Fluke PMU Calibrator:
A NIST ARRA Grant Project

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NASPI Workgroup Meeting

Denver, CO

June 5, 2012

Note: This presentation does not imply recommendation or endorsement by NIST.

PMU calibration today

- Few test sites
- Complex test setup
- Highly proficient operator
- Manual operation
- Two to six weeks per PMU configuration
- Uncertain traceability / test accreditation.

In February 2010, Fluke Calibration was awarded an ARRA grant from NIST to develop a commercially available PMU Calibration System

Grant Deliverables

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Calibration

Feb 2010	NIST grant announced
July 2010	Customer Requirements Survey
Dec 2010	Product Requirement Specification
Sept 2011	System hardware delivered to NIST
July 2012	Intercomparisons

Automated PMU calibration system:

- IEEE C37.118.1-2011 compliant
- Fast, automated
- Accurate, traceable
- Fully documented

Customer Requirements

Drawn from Fluke PMU Symposium in May, 2010.

- Attended by 13 PMU experts
- Each gave a presentation and participated in a formal requirements survey
- Bolstered by Fluke's understanding of National Metrology Institutes, primary, secondary and third party labs, and test accreditation

Customer needs identified and ranked:

Rank	Need
1	Minimize PMU test time
2	Minimize user interaction
3	Maximize accuracy and traceability
4	Minimize operator expertise
5	Maximize test report and data usefulness
6	Minimize time to create test reports

Product Requirements

- Electrical Calibration (the measure of error and uncertainty).
- Provide:
  - UTC aligned, accurate voltage and current sources
  - PMU data collection
  - analysis of error/uncertainty (e.g. TVE, Fe, RFe, Response time etc)
  - sophisticated result plotting, analysis displays, and data collection.
  - automated report and certificate creation.
- Compliant with IEEE C37.118.1™-2011
  - Steady State testing in accordance with Tables 3 and 4
  - Dynamic testing in accordance with Tables 5,6,7,8,9, and 10
- Uses test methodology documented in PC37.242 section 7.
- Test automation can run about 1000 individual tests in less than 24 hours.*

*CPU dependent: your times may vary

IEEE C37.118.1, Section 5.5.1, Compliance Certification

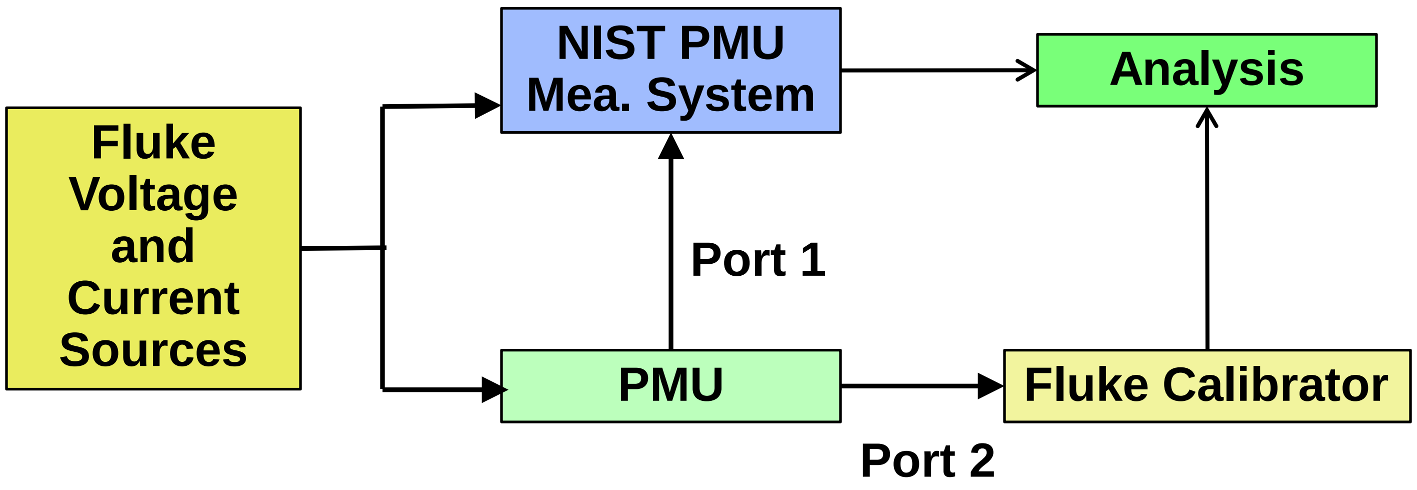
“Documentation shall be provided by any vendor claiming compliance with this standard that shall include the following information:

1. Performance class *(M=Measurement, P=Protection)*
2. Measurements that meet this class of performance
3. Test results demonstrating performance
4. Equipment settings that were used in testing
5. Environmental conditions during the testing

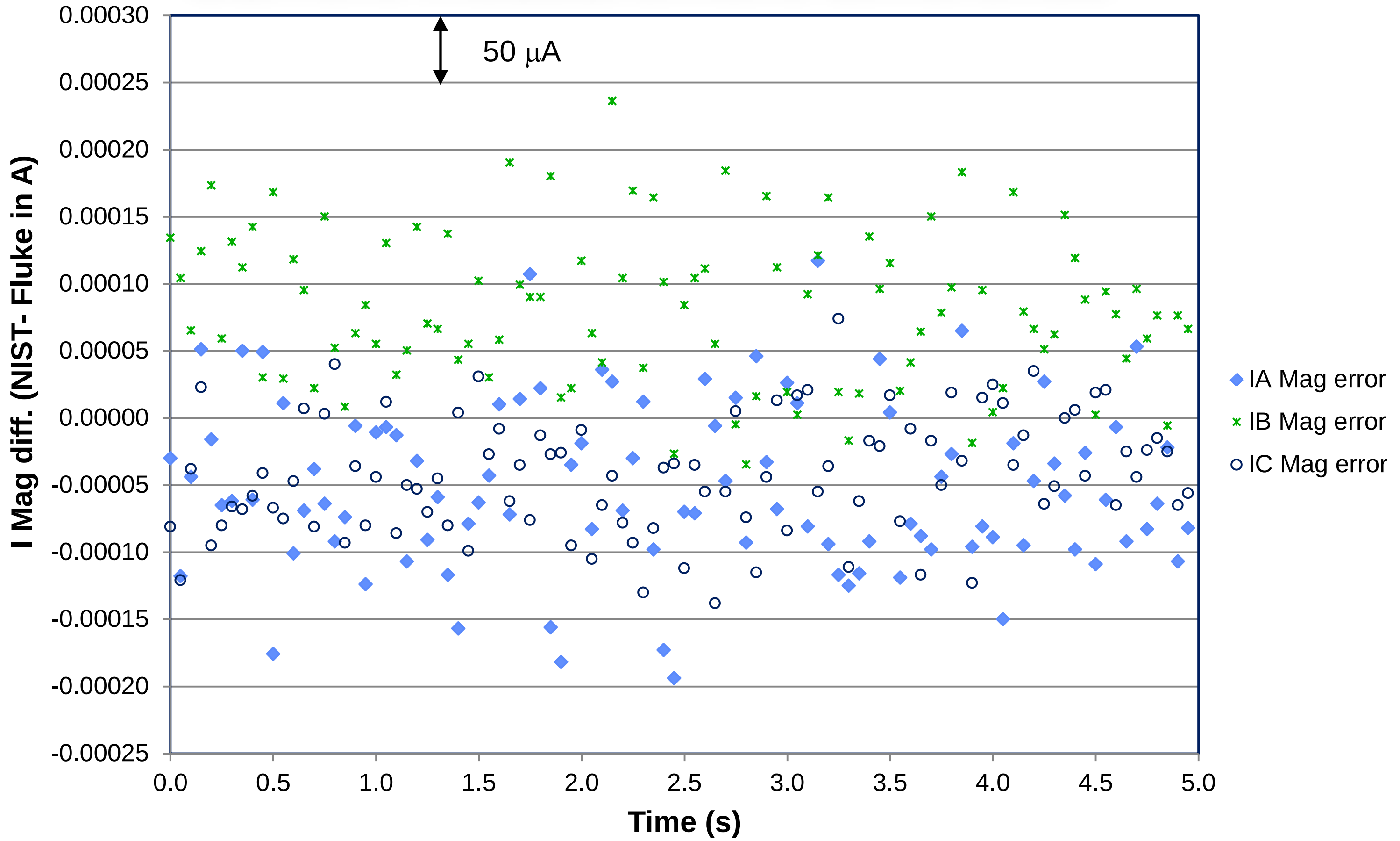
Accreditation requirements

- Signal source magnitude and absolute phase shall be traceable to first principles as represented by national standards
  - “absolute” phase is phase relative to time.
- “True” value uncertainty shall be verified.
  - “True” values are the values of the signal source which are compared to the PMU Under Test’s output to determine TVE, Fe, and RFe.
- Result calculations shall be verified to be compliant with IEEE C37.118.1:2011.
  - Result calculations include TVE, Fe, RFe, Step ResponseTime, Step Delay Time, and Step Overshoot.

Comparison between NIST and Fluke Systems



Current measurement difference



Nominal current 5A

Summary of current measurement comparison

	NIST - Fluke								
	IA Mag	IA Phase	IB Mag	IB Phase	IC Mag	IC Phase	IA TVE	IB TVE	IC TVE
Max	0.000117	0.000658	0.000236	-0.000541	0.000074	-0.000341	0.004779	0.005842	0.005224
Min	-0.000194	-0.002691	-0.000035	-0.002941	-0.000138	-0.002841	0.000230	0.001419	0.000921
Mean	-0.000051	-0.000980	0.000082	-0.001539	-0.000043	-0.001641	0.002482	0.003329	0.003123
STDEV	0.000063	0.000729	0.000056	0.000507	0.000044	0.000569	0.000984	0.000929	0.000962
DOF	99	99	99	99	99	99	99	99	99
SD mean	0.000006	0.000073	0.000006	0.000051	0.000004	0.000057	0.000099	0.000093	0.000097
Student t	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
Type A	0.000012	0.000145	0.000011	0.000101	0.000009	0.000114	0.000196	0.000185	0.000192
Max Rel. Diff in %	**0.0039**	**0.0027**	**0.0047**	**0.0029**	**0.0028**	**0.0028**	**0.0048**	**0.0058**	**0.0052**

Note: Current in A, phase in degree

Revised steady-state tests

IEEE C37.118.1-2011	Test Parameter	Range	Metrics (units)
Steady-state compliance tests Section 5.5.5	Signal frequency	±2 Hz for P = Protection class ±5 Hz for M = Measurement class	TVE (%) FE (Hz) RFE (Hz/s)
	Signal magnitude: voltage	80 to 120 % of nominal	
	Signal magnitude: current	20 to 200 % of nominal	
	Phase angle	± π radians	
	Harmonic distortion	1%, to 50th harmonic (P class) 10%, to 50^{th} harmonic (M class)	
	Interharmonics (M class only)	10%, for $F_s \geq 10$	

New ! Dynamic tests

NIST National Institute of Standards and Technology Technology Administration, U.S. Department of Commerce

FLUKE Calibration

IEEE C37.118.1-2011	Test Parameter	Range	Metrics (units)
Dynamic compliance tests Sections 5.5.6 through 5.5.8	Modulation of amplitude and phase, individually or in combination	0.1 to lesser of F_s/10 or 2 Hz (P) 0.1 to lesser of F_s/5 or 5 Hz (M)	TVE (%) FE (Hz) RFE (Hz/s)
	Linear ramp of system frequency	1.0 Hz/s over ±2 Hz (P), ±5 Hz (M)	
	Step changes in amplitude and phase.	Amplitude = ± 10% of nominal Phase angle ± 10° from nominal	Response time (s) Response delay (s) Overshoot (%)

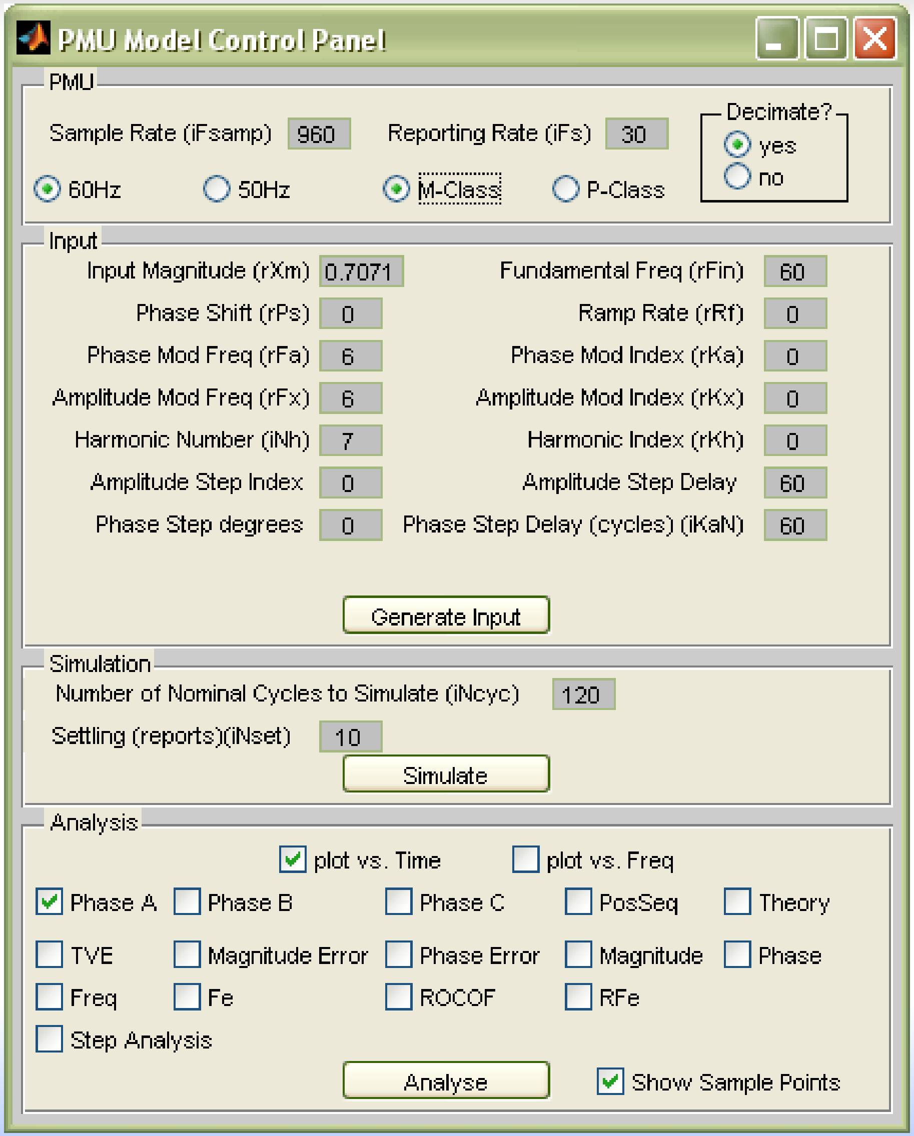
Benefits to the metrology community from NIST grant

- Access to a PMU Simulation via NASPI Phasor Tool Repository
- Interoperability across PMUs derived from new standards and procedures
  - IEEE C37.118:2011 Normative standard updated, published in two parts
    - 118.1 – Measurement; Dynamic tests added
    - 118.2 - Data Transfer

      Ratification September 2011, publication December 2011
  - IEEE C37.242 Informative Guideline created

    Publication late 2012
- An inter-comparison of PMU measurement performance using the calibration facilities of NIST and Fluke
- A commercially-available, automated PMU calibration system

Simulation Model per 118.1 Annex C



- PMU Settings
- Input Signal Settings
  - Steady State
  - Ramp
  - Amplitude & Phase Modulation
  - Step
- Simulation Settings
- Analysis Settings

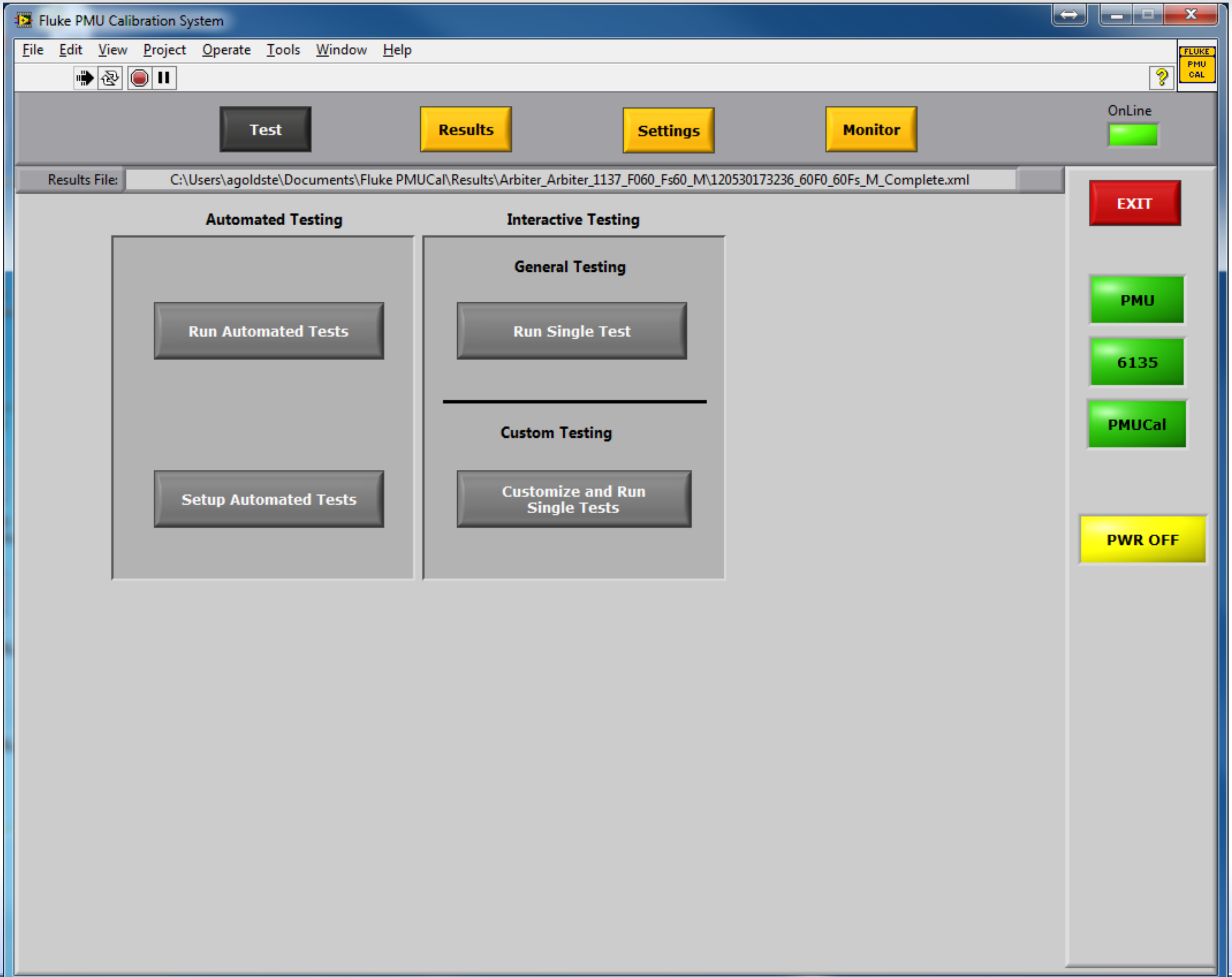
✓ Free and Open Source

Intercomparisons

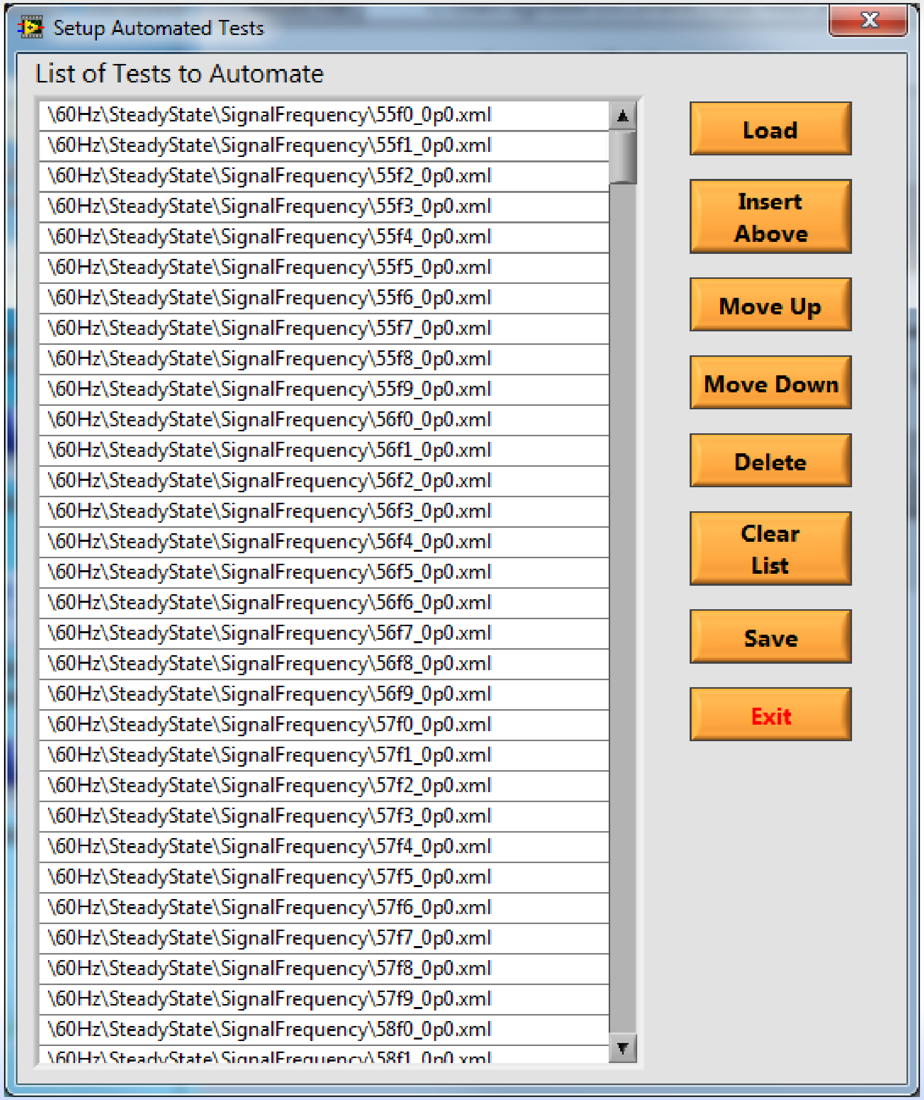
Fluke PMU Calibrator is now undergoing analysis at NIST :

- Voltage and current outputs for all test types are being captured by NIST's calibrated data acquisition system.
- The same outputs are also connected to a PMU reporting measurements via C37.118.2 protocol.
- Independent analysis tools at Fluke and NIST determine TVE, Fe and RFe of the Fluke "true" values (the values compared to the reports of the PMU under test) compared to the NIST measured values.
- Fluke Calibration System and NIST Calibration system both analyse the output from the PMU. Results are compared.
- Statistical analysis over many test runs is performed.

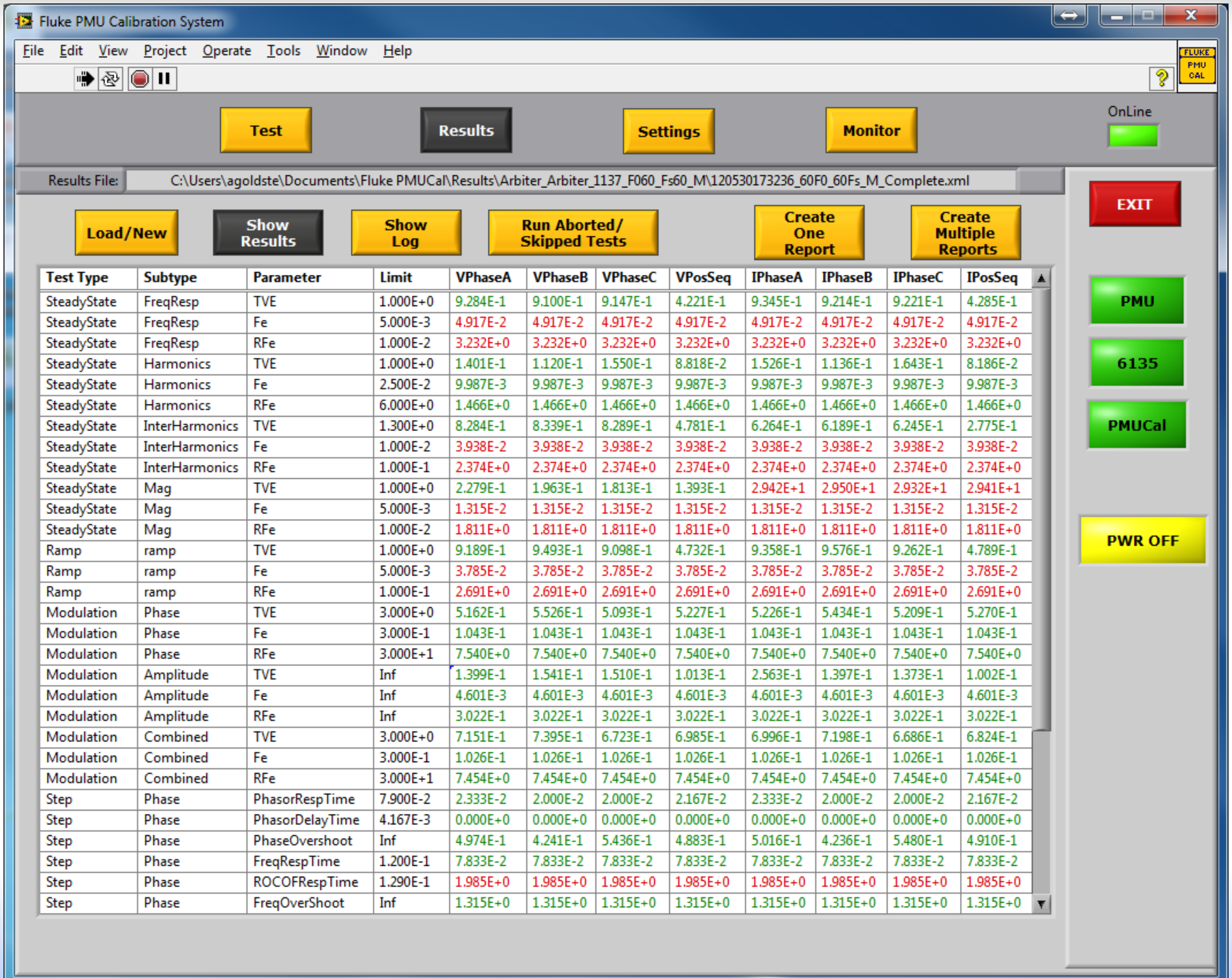
Top level test menu



Automated test list

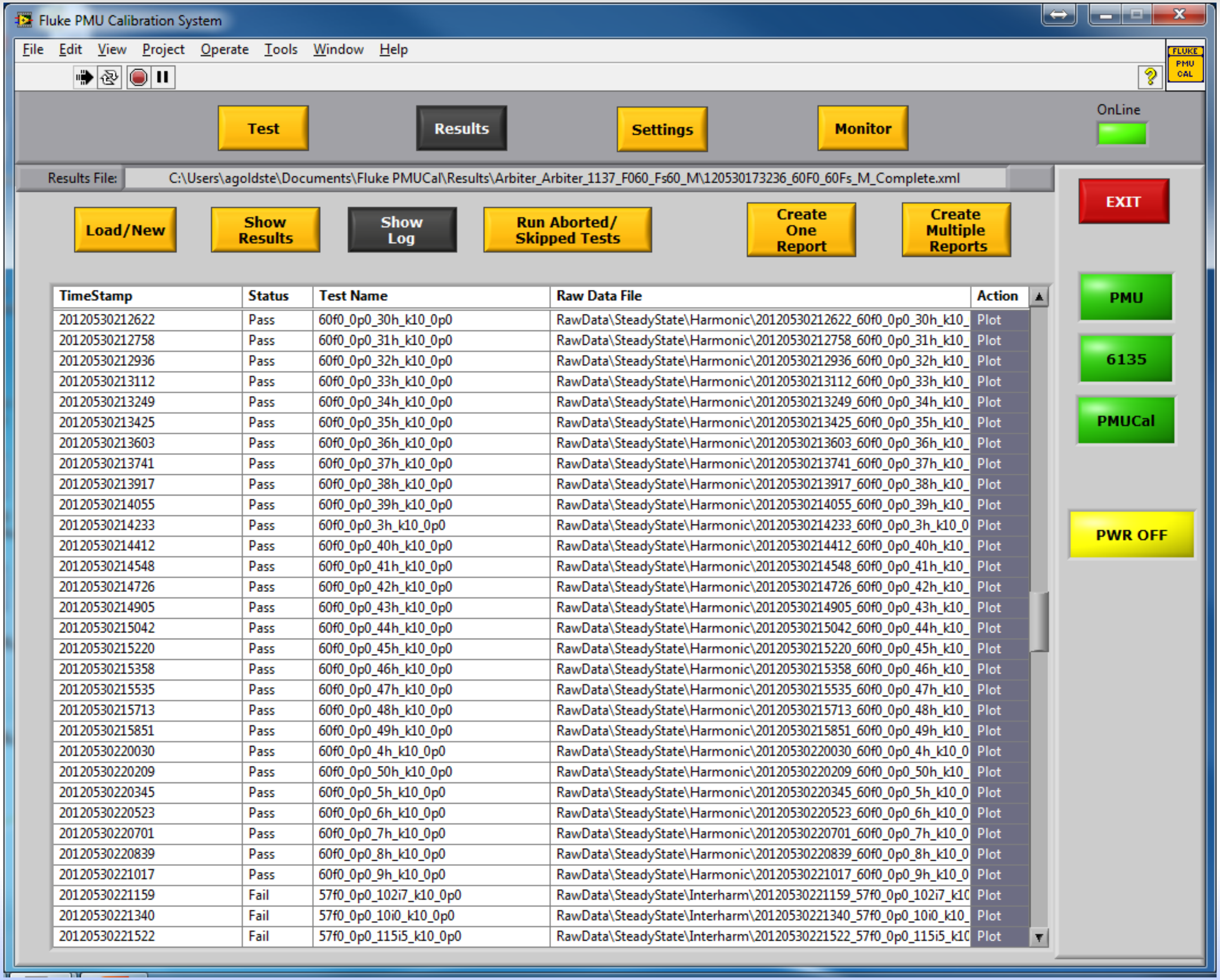


Test results



Test Type	Subtype	Parameter	Limit	VPhaseA	VPhaseB	VPhaseC	VPosSeq	IPhaseA	IPhaseB	IPhaseC	IPosSeq
SteadyState	FreqResp	TVE	1.000E+0	9.284E-1	9.100E-1	9.147E-1	4.221E-1	9.345E-1	9.214E-1	9.221E-1	4.285E-1
SteadyState	FreqResp	Fe	5.000E-3	4.917E-2	4.917E-2	4.917E-2	4.917E-2	4.917E-2	4.917E-2	4.917E-2	4.917E-2
SteadyState	FreqResp	RFe	1.000E-2	3.232E+0	3.232E+0	3.232E+0	3.232E+0	3.232E+0	3.232E+0	3.232E+0	3.232E+0
SteadyState	Harmonics	TVE	1.000E+0	1.401E-1	1.120E-1	1.550E-1	8.818E-2	1.526E-1	1.136E-1	1.643E-1	8.186E-2
SteadyState	Harmonics	Fe	2.500E-2	9.987E-3	9.987E-3	9.987E-3	9.987E-3	9.987E-3	9.987E-3	9.987E-3	9.987E-3
SteadyState	Harmonics	RFe	6.000E+0	1.466E+0	1.466E+0	1.466E+0	1.466E+0	1.466E+0	1.466E+0	1.466E+0	1.466E+0
SteadyState	InterHarmonics	TVE	1.300E+0	8.284E-1	8.339E-1	8.289E-1	4.781E-1	6.264E-1	6.189E-1	6.245E-1	2.775E-1
SteadyState	InterHarmonics	Fe	1.000E-2	3.938E-2	3.938E-2	3.938E-2	3.938E-2	3.938E-2	3.938E-2	3.938E-2	3.938E-2
SteadyState	InterHarmonics	RFe	1.000E-1	2.374E+0	2.374E+0	2.374E+0	2.374E+0	2.374E+0	2.374E+0	2.374E+0	2.374E+0
SteadyState	Mag	TVE	1.000E+0	2.279E-1	1.963E-1	1.813E-1	1.393E-1	2.942E+1	2.950E+1	2.932E+1	2.941E+1
SteadyState	Mag	Fe	5.000E-3	1.315E-2	1.315E-2	1.315E-2	1.315E-2	1.315E-2	1.315E-2	1.315E-2	1.315E-2
SteadyState	Mag	RFe	1.000E-2	1.811E+0	1.811E+0	1.811E+0	1.811E+0	1.811E+0	1.811E+0	1.811E+0	1.811E+0
Ramp	ramp	TVE	1.000E+0	9.189E-1	9.493E-1	9.098E-1	4.732E-1	9.358E-1	9.576E-1	9.262E-1	4.789E-1
Ramp	ramp	Fe	5.000E-3	3.785E-2	3.785E-2	3.785E-2	3.785E-2	3.785E-2	3.785E-2	3.785E-2	3.785E-2
Ramp	ramp	RFe	1.000E-1	2.691E+0	2.691E+0	2.691E+0	2.691E+0	2.691E+0	2.691E+0	2.691E+0	2.691E+0
Modulation	Phase	TVE	3.000E+0	5.162E-1	5.526E-1	5.093E-1	5.227E-1	5.226E-1	5.434E-1	5.209E-1	5.270E-1
Modulation	Phase	Fe	3.000E-1	1.043E-1	1.043E-1	1.043E-1	1.043E-1	1.043E-1	1.043E-1	1.043E-1	1.043E-1
Modulation	Phase	RFe	3.000E+1	7.540E+0	7.540E+0	7.540E+0	7.540E+0	7.540E+0	7.540E+0	7.540E+0	7.540E+0
Modulation	Amplitude	TVE	Inf	1.399E-1	1.541E-1	1.510E-1	1.013E-1	2.563E-1	1.397E-1	1.373E-1	1.002E-1
Modulation	Amplitude	Fe	Inf	4.601E-3	4.601E-3	4.601E-3	4.601E-3	4.601E-3	4.601E-3	4.601E-3	4.601E-3
Modulation	Amplitude	RFe	Inf	3.022E-1	3.022E-1	3.022E-1	3.022E-1	3.022E-1	3.022E-1	3.022E-1	3.022E-1
Modulation	Combined	TVE	3.000E+0	7.151E-1	7.395E-1	6.723E-1	6.985E-1	6.996E-1	7.198E-1	6.686E-1	6.824E-1
Modulation	Combined	Fe	3.000E-1	1.026E-1	1.026E-1	1.026E-1	1.026E-1	1.026E-1	1.026E-1	1.026E-1	1.026E-1
Modulation	Combined	RFe	3.000E+1	7.454E+0	7.454E+0	7.454E+0	7.454E+0	7.454E+0	7.454E+0	7.454E+0	7.454E+0
Step	Phase	PhasorRespTime	7.900E-2	2.333E-2	2.000E-2	2.000E-2	2.167E-2	2.333E-2	2.000E-2	2.000E-2	2.167E-2
Step	Phase	PhasorDelayTime	4.167E-3	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
Step	Phase	PhaseOvershoot	Inf	4.974E-1	4.241E-1	5.436E-1	4.883E-1	5.016E-1	4.236E-1	5.480E-1	4.910E-1
Step	Phase	FreqRespTime	1.200E-1	7.833E-2	7.833E-2	7.833E-2	7.833E-2	7.833E-2	7.833E-2	7.833E-2	7.833E-2
Step	Phase	ROCOFRespTime	1.290E-1	1.985E+0	1.985E+0	1.985E+0	1.985E+0	1.985E+0	1.985E+0	1.985E+0	1.985E+0
Step	Phase	FreqOverShoot	Inf	1.315E+0	1.315E+0	1.315E+0	1.315E+0	1.315E+0	1.315E+0	1.315E+0	1.315E+0

Test logs



TimeStamp	Status	Test Name	Raw Data File	Action
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20120530212936	Pass	60f0_0p0_32h_k10_0p0	RawData\SteadyState\Harmonic\20120530212936_60f0_0p0_32h_k10_	Plot
20120530213112	Pass	60f0_0p0_33h_k10_0p0	RawData\SteadyState\Harmonic\20120530213112_60f0_0p0_33h_k10_	Plot
20120530213249	Pass	60f0_0p0_34h_k10_0p0	RawData\SteadyState\Harmonic\20120530213249_60f0_0p0_34h_k10_	Plot
20120530213425	Pass	60f0_0p0_35h_k10_0p0	RawData\SteadyState\Harmonic\20120530213425_60f0_0p0_35h_k10_	Plot
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20120530213741	Pass	60f0_0p0_37h_k10_0p0	RawData\SteadyState\Harmonic\20120530213741_60f0_0p0_37h_k10_	Plot
20120530213917	Pass	60f0_0p0_38h_k10_0p0	RawData\SteadyState\Harmonic\20120530213917_60f0_0p0_38h_k10_	Plot
20120530214055	Pass	60f0_0p0_39h_k10_0p0	RawData\SteadyState\Harmonic\20120530214055_60f0_0p0_39h_k10_	Plot
20120530214233	Pass	60f0_0p0_3h_k10_0p0	RawData\SteadyState\Harmonic\20120530214233_60f0_0p0_3h_k10_0	Plot
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20120530220523	Pass	60f0_0p0_6h_k10_0p0	RawData\SteadyState\Harmonic\20120530220523_60f0_0p0_6h_k10_0	Plot
20120530220701	Pass	60f0_0p0_7h_k10_0p0	RawData\SteadyState\Harmonic\20120530220701_60f0_0p0_7h_k10_0	Plot
20120530220839	Pass	60f0_0p0_8h_k10_0p0	RawData\SteadyState\Harmonic\20120530220839_60f0_0p0_8h_k10_0	Plot
20120530221017	Pass	60f0_0p0_9h_k10_0p0	RawData\SteadyState\Harmonic\20120530221017_60f0_0p0_9h_k10_0	Plot
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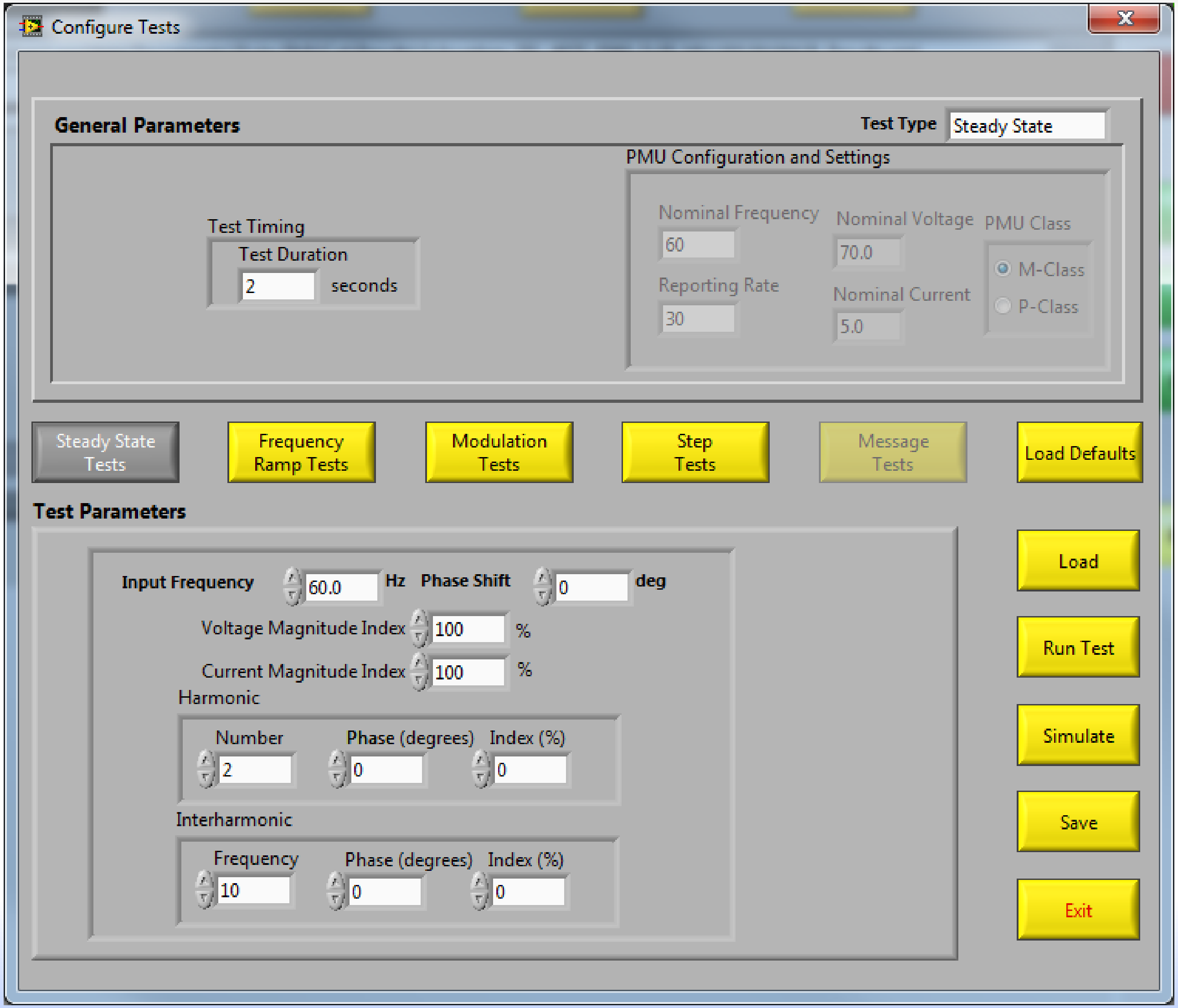
20120530221340	Fail	57f0_0p0_10i0_k10_0p0	RawData\SteadyState\Interharm\20120530221340_57f0_0p0_10i0_k10_	Plot
20120530221522	Fail	57f0_0p0_115i5_k10_0p0	RawData\SteadyState\Interharm\20120530221522_57f0_0p0_115i5_k10	Plot

Interactive testing for PMU analysis

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

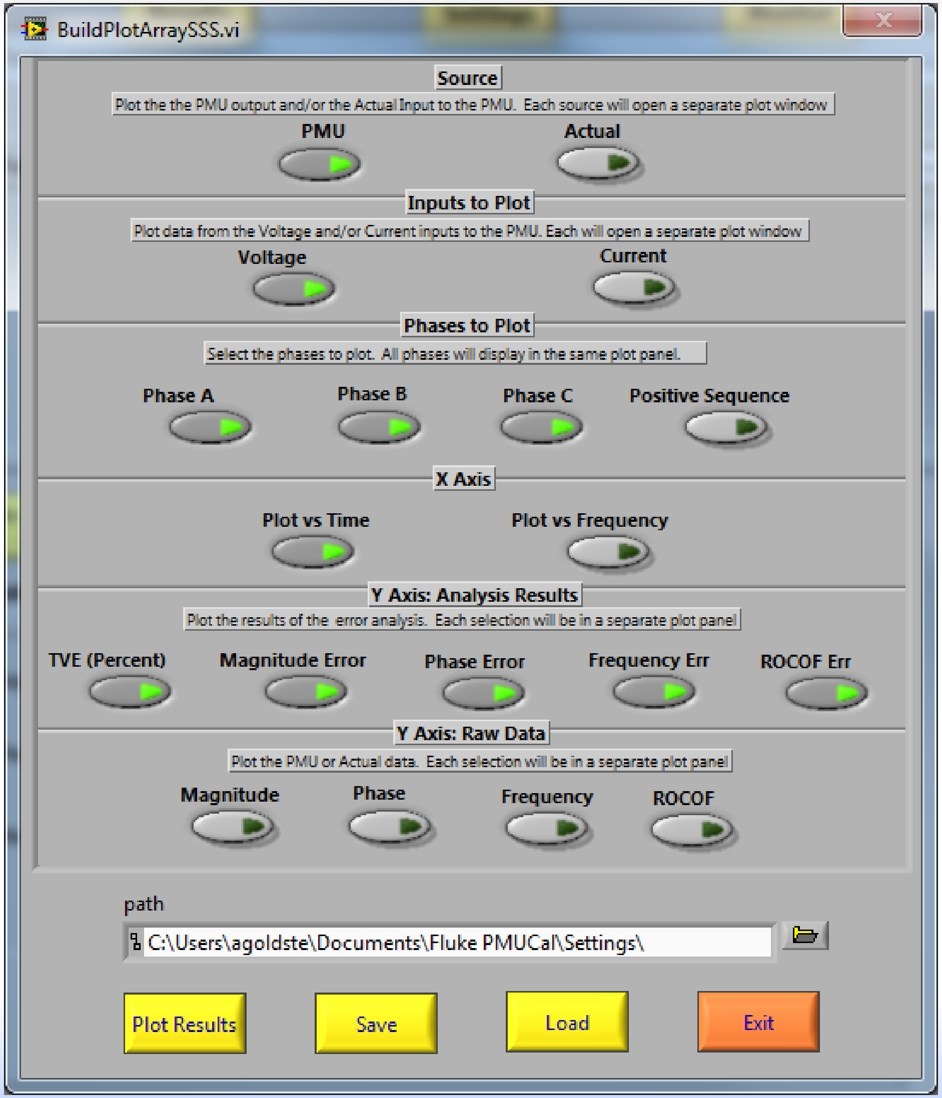
FLUKE
Calibration



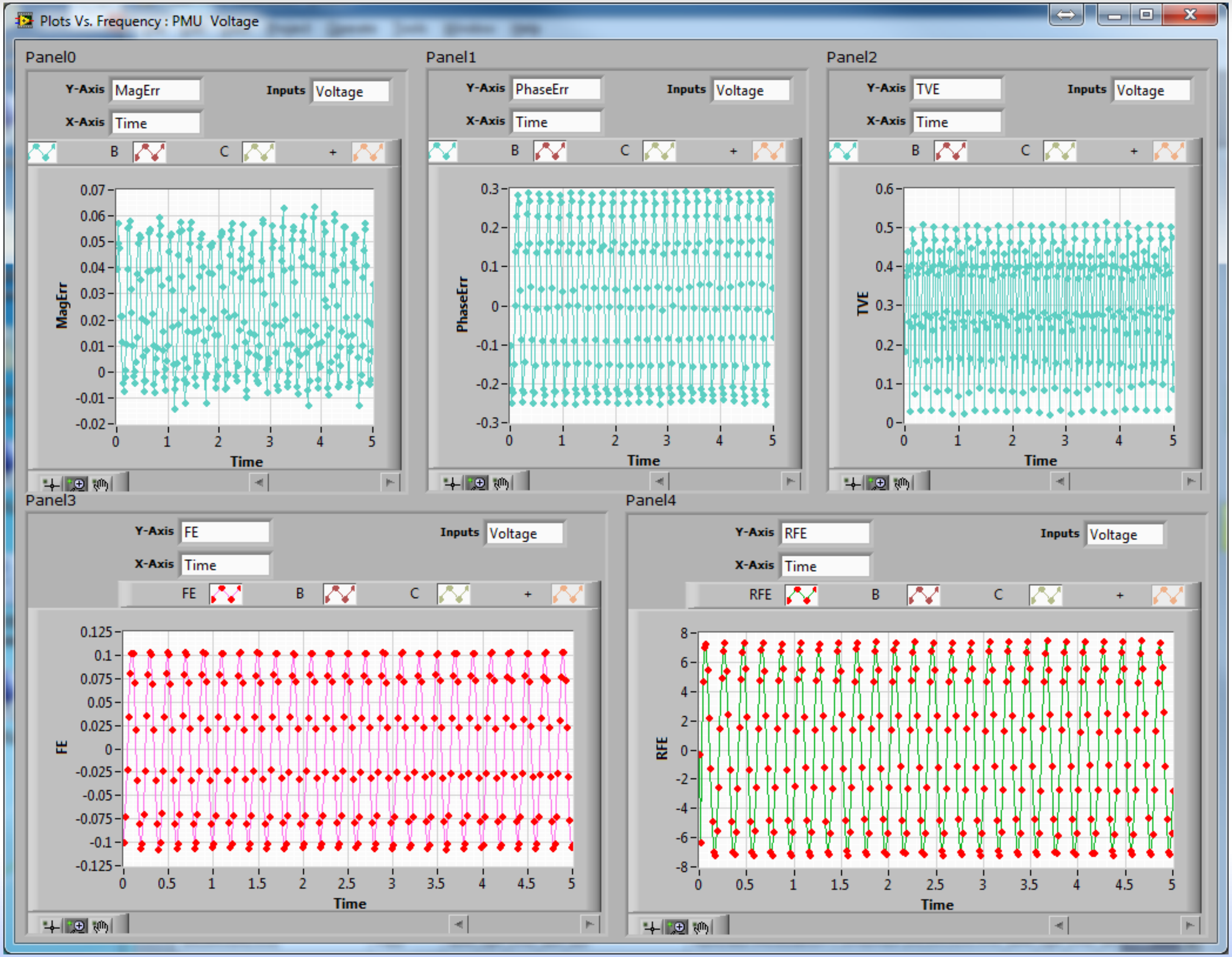
Versatile plot configuration

NIST National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

FLUKE Calibration



Plots versus time



Plots versus frequency

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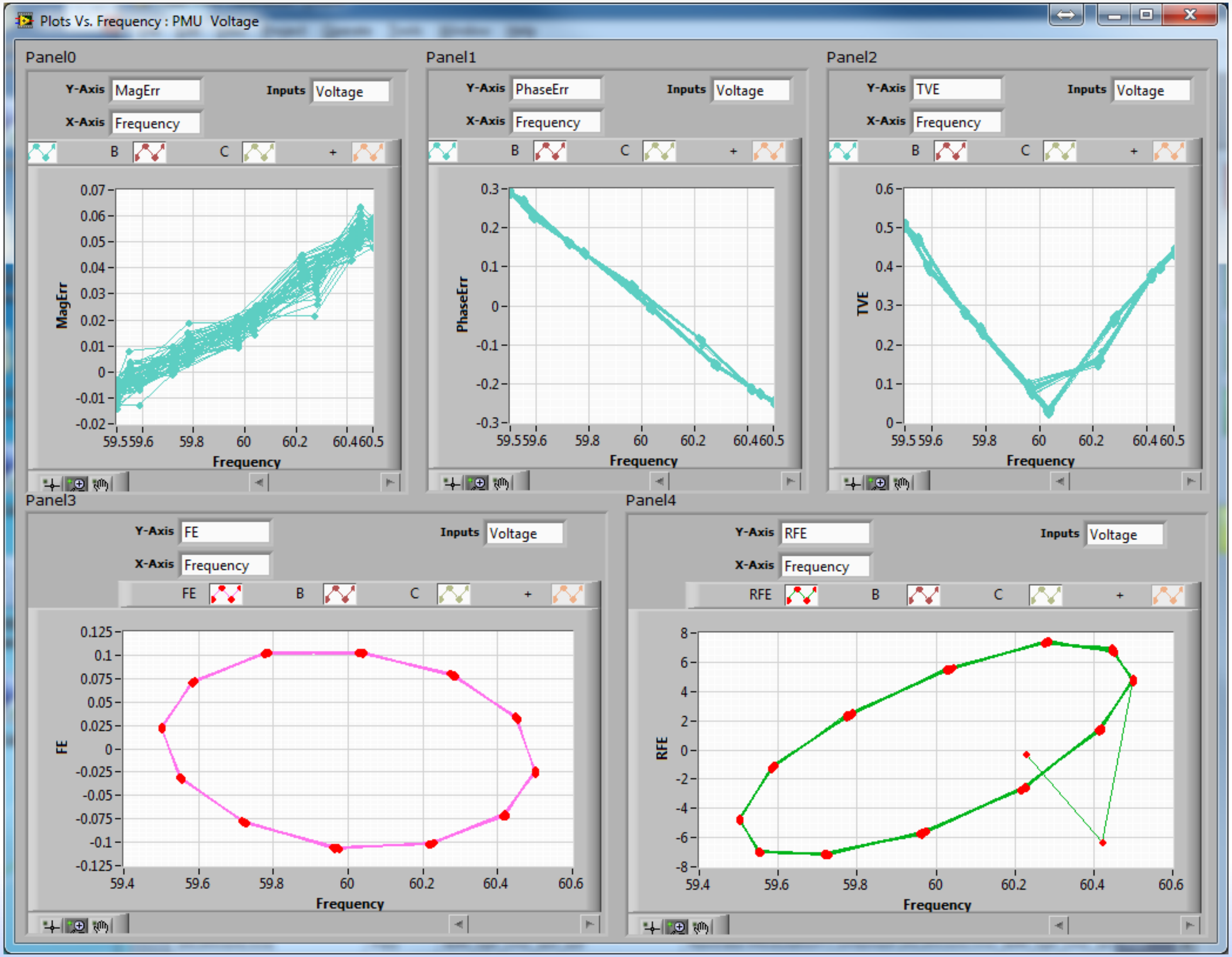
FLUKE
Calibration



ARRA Grant Success story

- NIST grant put five engineers and one marketing manager to work.
- Fluke / NIST contribution to revisions of PMU standards and guides:
  - IEEE C37.118.1 and 118.2
  - IEEE PC37.242
- Freely available, open source PMU Simulation tool.
- A new, commercially available PMU Calibration System:
  - Minimizes PMU test time
  - Minimizes user interaction
  - Maximizes accuracy and traceability
  - Minimizes operator expertise
  - Maximizes test report and data usefulness
  - Minimizes time to create test reports and certificates

Questions ?

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