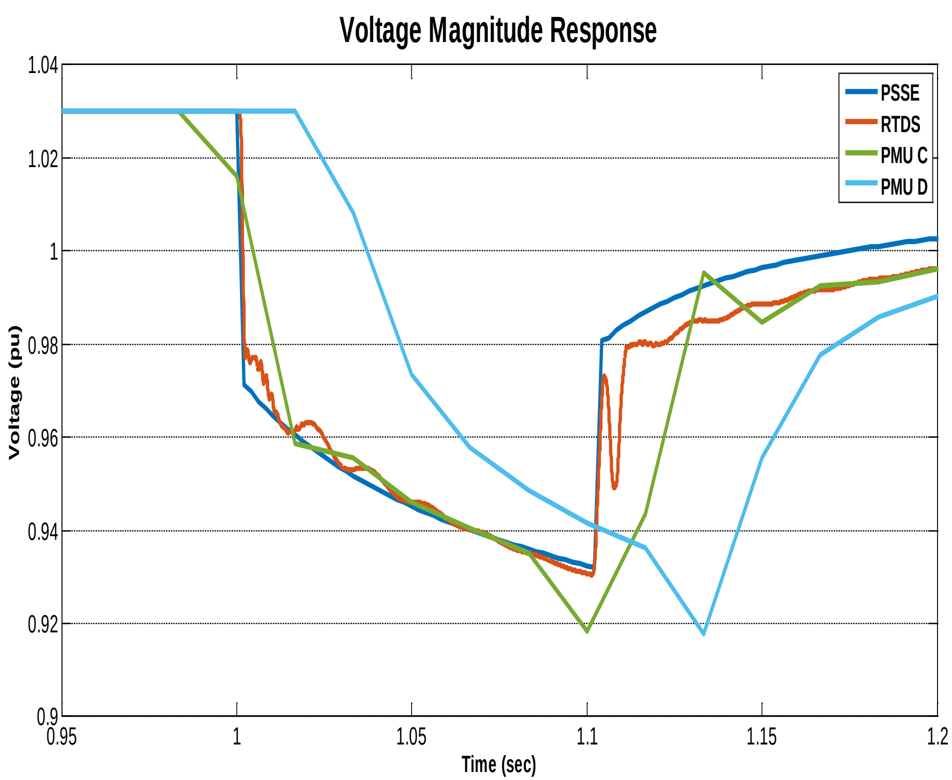
AVE from 0.95sec to 1.1sec
– Load Shed – PMU installed at Bus 2



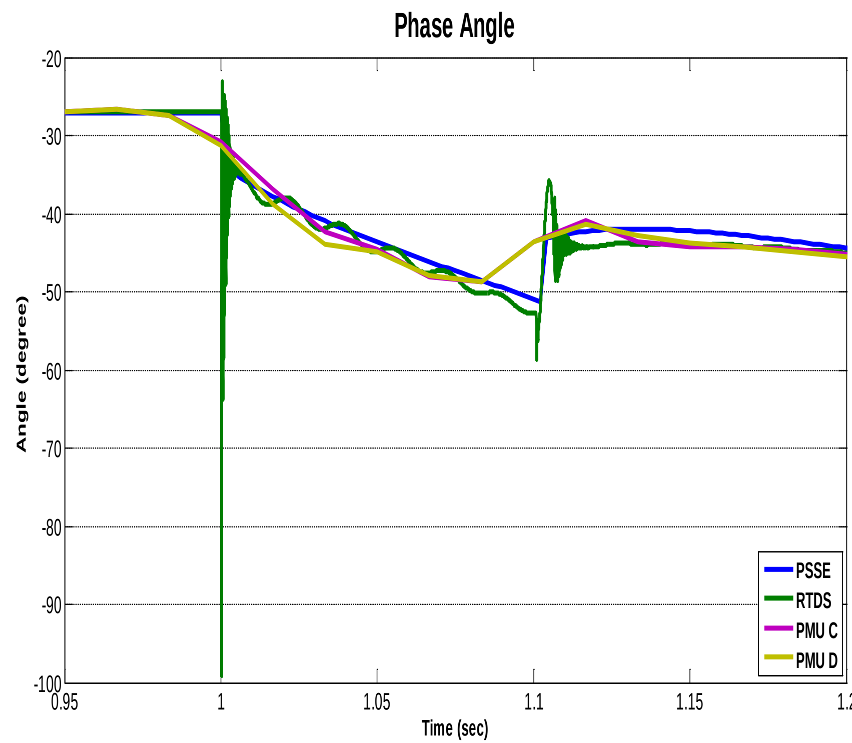
TVE from 0.95sec to 1.1sec
– Load Shed – PMU installed at Bus 2

Hardware in the Loop Benchmarking and PMU Filtering Effect

Kundur system: Bus Fault at Bus 6



Voltage Magnitude Response from 0.95sec to 1.2sec
– Bus Fault – PMU installed at Bus 3



Phase Angle from 0.95sec to 1.2sec
– Bus Fault – PMU installed at Bus 3

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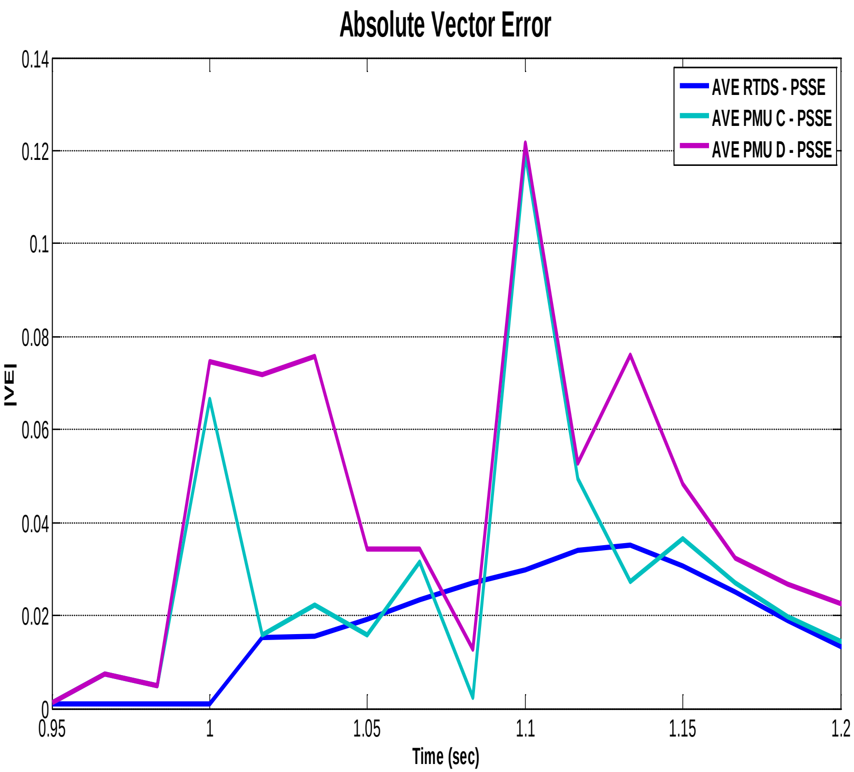
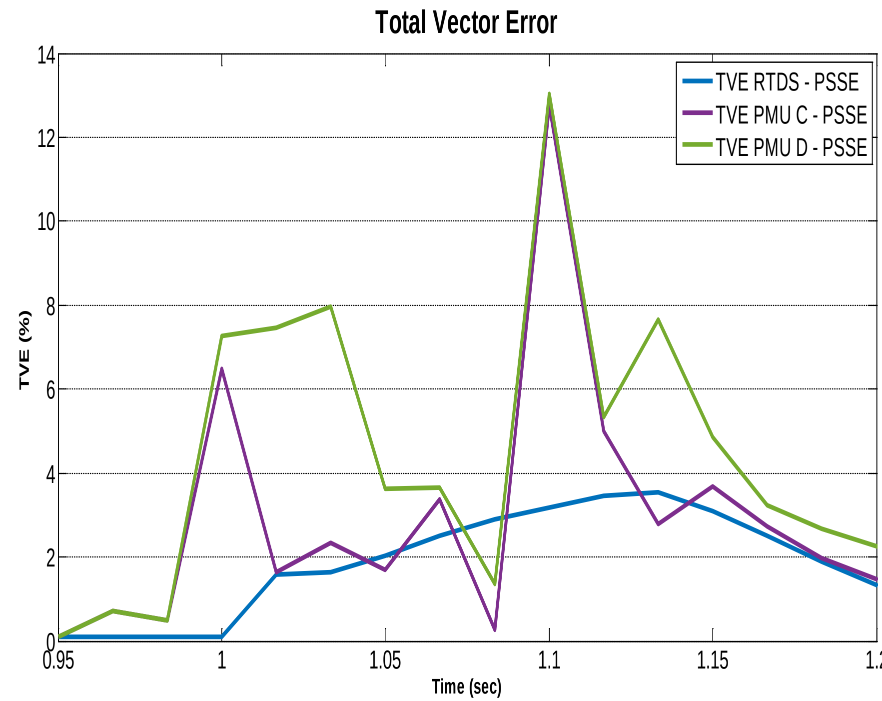
Kundur system: Bus Fault at Bus 6



AVE from 0.95sec to 1.2sec
– Bus Fault – PMU installed at Bus 3



TVE from 0.95sec to 1.2sec
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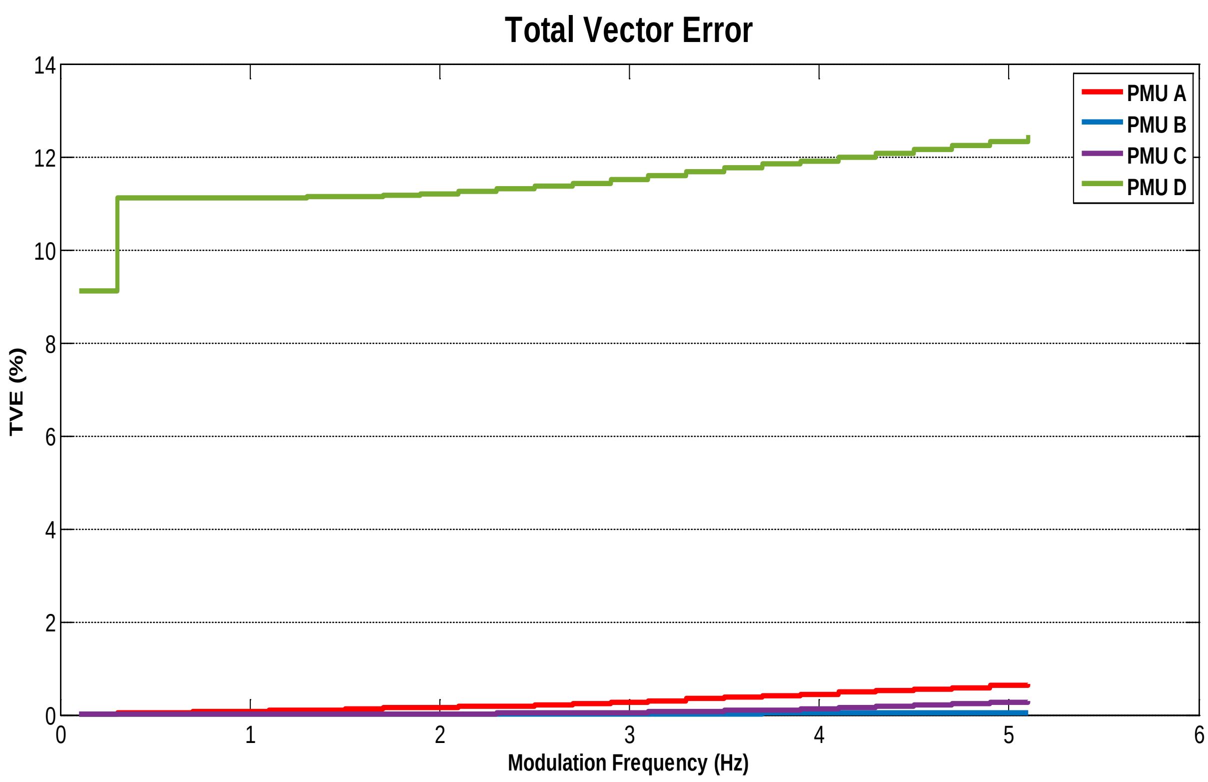
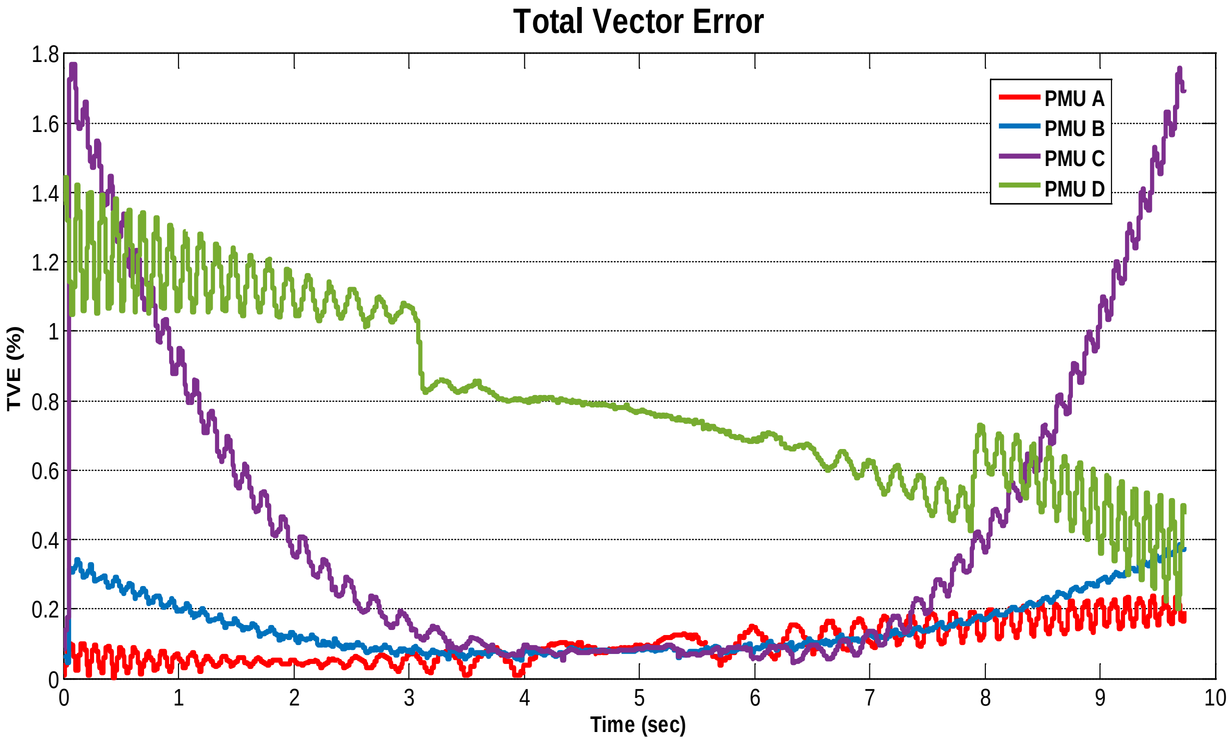


PMUs Total Vector Error for Joint Amplitude and Phase Modulated Signal

Hardware in the Loop Benchmarking and PMU Filtering Effect



PMUs Total Vector Error for Frequency Ramp

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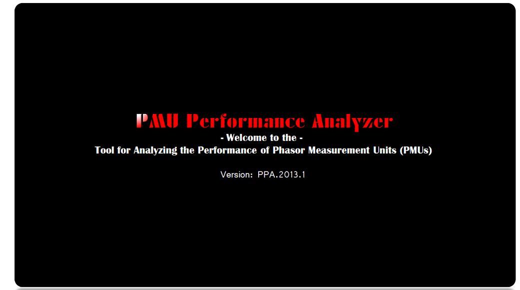
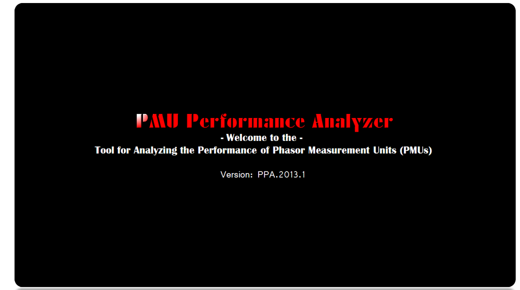


- ☑ The steady state power flow matches 0.005% of the TVE for both.
- ☑ The step response of the excitation system of individual generators resulted in magnitude error and the time error which are less than 0.5% and 0.04sec, respectively.
- ☑ The AVE of the PMU D, when installed at Bus 2 is 0.005 for around 3sec after the occurrence of the disturbance, then decreased to 0.002. The AVE of other three PMUs are equal to the AVE of RTDS and PSS/E.
- ☑ The AVE of PMU D is more than the AVE of other PMUs for 1 sec after the fault is cleared. The AVE of other PMUs are nearly same as the AVE of the RTDS and PSS/E.
- ☑ The TVE of RTDS meters for Joint AM-PM is observed to be less than 0.001%
- ☑ The TVE of PMU D is more than 10% for most of the modulation frequency.
- ☑ The TVE of the RTDS meters for the frequency ramp test is less than 0.15%
- ☑ The TVE of PMU D is more than 1% for frequency ranging from 55Hz to 58Hz

Conclusions



- ☑ The response of the DFR is observed to be different as compared to that of other PMUs
- ☑ The TVE of P class PMUs is also more than 1% for off nominal frequency more than 62Hz and lower than 58Hz
- ☑ M class PMUs accurately report the voltage phasor during slow to moderate disturbances.
- ☑ The application of PMU data just after the occurrence of the disturbance for modeling systems of very small time constants is a challenging task. Hence, suitable filters may be designed for PSS/E to match the system responses with P class and M class PMUs separately.