International Conference on Synchrophasor Measurement Applications, Brasil 2006

Tutorial on PMU Technology and Applications

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Outline

- General Concepts and Definitions
- Industry Needs
- Expected Benefits and Gaps
- Industry Projects and Experience
- System Architecture
- Challenges
- Standardization, Tests, and Certification
General Concepts and Definitions
Overview: Synchronized Measurements

- A PMU at a substation measures voltage and current phasors
  - Very precise synchronization, with μs accuracy is becoming standard
  - Compute MW/MVAR and frequency
- Measurements are reported at a rate of 20-60 times a second
  - Well-suited to track grid dynamics in real time (SCADA/EMS refresh rate is seconds to minutes)
- Each utility has its own Phasor Data Concentrator (PDC) to aggregate and align data from various PMUs based on the time tag
- Measurements from each utility’s PDC is sent to the Central Facility (e.g. TVA’s SuperPDC) where the data are synchronized across utilities
Synchronizing Signals Hundreds of Miles Apart

Phasors on the same diagram

PMU 1

PMU 2

Indirect
Comparison Between SCADA and PMUs

Source: CFE

PMU Measurements

SCADA Measurements

Time
Synchrophasor Definition

- **Synchrophasor** – Precision Time-tagged Positive Sequence Phasor measured at different locations
- **Phasor Measurement Unit (PMU)** – A transducer that converts three-phase analog signal of voltage or current into Synchrophasors
Overview: Synchronized Measurements

Phasor $X = \frac{\sqrt{2}}{N} \sum_{k=1}^{N} x_k (\cos k\theta - j \sin k\theta)$
Original algorithm

- Recursive algorithm calculate the fundamental frequency component as the phasor.
- Assumed the fundamental frequency is fixed at 60 Hz.
- Angles are affected at off-nominal frequencies.
- This problem has been corrected in modern PMUs using frequency tracking algorithms.

\[ x = x_r + jx_i = \sqrt{2} \frac{N}{N} \sum_{k=1}^{N} (x_k \cos \frac{2\pi k}{N} - jx_k \sin \frac{2\pi k}{N}) \]
Measurement Synchronization

- 24 Satellites
- 12 Hour Orbit Time
- Visibility: 5 to 8 Units from Any Point at Any Time
- Signal: Position, Velocity, Time
- Precise Positioning Service (PPS):
  - 22 meter Horizontal accuracy
  - 27.7 meter vertical accuracy
  - 100 nanosecond time accuracy
- Performance is 95% Reliable
Synchronization Sources

- Pulses
- Radio
- GOES
- GPS

The GPS Navigation Solution

The estimated ranges to each satellite are known within a small region when the receiver clock bias is correctly estimated and added to each measured relative range.
Industry Needs
Benefits as seen by DOE & FERC

The primary benefits of a real-time transmission monitoring system could be to:

- provide early warning of deteriorating system conditions, so operators can take corrective actions;
- limit the cascading effect of disturbances (by providing wide-area system visibility); and
- improve transmission reliability planning and allow for immediate post-disturbance analysis and visualization through the use of archived monitoring system data.

The secondary benefits of a real-time transmission monitoring system could be to:

- provide more diagnostic tools than are currently available;
- allow for the more effective use of automatic controls for self-correction such as automatic switching or controlling the flow of power; and
- improve computer models of the power system.

Wide Area Monitoring, Protection, and Control (WAMPAC): Industry Needs

- **System Vulnerability**
  - Response to emergencies
    (blackouts being the extreme case)
  - Emergency operations
    Prevent disturbance propagation:
    Planned islanding with well coordinated under-frequency load shedding scheme; Avoid tripping generators & lines too early; etc.
  - Faster system restoration (e.g. reclosing the tie line)
  - Compliance monitoring and reduction in post-mortem troubleshooting time and effort
- **Asset management/Aging infrastructure**
  - Capacity deferments
  - Increase transmission capacity and power reserve management
  - Condition assessment
Wide Area Monitoring, Protection, and Control (WAMPAC): Industry Needs

- **System Operations and Planning**
  - State est. improvements
  - Model validation
  - Benchmarking, etc.

- **Market Operations**
  - Congestion management
    - Nominal Transfer Capability (NTC) based on thermal, voltage, or stability limitations
    - Unused transfer capability and lost opportunity dispatch costs

- **DG monitoring, protection, and control**

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**WECC System Oscillations under stressed conditions — August 4, 2000**

08/04/00 Event at 12:55 Pacific Time (08/04/00 at 19:55 GMT)

- Vincent 500kV
- Mohave 500kV
- Devers 500kV
- Grand Coulee 500kV

Angle Reference is Grand Coulee 500kV

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Pacific Time

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (Pacific)</th>
<th>Time (GMT)</th>
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WECC System Oscillations under stressed conditions — August 4, 2000
WAMPAC Enablers

- **Application Modules**
  - Angular & voltage stability monitoring and control
  - Dynamic line models:
    - Overload monitoring and control and Fault location
  - Power oscillation monitoring & damping (e.g. PSS)
  - Critical equipment status and condition monitoring
  - Frequency and df/dt monitoring and protection
  - Monitoring machine excitation & governor systems
  - Adaptive relay settings and protection
  - Etc.

- **Technology**
  - Integrated system-wide communication infrastructure allowing flexible and secure data collection and transfer where and when needed
  - Synchronized measurements
  - Use of standard technology, such as IEC61850, for easier integration, configuration, engineering, and maintenance
  - Advanced sensors (line thermal monitors, equipment condition assessment, etc.)
  - Advanced visualization tools and algorithms
Expected Benefits and Gaps
Phase Angle Monitoring and Control

- **Needs:**
  - Provide operators with real-time angle and angle change between buses
  - Avoid incorrect out-of-step operation
  - Improved planned power system separation

- **Benefits:**
  - Improved real-time awareness, incl. neighboring systems
  - Improved out-of-step tripping and blocking
  - Separate the system on most-balanced way
  - Assist operator during manual reclosing of tie lines

- **Technology:**
  - Advanced algorithms using wide-area information
  - Visualization tools
  - Smart algorithms for instability and coherency detection, separation boundary
  - PMU system

- **Gap:**
  - Operator acceptance, incorporation in the utility/ISO process/rules
  - System studies and testing

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*August 14, 2003 Blackout*

- **Normal Phase Angle is approx. -25°**
- **Phase Angles Diverged Prior To Blackout**

Source: TVA
Enhanced State Estimation (SE)

- **Need:** Use phasors directly to enhance SE
- **Benefits:** Better network observability; robust performance due to more measurements; more precise derived calculations
- **Requirements:**
  - **Evolutionary solution**
    - Add phasor measurements to existing SE measurement set
    - Apply ‘meter placement’ methods to determine most beneficial PMU locations
    - Actively pursued by major EMS vendors
  - **Revolutionary solution: All-PMU State Calculation**
    - State estimate available much more frequently
    - Massive PMU deployment (30% - 50%) of buses
    - Foundation for “closed loop” control
    - Cost-benefit analysis required for justification for each user
  - **“Equivalent” solution: ISO/RTO applications use PMUs for “boundary conditions” for utility state estimators**
Enhanced State Estimation (SE)

• **Gap:**
  – Need for more PMUs to realize benefits
  – Measurement-error (accuracy) analysis for combined traditional telemetry and PMUs
    • What is redundancy with both traditional telemetry and PMU measurements?
  – As conventional SE uses app. 10s window, what is the level of improvements with PMUs?
  – Time skew impact to be quantified
  – Bad data detection (robustness) may be affected by accuracy issues
  – Will positive sequence measurement help as existing telemetry uses one or two phases?
  – Further develop “linear” SE application

*Scope and nature of SE enhancement is system/customer dependent*
Post-Disturbance Analysis and Compliance Monitoring

- **Need:** To reconstruct sequence of events after a disturbance has occurred
- **Benefits:** Savings in troubleshooting time (several orders of magnitude) and resources
- **Technology:**
  - PMU with low comm. requirements
  - Data storage in substations
  - “Smart Analyzer” to sift through vast amount of data for key info from an assortment of data loggers (DFR, SER, Relays, PMUs,...)
- **Gap:** No commercial products exist as Smart Analyzer
Under-voltage load shedding

- Operates when the voltage drops to a certain pre-selected level for a certain pre-selected time period
- UVLS is usually set with a longer (2 – 10 s) reaction time compared to SVC / STATCOM (0.1 – 1 s)
- Voltage recovery to be studied
- Use of other measurements:
  - Line and generator status
  - Dynamic VAR reserve at generators
  - Etc.
- Deployed world-wide

Issues with voltage as an indicator of voltage instability:
#1: UV relay trips unnecessarily
#2: UV relay fails to trip
Voltage Instability Predictor*

- Maximal power transfer $\Leftrightarrow |Z_{app}| = |Z_{Thev}|$ is point of collapse
- Measuring the proximity to instability - improvement to UV LS
- Corridor version: Two PMUs on the both side of the line
  - More accurate Thevenin equivalent

Real-Time Congestion Management

- **Need:** Improve calculation of real-time path flows and increase transfer limits for optimal market dispatch
- **Benefits:** Avoid large congestion costs
  - Avoids unused transfer capability and lost opportunity dispatch costs through more accurate real-time ratings
  - Experience from real-time ratings will help hour-ahead, and day-ahead limits
  - Leads to better utilization of generation resources and less load curtailment
- **Technology:**
  - Adequate visibility of corridors with incorporation of improved basic modules to EMS/SE: Angular stability, Voltage stability, Thermal constraints
  - PMU applications
- **Gap:**
  - Industry and staff adoption of new rules and procedures and PMU-based calculations
Wide-Area Power System Stabilizer (PSS)

- **Need**: Generator control to suppress low-freq. oscillations in interconnected grids
- **Benefits**: Better system damping by feeding multi-input PSS with wide-area signals
- **Technology**:
  - Selection of signals; design and tuning of algorithm
  - Fall-back scheme: use local signals when remote ones are disrupted
- **Gap**:
  - Dedicated communications link
  - Quantified benefits of WA-PSS

A: Conventional PSS.
B: Multi-input PSS; local signals.
C: Multi-input PSS; wide-area signals.

Source: Hitachi.
Dynamic Line Models

• **Need:**
  1. Dynamic rating by real-time assessment of transmission lines thermal limits
  2. More accurate line parameter detection for accurate fault-location

• **Benefits:**
  1. Operator can determine the proper loading
  2. Faster restoration for permanent faults and better detection of week spots for temporary faults

• **Technology:**
  – Sagometers
  – Temperature measurements
  – PMUs in substations

• **Gap:**
  – Industry acceptance
Power-System Restoration

- **Need:** Use of phase-angle monitoring to assist operator during restoration
- **Benefits:** Time savings
  - Operator knows if it is feasible to reclose the tie line
  - Valuable tool for operator who works under stress to reenergize grid.
- **Technology:**
  - PMU system
- **Gap:**
  - Operator training required
  - Simulators need to provide trainee with feedback signals that simulate direct measurements
Monitoring/Protection/Control for DG

- **Need:** Better monitoring/protection/control methods
- **Benefits:** Determination of unintentional islanding
- **Technology:**
  - A pair of PMUs has been shown to detect islanding cases where local-based methods could not
- **Gap:**
  - Field experience still lacking
  - Cost requirements
Adaptive Protection

• **Need:** To use synchronized phasors to allow relays to adapt to prevailing system conditions

• **Benefits:**
  – Line relays: to better handle complex configurations (e.g., multi-terminal lines, series-compensated lines)
  – Adaptive Security & Dependability to avoid cascading (2 out of 3)
  – Improved backup protection

• **Technology:**
  – PMU signals
  – Advanced algorithms

• **Gap:**
  – More field experience needed
  – Acceptance by engineers
Dynamic Relay Settings

- **Needs:**
  - Reduce complexity of implementation, maintenance, testing, and verification of relay settings with multi-function IEDs
  - Avoid that equipment protection operates incorrectly under stressed system conditions not set and designed for

- **Benefits:** Ease of applying and changing settings with IEDs
  - Automated review and update of relay settings as system conditions change (e.g. load growth, new equipment installations)
  - Dynamic setting adjustments under stressed system conditions (e.g. line overload, voltage and angular instability)

- **Technology:**
  - Enterprise level process and tools
  - WAMS high-resolution “system data” data, detect stressed conditions and system changes
  - First level alarm => Second level automated adjustments

- **Gap:** Industry acceptance
Industry Projects and Experience
Deployment Status

- Synchronized Measurement (SM) and Synchronized Phasor Measurement (SPM) devices are available from many vendors
  - ABB, AMETEK, Arbiters, GE, Macropyne, Mehta Tech, SEL, …
- Systems are already installed and operating
- Large scale deployment
  - WECC, EIPP, ONS-Brazil, etc.
- New IEEE C37.118 standard has been approved
- Many ongoing SM/SPM application researches/studies
Eastern Interconnection Phasor Project (EIPP)

Under DOE leadership, EIPP participation has been unprecedented:

- Number of utilities: 32
- Number of research organizations: 14
- Number of vendors: 27
- DOE investment in EIPP: $3 million (since 2002)
- Industry investment in EIPP: $15 million (5 to 1 leverage)
- Future DOE investment needed: $5 million (yearly)
- Number of years needed: 5 years

Source: EIPP
Eastern Interconnection Phasor Project (EIPP)

EIPP PMU Companies*
- Ameren
- AEP
- ConEdison
- Entergy
- Excelon/ComEd
- Excelon/PECO
- First Energy
- Hydro 1
- LIPA
- Manitoba Hydro
- METC
- Midwest ISO
- NY ISO / NYPA
- PPL Corp.
- Southern Company
- TVA

* Companies with PMUs Planned or In Service
PMUs offer Wide-Area Visibility
RTDMS VISUALIZATION – SAMPLE DISPLAY

Monitor:
- voltage angles and magnitudes
- color coded
- quickly identify low or high voltage regions

Monitor:
- voltage angle and magnitude tracking at selected location

Compare angles selected

Historical tracking and comparison over specified time duration

Source: EPG
Conceptual Proposal for Build-out of a WECC Synchronized Phasor Network

**WECC TOTALS**
- 50 PMUs
- 339 Phasors

**CAISO TOTALS**
- 37 PMUs
- 221 Phasors

**CONVENTIONS**
- States with PMU Installations
- Macodyne PDC (Not in Service)
- BPA PDC
- Network connection
- SCE-LDWP-BPA Microwave Circuit
- Future Network Connection
- (aa/bb) # PMUs / # Phasors
Phasor-Assisted State Estimation, NYPA/EPRI

- Goal: with PMU data, State Estimation can be solved non-iteratively delivering much improved performance.

- Experience:
  - First PMU installed in 1992; now 6+ units in NY State
  - On-line data streamed from PMUs to the EMS computer via dedicated communication channels
  - Modified the traditional State Estimation algorithm
  - Tested to confirm improvements to the traditional SE
  - Adopted phasors as integral part of the EMS

Source: Bruce Fardenesh, NYPA
Entergy/TVA PMU-SE Project Objectives

- **Phase 1: Benefits using PMU measurements in the State Estimator**
  Partners: Entergy, TVA, AREVA
  - Off-line case studies with captured real-time data from TVA and ENTERGY control centers
  - Use captured real-time PMU data synchronized with SCADA
  - Demonstrate results

- **Phase 2: Online EMS SE Demonstration**
  Partners: AREVA, TVA, Entergy, PG&E, and Manitoba Hydro with expressed interest from Idaho Power, WECC, First Energy, and BPA
  - Automate transfer of PMU/PDC data to EMS
  - Selection of PMU data relevant to current SCADA data for SE
  - Test online TVA State Estimator using PMU measurements from TVA’s Super Phasor Data Concentrator
  - Assess and quantify benefits using online performance metrics
  - Implement & demonstrate at TVA control center, on a parallel (non-operational), online SE which uses PMU data
State Estimation-PMU Data exchange-Phase 1

- **PMU Data Processing**
  - TVA-Super PDC
  - Time point Tables for all PMU
  - Processed data
  - Monitoring
  - Applications Input

- **Measurements**
  - PMU
  - PMU

- **PMU Data Converter**
  - 30 samples/second

- **SCADA**
  - TVA-ICCP (60 s)
  - ENTERGY~2-4 secs

- **Real-time State Estimator**
  - Time “T”
  - RTNET Savecase

- **ENTIRE Savecase**

- **Study State Estimator**

- **GRID (XLS)**

- **Source: TVA**

- **EMP2.3+**
  - “5” minutes
  - Case #1
  - Case #2
  - Case #3
  - Case #4
  - ....
Wide-Area Stability and Voltage Control System (WACS)

- On-line demonstration project
- Inputs from 8 PMUs (2005)
- Fiber optic communications (SONET)
  - Data rate: 30 packets per second
- Existing Remedial Action Scheme (RAS) transfer trip from control center to power plants and substations
- Computer at control center:
  - LabVIEW real-time HW and SW
  - Algorithms based on: voltage magnitudes and generator VARs
  - Actions: Generator tripping and capacitor/reactor switching

“Model studies predict that when WACS is fully accepted, an additional 300 MW could be routed down the Pacific Intertie, resulting in a conservative estimate of $7.2 million per year benefit.” Source: BPA.
Iceland has a strong 220kV grid connected to a weak 132kV ring.

Power oscillation occurs when the ring is opened (due to line fault).

Two PSS designs have been studied for Plant #1:

- Conventional PSS -- use (local) shaft speed as input.
- Wide-area PSS -- use remote signal (PMU#2’s freq.) and local signal (PMU#1’s freq.) to produce $\Delta f$ as input.

Source: Landvirkjun (Iceland’s National Power)
WAMS as a tool during UCTE Reconnection

- Wide Area Monitoring system provided more confidence and security during the reconnection of UCTE:
  - Zone 1: Green
  - Zone 2: Blue

- Critical grid oscillations/separations could be detected fast

Sources: ETRANS, UCTE
1999: ISO study of a PMU-based recording system for:
- Post-disturbance analysis (inter-area oscillations)
- Dynamic model evaluation

2003: Experiment project by university:
- 3 PMUs and 1 PDC; All locally made.
- Monitoring 3-ph distribution voltage at three universities in Southern Brazil.
- Applications: Frequency monitoring, disturbance detection, phase-angle monitoring.

2006: Brazilian ISO, “ONS”, prepares for wide-area deployment:
- “Specification of the Phasor Measurement System” as a blueprint for how the system will be built.
- Local utilities will buy and install PMUs and PDC according to the blueprint’s specs.
- Master PDC at the ISO control center.
- Anticipated uses include: forensic analysis of grid disturbances; validation of model parameters; evaluation of protection-system performance.
WAMS in China

- 15% annual growth in consumption; Generation and tie lines are being added:
  - Interconnecting of six regional networks have rendered challenges to operations
  - Low-freq. oscillations; Volt/VAR problems
- Power shortage costs economy 2 BUSD/year
- Systems and Apps under development
- 10 WAMS; PMUs--80 installed, 60 planned

**Basic function:**
- BF1: integrated Phasor data platform
- BF2: Wide Area Dynamic monitoring and analysis
- BF3: on-line synchronizing recording and redisplay

**Advanced function:**
- AF1: Generator State P/Q
- AF3: hybrid state estimation
- AF4: emergency cont. decision
- AF5: Angle Stab. Predict. & alert
- AF6: on-line disturb. Identi.
- AF7: Voltage dyn. monitoring
- AF8: model/parameter identi.
- AF9: simulation validation
- AF10: AVC (Aux. Vol. Con.)
System Architecture
Architecture Today

- Most installations consist of one-PDC architecture with a limited number of PMUs

- WECC and EIPP systems
  - Multiple PDCs with a master data concentrator
    - The master data concentrator
      - Aggregate real-time PMU data and rebroadcast to other PDCs
      - Provide online/archived data for non-real-time applications
      - Custom developed
  - Evolved from interconnecting single-PDC based systems of the participating utilities
TVA SuperPDC Architecture (EIPP)

- System performance depends on the weakest link (e.g. low-performance PDC connected to SPDC will affect all users)
- Time delay about 5 seconds
- Mainly perform data archiving and rebroadcast
System Architecture - Today

- Managed Optical Ethernet Switches - LAN 1
- Managed Optical Ethernet Switches - LAN 2
- Line A Relay 1
  IEC 61850 & DNP 3.0
- PMU 1
  COMTRADE / IEEE C37.118 §
- Xfmr Relay 1
  IEC 61850 & DNP 3.0
- Bus Relay 1
  IEC 61850 & DNP 3.0
- Super Phasor Data Concentrator (SPDC)
  at TVA (EIPP)
- Line A Relay 2
  IEC 61850 & DNP 3.0
- PMU 2
  COMTRADE / IEEE C37.118 §
- Xfmr Relay 2
  IEC 61850 & DNP 3.0
- Bus Relay 2
  IEC 61850 & DNP 3.0
- Bus Relay 3
  IEC 61850 & DNP 3.0

Corporate WAN
via Primary and Backup
Data Communications Services:
- Utility owned WAN, and/or
- Common carrier MPLS service
  = VPN defined WAN

IN SUBSTATION

- Physical and electrical isolation of redundant protection systems
- DFR Data Host
- Local Historian
- Monitoring IEDs Serial Comms Protocol
- SCADA/EMS
- Utility Enterprise
- Service Providers
- Other Substation LANs
- Managed Optical Ethernet Switches - LAN 3
- Managed Optical Ethernet Switches - LAN 1

Example Substation

Utility Owned PDC
Data Stream Collection and
Analysis Server - for control and protection.

T N MI

Super Phasor Data Concentrator (SPDC)
Utility Enterprise

Utility Enterprise

Corporate WAN
via Primary and Backup
Data Communications Services:
- Utility owned WAN, and/or
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  = VPN defined WAN

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Example Substation

Utility Owned PDC
Data Stream Collection and
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PG&E – Improvements on Remedial Action Scheme

Controller-A
- OPC
- IEC 61850
- GPS Clock
- SOE OSC
- Hub

Controller-B
- OPC
- IEC 61850
- GPS Clock
- SOE OSC
- Alternate Hub

Substation
- Scheme A
- Scheme B
- Watts, VAR, Freq., Temp., Thermal, Phasor

GPS Clock
- Status & Actions
- Host Computer

Watts, VAR, Freq., Temp., Thermal, Phasor
- V/A Status
- Control

Source: Vahid Madani, PG&E
System Architecture

- How to connect SMs/SPMs with Applications?

- Device management?
- Application management?
- Data flow management/optimization?
- Archive/access management?

SMs/SPMs

Applications

System Architecture?

- Initial cost
- Operating cost
- Other costs

- Performance
- Flexibility
- Ease of use
PDC Status

- Lack of mature off-the-shelf PDCs
  - Custom developed PDCs
  - Vendor PDCs: Not fully productized
    - Limitations unknown
    - Interoperability with other PMUs/PDCs
- Limits of a master PDC – max. number of PMU/PDC data streams that it can process?
  - Varies depending on types of PDC, and Data volume (# of phasors/data and data rate) and Processing tasks
- Pros/cons of using intermediate PDCs
  - Data flow, latency, bandwidth, configuration, etc.
Need for New Architecture

• Standardized system architecture design
  – Meet the diverse requirements of different applications
  – Enable data sharing \(\rightarrow\) minimize overall cost
  – Use off-the-shelf products (e.g. process automation)
  – Be supported by available communication infrastructure
    • Bandwidth, protocol, latency
  – Can be easily integrated and configured
    • Highly scalable and flexible
    • Reliable and secure
    • Easy to install, operate, and maintain
    • Easy to interface with other systems
Experience you can trust.

Challenges
Challenges

- Disparity among algorithms used by PMU vendors (e.g. phase angle calculations)
- Challenges for data analysis
  - Disparate sampling rates
  - Disparate filtering techniques
  - Data compression practices
- Unaccountability of instrumentation errors
- C37.118 is for Steady State Operation
- Visualization of vast amount of data
- Secure and non-corrupted data through data links
- Scalability: Design architecture to accommodate application additions
- High accuracy and data bandwidth requirements
Phase measurement vs. frequency

4 PMUs show difference in phase angle at different frequencies. Example of importance of PMU testing and standards development.

Source: Ken Marin, BPA
## Transducer Accuracy - ANSI

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<th>ANSI CT Type</th>
<th>Load Current</th>
<th>Max. Magnitude Error pu</th>
<th>Max. Phase Error (degrees)</th>
<th>Max. Phase Error (µs)</th>
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<td></td>
<td>100%</td>
<td>0.006</td>
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<td>RELAY TYPE 10P</td>
<td>100%</td>
<td>0.1</td>
<td>Not tested</td>
<td>Not tested</td>
</tr>
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<td></td>
<td>max. limit</td>
<td>0.5</td>
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<td>Not tested</td>
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<tr>
<td>Relay Type 5P</td>
<td>100%</td>
<td>0.3000</td>
<td>2.000</td>
<td>92.6</td>
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<td>max. limit</td>
<td>1.0000</td>
<td>2.000</td>
<td>92.6</td>
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<td>Metering Type 1.0 Accuracy</td>
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<td>0.0300</td>
<td>6.000</td>
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<td>20%</td>
<td>0.0150</td>
<td>3.000</td>
<td>138.9</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>0.0100</td>
<td>2.000</td>
<td>92.6</td>
</tr>
<tr>
<td></td>
<td>120%</td>
<td>0.0100</td>
<td>2.000</td>
<td>92.6</td>
</tr>
<tr>
<td>Metering Type 0.5 Accuracy</td>
<td>5%</td>
<td>0.0150</td>
<td>3.000</td>
<td>138.9</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>0.0075</td>
<td>2.000</td>
<td>92.6</td>
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<tr>
<td></td>
<td>100%</td>
<td>0.0050</td>
<td>1.000</td>
<td>46.3</td>
</tr>
<tr>
<td></td>
<td>120%</td>
<td>0.0050</td>
<td>1.000</td>
<td>46.3</td>
</tr>
<tr>
<td>Metering Type 0.2 accuracy</td>
<td>5%</td>
<td>0.0075</td>
<td>1.000</td>
<td>46.3</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>0.0035</td>
<td>0.500</td>
<td>23.1</td>
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<tr>
<td></td>
<td>100%</td>
<td>0.0020</td>
<td>0.167</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>120%</td>
<td>0.0020</td>
<td>0.167</td>
<td>7.7</td>
</tr>
<tr>
<td>Metering Type 0.1 Accuracy</td>
<td>5%</td>
<td>0.0040</td>
<td>0.500</td>
<td>23.1</td>
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<tr>
<td></td>
<td>20%</td>
<td>0.0020</td>
<td>0.333</td>
<td>15.4</td>
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<td>100%</td>
<td>0.0010</td>
<td>0.167</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>120%</td>
<td>0.0010</td>
<td>0.167</td>
<td>7.7</td>
</tr>
</tbody>
</table>
System Accuracy

• Input signal accuracy affected mainly by signal transducers
• Input circuits and algorithms (analog and digital filtering, DFT window, signal processing, data concentrators, multiplexers)
• Timing reference
  – GPS today can provide accuracy that is less than 1 µs or 0.022° at 60 Hz
• Fix delay $T_f \sim 75$ µs

• Propagation delay $T_p \sim 25$ µs
• Data transmission delay $T_d$ for a typical PMU (12 phasors and 10 DI, data frame 680 bits, header frame 200 bits and configuration frame 2.8 kbits)
  – $110$ µs on a 33.6 Kbps telephone line channel (worst case)
  – Negligible for fiber optic cable

• The total delay $T_f + T_p + T_d \sim 210$ µs (telephone line) and $\sim 100$ µs (fiber)
Standardization, Tests, and Certification

- IEEE Std 1344-1995 (R2001)
- IEEE Standard C37.118-2005
- EIPP/PRTT activities

June 5 – 7, 2006
How to exchange PMU data?

- PMU configuration information
  - Data format definition
  - Static after setup

- Synchrophasor data
  - Real-time data stream
    - Reporting rate
    - Format
      - Fixed or floating point
      - Polar or rectangular
IEEE Std 1344-1995 (R2001)

- IEEE Standard for Synchrophasors for Power System
  - Approved December 1995 and reaffirmed 2001 (no change)
- Main achievement
  - Defined a consistent and accurate time-tagging method
  - Allowed the use of both synchronized and non-synchronized sampling
  - Not locked at the nominal frequency but follows the frequency of the signal (steady-state)
  - Defined angle convention independent of window size
  - Required the correction of internal phase angle delays
IEEE Std 1344-1995 (R2001)

• Main achievement (cont’)
  – Defined the data format of phasors being transmitted
    • Configuration frame
    • Header frame
    • Phasor Information frame

IEEE Std-1344 Phasor Information Data Frame
Limitations of 1344-1995 (R2001)

- Defined angle convention only at Zero-crossing
  - Phasor angle requirements set at 1 PPS mark but not inside the 1 second window
- Limited to steady-state conditions
  - The standard accepts different responses for non-steady-state conditions
- Data format not fully compatible to network communications
  - COMTRADE style aimed for serial communication links
- Limited implementation by manufacturers
PMU comparative test – May 2003
**Test Conclusions on Exiting PMUs May 2003**

<table>
<thead>
<tr>
<th></th>
<th>Unit A</th>
<th>Unit B</th>
<th>Unit C</th>
<th>Unit D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1344 Compliance</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Data Format</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Time Synchronization</td>
<td>Yes*</td>
<td>Partial</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
IEEE C37.118 – The new standard

• Approved December 2005
• Main improvement over IEEE Std 1344
  – Defined an “Absolute Phasor” referenced to GPS-based and nominal frequency phasors
  – Defined a better time-tagging method
IEEE C37.118 – The new standard

- Main improvement over IEEE Std 1344 (cont’)
  - Introduced TVE (Total Vector Error) for quantifying phasor measurement errors

\[
TVE = \sqrt{\left(\frac{X_i(n) - X_r}{X_r + X_i}\right)^2 + \left(\frac{X_i(n) - X_i}{X_r + X_i}\right)^2}
\Rightarrow \frac{\bar{X}_{\text{Measured}} - \bar{X}_{\text{Ideal}}}{\bar{X}_{\text{Ideal}}}
\]
Total Vector Error

\[ \text{TVE} = \frac{|\bar{V}_{\text{Ideal}} - \bar{V}_{\text{Measured}}|}{|\bar{V}_{\text{Ideal}}|} \]

- ±5 Hz frequency range resulting in:
  - Magnitude Errors
  - Angle Errors
- 10% Total Harmonic Distortion
- 10% Interfering Signal

TVE from all Sources must be < 1%
IEEE C37.118 – The new standard

- Main improvement over IEEE Std 1344 (cont’)
  - Recommended PMU steady-state performance compliance test requirement

### Error Limits for Compliance Level 0 and 1

<table>
<thead>
<tr>
<th>Influence quantity</th>
<th>Reference condition</th>
<th>Level 0 Range</th>
<th>Level 1 Range</th>
<th>Level 1 TVR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal frequency</td>
<td>( F_{\text{nominal}} \pm 0.5 ) Hz</td>
<td>( \pm 5 ) Hz</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Signal magnitude</td>
<td>100% rated</td>
<td>30 – 120% rated</td>
<td>10 – 120% rated</td>
<td>1</td>
</tr>
<tr>
<td>Phase angle</td>
<td>0 radians</td>
<td>0 radians</td>
<td>0 radians</td>
<td>1</td>
</tr>
<tr>
<td>Harmonic distortion</td>
<td>&lt;0.2% (THD)</td>
<td>10% harmonic up to 50 Hz</td>
<td>10% harmonic up to 50 Hz</td>
<td>1</td>
</tr>
<tr>
<td>Out of band interfering signal, at frequency ( f_0 ) where (</td>
<td>f_0 - f_s</td>
<td>&gt; \frac{f_s}{2} ), ( f_s = ) phase reporting rate, ( f_0 = ) ( F_{\text{nominal}} )</td>
<td>&lt;0.2% of input signal magnitude</td>
<td>10% of input signal magnitude</td>
</tr>
</tbody>
</table>
IEEE C37.118 – The new standard

- Main improvement over IEEE Std-1394 (cont’)
  - Defined data format compatible with other standards (e.g. IEC 61850)
IEEE C37.118 Limitations

- Recommended but not required the dynamic performance compliance
IEEE C37.118 Limitations (cont’)

- Lack of frequency measurement accuracy requirement makes TVE not constant in a time window.

In this example a frequency mismatch produces $TVE = 0$ only at the center sample window but varies for any other time window.
IEEE C37.118 Does Not

- Define a common phasor reference in a power system
- Provide detailed test setup and test procedures for steady-state performance compliance test
- Address some practical application issues
  - PMU field installation and commission
  - PMU connection to Phasor Data Concentrators
EIPP Performance Requirements Task Team (PRTT)

- Requirements and protocols for data collection, communications, and security through guidelines and standards

**Eastern Interconnection Phase Angle Reference**

- **Document**: “Definition and Implementation of a System-Wide Phase Angle Reference for Real-Time Visualization Applications” (approved).
- **Implementation** of Virtual Bus Angle Reference at TVA SuperPDC

**Phasor Requirements for State Estimation**

- **Document** approved by PRTT
- In the EIPP acceptance process

**Phase Inconsistency**

- Address phase inconsistency issue with corrective actions included.
- **Document** posted
EIPP Performance Requirements Task Team (PRTT)

PMU Installation/Commissioning/Maintenance Survey
- Understand current practices and provide reference for others.
- **Document**: “Survey on PMU Installation and Maintenance” (posted).

Installation costs for one PMU

PMU Acceptance Checklist for Connecting to SuperPDC
- Facilitate connecting PMUs to SuperPDC (current critical path of EIPP)
- **Document** developed
PRTT Top 3 Items

Guide for calibration standards and testing procedures (including dynamic) to assure performance and interoperability
- Standardize testing facility/signals/cases/criteria ➔ NERC Standard
- Draft guide under review - Target complete date December 2006

Synchrophasor Accuracy Characterization
- Characterize phasor accuracy in the instrumentation channel including PTs/CTs, instrumentation, communication channels, and PMUs
- Draft document under review - Target complete date December 2006

PMU Installation/Commissioning/Maintenance Guide
- Start with survey results, provide guidelines for PMU installation/commissioning/maintenance
- Staged methods
  - Part I: PMU acceptance test May 2006
  - Part II: PMU Installation procedures December 2006
  - Part III: PMU maintenance procedures May 2007
  - Part IV: PMU commissioning procedures October 2007
Guide for Calibration Standards and Testing Procedures

• **Scope**
  – Performance and Interoperability of PMUs
  – Covers static tests as described in IEEE C37.118
  – Covers dynamic tests beyond C37.118
  – System tests

• **Purpose**
  – To provide clear guidelines for conformance tests and certification
    • Test equipment
    • Test requirement (steady-state and **dynamic**)
    • Test setup and test procedures
    • Data frame conformance verification
  – Laboratory and Utility Environments
  – Compatibility with PDCs and System Requirements

• **To become a NERC standard**
Status of Calibration System

- System performed frequency, amplitude, and phase tests on PMUs
- Preliminary Calibrations Show that the System will meet
  - Less than 0.01 % magnitude error
  - Less than 0.2 µs time error
  - Less than 0.013 % TVE
- Plans
  - Program and Test PMU for:
    - Harmonic Distortion sensitivity
    - Inter-harmonic Sensitivity
    - Frequency Ramps
  - Develop Additional Dynamic Tests
Document transducer errors
Summary

- IEEE C37.118 has provided a good foundation for Synchrophasor applications
- There are still some pressing issues that C37.118 did not address
- EIPP PRTT is currently working on these issues to fill in the gap
- Results of EIPP PRTT activities are critical for the successful applications of the Synchrophasors and PMUs
Conclusions and Next Steps

- Advances in sensing, communication, computing, visualization, and algorithmic techniques for Wide Area Monitoring, Protection, and Control Systems provide cost effective solutions to reduce costs, improve system performance, and minimize risks.

- Need for WAMPAC application and deployment roadmap based on “business case” analysis to support utilities, regulators, and vendors.

- Leverage benefits through integration of applications.

- Early adopters lead the industry – Need for wider deployment.

- Needs for education, training, and process and culture change.
  - Ownership within a utility and how to share benefits among groups.

- System-wide implementation and common architecture.

- Uniform requirements and protocols for data collection, communications, and security achieved through guidelines/standards.

- Sharing experience and best practices (e.g. EIPP).
Thank you!

Any questions?