Fluke PMU Calibrator: A NIST ARRA Grant Project

Allen Goldstein
Technical Project Manager
Fluke Calibration
allen.goldstein@fluke.com

Dr. Yi-hua Tang
Quantum Measurement Division
NIST
yi-hua.tang@nist.gov

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 2010</td>
<td>NIST grant announced</td>
</tr>
<tr>
<td>July 2010</td>
<td>Customer Requirements Survey</td>
</tr>
<tr>
<td>Dec 2010</td>
<td>Product Requirement Specification</td>
</tr>
<tr>
<td>Sept 2011</td>
<td>System hardware delivered to NIST</td>
</tr>
<tr>
<td>July 2012</td>
<td>Intercomparisons</td>
</tr>
</tbody>
</table>

### 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:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimize PMU test time</td>
</tr>
<tr>
<td>2</td>
<td>Minimize user interaction</td>
</tr>
<tr>
<td>3</td>
<td>Maximize accuracy and traceability</td>
</tr>
<tr>
<td>4</td>
<td>Minimize operator expertise</td>
</tr>
<tr>
<td>5</td>
<td>Maximize test report and data usefulness</td>
</tr>
<tr>
<td>6</td>
<td>Minimize time to create test reports</td>
</tr>
</tbody>
</table>
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 C37.118.1TM-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
“Documentation shall be provided by any vendor claiming compliance with this standard that shall include the following information:

1. Performance class \( (M=\text{Measurement}, \ P=\text{Protection}) \)
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

Fluke Voltage and Current Sources → NIST PMU Mea. System → Analysis

NIST PMU Mea. System → Port 1

PMU → Fluke Calibrator

Port 1

Port 2
Current measurement difference

Nominal current 5A
## Summary of current measurement comparison

<table>
<thead>
<tr>
<th></th>
<th>NIST - Fluke</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IA Mag</td>
<td>IA Phase</td>
<td>IB Mag</td>
<td>IB Phase</td>
<td>IC Mag</td>
<td>IC Phase</td>
<td>IA TVE</td>
</tr>
<tr>
<td>Max</td>
<td>0.000117</td>
<td>0.000658</td>
<td>0.000236</td>
<td>-0.000541</td>
<td>0.000074</td>
<td>-0.000341</td>
<td>0.004779</td>
</tr>
<tr>
<td>Min</td>
<td>-0.000194</td>
<td>-0.002691</td>
<td>-0.000035</td>
<td>-0.002941</td>
<td>-0.000138</td>
<td>-0.002841</td>
<td>0.000230</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.000051</td>
<td>-0.000980</td>
<td>0.000082</td>
<td>-0.001539</td>
<td>-0.000043</td>
<td>-0.001641</td>
<td>0.002482</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.000063</td>
<td>0.000729</td>
<td>0.000056</td>
<td>0.000507</td>
<td>0.000044</td>
<td>0.000569</td>
<td>0.000984</td>
</tr>
<tr>
<td>SD mean</td>
<td>0.000006</td>
<td>0.000073</td>
<td>0.000006</td>
<td>0.000051</td>
<td>0.000004</td>
<td>0.000057</td>
<td>0.000099</td>
</tr>
<tr>
<td>Student t</td>
<td>1.98</td>
<td>1.98</td>
<td>1.98</td>
<td>1.98</td>
<td>1.98</td>
<td>1.98</td>
<td>1.98</td>
</tr>
<tr>
<td>Type A</td>
<td>0.000012</td>
<td>0.000145</td>
<td>0.000011</td>
<td>0.000101</td>
<td>0.000009</td>
<td>0.000114</td>
<td>0.000196</td>
</tr>
<tr>
<td>Max Rel. Diff in %</td>
<td>0.0039</td>
<td>0.0027</td>
<td>0.0047</td>
<td>0.0029</td>
<td>0.0028</td>
<td>0.0028</td>
<td>0.0048</td>
</tr>
</tbody>
</table>

Note: Current in A, phase in degree
## Revised steady-state tests

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

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>Range</th>
<th>Metrics (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation of amplitude and phase, individually or in combination</td>
<td>0.1 to lesser of $F_s/10$ or 2 Hz (P)</td>
<td>TVE (%)</td>
</tr>
<tr>
<td></td>
<td>0.1 to lesser of $F_s/5$ or 5 Hz (M)</td>
<td>FE (Hz) RFE (Hz/s)</td>
</tr>
<tr>
<td>Linear ramp of system frequency</td>
<td>1.0 Hz/s over ±2 Hz (P), ±5 Hz (M)</td>
<td></td>
</tr>
<tr>
<td>Step changes in amplitude and phase.</td>
<td>Amplitude = ± 10% of nominal</td>
<td>Response time (s) Response delay (s)</td>
</tr>
<tr>
<td></td>
<td>Phase angle ± 10° from nominal</td>
<td>Overshoot (%)</td>
</tr>
</tbody>
</table>
• 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
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
Interactive testing for PMU analysis
Versatile plot configuration
Plots versus time
Plots versus frequency
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?

Allen Goldstein
Technical Project Manager
Fluke Calibration
allen.goldstein@fluke.com

Dr. Yi-hua Tang
Physicist
NIST
yi-hua.tang@nist.gov