OPAL-RT TECHNOLOGIES

FROM IMAGINATION TO REAL-TIME

Synchrophasor Application Studies using Real-Time Simulators

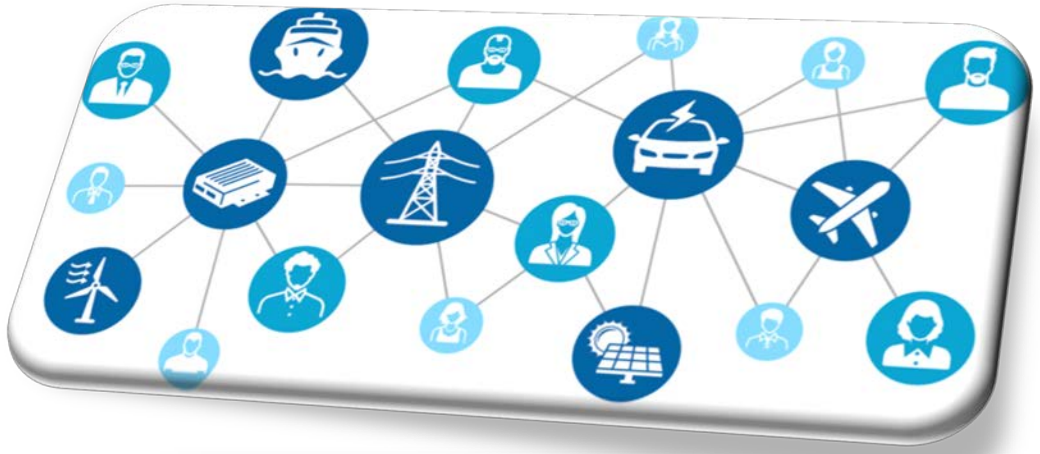
Overview

- Company Backgrounds
- Collaboration between OPAL-RT and VIZIMAX
  - PMU Test Setup
  - Tests Applied to the VIZIMAX PMU
- Comparison of Test Results for Different PMU Algorithms
- Advanced Applications using Model-Based Design, Studies and Testing
  - The Mont-Rothery Wind Farm in Canada
  - Protection Applications using PMUs
  - Control Design and Prototyping using Virtualized PMUs
- Conclusions

Company Backgrounds

About OPAL-RT TECHNOLOGIES

- **Some Facts**
  - Established in 1997 – Corporate office in Montreal
  - Over 140+ Employees worldwide
  - More than 500 customers worldwide
  - Real-time simulators available for power systems, power electronics, automotive and aerospace industries
  - Power grid simulators scalable from 10 to 10,000 electrical nodes or more
- **Corporate Mission**
  - To provide solutions and expert services for design research, studies and testing in the fields of electrical and power electronics systems
  - To provide Engineers with open simulators that use the latest COTS computer technology
- **Long-Term Vision**
  - A real-time simulator on each engineer's or researcher's desk
  - Simulators interconnected and working for designing and studying large and multi-disciplinary systems.
  - Imagination will be the only real limit to complex system design.



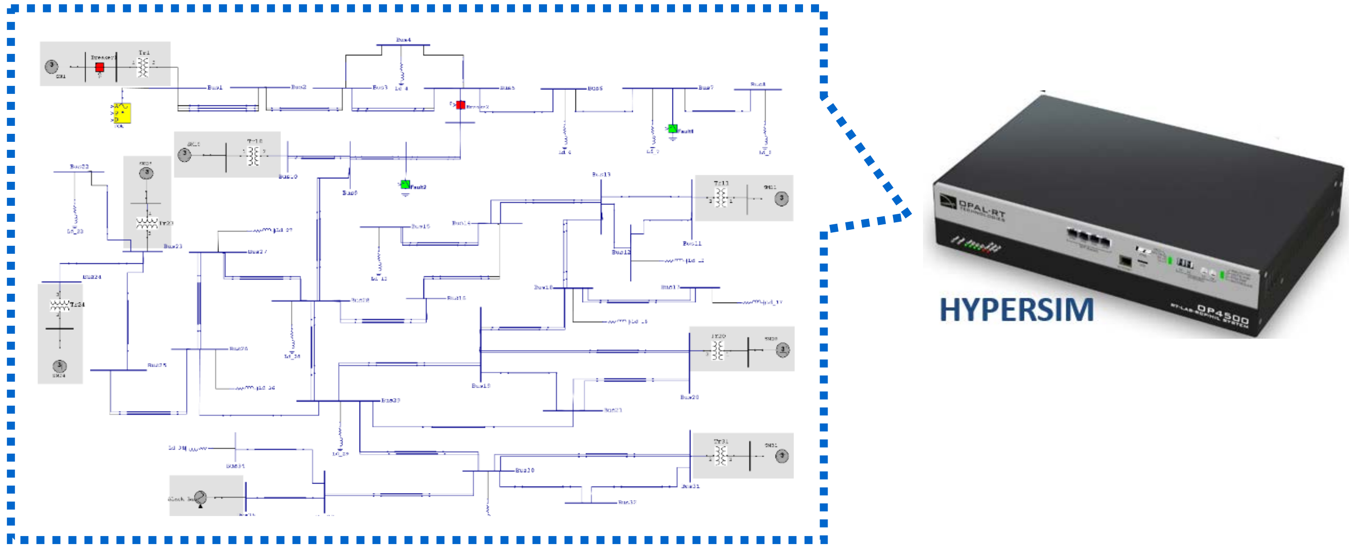
About vizimax ENERGY 3.0

- **The Company**
  - Established in 2008 from a merger between Snemo (1977) and STR (1988)
  - Provides innovative solutions for energy applications – Power Grids, Power Generation , HV/MV Equipment, Heavy Industry
  - Customers in over 35 countries
- **Products**
  - Phasor Measurement Unit
  - Analog Merging Unit
  - SynchroTeq™: Controlled switching device (CSD)/Inrush current limiter
  - RightWON™: Substation automation controller
- **Mission**
  - To help optimize how Energy is Generated, Transported & Distributed
  - To protect as much as possible their customers' assets by focusing on innovation, quality, and customer service

Collaborations with Hydro-Quebec Research Institute (IREQ)

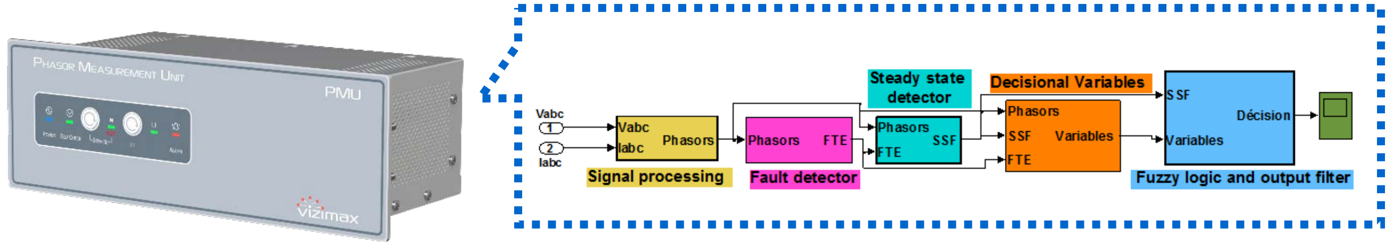
OPAL-RT TECHNOLOGIES

- OPAL-RT and IREQ signed a strategic collaboration agreement for the shared commercialization and development of HYPERSIM (2012)



vizimax ENERGY 3.0

- Agreement for integration of estimation algorithms resulting from research at IREQ. Algorithms have been enhanced by VIZIMAX for accurate real-time estimation and standard compliance.



- Other collaborations for validation of automation and control equipment and certification for use on the Hydro-Quebec grid.

Collaboration VIZIMAX  OPAL-RT

OPAL-RT TECHNOLOGIES

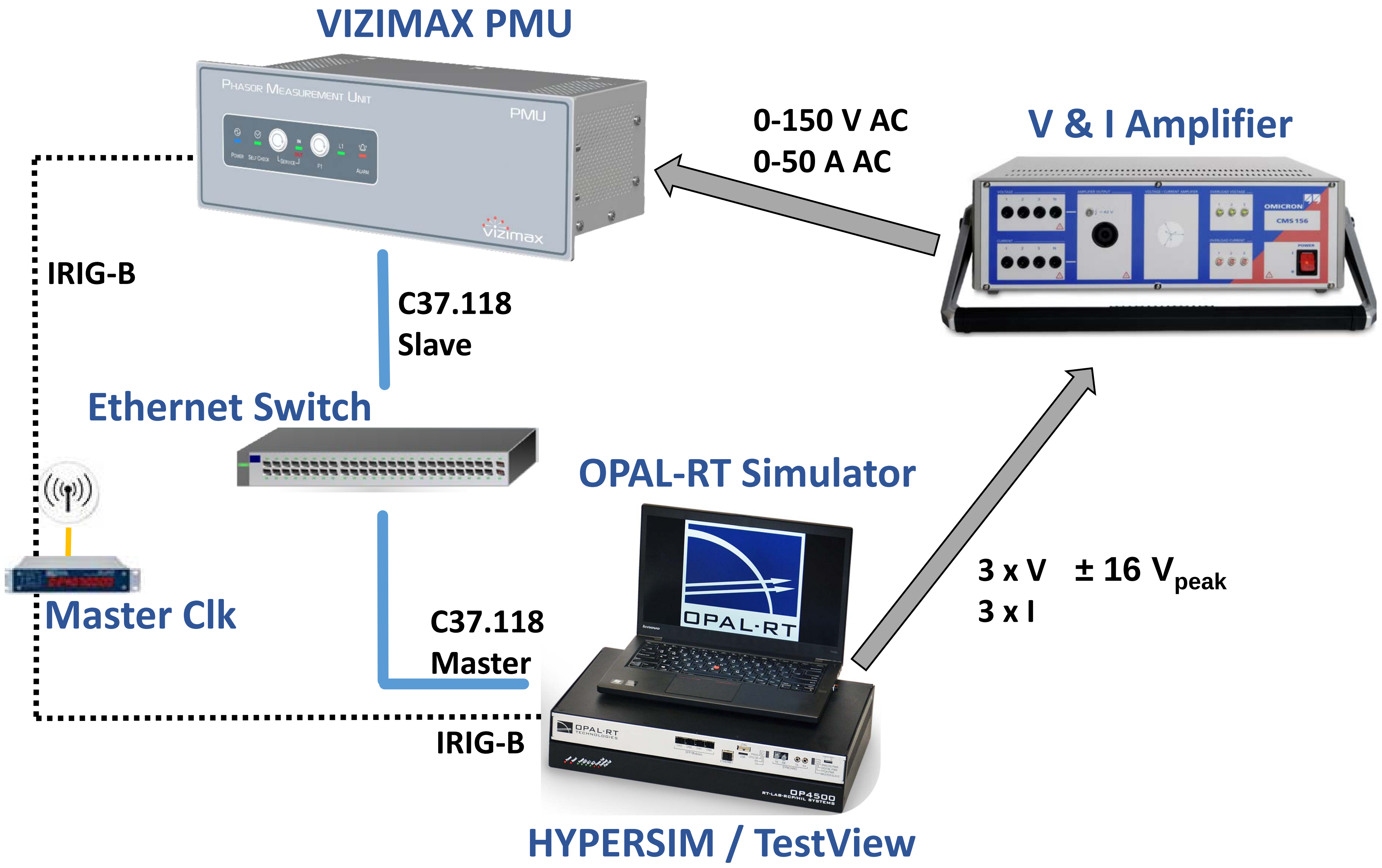
- **Automated testing of PMUs based on C37.118.1**
  - Study requirements of the IEEE std
  - Program test sequence using OPAL-RT Hardware and TestView software
  - Calibration of the test equipment
  - Help validating the VIZIMAX PMU using automated test-set – faster and larger test coverage

vizimax ENERGY 3.0

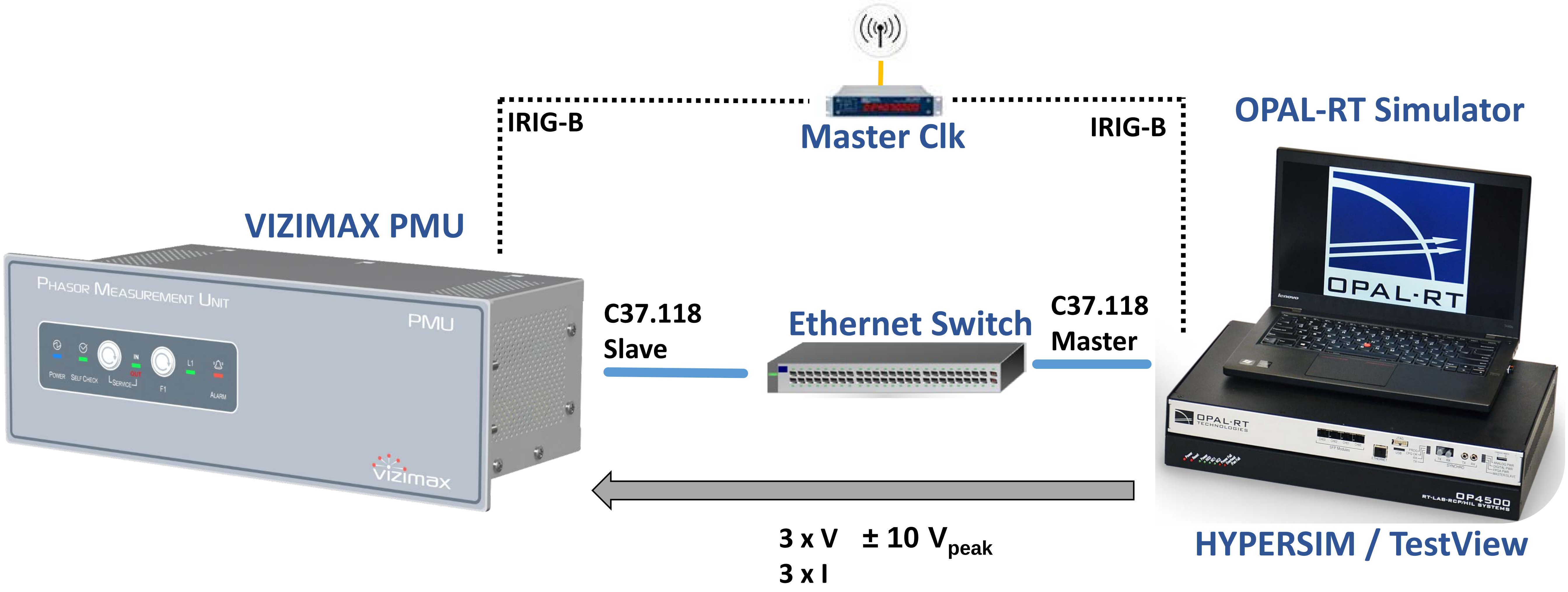
- **Develop a PMU - foreseeing IEEE-ICAP certification**
  - Develop their own test bench using an OMICRON CMC-256plus universal calibrator
  - Provide a low-voltage input version of their PMU to OPAL-RT
  - Help validating the performance of OPAL-RT test equipment on specific tests

PMU Test Setup

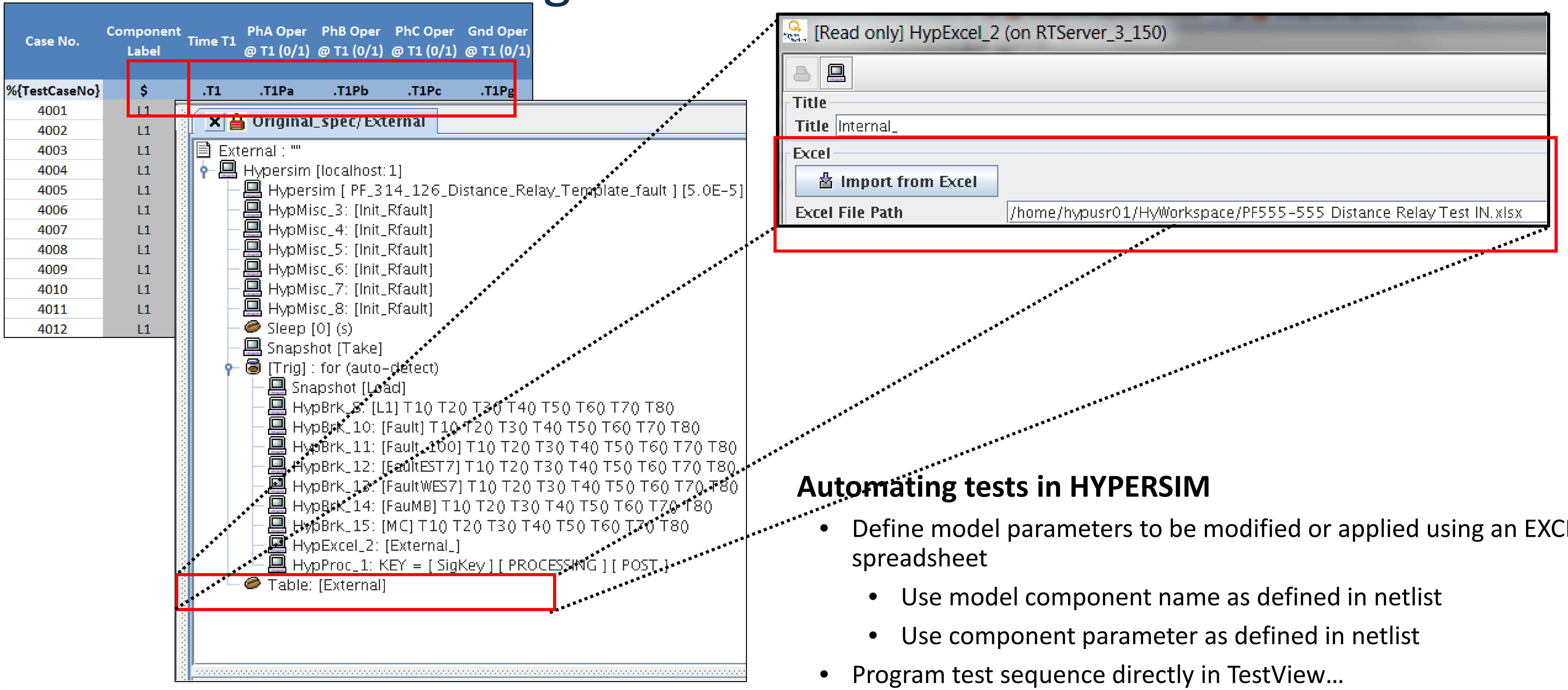
Typical PMU Test Setup



PMU Test Setup using Low-Voltage Interface



Test Automation using TestView



Automating tests in HYPERSIM

- Define model parameters to be modified or applied using an EXCEL spreadsheet
  - Use model component name as defined in netlist
  - Use component parameter as defined in netlist
- Program test sequence directly in TestView…
- Or import EXCEL test sequence

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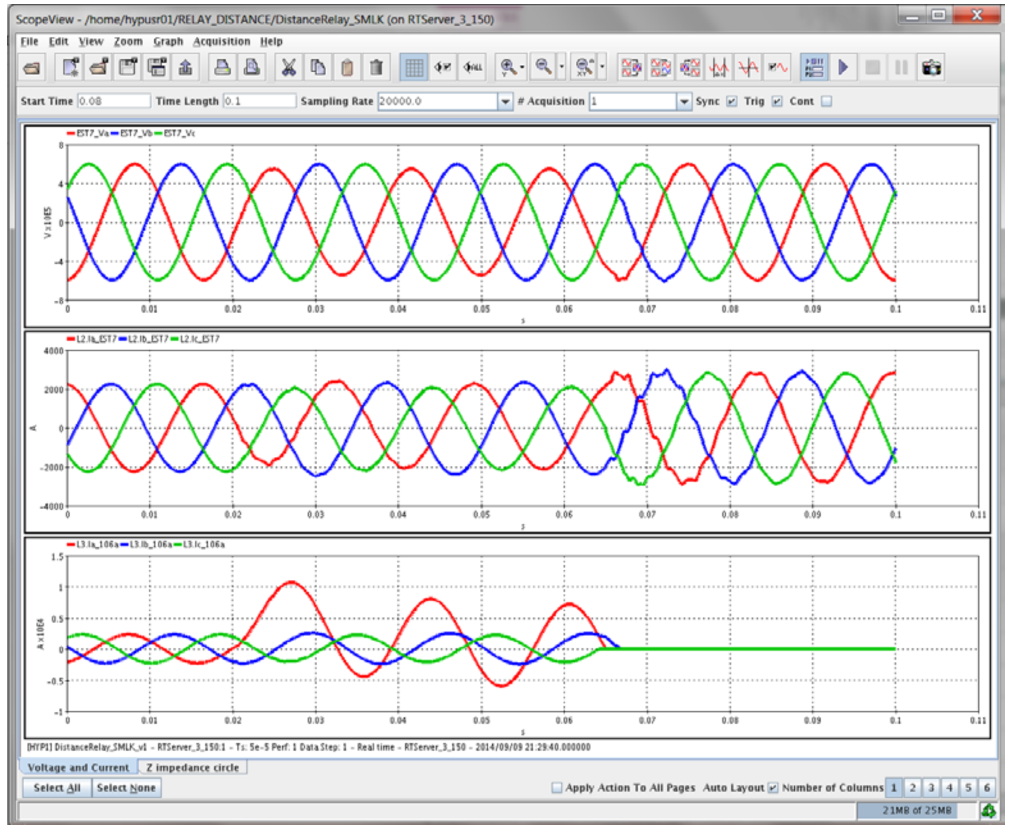
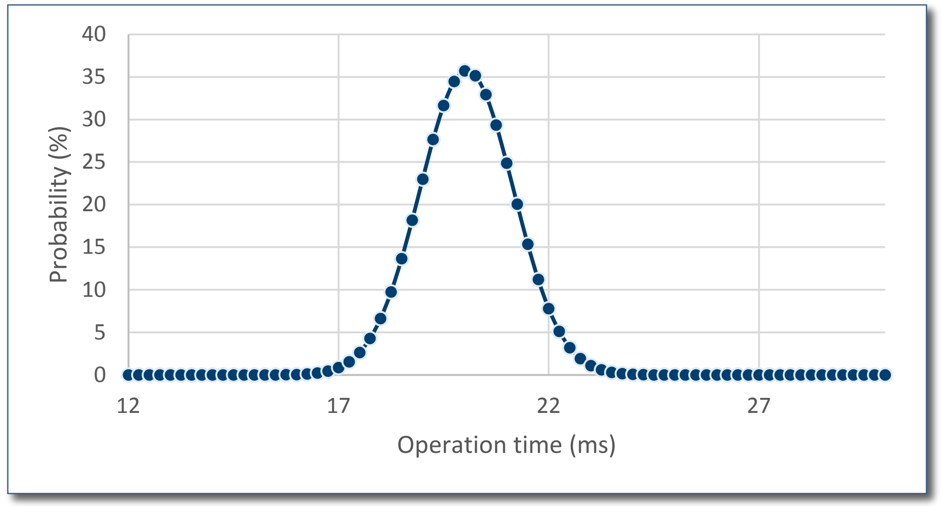
Test Automation using TestView



	Client:	OPAL-RT Technologies Inc.			Date:	10/11/2014
					Project No.:	PF555-555
	Title:	TestView Sequence			Rev. :	2.0

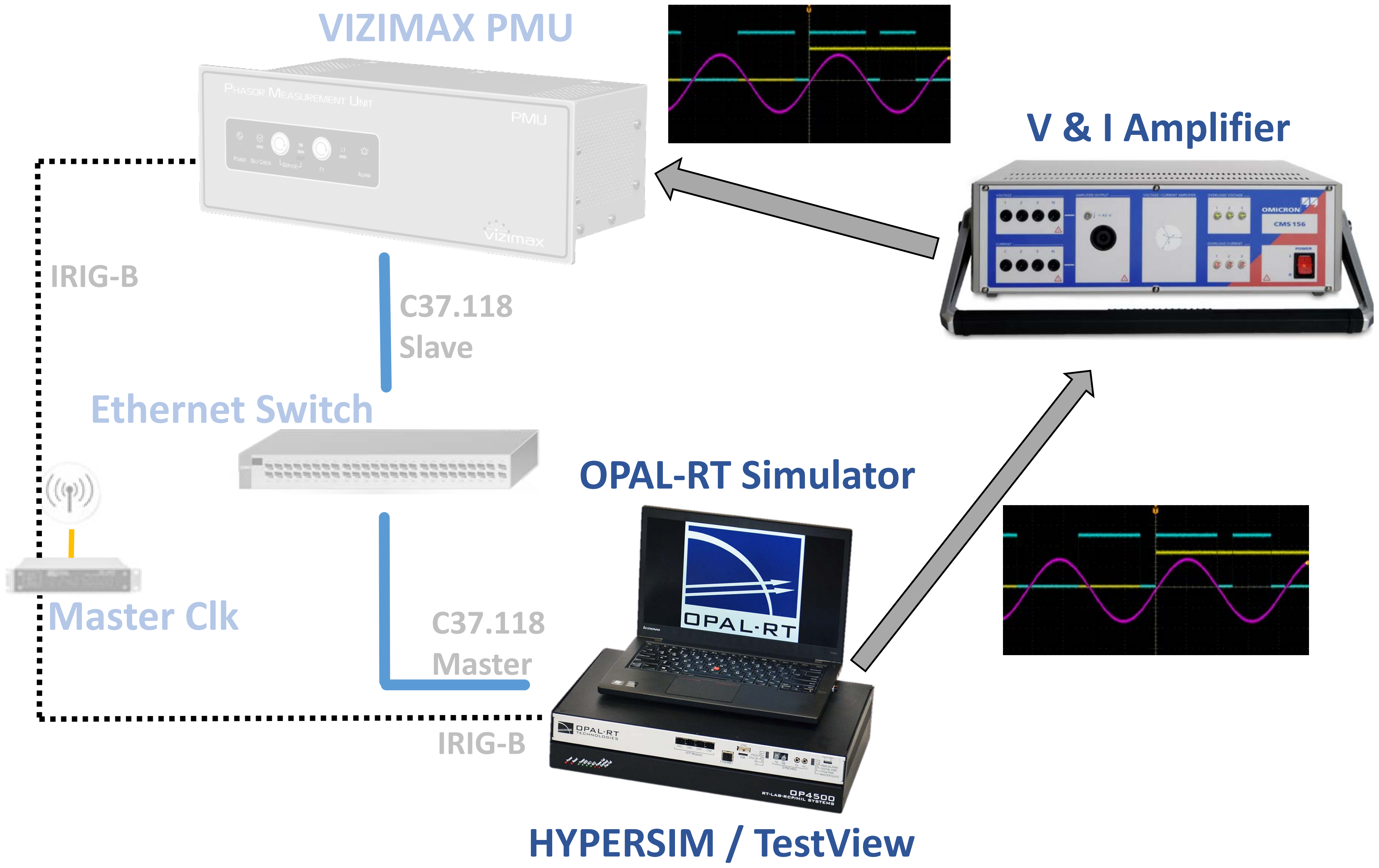
Test	Seq.	StartDate	Fault Type	Location	POW	Rf
Internal-1	1	Wed, 15 Oct 2014 16:36:30:994 EDT	A-gnd	0	0	0.01
Internal-1	2	Wed, 15 Oct 2014 16:36:30:994 EDT	A-gnd	0	0	15
Internal-1	3	Wed, 15 Oct 2014 16:36:30:994 EDT	A-gnd	0	45	0.01
Internal-1	4	Wed, 15 Oct 2014 16:36:30:994 EDT	A-gnd	0	45	15
Internal-1	5	Wed, 15 Oct 2014 16:36:30:994 EDT	A-gnd	0	90	0.01



Generate test reports

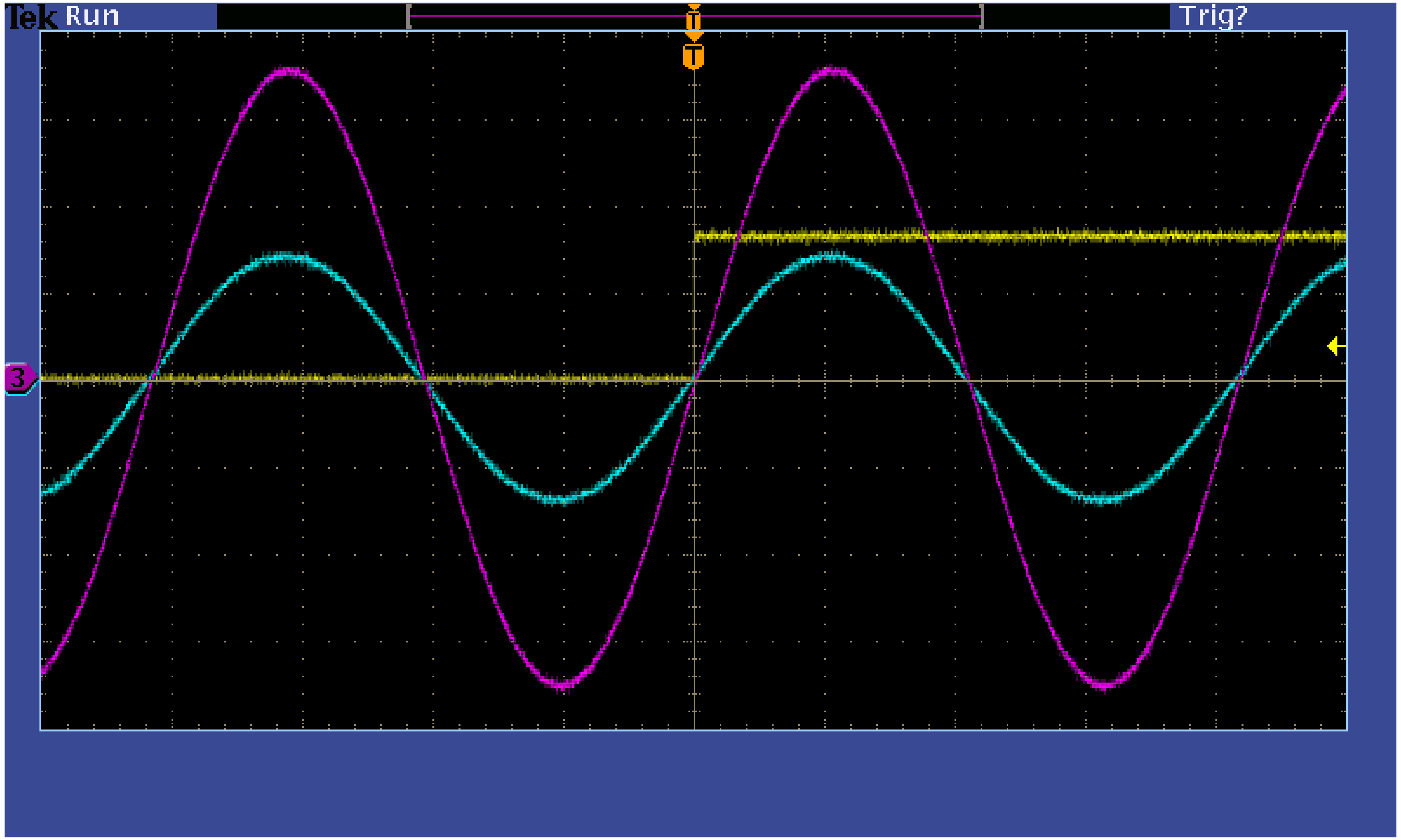
- View test waveforms in ScopeView and automate printing of .pdf report for each test
- Output post-processed values calculated during test in a pre-formatted EXCEL spreadsheet
- Analyze data in EXCEL or ScopeView

Calibration capability of the test setup



Calibration capability of the test setup

- 1 PPS from Master Clock
- Simulator Output
- Amplifier Output



$$V_{ref} = \delta a \cdot \{A \sin(2\pi f \cdot [t + \Delta t] + \varphi)\}$$

Basic calibration variables

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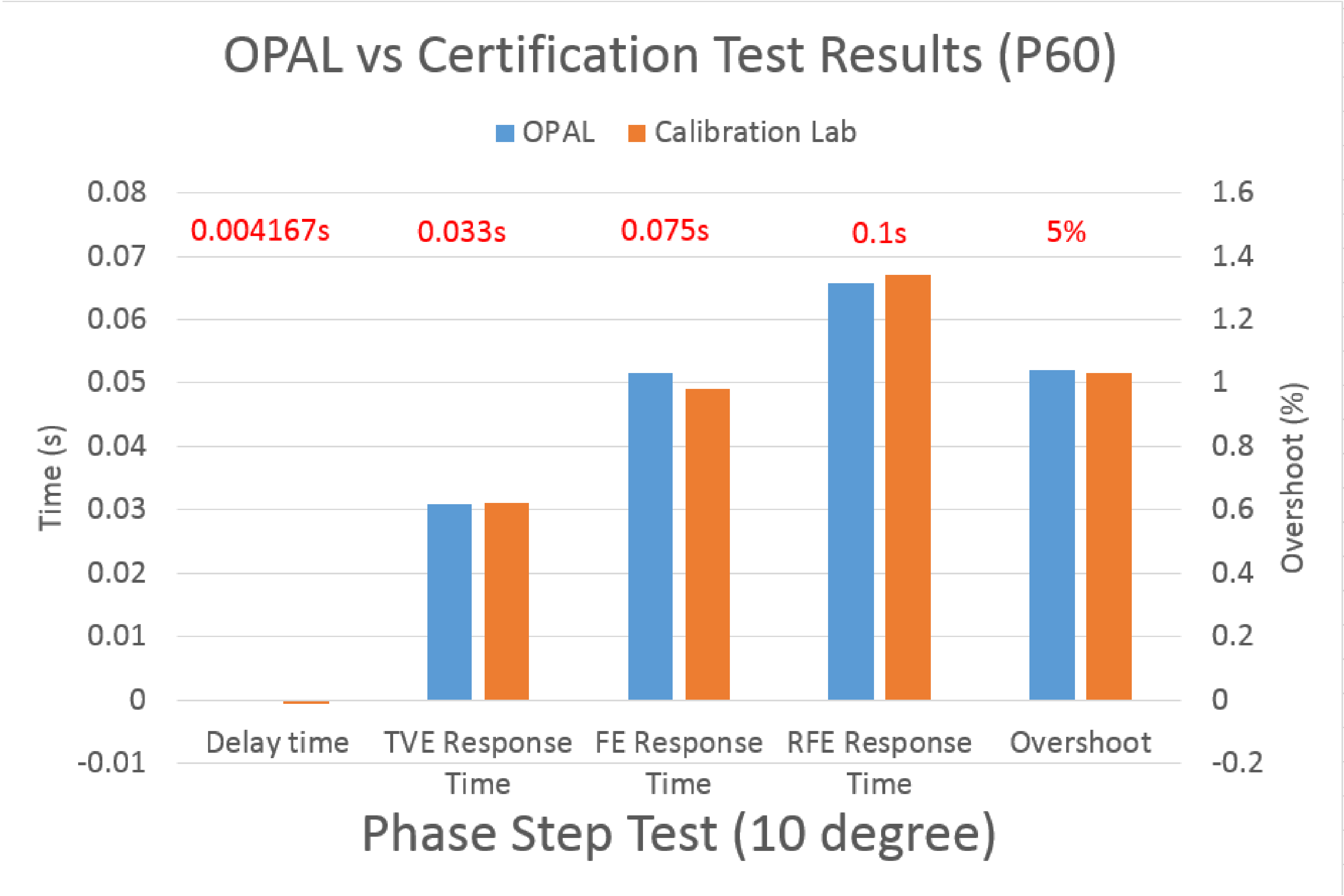
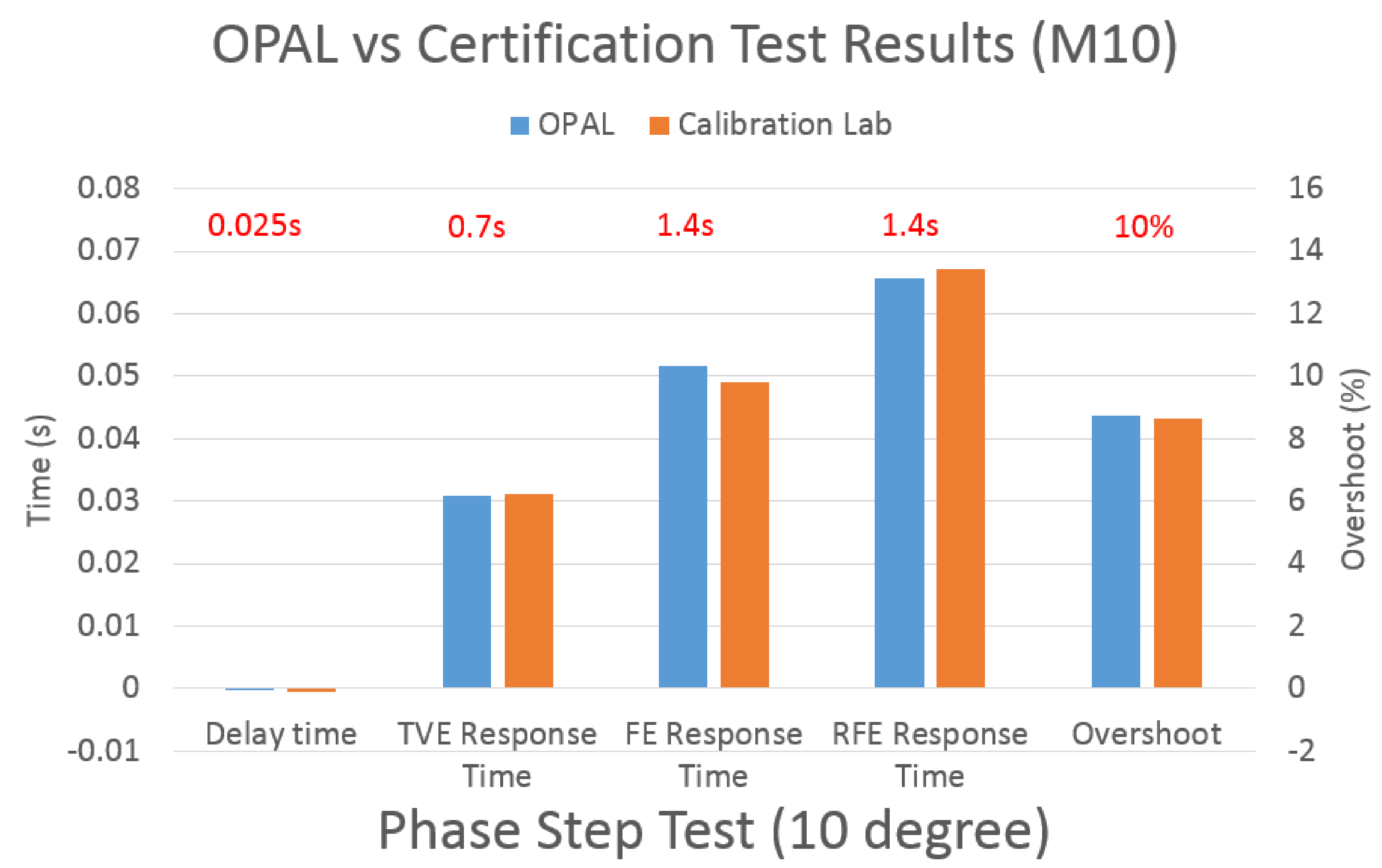
Tests Applied to the Vizimax PMU

Summary of C37.118.1 Tests

Test	Influence quantity	P Class Criteria	M Class Criteria
Signal freq. Range	Signal frequency ±2Hz for P class ±5Hz for M class	TVE <1% FE <0.005Hz RFE <0.4Hz/s	TVE / FE / RFE <1% / <0.005Hz / <0.1Hz/s
Signal Mag. (V/I)	Voltage magnitude 80% to 120% for P class 10% to 120% for M class Current magnitude 10% to 200%	TVE <1% FE<0.005Hz RFE<0.4Hz/s	TVE <1% FE<0.005Hz RFE<0.1Hz/s
Harmonic Dist.	2nd to 50th harmonic 1% for P class 10% for M class	TVE <1% FE<0.005Hz RFE<0.4Hz/s	TVE <1% FE<0.025Hz
Out-of-Band Interf.	10Hz - f0-Fs/2 and f0+Fs/2 – 120Hz 10% for M class only	No requirement	TVE <1.3% FE<0.01Hz
Meas. BW Phase & Amp. Modulation	0.1Hz – min (Fs/10, 2) for P class 0.1Hz – min (Fs/5, 5) for M class	TVE <3% FE<0.003*Max Mod Freq RFE<0.18*pi*Max Mod Freq^2	TVE <3% FE<0.003*Max Mod Freq RFE<0.18*pi*Max Mod Freq^2
Freq. ramp	±2Hz for P class ±5Hz for M class	TVE <1% FE<0.01Hz, RFE<0.4Hz/s	TVE <1% FE<0.01Hz, RFE<0.2Hz/s
Phase step change Mag. Step change	±10° ±10% of nominal magnitude	Delay time 1/(4*Fs) TVE response time 2/f0 Overshoot, undershoot 5% of step FE response time 4.5/f0 RFE response time 6/f0	Delay time 1/(4*Fs) TVE response time 7/Fs Overshoot, undershoot 10% of step FE response time max(14/f0, 14/Fs) RFE response time max(14/f0, 14/Fs)
Reporting latency	1000 consecutive reports	2/Fs	7/Fs

Comparison with Certification Results—Step Change Test





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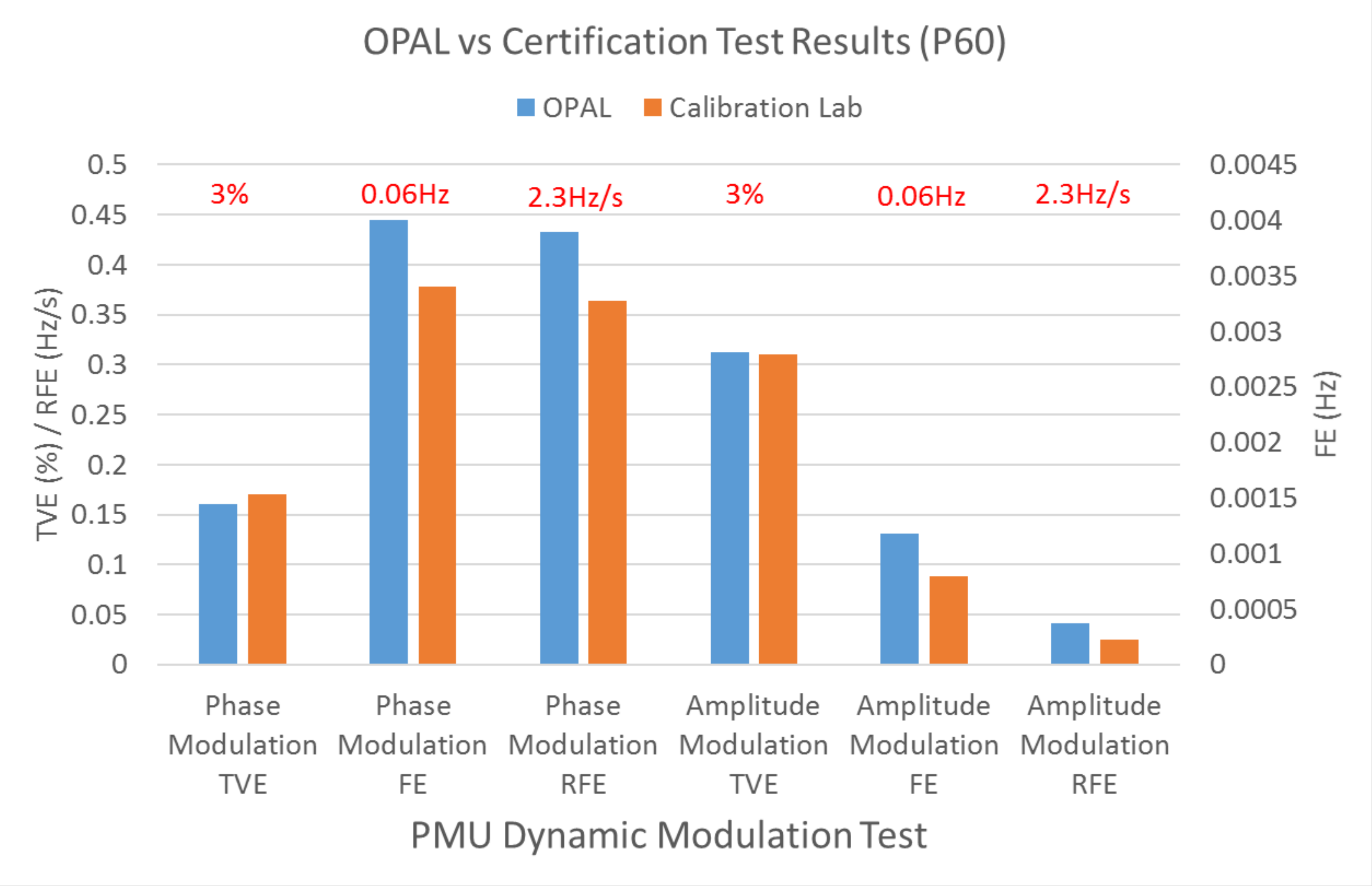
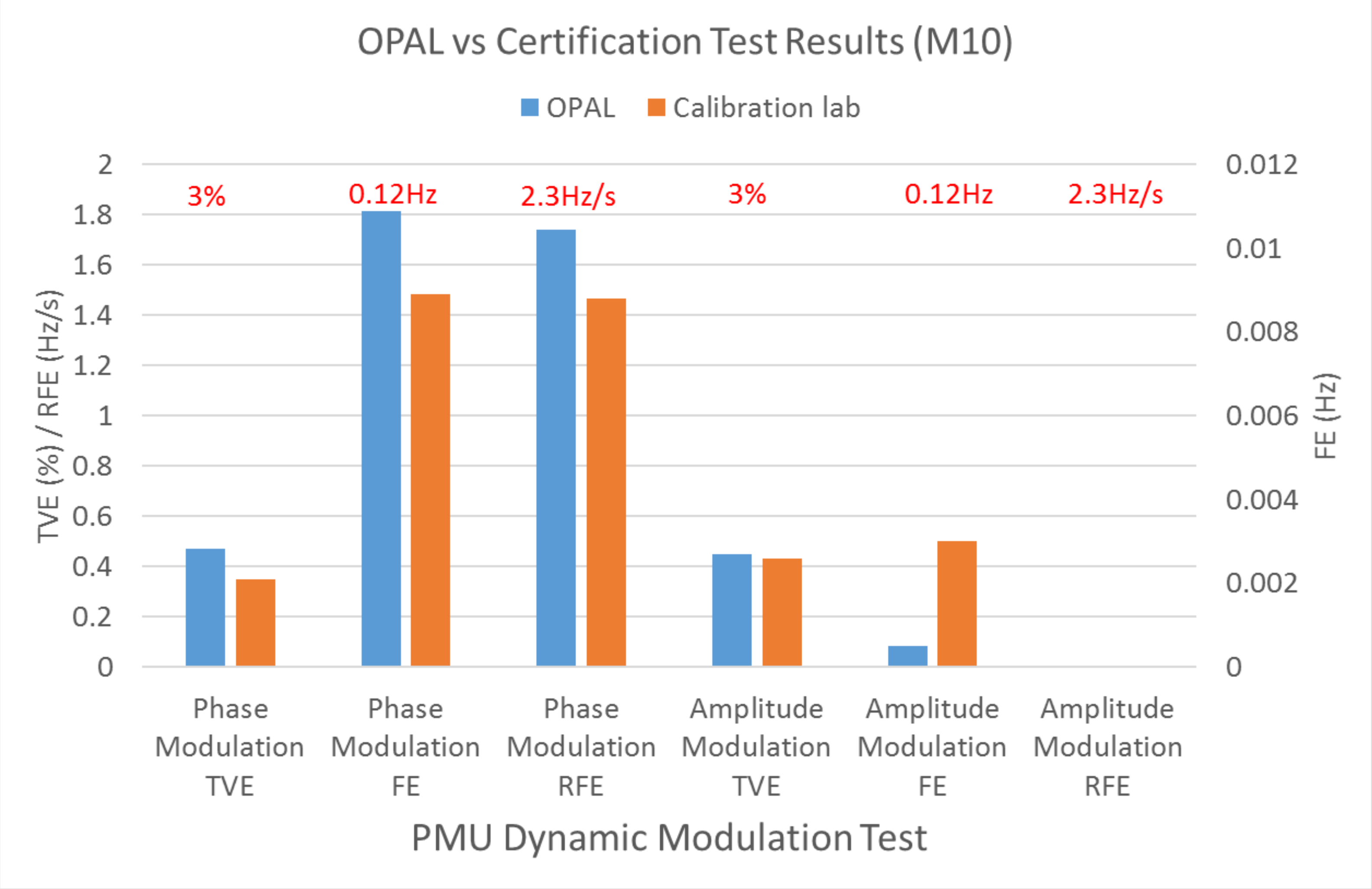
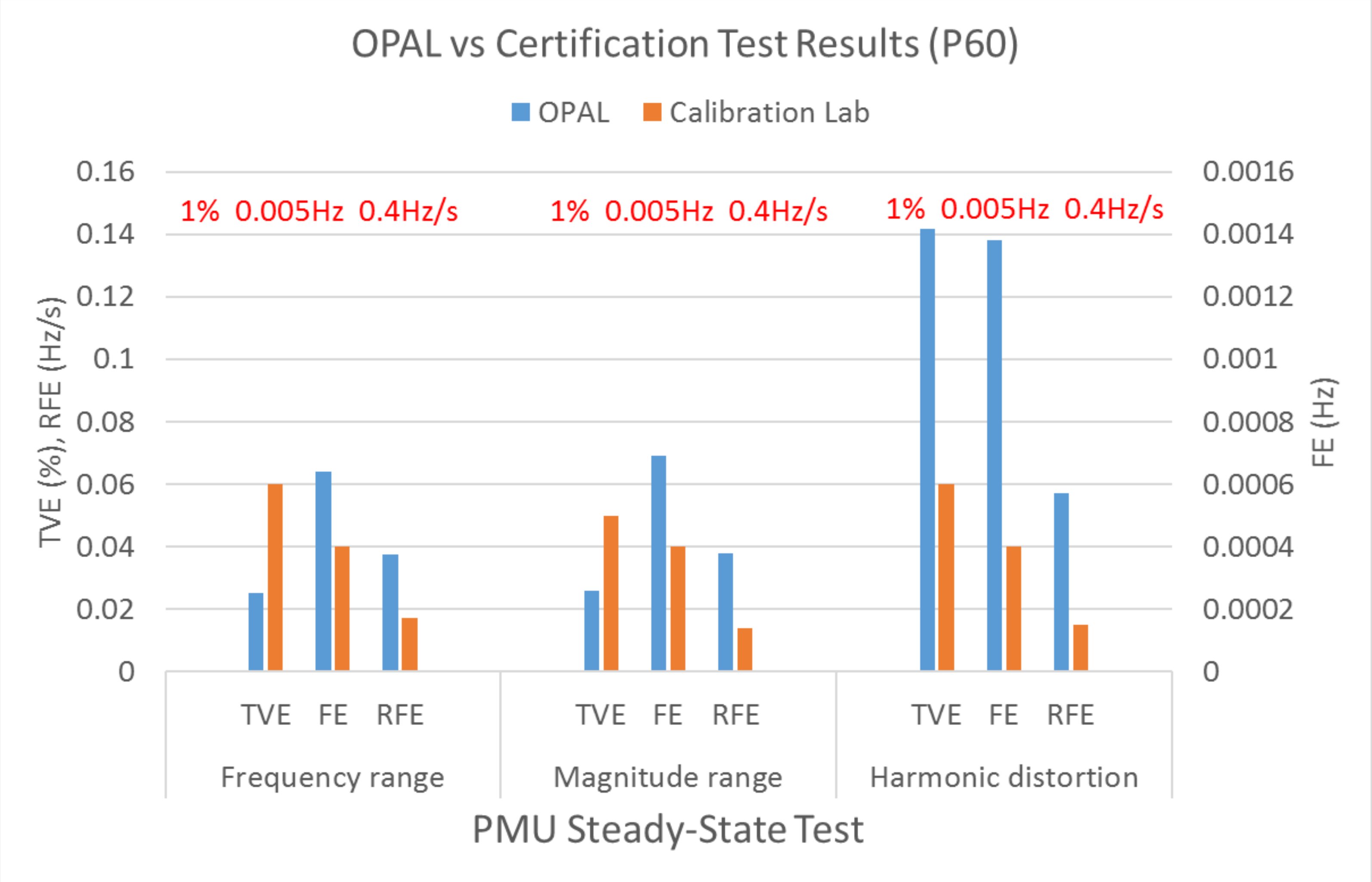
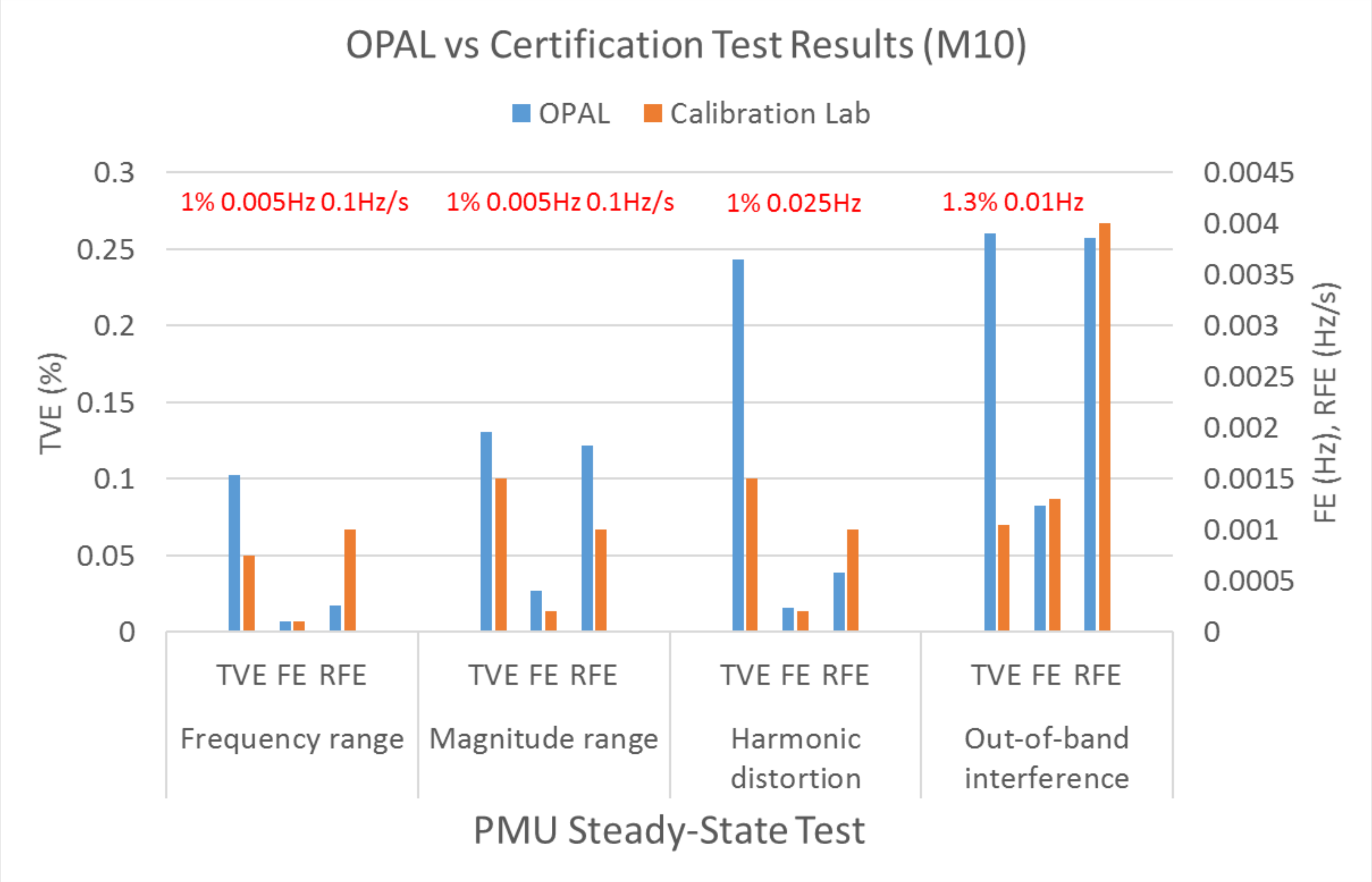
Comparison with Certification Results—Dynamic Modulation Test





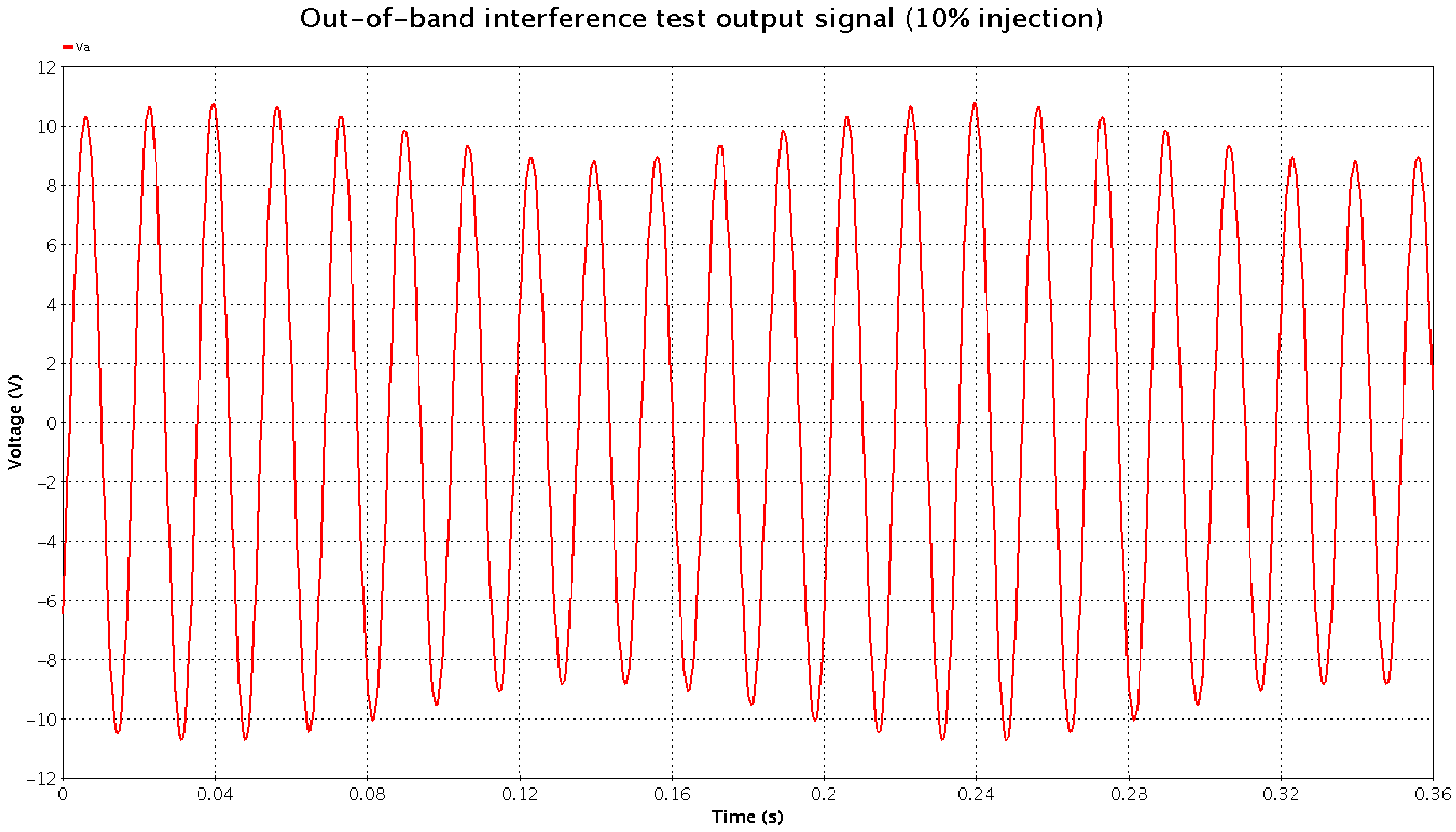
Comparison with Certification Results—Steady-State Test





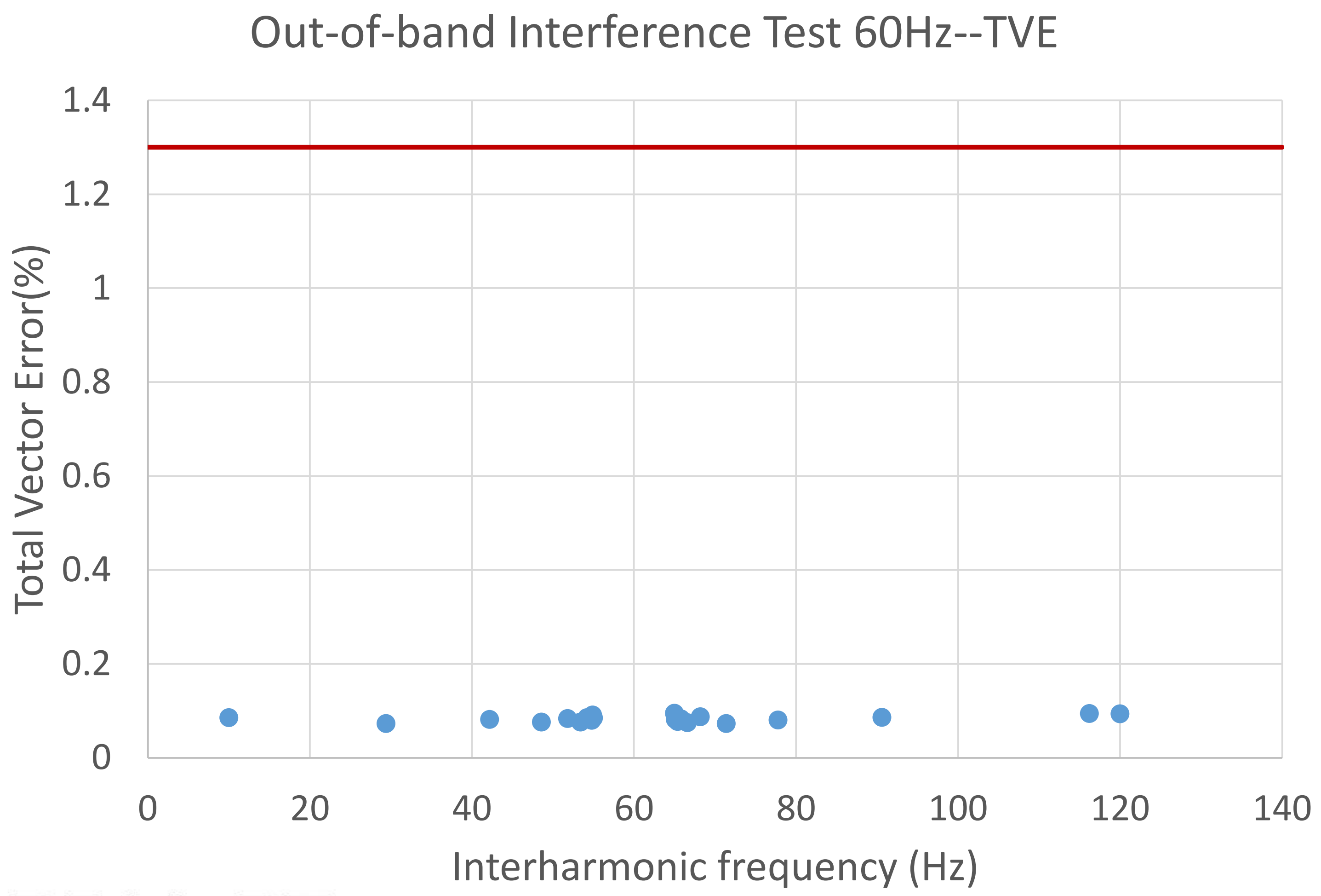
Out-of-Band Interference Test Signal

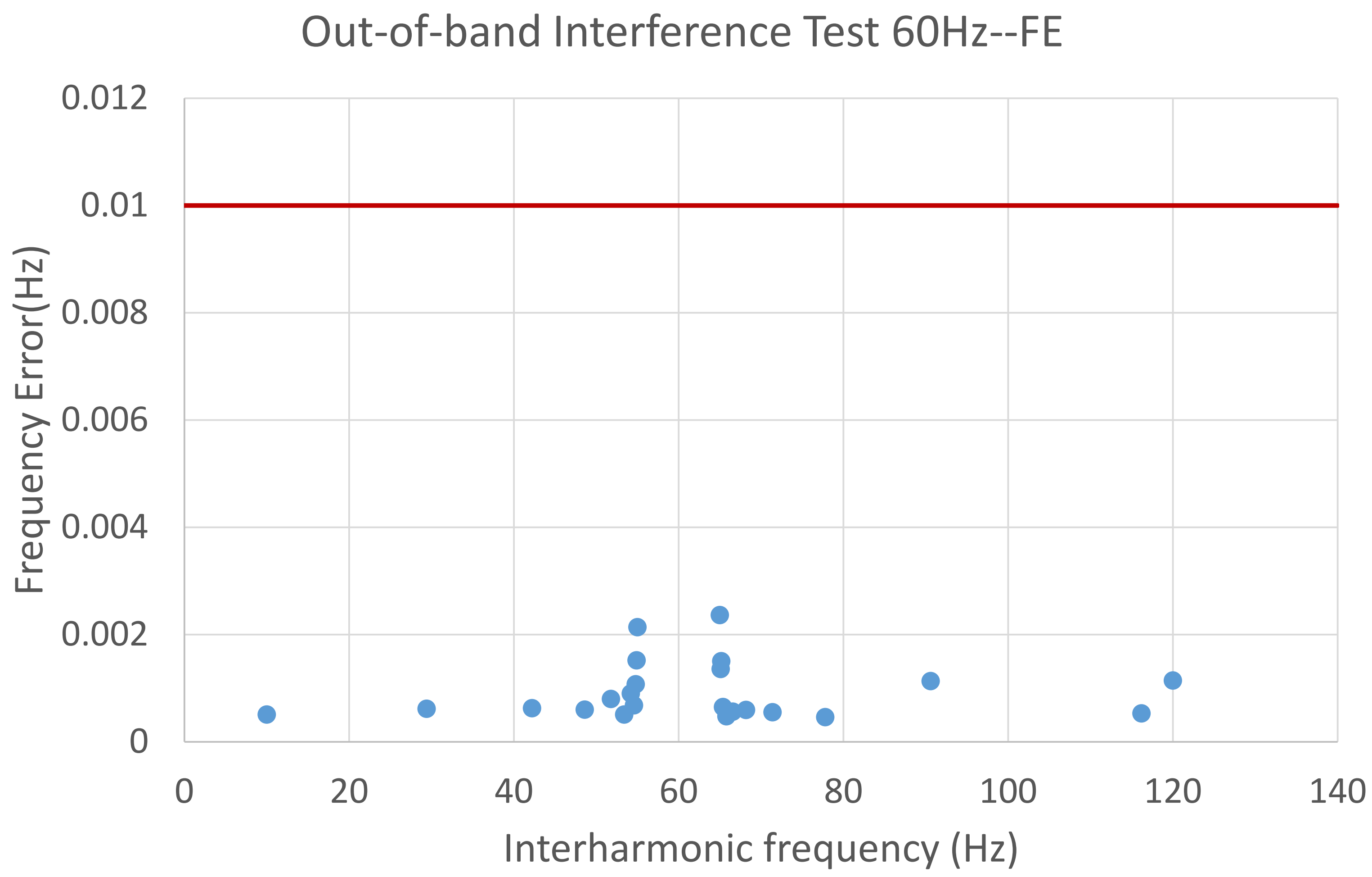
$$X(t) = X_m \cdot cos(2\pi f t + \varphi) + 0.1 \cdot X_m \cdot cos(2\pi f_i t + \varphi)$$



P Class Out-of-Band Interference Test– 60Hz, 60 fps

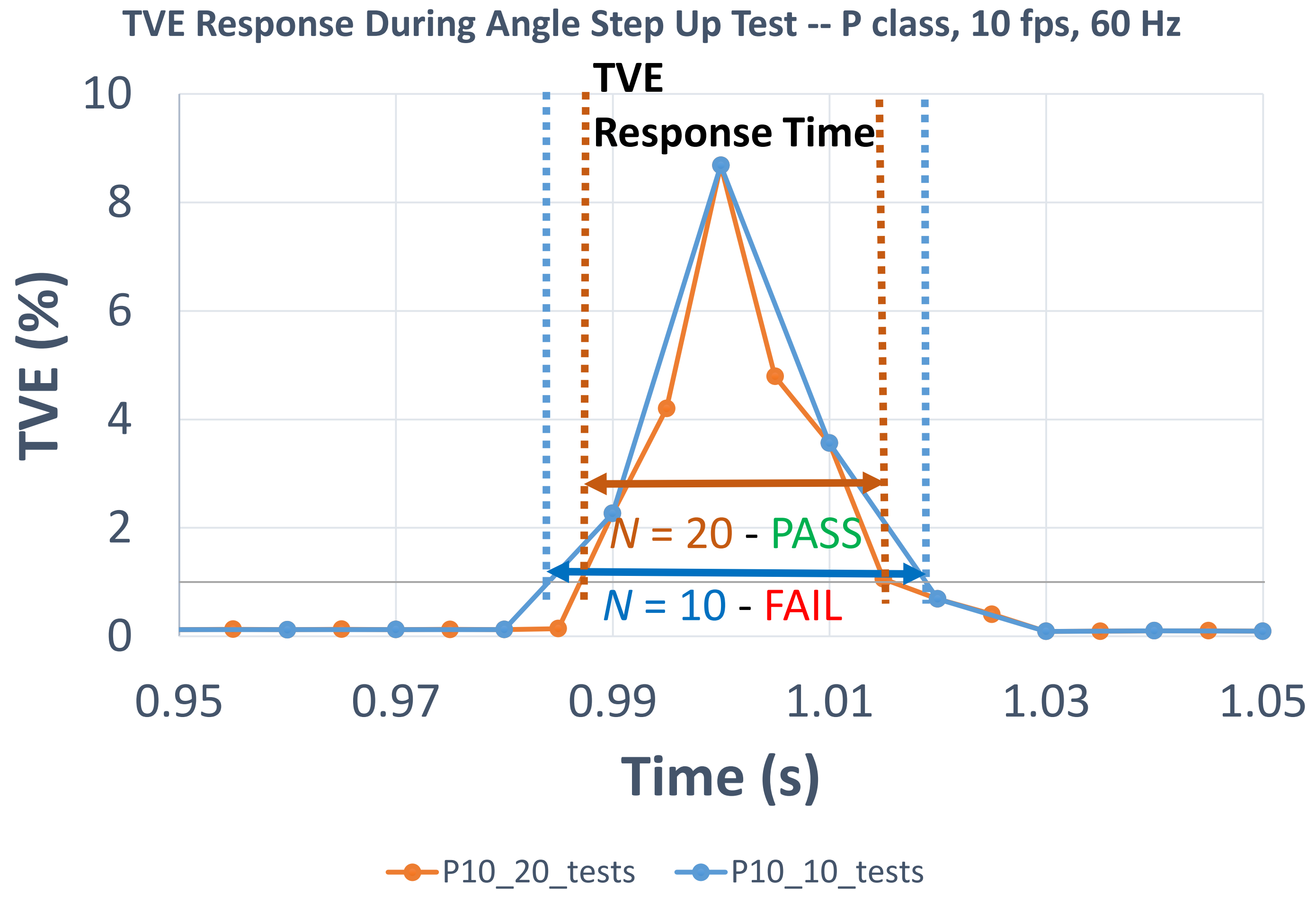
- Interference range: 10-55Hz and 65-120Hz
- Injection level: 10%





Performance under step changes at 10 fps (P Class) VS C37.118.1 Requirements

Reporting Interval (s)	Response Time (s) $2/f_0$	Delay Time (s) $1/4F_S$	Freq. Resp. Time (s) $4.5/f_0$	ROCOF Resp. Time (s) $6/f_0$
0.1	0.0333	0.025	0.075	0.1



- A series of tests (*N* tests, where *n=[1,N]*) with the step applied at varying times relative to the reporting times can be used to 'fill in' the response curve.

IEEE Std C37.118.1-2011 :

- In general, an accurate measurement of the PMU response time, the delay time, and the overshoot percentage can be made with *n(e.g. N)* = 10.

IEEE Std C37.118.1a-2014 :

- The time when error limits (TVE = 1%) are crossed shall be determined to an accuracy of one-tenth of the reporting rate (ten times the reporting rate?) that is being tested.

- Here, *N*=10 is too small to measure TVE response time at lower F_S

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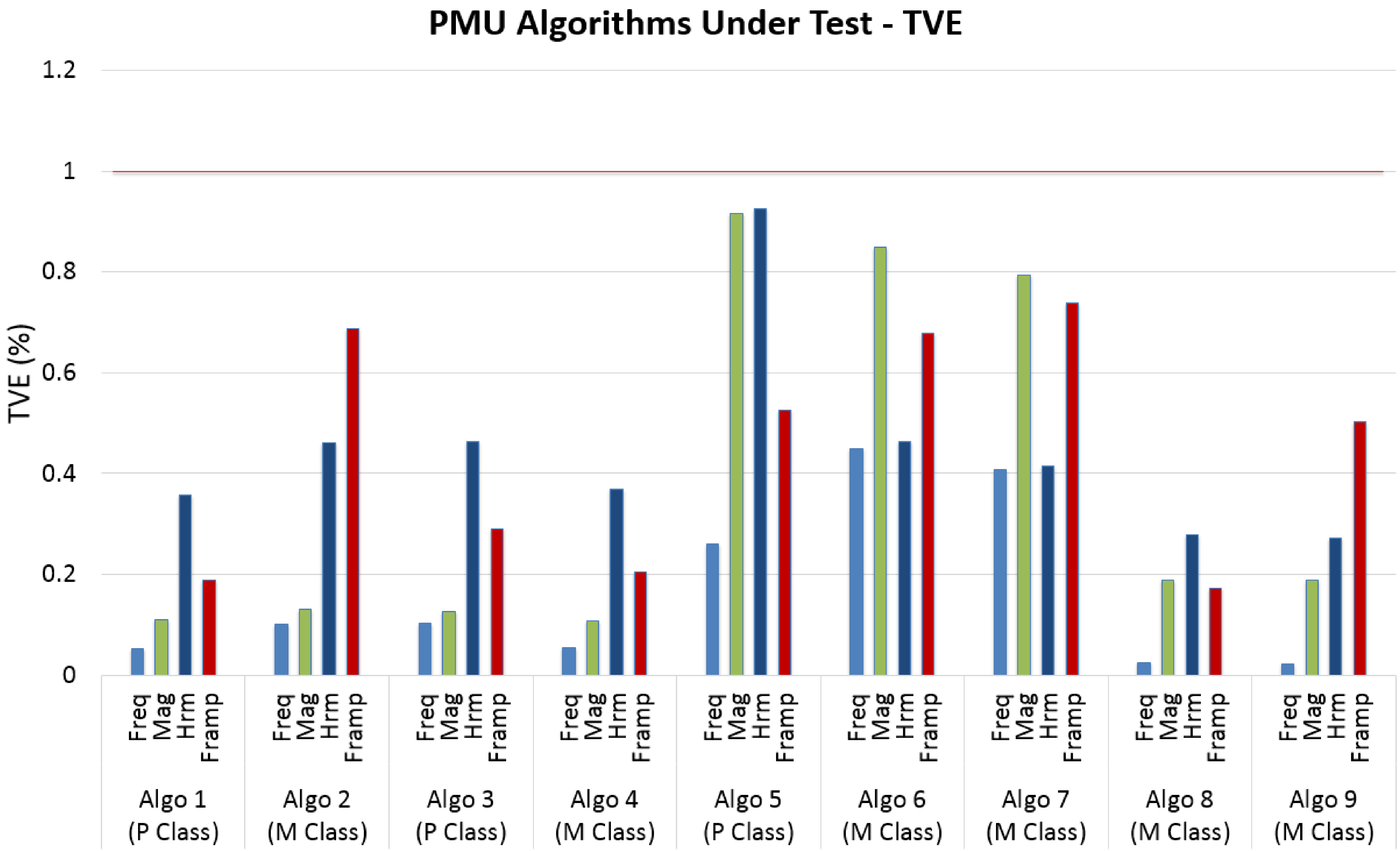
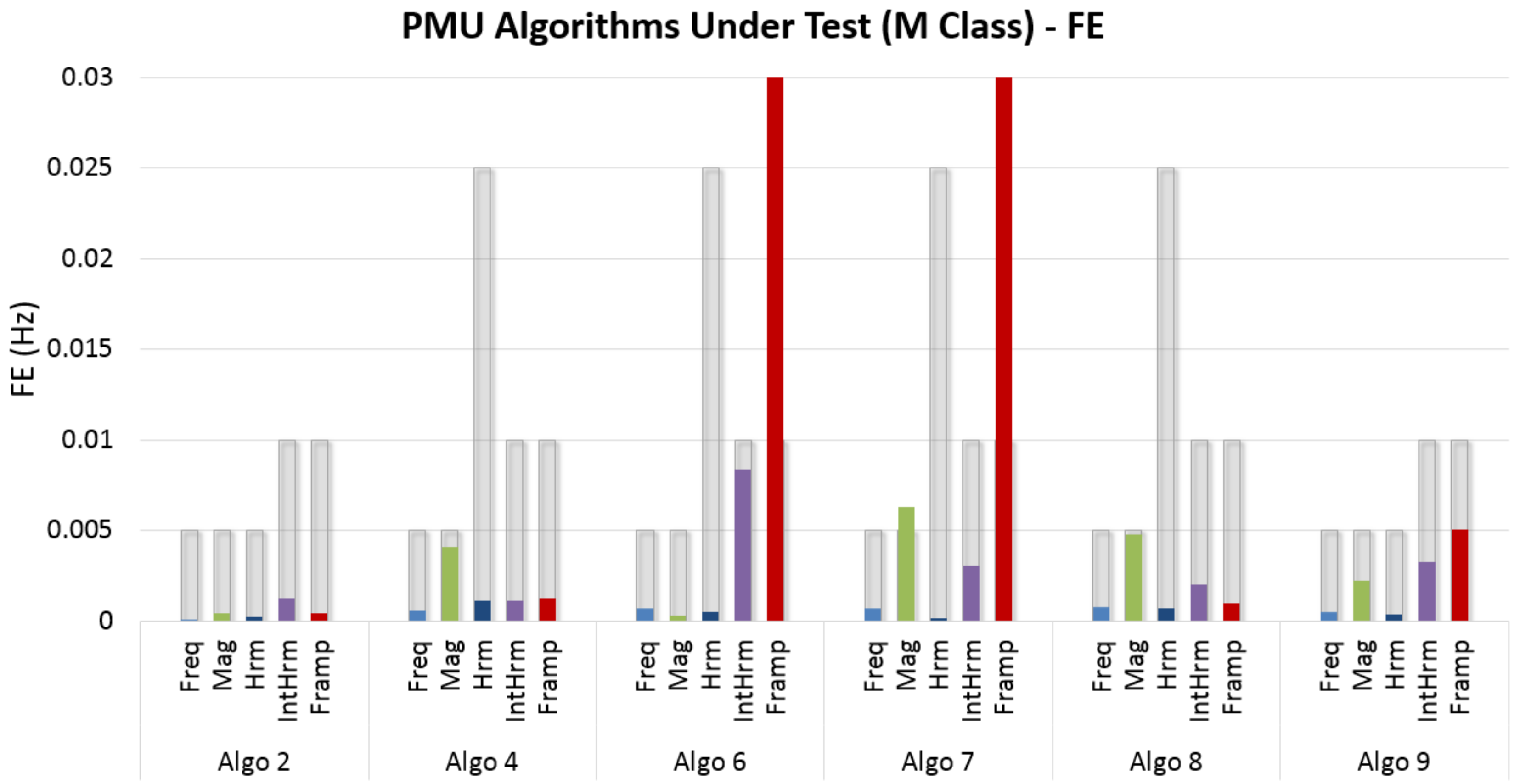
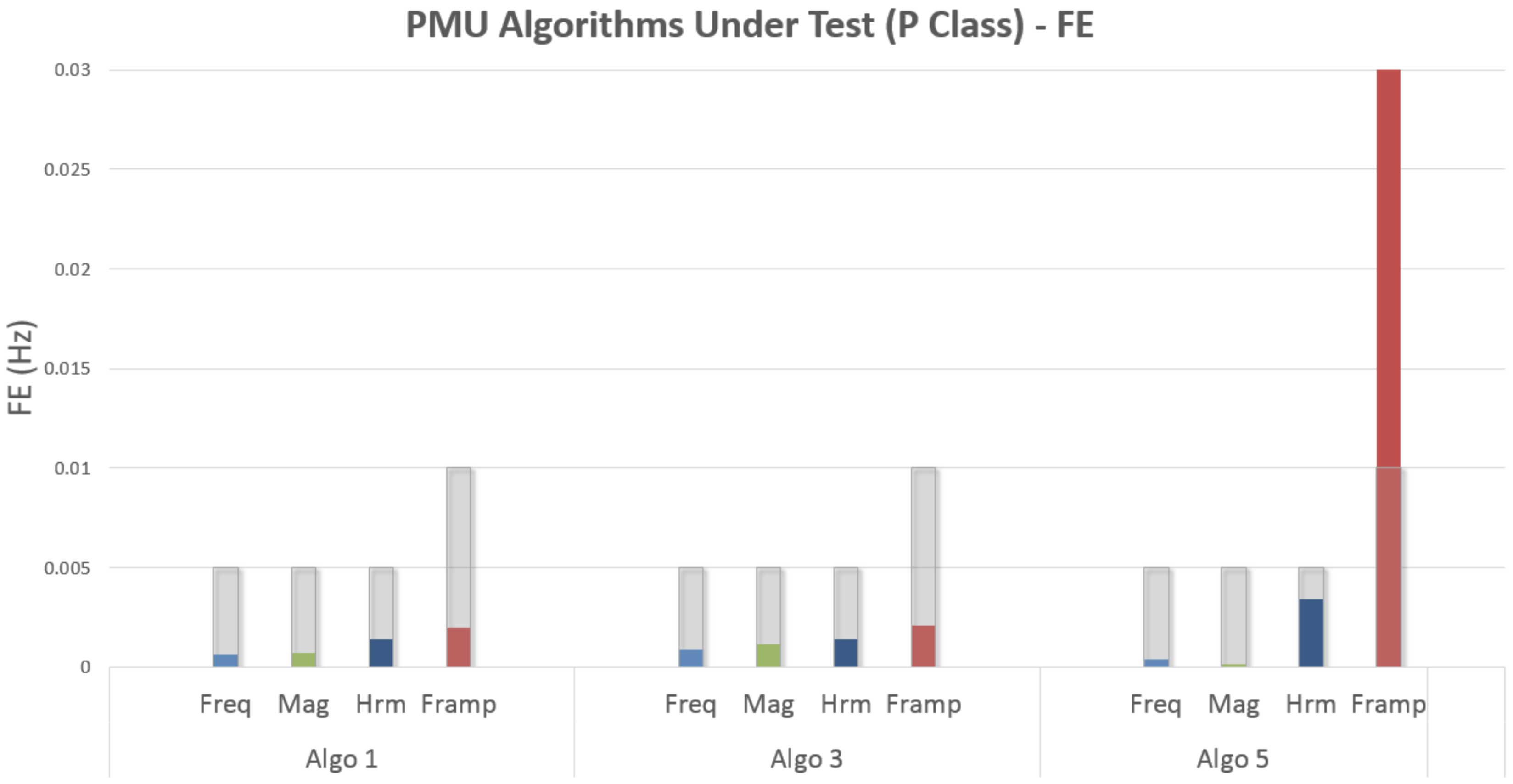
Comparison of Test Results for Different PMU Algorithms

Comparison of Test Results for Different Algorithms



Comparison of Test Results for Different Algorithms





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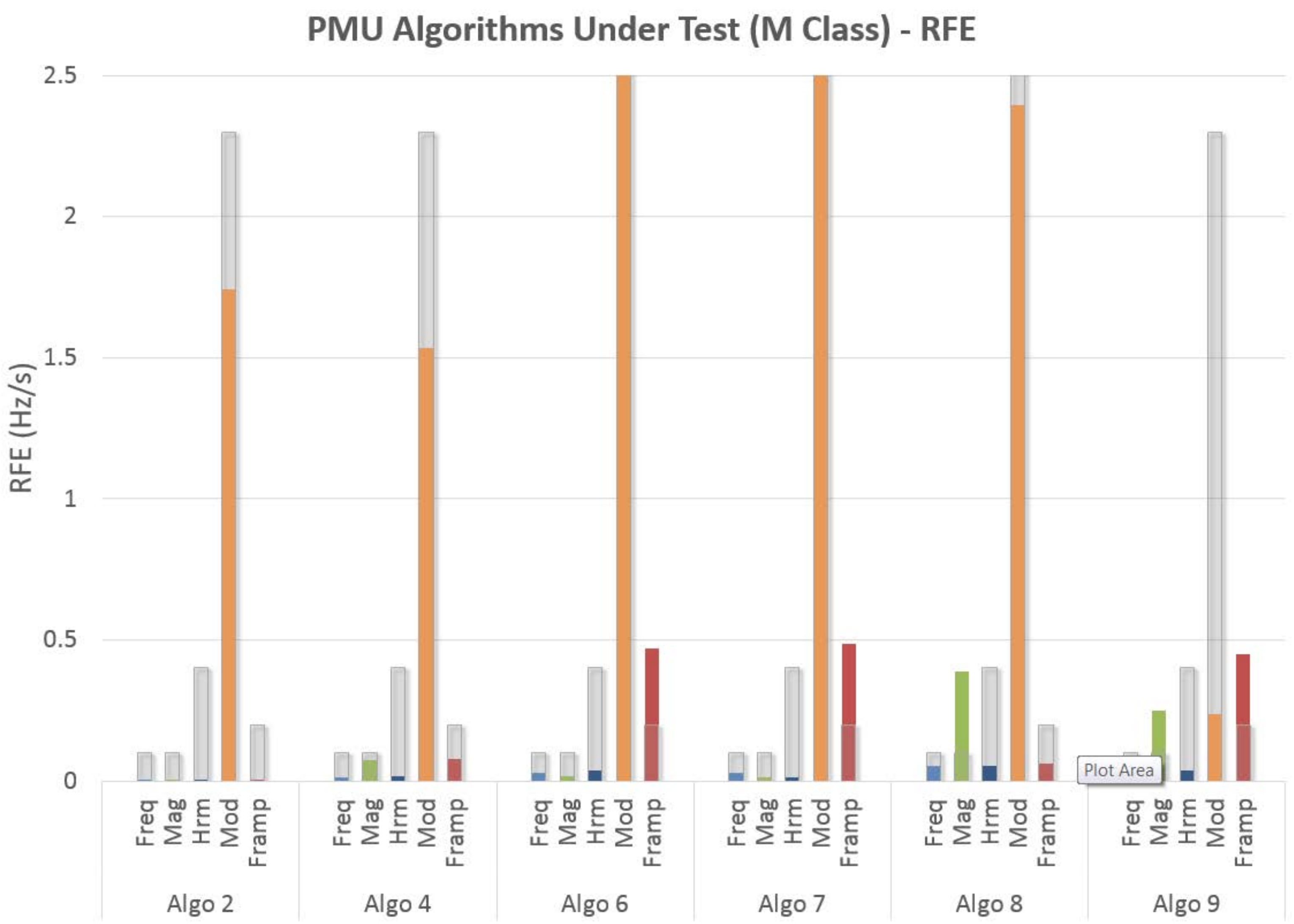
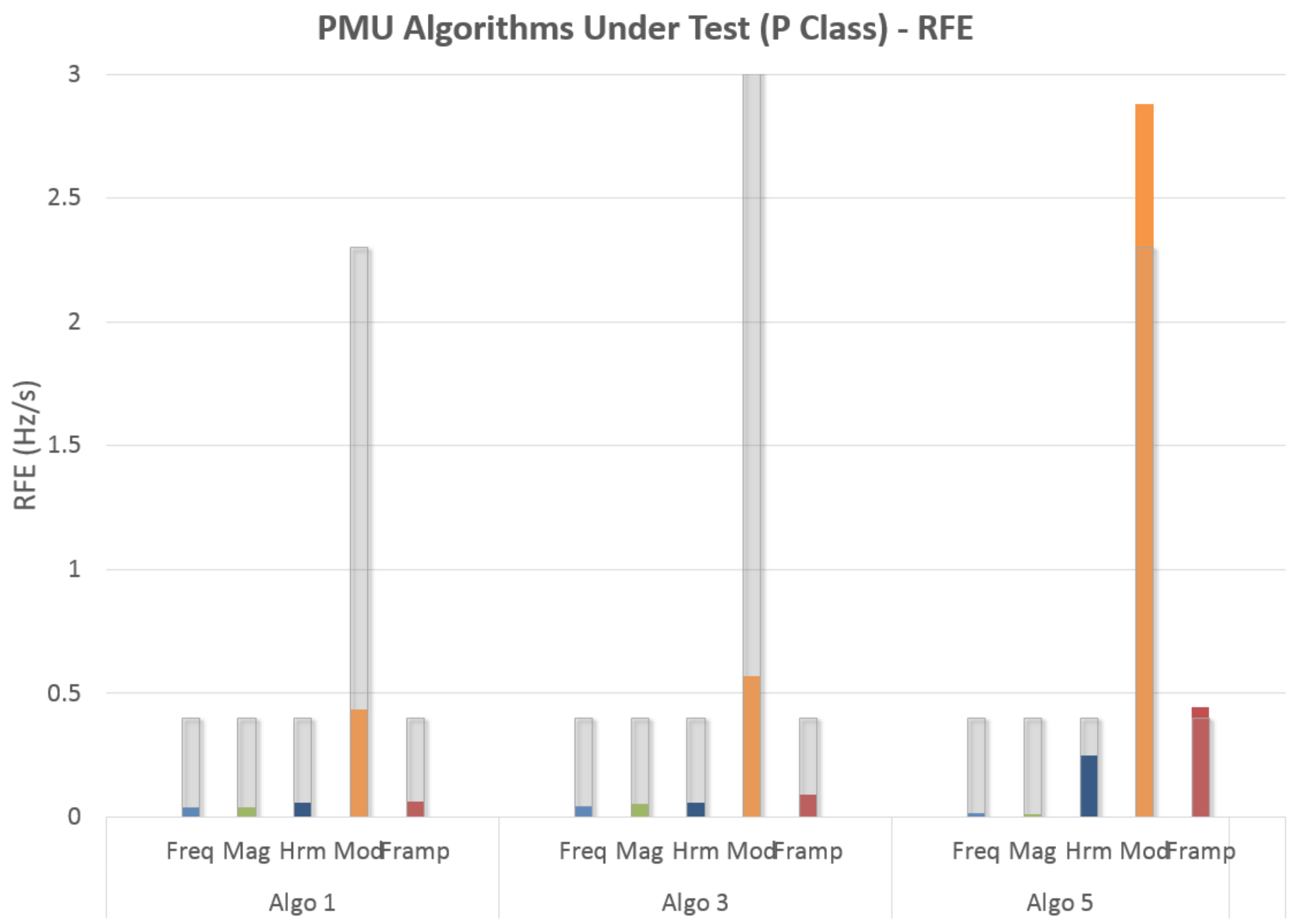
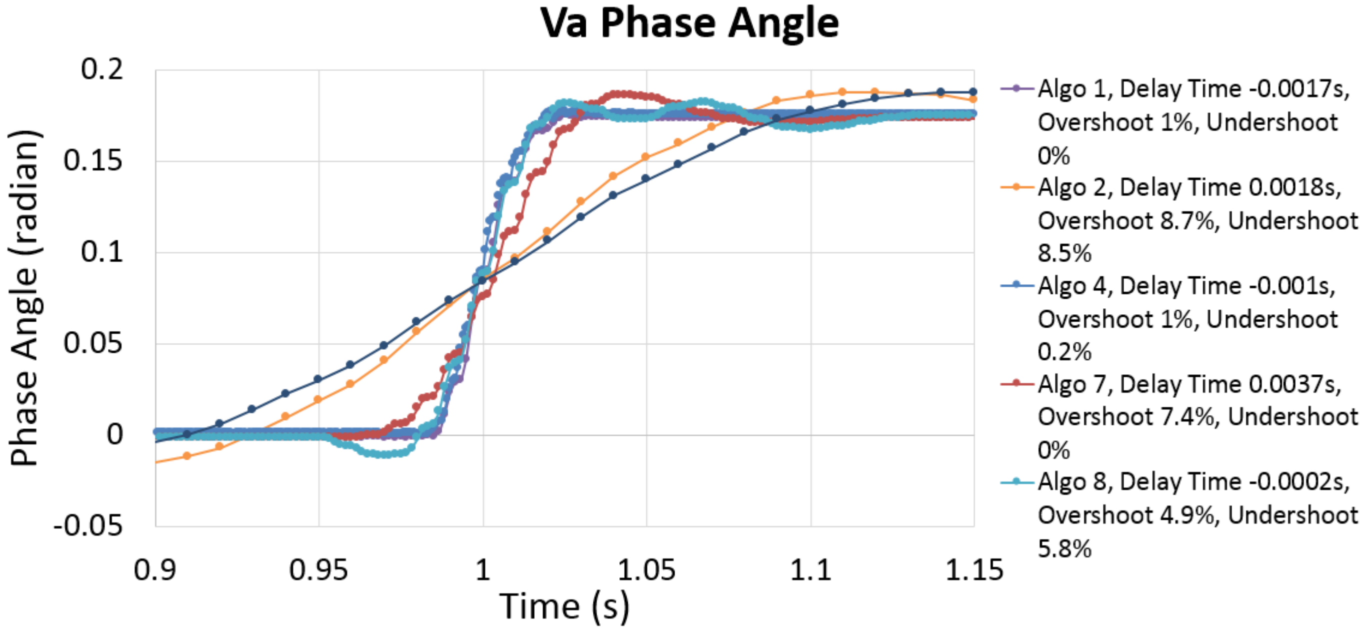
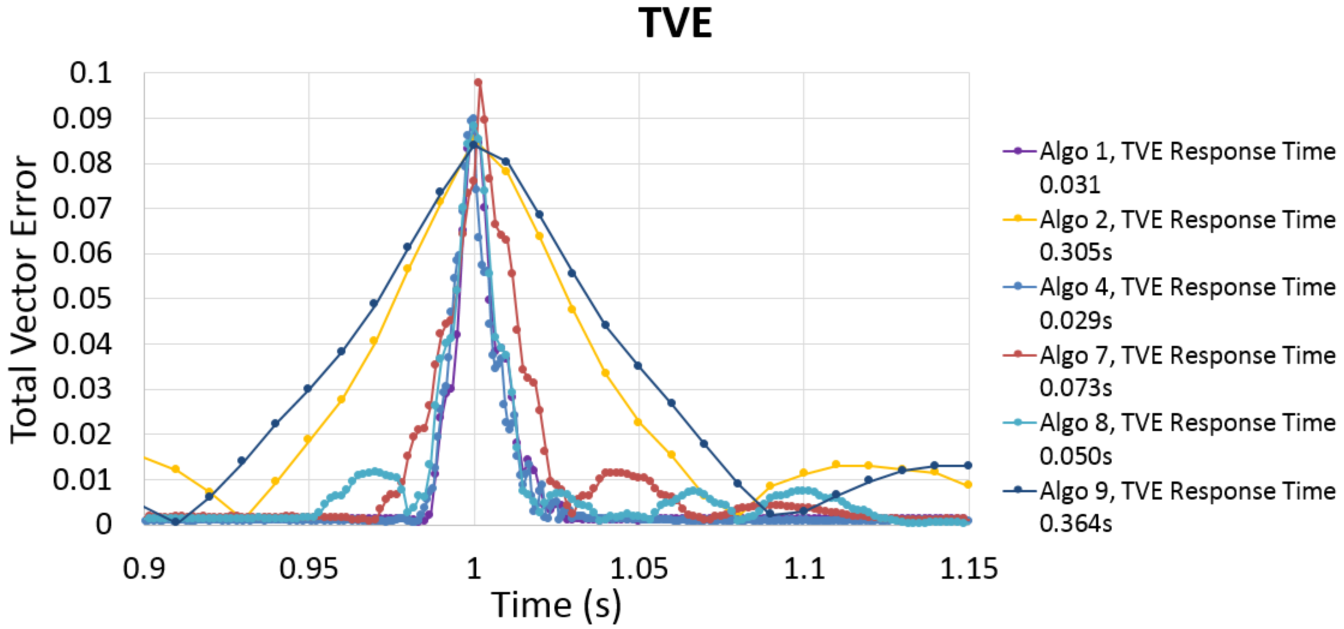
Comparison of Test Results for Different Algorithms

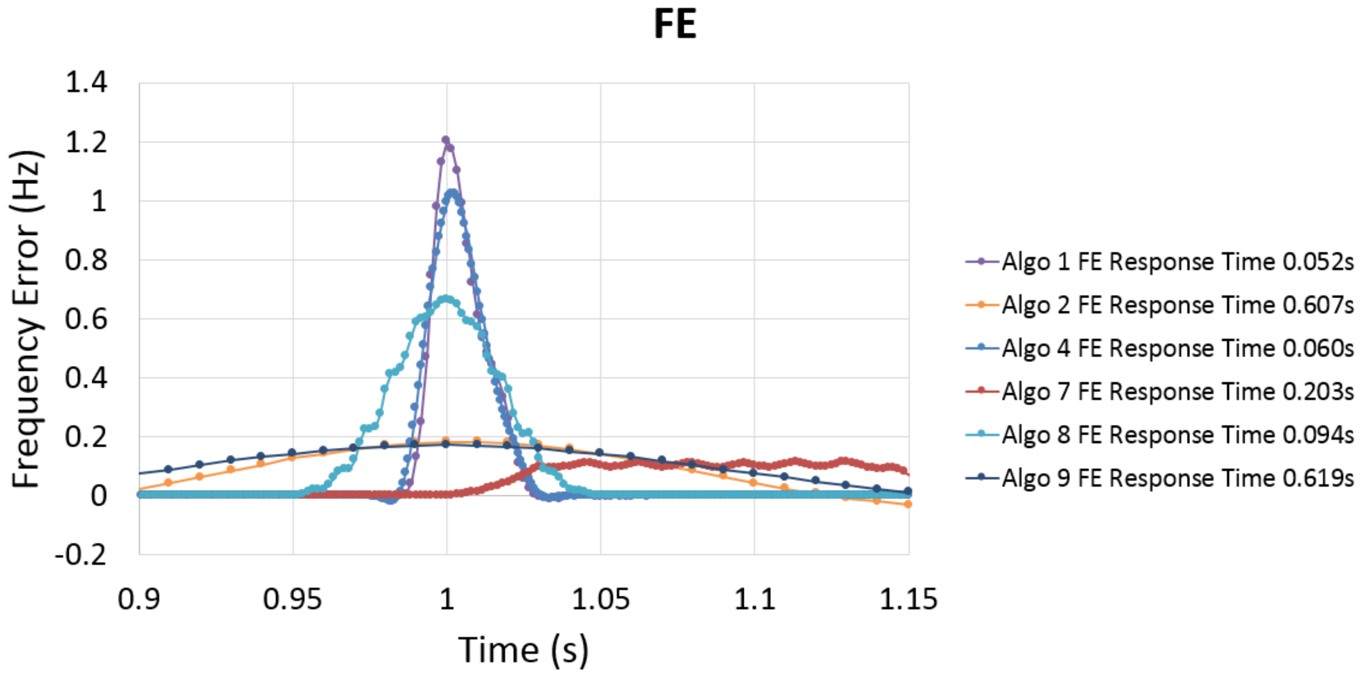




Phase Angle Step Response Test for Different Algorithms



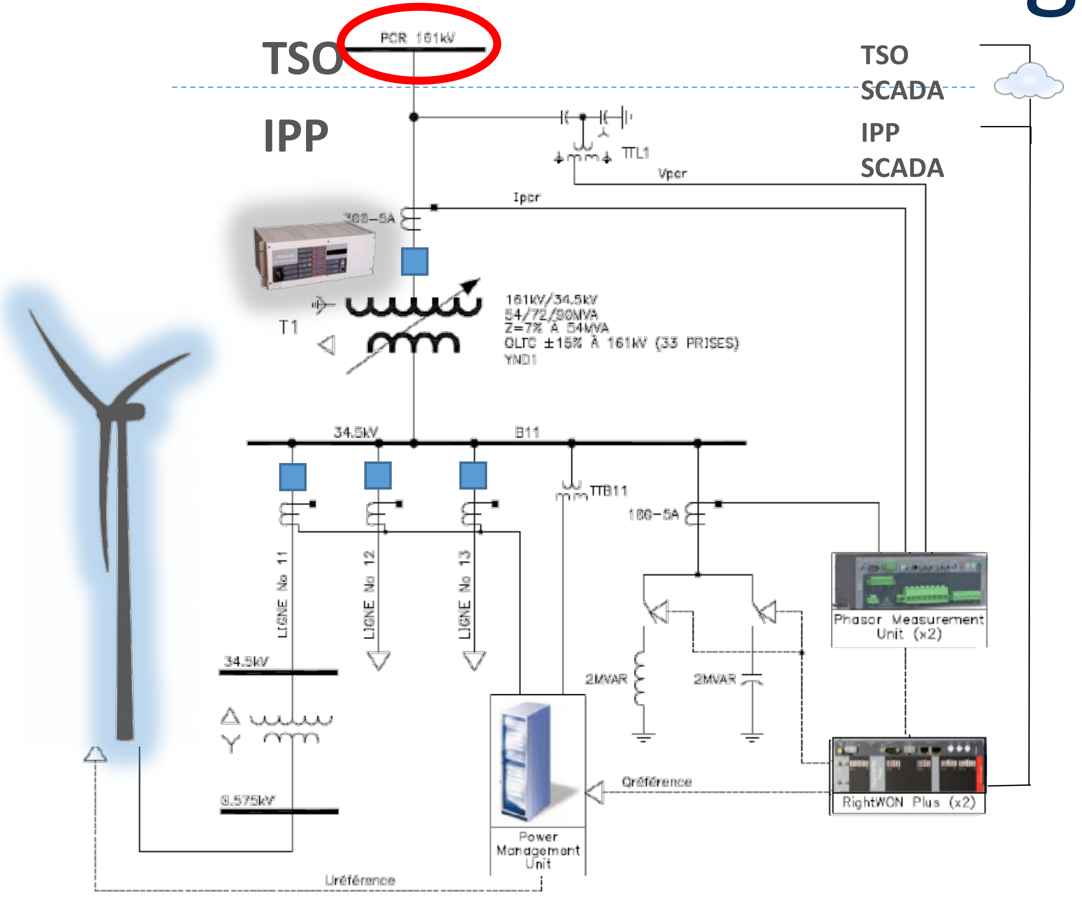


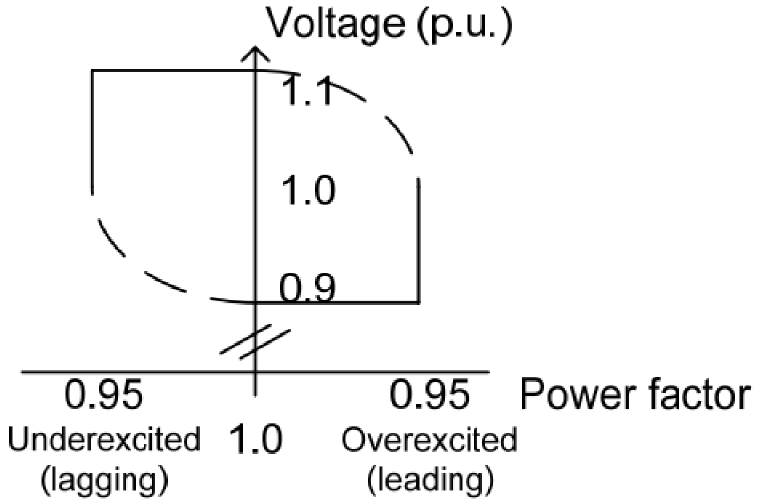


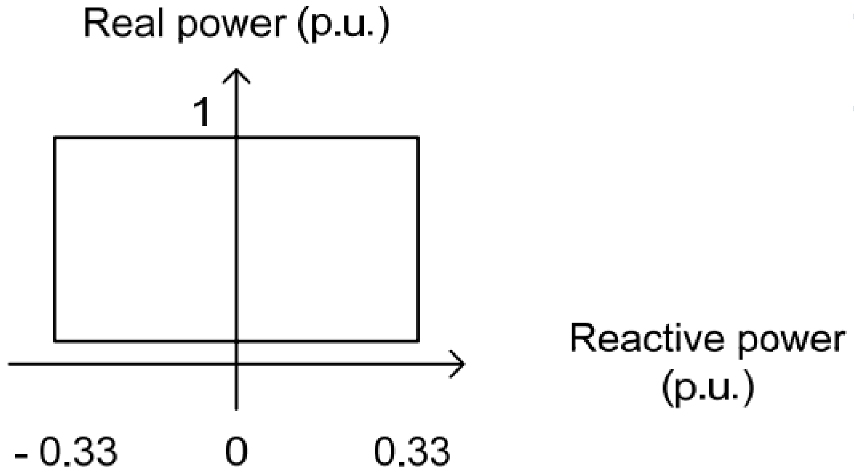
OPAL-RT TECHNOLOGIES

Advanced Applications using Model-Based Design, Studies and Testing

Model-based design – Mont-Rothery Wind Farm in Canada

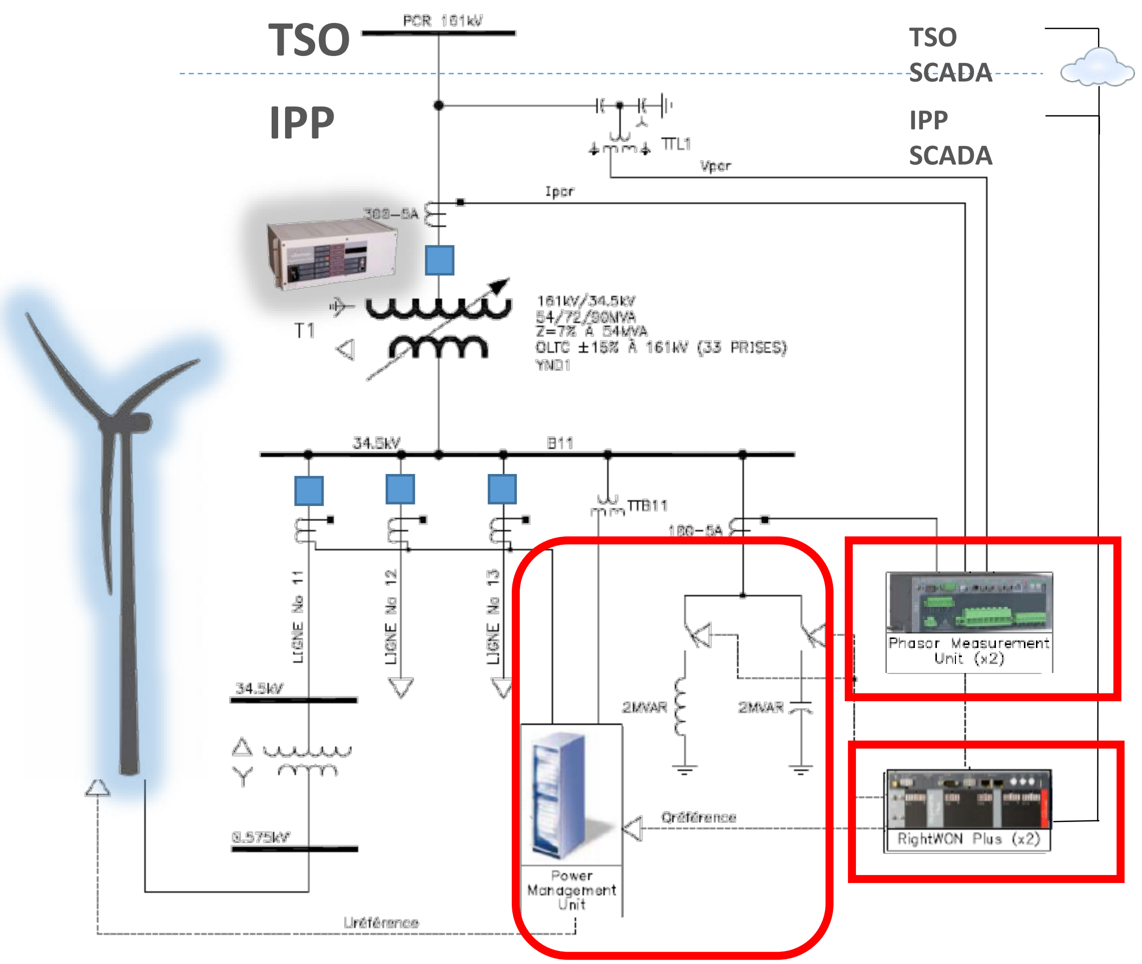






- Wind farms and other Independent Power Producers (IPP) have to comply with a number of network grid requirements
- This usually means installing complex and costly Static VAR Compensators (SVC) and/or mechanically switched capacitor banks and shunt reactors.

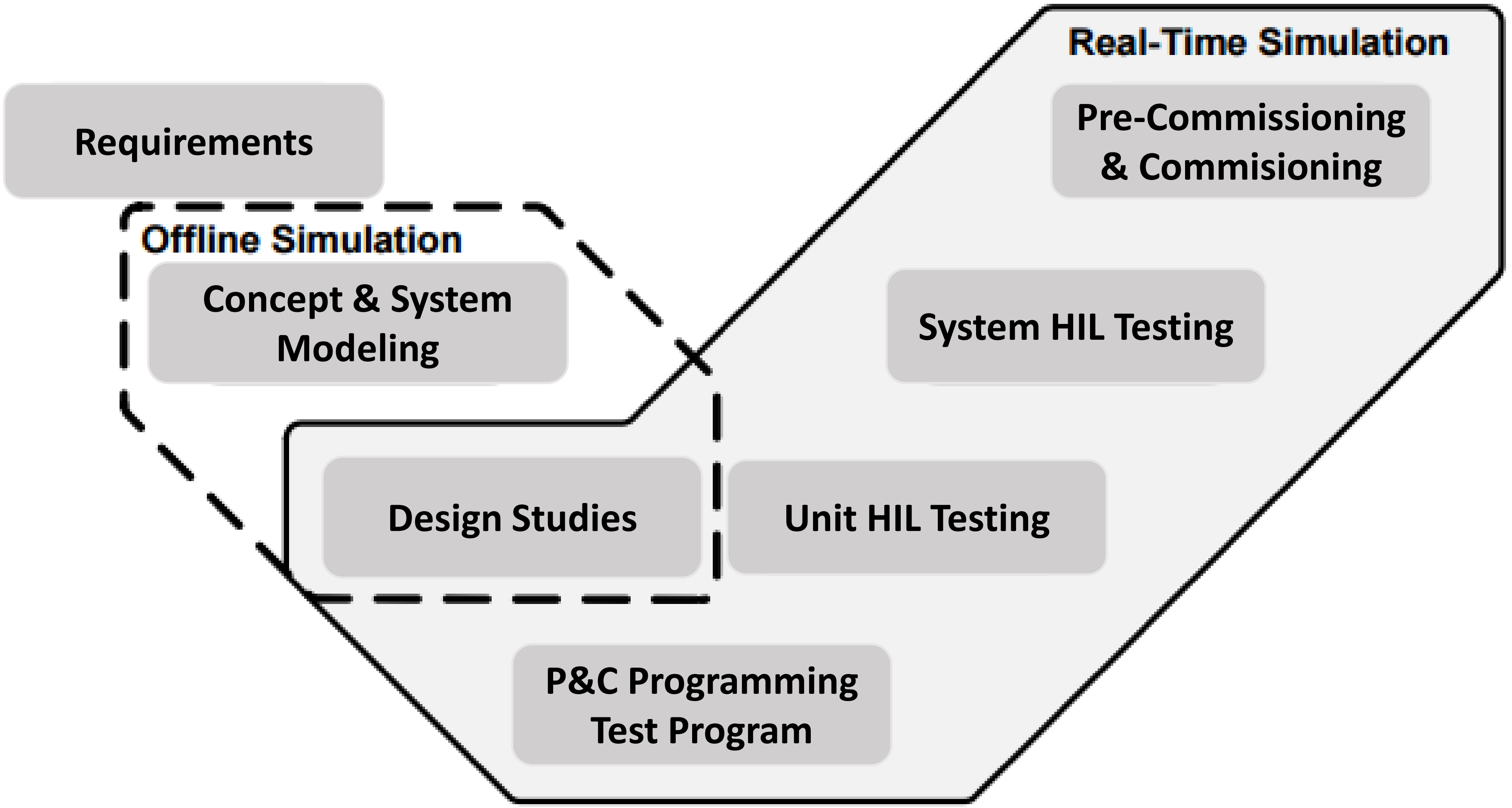
Model-based design - Mont Rothery Wind Farm in Canada



- Uses a VIZIMAX PMU to measure voltages and currents at the PCC (120 fps)
- An industrial controller receives C37.118 streams, does the calculations, corrections using PID loops and makes decisions
- The controller sends setpoints to the Wind Power Control Unit.
- The controller also controls mechanically switched capacitor banks and shunt reactors that allow meeting the requirements.

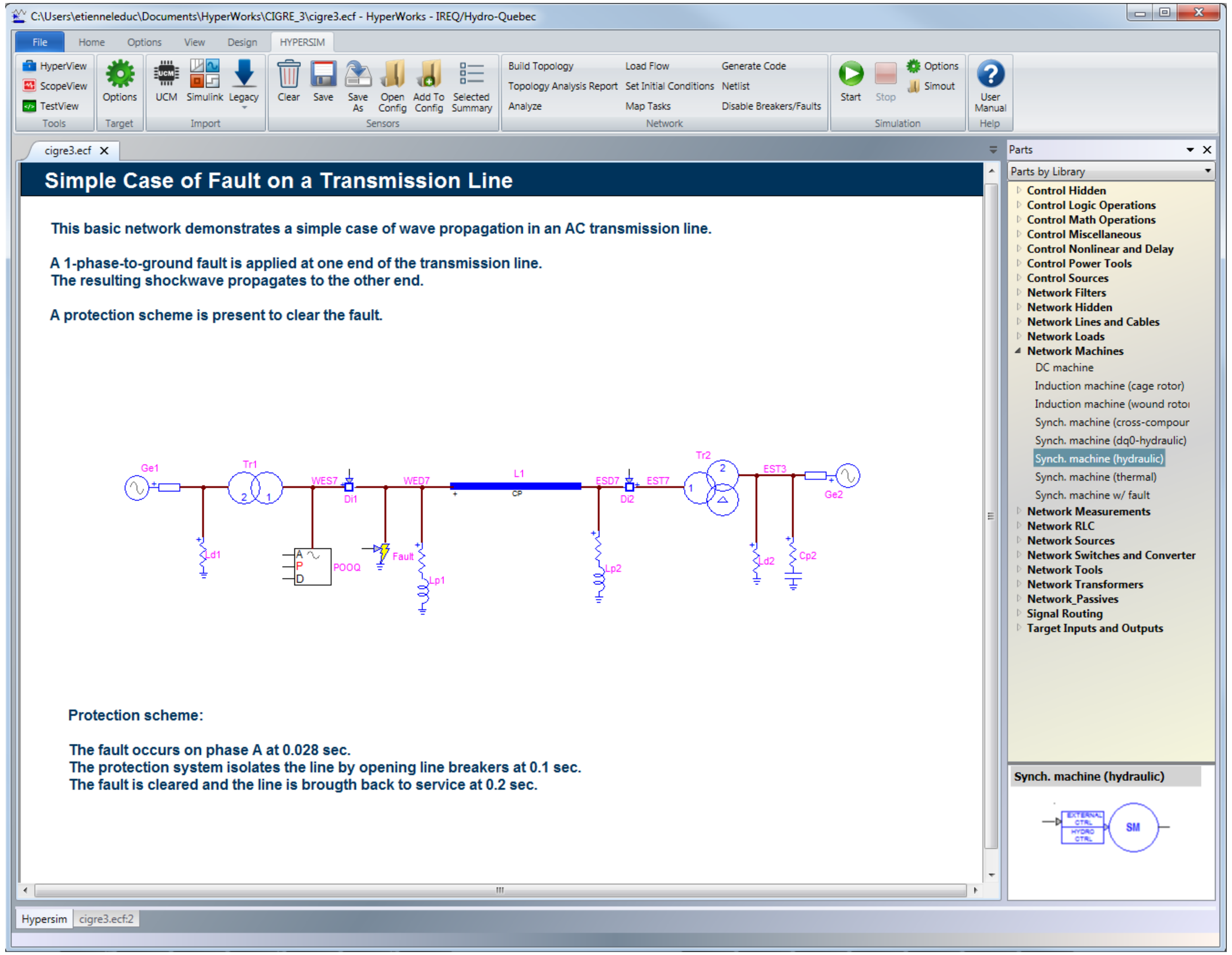
- Time to commission the system with full test coverage ?

Model-Based design in Power System Engineering



- Typically, a number of studies are required in Engineering design (power plants, T&D, P&C upgrade, etc.)
- Different studies usually require different analysis and simulation tools
- For equipment design, special control and protection prototyping and testing:
  - Goes from offline studies to real-time HIL testing…
  - … Without increasing the modeling efforts is a huge advantage

Model-Based Design – Matlab/eMEGAsim, EMTP-RV/HYPERSIM



- eMEGAsim is already compatible with Matlab/Simulink/SimPowerSystems
- HYPERSIM will have the same graphical engine than EMTP-RV released in April 2016
- Working on full compatibility with EMTP-RV models

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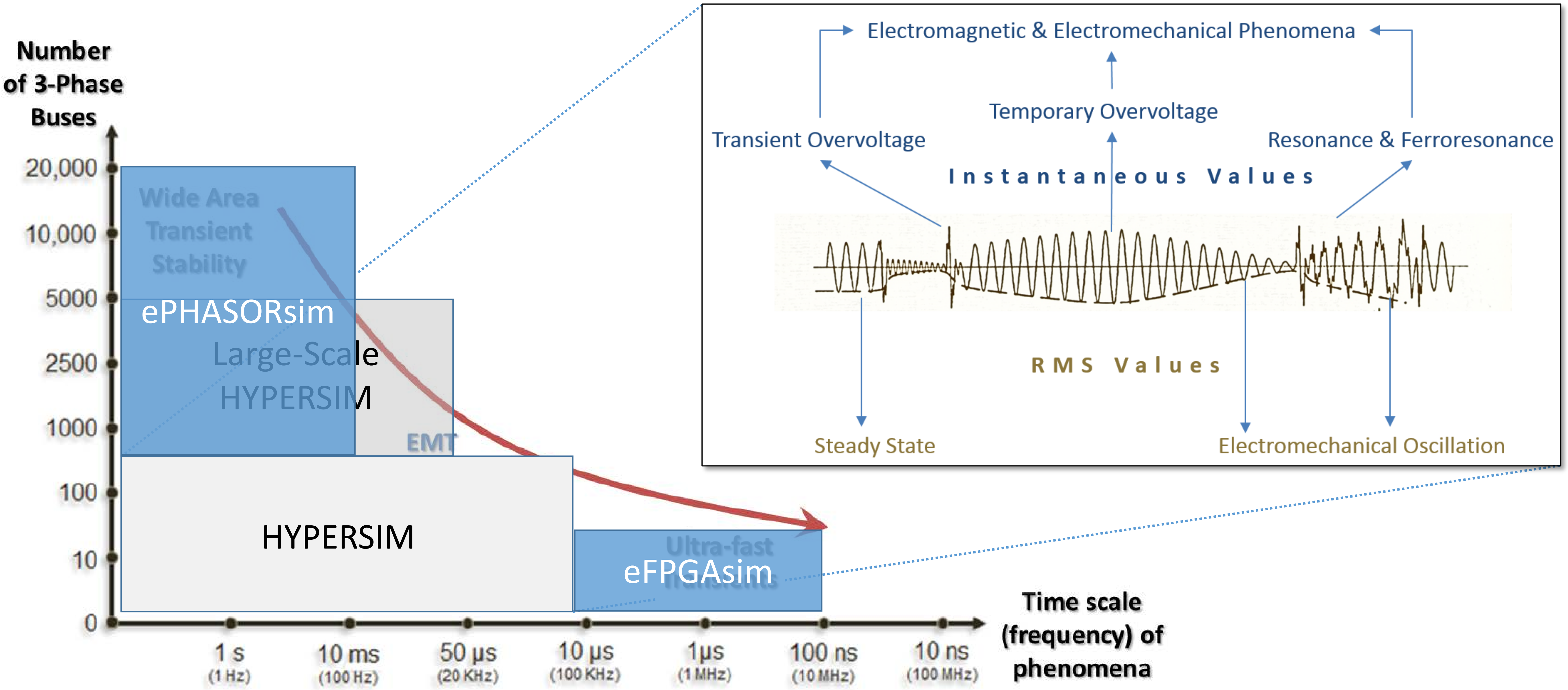
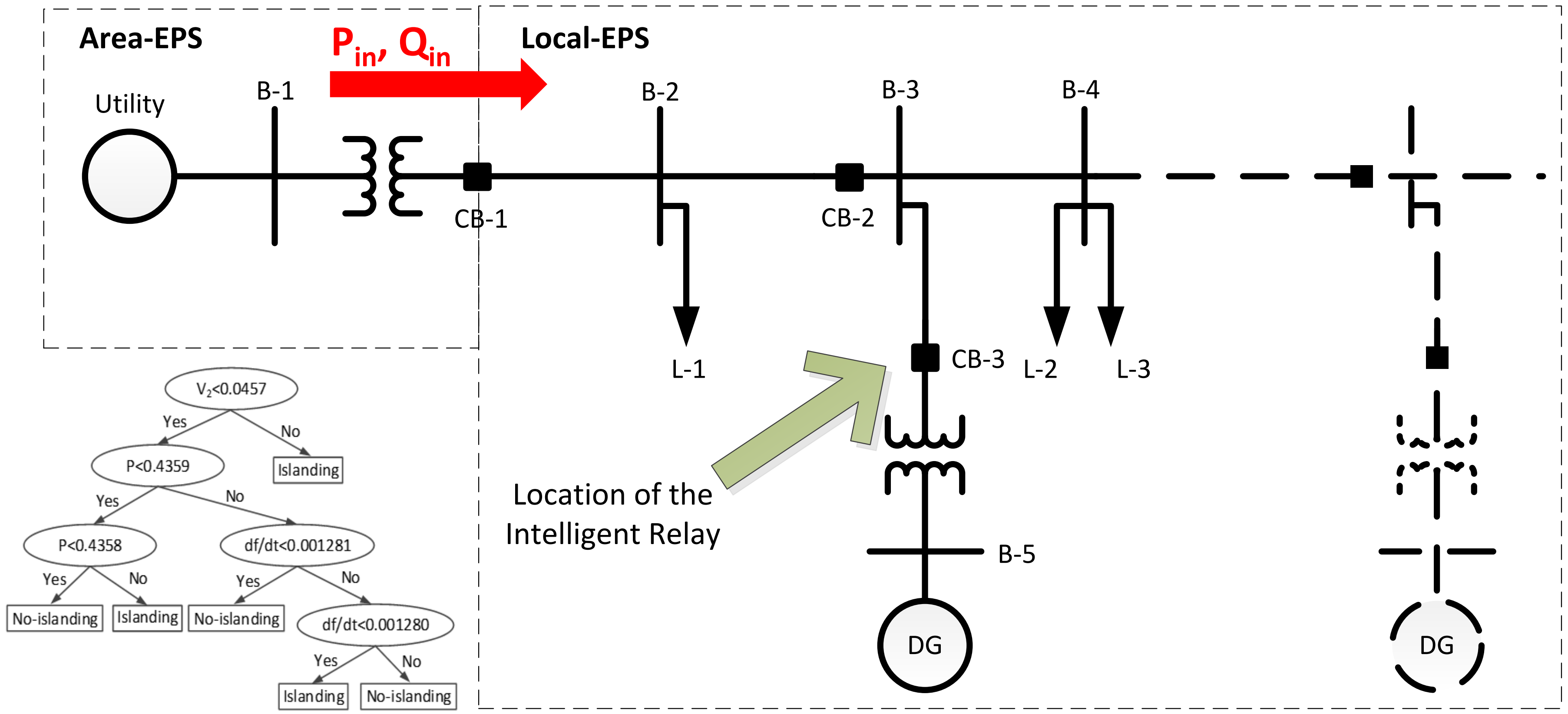
Phenomena Simulated Using OPAL-RT Simulators



OPAL-RT TECHNOLOGIES

Protection Applications using PMUs

Intelligent Relay Design and Testing For Distributed Generation



- Data-mining based relay setting methodology using automated simulations
- Short tripping time and high dependability and security
- Smaller Non-Detection-Zone
- **BEST PAPER AWARD – IET DPSP 2016 Conference**

Supervised Training

Define training events, perform simulation and obtain feature database.

Data Mining

Based on the training database, generate Decision-tree based protection logic using Data Mining techniques.

Testing

Perform testing with unknown events, analyze the acquired intelligent relay performance.

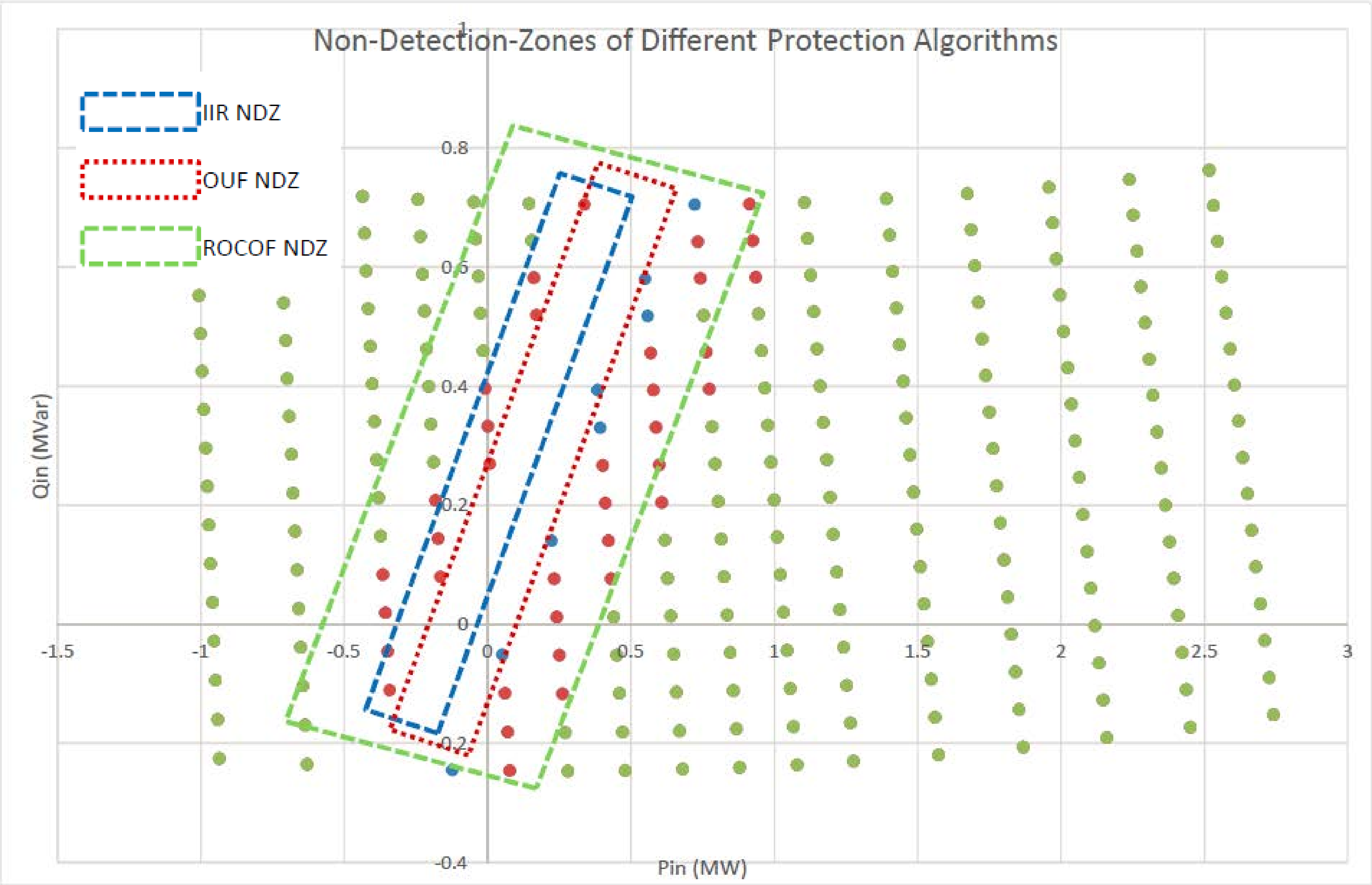
Q. Cui, S. Li, K. El-Arroudi, G. Joos, *Multifunction Intelligent Relay for Inverter-based Distributed Generation*, Presented at the 13th IET International Conference on Developments in Power System Protection, Edinburgh, U.K., 7-10 March 2016

Intelligent Relay Design and Testing For Distributed Generation

Number of tested operating conditions: 256
Test Duration: 1h56m49s

Selected key variables used for the Intelligent Relay Decision-Tree:

- V_{012}, V_{abc}
- I_{012}, I_{abc}
- *Δf, df/dt, df/dP, df/dQ*
- *ΔV, dV/dt, dV/dP, dV/dQ*
- *dP/dt*
- *dQ/dt*
- *pf, dpf/dt*



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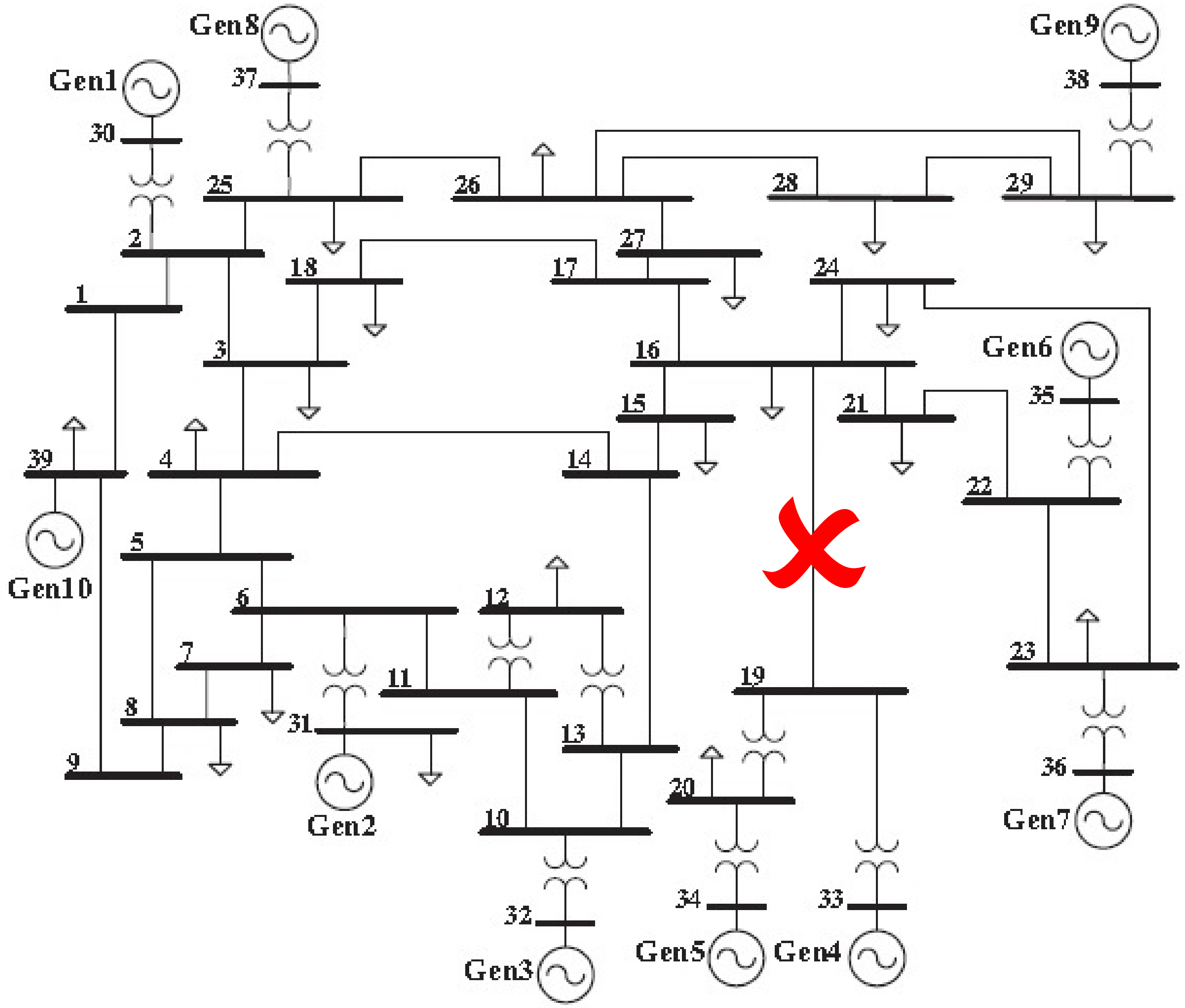
Control Design and Testing using Emulated or Virtualized PMUs

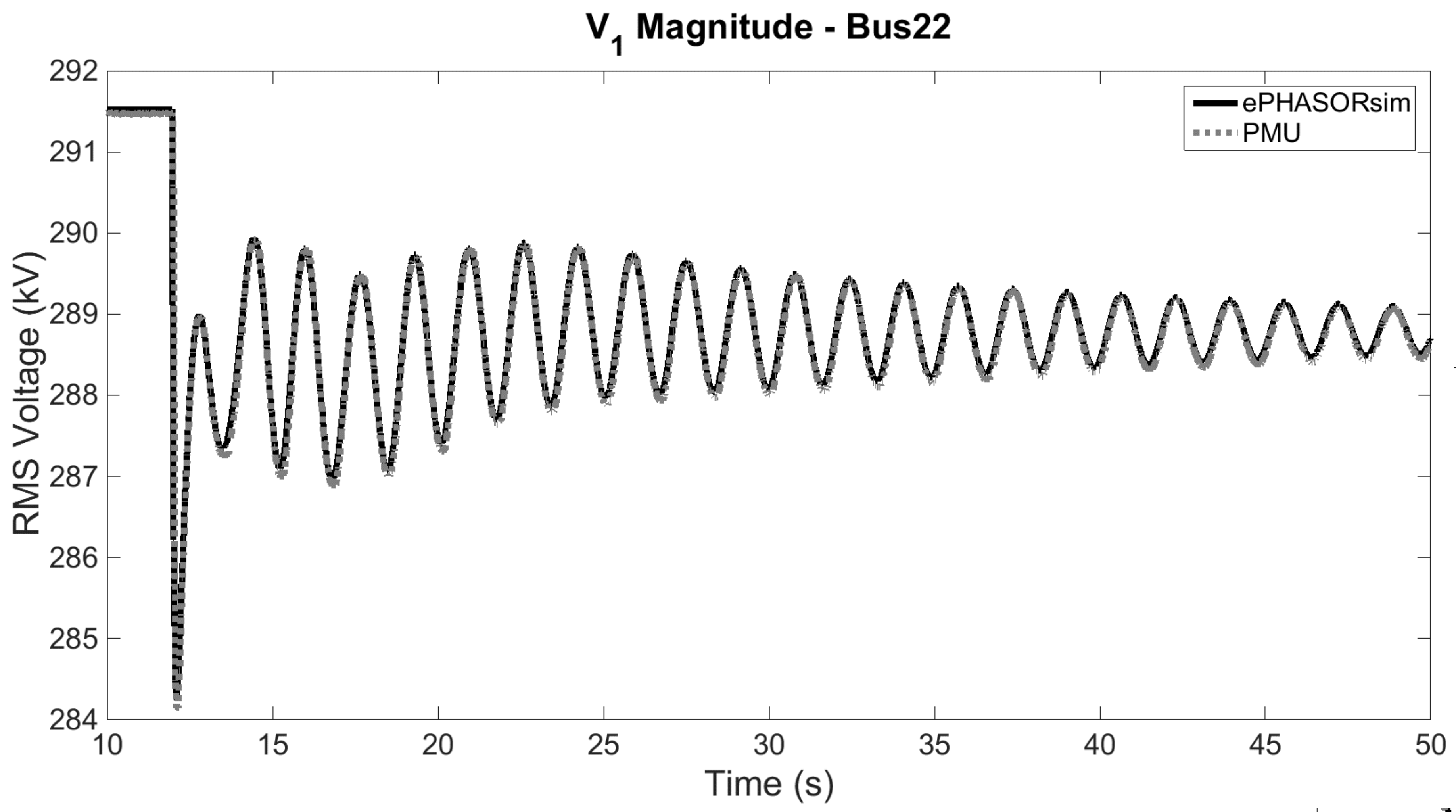
Virtualized PMU Dynamics with ePHASORsim

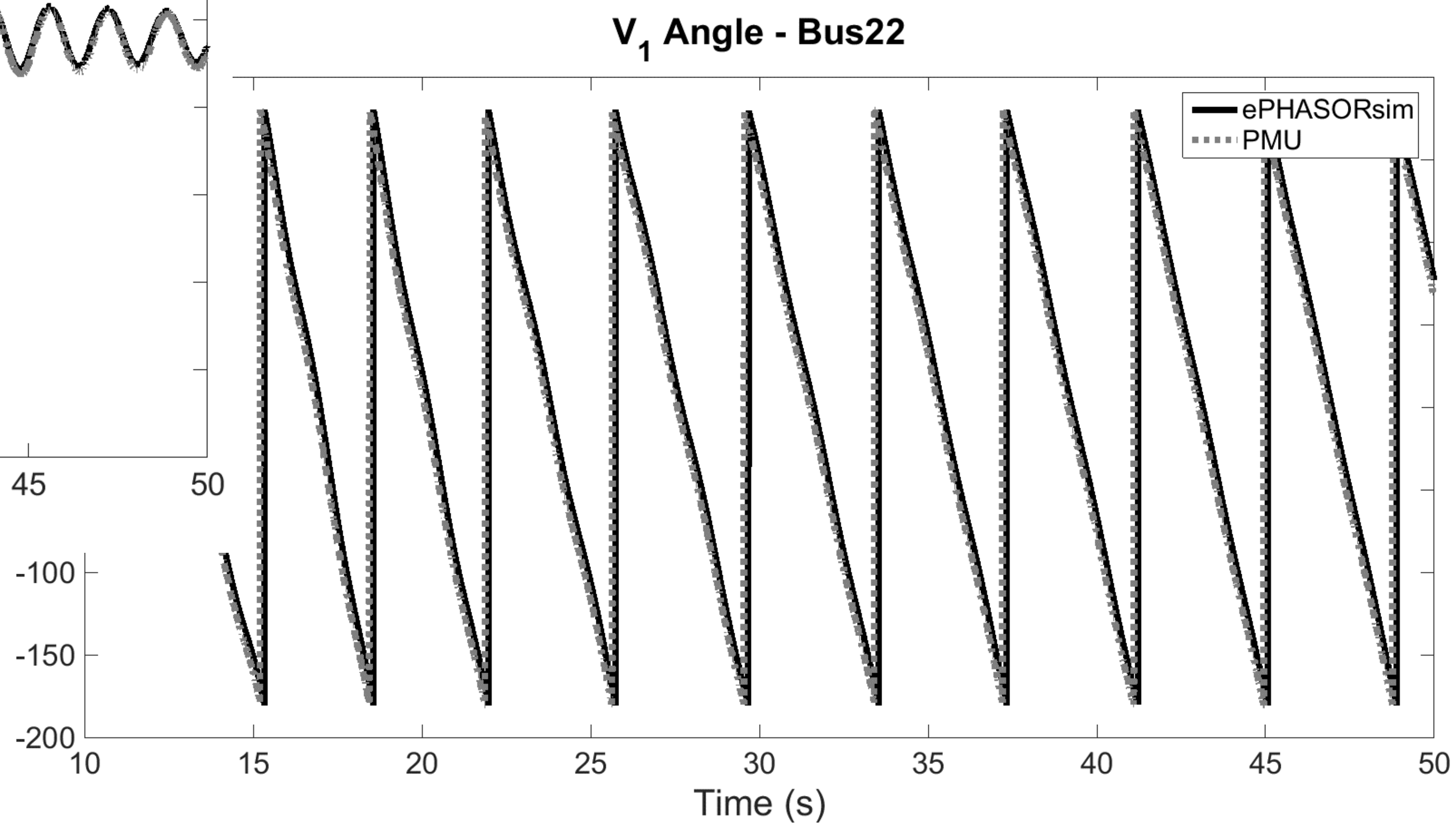


- How to simulate PMUs in Real-Time?
- How to design, study, and test a Wide-Area Control and Protection Schemes?
- How to ensure sufficient test coverage?

- Let's look at the dynamic response of a PMU compared to ePHASORsim…

Virtualized PMU Dynamics with ePHASORsim





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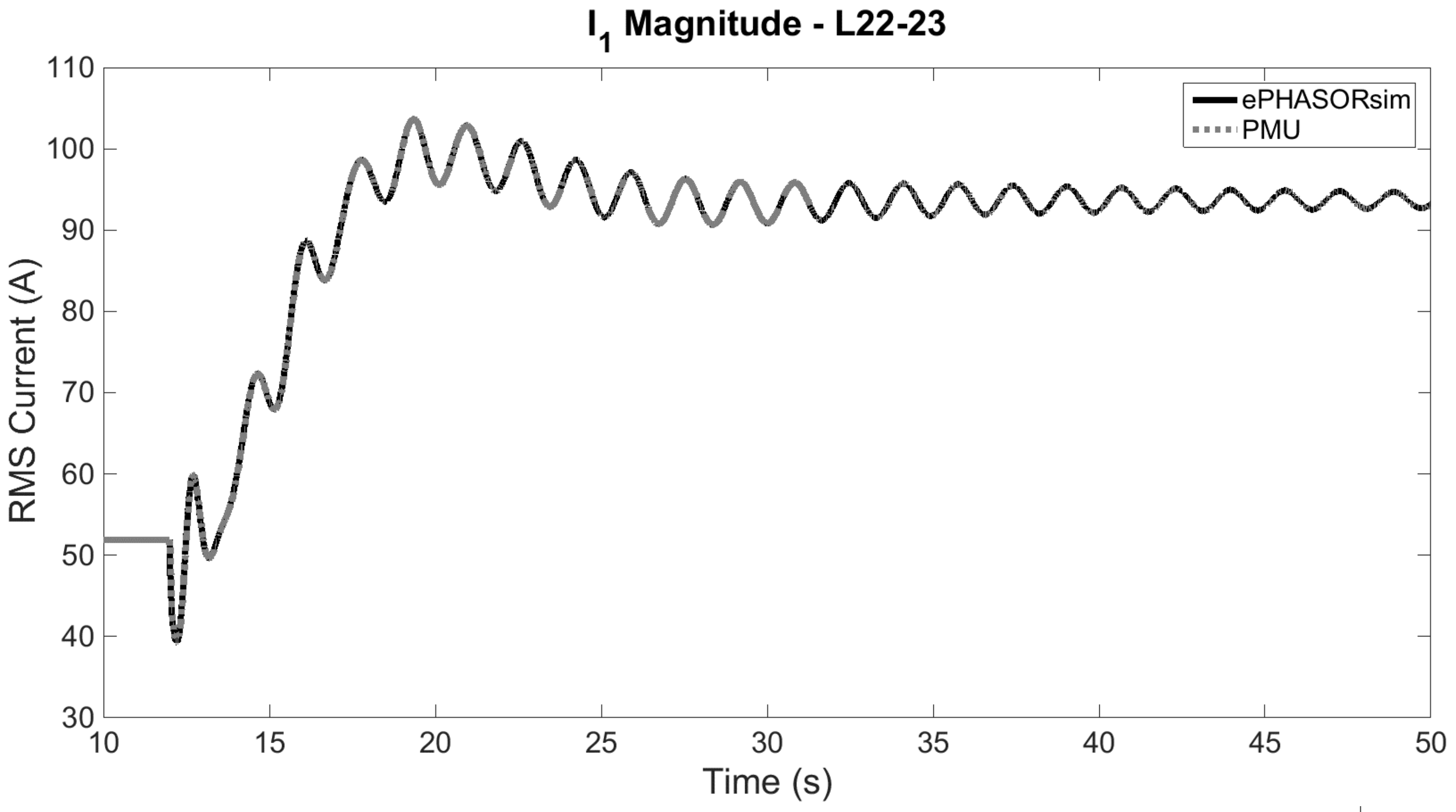
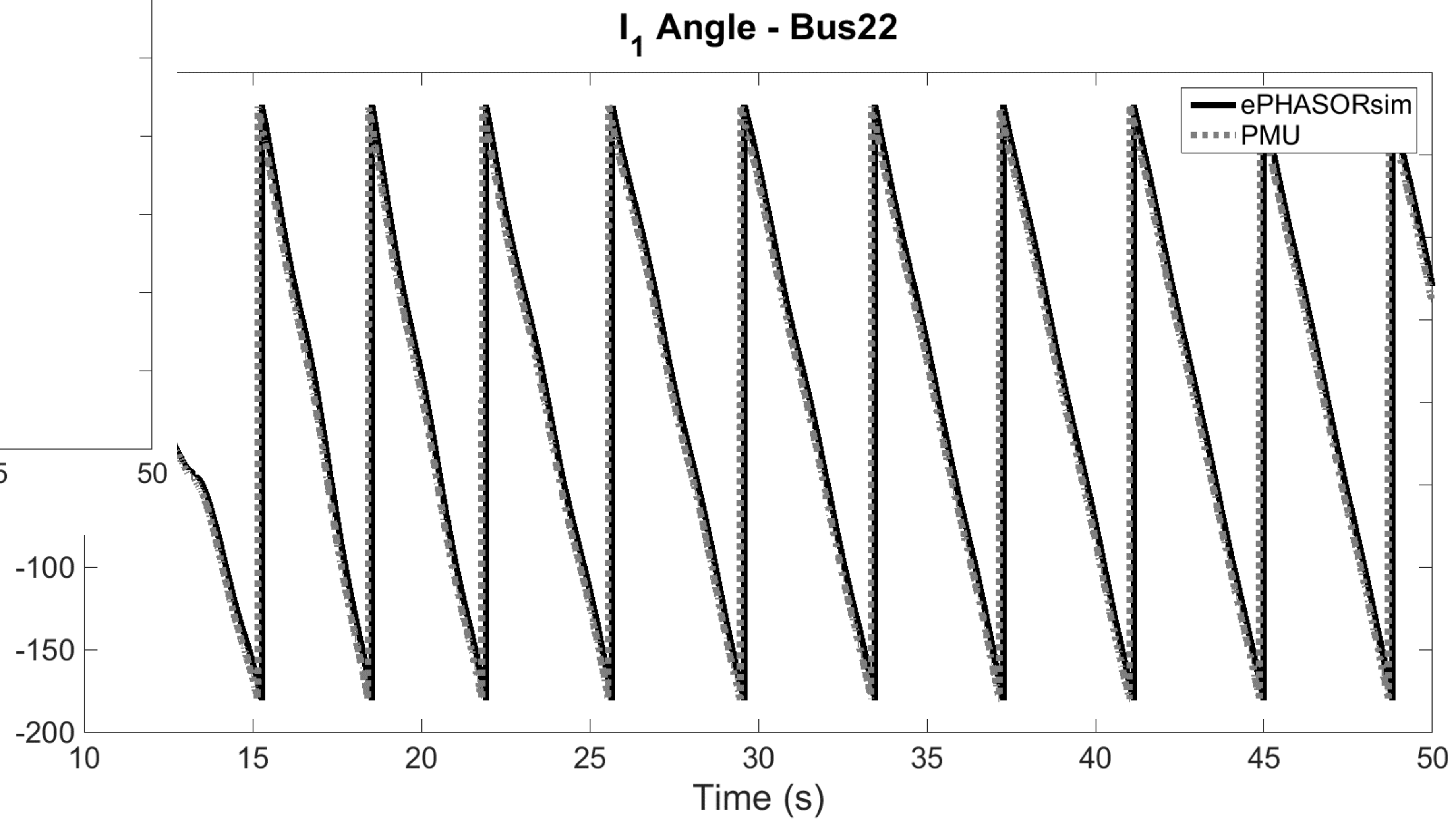
Virtualized PMU Dynamics with ePHASORsim





Conclusions

- PMUs are becoming a key part of ensuring grid reliability, but applications are numerous and need specialized studies and testing
- It was demonstrated that the use of a real-time simulator providing analysis capability is valuable for:
  - Pre-certification test of monitoring, control, protection devices such as PMU, with an accuracy comparable to that of calibration lab equipment and the capability to go beyond the standard requirements
  - Increasing test coverage by simulating (otherwise) « destructive tests » or contingencies with lower probability of occurrence by that have higher potential economical impact
  - Equipment and power grid design studies as well as real-time testing using the same models throughout the Engineering efforts
  - Development and study of various protection applications using IEDs with new algorithmic approaches as well as legacy functionalities
  - Design and real-time testing of Wide-Area Protection and Control schemes by emulating PMU dynamic response

Thanks!

Questions?

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