
Zhenyu (Henry) Huang, and Jeff Dagle
Pacific Northwest National Laboratory
Richland, Washington
USA

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Massive PMUs are being put in operation
- Steady increase of PMUs installations
- Mandatory PMU installations, e.g. in China
- Conversion of existing measurement devices, e.g. relays

Higher PMU sample rates are used
- Sample rate from 25/30 sps to super-synchronous rate, e.g. 100/120 sps.

Frequency tracking and frequency compensation become popular in phasor algorithms

Dynamic performance of phasors becomes critical as driven by applications
Emerging Challenges

- Need capability to handle massive PMUs in phasor networks → new phasor architecture
- Need to evaluate phasor measurement from a dynamic perspective
- Need to evaluate phasor measurement from a system-wide perspective
- Need to study the implication of phasor quality for phasor applications
<table>
<thead>
<tr>
<th></th>
<th>Class A (e.g. Small Signal Stability Monitoring)</th>
<th>Class B (e.g. State Estimation Enhancement)</th>
<th>Class C (e.g. Post Event Analysis)</th>
<th>Class D (e.g. Visualization)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Latency</td>
<td><img src="circle" alt="Not very important" /></td>
<td><img src="half-circle" alt="Somewhat important" /></td>
<td><img src="circle" alt="Fairly important" /></td>
<td><img src="full-circle" alt="Critically important" /></td>
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<tr>
<td>Reliability Availability</td>
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<tr>
<td>Accuracy</td>
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<td><img src="full-circle" alt="Critically important" /></td>
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<tr>
<td>Time Alignment</td>
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<tr>
<td>Message Rate</td>
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</tbody>
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**Legend:**
- ![Not very important](circle)
- ![Somewhat important](half-circle)
- ![Fairly important](circle)
- ![Critically important](full-circle)

* Source: NASPI Data and Management Task Team
Phasor Architecture – WECC WAMS

* Source: J. Hauer, with modifications
Phasor Architecture – Eastern Interconnection

* Source: NASPI Data and Management Task Team
Phasor Architecture – Future

* Source: NASPI Data and Management Task Team
Next Generation PDC

PDC 10¹
- Ruggedised PCs
- Substation Use
- Local buffer
  - Comms failure
  - On Demand
- Hub (Multiple WAMS)
- Limited Applications
- <10 PMUs

PDC 10²
- Single Datacentre Server
- Regional/National Use
- Variety of Applications
- Offline and Control Room
- <100 PMUs

PDC 10³
- Multiple Servers
- Large connected areas
- Parallel/redundant use
- Security
- Management tools
- <1000 PMUs

* Source: NASPI Performance and Standards Task Team
PMU Testing with Super-synchronous Rates
60Hz@120sps Amp Modulation 88.3Hz (1)

Voltage Channels

60Hz@120sps_Amod@88.3Hz
06/28/08_17:50:44

PMU1 Voltage 1A VMag
PMU1 Voltage 1B VMag
PMU1 Voltage 1C VMag
PMU1 Voltage 1 VMag

Time in Seconds since 14-May-2008 17:45:00.000
Voltage and Frequency Channels

PMU Testing with Super-synchronous Rates
60Hz@120sps Amp Modulation 88.3Hz (2)
Prony Analysis – Modes of Voltages

In CompassPlotsA: caseID=Test080514_120sps    casetime=05/19/08_10:11:30

<table>
<thead>
<tr>
<th>Sorted Mode Table for pole1: Fast noise</th>
</tr>
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<tbody>
<tr>
<td><strong>Signal</strong></td>
</tr>
<tr>
<td>PMU1 Voltage 1A VMag</td>
</tr>
<tr>
<td>PMU1 Voltage 1B VMag</td>
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<td>PMU1 Voltage 1C VMag</td>
</tr>
<tr>
<td>PMU1 Voltage 1 VMag</td>
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<table>
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<th>Sorted Mode Table for pole3: Fast noise</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
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<tr>
<td>PMU1 Voltage 1A VMag</td>
</tr>
<tr>
<td>PMU1 Voltage 1B VMag</td>
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<tr>
<td>PMU1 Voltage 1C VMag</td>
</tr>
<tr>
<td>PMU1 Voltage 1 VMag</td>
</tr>
</tbody>
</table>
Prony Analysis – Mode Shapes of Voltages

Scaled Compass Plot for mode 31.7 Hz

Scaled Compass Plot for mode 31.8 Hz
Timing Inconsistency Due to Filtering
– Northwest Generation Trip Event on April 18, 2002

Timing Inconsistency Due to Filtering
– Northwest Generation Trip Event on April 18, 2002
Timing Inconsistency Due to Poor Synchronization
– BC Hydro Fault Test on October 25, 2003
System-wide Phasor Evaluation with Actual Event Data – Timing (3)

◆ Improved Timing of Voltage Signals
   – BC Hydro Fault Test on December 3, 2003

![Graph showing improved timing of voltage signals with old and new software versions.]

- ING1 5L52 Voltage (PMU typeA, new software)
- ING2 5L52 Voltage (PMU typeB)
- SEL1 5L91 Voltage (PMU typeA, old software)
- MPLV Maple Voltage (PMU typeC)
Delay in input leads to unexpected control output, and thus unexpected (usually deteriorated) control performance.

Constant delay can be compensated with pre-processing logic.

Random delay needs to be accommodated with robust control design.
Parasitic Voltage Oscillations
– Northwest Oscillation on October 9, 2003

0.22 Hz parasitic oscillations with light damping

Data from Harry Lee, BCH
Parasitic oscillations lead to false alarming
Parasitic oscillations lead to false arming of special stability controls

PMUs need to be tested in a lab environment to determine the level of aliasing
Parasitic oscillations need to be identified with careful examination of actual phasor measurements
Lab testing and field measurement examination help to determine PMU setting and, if necessary, to improve PMU logic
System-wide Phasor Evaluation with System Test

**WECC staged system tests**
- Large Disturbance: Chief Joseph 1400 MW Brake Insertion
- Small Disturbance: ±125 MW HVDC Modulation (PDCI)
- “Noise” Probing: ±10/20 MW HVDC Modulation (PDCI)
Continuous System-wide Dynamic Monitoring

- Power Grid
  - WAMS
    - Preprocessing (filtering, de-trending, decimation)
    - ModeMeter Setting (event detection, window size, model order)
      - ModeMeter (frequency, damping, mode shape)
  - Evaluation
    - Operator Display
    - Modal Control

- "Noise" Probing
- Probing Signal Design
Closing Remarks

- Phasor quality has been improved tremendously with the joint efforts of users, vendors and researchers
- New issues are emerging because of new development (e.g. more and faster PMUs)
- Phasor quality affects phasor applications, but in different degrees
- Deployment of phasor measurement units and phasor networks need to consider applications
Acknowledgement

- John Hauer, PNNL
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- Ning Zhou, PNNL
- Manu Parashar, EPG

- NASPI Data and Management Task Team
- NASPI Performance and Standards Task Team

www.naspi.org
Questions?

Zhenyu (Henry) Huang, PNNL 1(509) 372-6781, zhenyu.huang@pnl.gov
60Hz@720sps Amp Modulation 88.3Hz
Model Studies
– one-sided spectrum of input signal

P 3: Autospectrum for POW signal 1
caseID=PMUmod_6006M8830threeP casetime=09/14/07_13:19:44

Frequency in Hertz

Autospectrum in dB

Positive image of “negative” frequency

28.24 Hz

148.36 Hz
25 Hz @ 720 sps Amp Modulation 88.3 Hz
Model Studies
- one-sided spectrum of single-phase voltage

P43: Autospectrum for phasor magnitude
caseID=PMUmod_6006M8830singleP  casetime=09/14/07_12:41:14

Frequency in Hertz

Autospectrum in dB

-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60

0 20 40 60 80 100 120 140 160 180 200

~120.121
~88.298
~31.826
~151.987

~120.121
~88.298
~31.826
~151.987

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60Hz@720sps Amp Modulation 88.3Hz Model Studies
– one-sided spectrum of three-phase voltage

P43: Autospectrum for phasor magnitude
caseID=PMUmod_6006M8830threeP casetime=09/14/07_13:19:44

~88.300 Hz