Synchrophasor Technology and Systems

Jeff Dagle, PE
Chief Electrical Engineer and Team Lead
Electricity Infrastructure Resilience
Pacific Northwest National Laboratory
Richland, Washington
+1 (509) 375-3629
jeff@pnnl.gov

CIGRE-NASPI SYNCHROPHASOR TECHNOLOGY TUTORIAL
Houston, Texas
October 19, 2014
Synchrophasor technology and systems (this presentation)
- Time-synchronized measurements
- What’s a PMU?
- Data collected by PMUs; PMU v. SCADA
- PMU data networks -- network, PDC, analytics, gateway
- PMU deployments across North America
- Technical standards and protocols
- Data quality and availability
- Security and NERC CIP

Synchrophasor uses and applications (Dmitry Kosterev)

Synchrophasor technology benefits and business case (Matt Gardner)

The future of synchrophasor technology (Alison Silverstein)

Q&A
What is a “Phasor”?  

- Like a vector, a phasor represents both magnitude and relative phase angle.

Source: CERTS, Phasor Technology Overview
Mathematical concept of physical quantities

Phasors rotate counterclockwise, each corresponding to a sinusoidal parameter

The rotating frame of reference can be modified (e.g., relative phase angle)

60 Hz = 0.01667s
By synchronizing the sampling processes for different signals - which may be hundreds of miles apart, it is possible to put their phasors on the same phasor diagram.

Credit: A.G. Phadke
Except for synchronization, the hardware is the same as that of a digital fault recorder or a digital relay.

Credit: A.G. Phadke
Phasor Measurement Unit

sample clock trigger

GPS receiver

symmetrical component transformation

frequency and rate of change of frequency

positive phase sequence component

phase sequence components

synchrophasor streaming output

triggers and disturbance recording

analog input waveforms

synchronized A/D conversions

Va(t)

Vb(t)

Vc(t)

time

GPS antenna

DFT

DFT

DFT

Credit: A.G. Phadke
Wide Area Measurement System Overview

- Phasor Measurement
- Power System Monitors
- Global Positioning System
- Time-Stamped
- Useful Information
- Control Center
Substation PMU Installation

Phase Conductor

Current Transformer

Potential Transformer

Instrumentation Cables

Phasor Measurement Unit

Computer
Wide Area Measurement System (WAMS)

Data acquisition devices (continuously recording and time synchronized)

- Phasor Measurement Units (PMU)
  - Inputs from potential transformers (PT) and current transformers (CT)
- Analog signal recorders (with transducer inputs)
- Point-on-wave (POW) recorders (with PT, CT inputs)
- Controller monitors (generators, HVDC, FACTS)
  - Inputs from the controller interface or the controlled device
- Advanced relays and other Intelligent Electronic Devices (IED)
- Digital fault recorders and other sequence of events recorders

What we are covering today is **NOT** supervisory control and data acquisition (SCADA) technology

- SCADA traditionally relies on a polling style communication architecture
- Older SCADA protocols do not include time with the data, the time is applied when the data is logged into the energy management system
  - This can sometimes result in significant delay between when the event occurs and when it is time stamped
WAMS technology is being rapidly deployed by several utilities throughout the world and across North America.

Both on-line and off-line applications are emerging, particularly those that require faster time synchronized measurements than are available from existing technology.

The measurement infrastructure is tailored to the requirements of the installation.

Vendors are providing new solutions including measurement technology, networking, and applications.

Data Collection Rate

- AMR
- SCADA
- WAMS
- Protective Relays / DFR

Time synchronized WAMS data is gathered at sample rates much faster than SCADA systems, and provide the missing link between localized digital fault recorders (DFR) and SCADA systems, which are much slower. However, unlike most SCADA systems, WAMS utilizes Internet protocols to exchange measurement information.
Filling a Measurement Gap

- WAMS Technology
- Sequential Event Recorders
- Digital Fault Recorders
- SCADA
- Chart Recorders

Event duration (Seconds)
How accurate does your time need to be?

- The phase angle is determined by the time reference.
- If \( t = 0 \) is displaced by \( x \) seconds, the phase angle will be rotated by \( x/46 \times 10^{-6} \) degrees (1° ~ 46 µs at \( f_0 = 60 \) Hz).
- Note the error ONLY effects phase angle – magnitude ok.

\[
v(t) = \sqrt{2} A \cos (2 \pi \omega_0 t + \phi)
\]

\[
V = A e^{i\phi}
\]

Credit: K. Martin
Testing the Susceptibility of Satellite Clocks to Spoofing (Deliberate Error)
Satellite Clock Spoofing Test Results

Phase Angle Difference

angle difference (deg)

0  200  400  600  800  1000  1200  1400  1600

0  10  20  30  40  50  60  70  80

0  1  2  3  4  5

time (s)
All three satellite clocks that we tested were susceptible to time errors being introduced

- Some differences in the rate of change that could be implemented (defeating the internal error checking algorithms)
- Some differences in how the clocks responded when the spoofing signal was turned off

Need to find alternative methods for ensuring critical applications cannot be undermined

- Currently investigating various alternatives including the IEEE 1588 Precision Time Protocol Standard
WAMS Deployment in the Western Interconnection

Dynamic monitor network that supports advanced situational awareness and analysis

“Better information supports better - and faster - decisions.”

Disturbances

System planning

System operation

Automatic control

Power System

Decision Processes

Measurement Based Information System

Unobserved response

Observed response

Information
August 10, 1996 Post-Disturbance Analysis

Better Models Were Needed!
System Disturbance August 4, 2000

Observed COI Power (Dittmer Control Center)

Simulated COI Power (base case)

Graphics by D. N. Kosterev, Bonneville Power Administration
A More Recent Example --- The Models Have Been Improved Significantly!

Loss of major generator in WECC, actual and modeled

Signals offset for clarity
The U.S. Department of Energy (DOE) and EPRI are working together closely with industry to enable wide area time-synchronized measurements that will enhance the reliability of the electric power grid through improved situational awareness and other applications.

“Better information supports better - and faster - decisions.”
Networking and Data Sharing are Key Elements of the Technology
Logical Measurement Data Network

Org A

Org B

Org C

Super PDC

Org A PDC

Org B PDC

PMU X

PMU A

PMU B

PMU C

PDC 1

PMU M

PMU N

PDC 2

PMU O

PMU P
Phasor Data Concentrator (PDC)

- A PDC gathers data from a number of devices and forwards it as a single stream
- PDC as defined in IEEE C37.244:
  - A function that collects phasor data, and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications
- PDC as defined in IEEE C37.118.1/2
  - A device used in phasor measurement systems that combined data from several sources
  
  Security requirements are a function of the “box”

- Definitions basically equivalent, but the semantic difference is debated
- IEEE PDC Guide C37.244-2013
  - Covers definitions, functions, performance, and testing
Basic PDC Functions

- Input data from PMUs
  - Decode, error check, and manage communications
- Combine input data, generally by timetag
- Output data to applications
  - Construct message and manage communications
- Manage measurement system
  - Create record of outages, errors
  - Provide real-time monitor of operation
- Phasors must be matched by timetag to compare phase angles across system
Credit to Paul Myrda, former Data Mgmt Task Team Lead
The NASPInet Vision –
A Distributed Network for Data Exchange and Sharing

![Diagram of NASPInet Vision]
<table>
<thead>
<tr>
<th>Class</th>
<th>Basic Description</th>
<th>Sampling/ Data Rate</th>
<th>Required Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Feedback Control</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>B</td>
<td>Open Loop Control</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>C</td>
<td>Visualization</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>D</td>
<td>Event Analysis</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>E</td>
<td>Research/Experimental</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Data Quality Requirements

- Measurement accuracy
- Data availability
- Data delivery speed

  - Includes cumulative latency throughout the entire measurement, communications, and processing system infrastructure

*Highly dependent on the application requirements!*

- Some examples of data quality issues:
  - PMU device
    - Including configuration settings, hardware or software failure
  - PDC device
    - Same as above
  - Instrument transformers, including substation cabling
  - Communications infrastructure including routers, firewalls, etc.
  - Applications, including servers, data historians, software compatibility

November 7, 2014
### Data Availability Example

<table>
<thead>
<tr>
<th>Entity</th>
<th>Percent Availability</th>
<th>PMU Count</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>8/25/2014 - 8/31/2014</td>
<td></td>
</tr>
<tr>
<td>94.09%</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>94.99%</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>81.76%</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>99.86%</td>
<td></td>
<td>55</td>
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<tr>
<td>83.13%</td>
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<td>20</td>
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<tr>
<td>99.58%</td>
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<td>15</td>
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<tr>
<td>69.14%</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>62.91%</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>73.19%</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>0.00%</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>75.86%</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>38.07%</td>
<td></td>
<td>7</td>
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<tr>
<td>99.86%</td>
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<td>4</td>
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<tr>
<td>99.89%</td>
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<td>1</td>
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<tr>
<td>100.00%</td>
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<td>2</td>
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<tr>
<td>98.45%</td>
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<td>2</td>
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<tr>
<td>99.81%</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td><strong>Overall:</strong></td>
<td><strong>90.13%</strong></td>
<td><strong>177</strong></td>
</tr>
</tbody>
</table>
Other Important Standards

- IEEE C37.118
  - Part 1 - This standard defines synchrophasors, frequency, and rate of change of frequency (ROCOF) measurement under all operating conditions.
  - Part 2 - This standard specifies messaging that can be used with any suitable communication protocol for real-time communication between phasor measurement units (PMU), phasor data concentrators (PDC), and other applications.

- IEC 61850.90-5.1 and 90-5.2
  - 90-5 is the synchrophasor profile for IEC 61850, substation automation

- IEEE 1588 – time synchronization
Synchrophasors are becoming part of the bulk electric system and will require physical and cyber security

- But these systems shouldn’t be treated any differently than other forms of measurement and control telemetry

Synchrophasor systems will coexist with other bulk electricity system (BES) cyber infrastructure and will have similar dependencies on common communications and network elements

System designers and owners are aware of emerging cyber-security standards and technologies

Currently available phasor applications require further data analysis, software refinement and operational validation to be fully effective; many are in advanced development and testing and are not in full operational use

- Therefore, many of these systems are not currently considered critical cyber assets

Due to nature of continuous, high-volume data flows, new technology will likely be required for measurement, communications, and applications

- Technology anticipated to undergo rapid change and refinement over the next several years
Different Types of PMUs

- **P class (protection)**
  - Minimal filtering
  - Possible aliasing of higher frequency components
  - Less delay in estimation
  - Important for real-time controls requiring minimum delay

- **M class (measurement)**
  - Some anti-alias protection
  - Wider frequency response, lower noise
  - Latency longer (depends on reporting rate)
  - Important for situations with higher frequencies present

- **Both classes**
  - Essentially the same measurement in all other respects

Credit: K. Martin
Phasor Applications Taxonomy

**RESEARCHERS**
- Automatic alarming of remedial action schemes
- Out of step protection
- Short/long-term stability control
- Feedback control

**PLANNERS**
- Post-mortem analysis
- Model validation
- Phasor network performance monitoring & data quality
- Email notifications
- Test new real-time applications

**OPERATORS**
- Situational awareness dashboard
- Real time compliance monitoring
- Frequency Instability Detection/Islanding
- Real time performance monitoring
- Real time alerts and alarms
- Event detection, disturbance location
- Suggest preventive action
- Interconnection state estimation
- Dynamic ratings

Credit to Terry Bilke (MISO), Former leader of the Operations Implementation Task Team
http://www.naspi.org/