PHASOR MEASUREMENT UNITS,
WAMS,
AND THEIR APPLICATIONS

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Lecture outline

1. Birth of PMUs – Virginia Tech
2. Phasor Measurement Techniques
3. Synchronization
4. Standards
5. Wide Area Measurement Systems - WAMS
6. Applications of PMUs and WAMS
7. Conclusions
1. Birth of PMUs – Virginia Tech
Symmetrical Component Distance Relay Development

We at AEP wanted to work on line relaying using IBM System 7, and it was necessary to fit the algorithm in one cycle to make a high-speed relay.

DISTANCE RELAYS FOR 3-PHASE SYSTEMS

• Need to cover 10 fault types
• Six distance relays at each terminal
• Three ground distance relays: a-g, b-g, c-g
• Three phase distance relays: a-b, b-c, c-a
DISTANCE RELAYS ON 3-PHASE SYSTEMS

Six equations have to be solved:

- a-g relay responds to $E_a/(I_a + mI_0)$
- b-g relay responds to $E_b/(I_b + mI_0)$
- c-g relay responds to $E_c/(I_c + mI_0)$

- a-b relay responds to $(E_a - E_b)/(I_a - I_b)$
- b-c relay responds to $(E_b - E_c)/(I_b - I_c)$
- c-a relay responds to $(E_c - E_a)/(I_c - I_a)$
One equation (instead of six) with symmetrical components (SCDR):

\( k_0 \) etc. are defined in terms of symmetrical component voltages and currents. Then the distance to the fault is given by:

\[
\text{Fault distance} = \frac{k_1 + k_2k_2' + k_0k_0'}{1 + k_1 + k_2' + k_0'}
\]

For all fault types!

This was a nice algorithm, and I did get a patent on this. Made some money too.
Computer relaying development laboratory at AEP

Ted Hlibka and Mark Adamiak
The microcomputers became quite fast in time, and there was no particular benefit in making SCDR for distance relaying. However, a realization came that the sequence measurement part of the algorithm is very valuable in many power system applications. That was the birth of the PMU.
Proto-type of complete PMUs at Virginia Tech

- GPS receiver
- PMU
- Signal conditioning unit
- User Interface
Virgilio Centeno went to Macrodyne after getting his Ph.D. and worked with Jay Murphy to design the first commercial PMU.
2. Phasor Measurement Techniques
• Introduction to phasors

The starting time defines the phase angle of the phasor.
This is arbitrary.
However, differences between phase angles are independent of the starting time.
- Sampling process, Fourier filter for phasors

\[ \text{Input signal} \]

\[ \begin{align*}
\text{Data samples:} & \quad x_n, x_{n-1}, \ldots, x_1 \\
\text{cosines:} & \quad \cos \theta, \cos (\theta + \phi), \ldots, \cos (\theta + (N-1)\phi) \\
\text{sines:} & \quad \sin \theta, \sin (\theta + \phi), \ldots, \sin (\theta + (N-1)\phi)
\end{align*} \]

\[ \text{Phasor } X = \frac{\sqrt{2}}{N} \sum_{k=0}^{N-1} x_k (\cos k \theta - j \sin k \theta) \]
• Non-recursive phasor calculations

\[ \theta_2 = \theta_1 + k\phi \]

The non-recursive phasor rotates in the forward direction, one sample angle per sample.
The recursive phasor remains fixed if the input waveform is constant.
- Effect of noise on phasor calculations

- Harmonics eliminated correctly if Nyquist criterion is satisfied.

- Non-harmonic components

- Random Noise
Measurement of frequency and rate of change of frequency:

Phase angle of positive sequence voltage is constant when input is at nominal frequency and constant.

At constant off-nominal frequencies, the phase angle changes linearly.

Using angles over a window, and assuming them to be a quadratic function of time, the rate of change of angle provides frequency measurement, and the second derivative provides rate of change of frequency very accurately.
3. Synchronization
Motivation for synchronization

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.
• Sources for Synchronization

• Pulses
• Radio
• GOES
• GPS
• A phasor measurement unit

Except for synchronization, the hardware is the same as that of a digital fault recorder or a digital relay.
4. Standards
IEEE standard for SYNCHROPHASORS for Power Systems

Evolution of Synchrophasor Standards

IEEE Std 1344-1995
IEEE Std C37.118-2005
IEEE Std C37.118.1-2011
IEEE Std C37.118.2-2011
IEC 61850-90-5-2011
C37.118.1
Synchrophasor Measurements for Power Systems
Measurement accuracy defined: Total Vector Error (TVE)

A pure sinusoid is generated and input to the PMU

It corresponds to a theoretical phasor value \( X = X_r + j X_i \)

PMU produces a measurement at \( t_0 : X(t_0) \)

\[ X(t_0) = X_r(t_0) + j X_i(t_0) \]

TVE is defined as follows:

\[
TVE = \sqrt{\frac{[X_r(t_0) - X_r]^2 + [X_i(t_0) - X_i]^2}{X_r^2 + X_i^2}}
\]
Measurement accuracy defined: Total Vector Error (TVE)

Two classes of PMU performance are defined:

P class: Fast responding, minimum filtering, minimum delay (Mainly used for protection and control)

M class: Slower responding, significant filtering, longer delay (Mainly used for measurements in the presence of out-of-band signals)

P and M classes replace the ‘0’ and ‘1’ classes of C37.118
Steady State tests:

- Off-nominal frequency
- Harmonic signals
- Non-harmonic signals

Dynamic tests:

- Sinusoidal modulation
- Ramp variation of frequency
- Step changes in magnitude and phase
DYNAMIC TESTS FOR PMUS

Signals to be generated according to formulas

Anti-aliasing Filter

PMU

Expected output
Positive sequence
Phasor magnitude and angle.
Frequency, rate of change of frequency

PMU output
Positive sequence
Phasor magnitude and angle.
Frequency, rate of change of Frequency
At designated reporting instants

Balanced three phase inputs

Error Report

1. Sinusoidal modulations

2. Ramps
Example: Sinusoidal modulation

67 volt rms nominal signal

Amplitude modulation 0.2 pu

\[ y_a = \sqrt{2} \times 67 \times \left\{ 1 + 0.2 \times \sin(2\pi \times 0.2 \times t) \right\} \times \sin\left(120\pi t + 2\pi \times 1.0 \times \sin(2\pi \times 0.2 \times t)\right) \]

Modulation frequency 0.2 Hz

\[ y_b = \sqrt{2} \times 67 \times \left\{ 1 + 0.2 \times \sin(2\pi \times 0.2 \times t) \right\} \times \sin\left(120\pi t + 2\pi \times 1.0 \times \sin(2\pi \times 0.2 \times t) - 2\pi/3\right) \]

Frequency modulation amplitude 1.0 Hz

\[ y_c = \sqrt{2} \times 67 \times \left\{ 1 + 0.2 \times \sin(2\pi \times 0.2 \times t) \right\} \times \sin\left(120\pi t + 2\pi \times 1.0 \times \sin(2\pi \times 0.2 \times t) - 4\pi/3\right) \]
Example: Sinusoidal modulation; Simulation Results from Matlab

- True Phasor rms amplitude
- Frequency Estimates
- df/dt estimates
- True Phasor Phase Angle

Volts, Radians/sec, Radians/sec^2

Seconds
Example: Ramp modulation

67 volt rms nominal signal

Nominal frequency $120 \times \pi$

\[ y_a = \sqrt{2} \times 67 \times \sin\{120 \times \pi + 2\pi \times (0.2/2) \times t\} \times t \]

\[ y_b = \sqrt{2} \times 67 \times \sin\{120 \times \pi + 2\pi \times (0.2/2) \times t\} \times t - 2\pi/3 \]

\[ y_c = \sqrt{2} \times 67 \times \sin\{120 \times \pi + 2\pi \times (0.2/2) \times t\} \times t - 4\pi/3 \]
Example: Ramp modulation; Simulation Results from Matlab

- True Phasor rms amplitude
- True Phasor Phase Angle
- Frequency Estimates
- df/dt estimates
C37.118.2
Synchrophasor Data Transfer for Power Systems
**Phasor reporting rates:**

Data reporting frequency $F_s$ is in data frames per second, and is defined for a 50 Hz or 60 Hz system:

<table>
<thead>
<tr>
<th>System frequency</th>
<th>50 Hz</th>
<th>60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_s$</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

The first reporting instant is at the roll-over of the UTC second, and all others follow at multiples of the nominal power frequency period $T$. Example: $F_s = 30$, for 60 Hz.

<table>
<thead>
<tr>
<th>UTC roll-over</th>
</tr>
</thead>
<tbody>
<tr>
<td>2T</td>
</tr>
<tr>
<td>4T</td>
</tr>
<tr>
<td>6T</td>
</tr>
<tr>
<td>8T</td>
</tr>
</tbody>
</table>
Reporting time and data window:

Data samples used for phasor estimation

The standard does not specify the positioning of the data window in relation to the reporting instant.
## Bandwidth requirements:

Bits per second using UDP/IP over Ethernet

<table>
<thead>
<tr>
<th>$F_s$</th>
<th>10</th>
<th>12</th>
<th>15</th>
<th>25</th>
<th>30</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 phasors integer</td>
<td>6720</td>
<td>8064</td>
<td>10080</td>
<td>16800</td>
<td>20160</td>
<td>33600</td>
<td>40320</td>
</tr>
<tr>
<td>2 phasors fl-point</td>
<td>7680</td>
<td>9216</td>
<td>11520</td>
<td>19200</td>
<td>23040</td>
<td>38400</td>
<td>46080</td>
</tr>
<tr>
<td>12 phasors integer</td>
<td>9920</td>
<td>11904</td>
<td>14880</td>
<td>24800</td>
<td>29760</td>
<td>49600</td>
<td>59520</td>
</tr>
<tr>
<td>12 phasors, 2 an. 2 dig. integer</td>
<td>10560</td>
<td>12762</td>
<td>15840</td>
<td>26400</td>
<td>31680</td>
<td>52800</td>
<td>63360</td>
</tr>
</tbody>
</table>
IEC 61850-90-5-2011

Complete 61850 solution for synchrophasor communication
5. Wide Area Measurement Systems - WAMS
Wide Area Measurement System

System Architecture

Super Data Concentrator

Data Concentrator

Applications

PMUs located in substations

Data storage

PMUs
6. Applications of PMUs and WAMS
Wide Area Measurement System

PMUs measure (synchronously):

- Positive sequence voltages and currents
- Phase voltages and currents
- Local frequency
- Local rate of change of frequency
- Circuit breaker and switch status

PMU data reporting rates:

- Data reported at up to once per cycle
• State estimation
• Instrument transformer calibration
• Network parameter estimation
• Protection systems
• System Control
Three-phase transducer calibration
Three-phase transducer calibration

\[
\begin{bmatrix}
E^a_{q0} \\
E^b_{q0} \\
E^c_{q0}
\end{bmatrix} = \begin{bmatrix}
E^a_{p0} \\
E^b_{p0} \\
E^c_{p0}
\end{bmatrix} - \begin{bmatrix}
Z^a_{pq} & Z^{ab}_{pq} & Z^{ac}_{pq} \\
Z^{ab}_{pq} & Z^b_{pq} & Z^{bc}_{pq} \\
Z^{ac}_{pq} & Z^{bc}_{pq} & Z^c_{pq}
\end{bmatrix} \begin{bmatrix}
I^a_{pq0} \\
I^b_{pq0} \\
I^c_{pq0}
\end{bmatrix} - \begin{bmatrix}
B^a_p \\
B^{ab}_p \\
B^{ac}_p \\
B^b_p \\
B^{bc}_p \\
B^c_p \\
E^a_{p0} \\
E^b_{p0} \\
E^c_{p0}
\end{bmatrix}
\]

- PMUs are installed at two substations
- Voltages: PT CVT
- Currents: CT
Error model of transducers

- Error model of PTs and CTs:

\[
\begin{bmatrix}
E^a \\
E^b \\
E^c
\end{bmatrix} = \begin{bmatrix}
e^a & 0 & 0 \\
0 & e^b & 0 \\
0 & 0 & e^c
\end{bmatrix}\begin{bmatrix}
E_m^a \\
E_m^b \\
E_m^c
\end{bmatrix}
\]

\[
\begin{bmatrix}
I^a \\
I^b \\
I^c
\end{bmatrix} = \begin{bmatrix}
i^a & 0 & 0 \\
0 & i^b & 0 \\
0 & 0 & i^c
\end{bmatrix}\begin{bmatrix}
I_m^a \\
I_m^b \\
I_m^c
\end{bmatrix}
\]

Here, \( e \) and \( i \) are the ratio correction factor (RCF)

\(|e|, |i| \sim \text{Uniform}(0.96,1.04) ; \ \text{angle}(e), \ \text{angle}(i) \sim \text{Uniform}(-3,3) \) degree

- Simple error model. With the assumption, in short time period, the errors of transducers are constants.

- Several sets of measurements by PMUs, during 24 hour under different load conditions, provide redundancy to solve the errors. (20 cases for 47-bus and 53-branch system)
24-hour load cases

- At each point, the load condition changes. PMUs can measure three-phase voltages and currents under each condition. And all of these set satisfy OHM law.
• Get linear equations  

No NR iteration

Branch with perfect PT

\[
(Y_{12} + B_{12})E_1 = i_{12}I_{12} + Y_{12}e_2E_2 \\
Y_{12}E_1 = -i_{21}I_{21} + (Y_{12} + B_{12})e_2E_2
\]

Branch with two buses to be calibrated

\[
0 = -i_{rs}I_{rs} + (Y_{rs} + B_{rs})e_rE_r - Y_{rs}e_sE_s \\
0 = -i_{sr}I_{sr} + (Y_{rs} + B_{rs})e_sE_s - Y_{rs}e_rE_r
\]

\[
X = \begin{bmatrix} D(I) & Y_A E \end{bmatrix}
\]

\[
X = ([D(I) Y_A E]^{-1}E_{ref}
\]

\[
E_{ref}
\]
DVP 500kv system
$e^{abc}_{\text{true}} - e^{abc}_{\text{calibrated}}$

$\angle(e^{abc}_{\text{true}}) - \angle(e^{abc}_{\text{calibrated}})$
• Network parameter estimation
• Protection system improvements with WAMS
• Moving towards fewer and less intense blackouts

Protection system performance issues

(1) Inappropriate settings for prevailing conditions

(2) Hidden failures in protection systems

(3) Security-Dependability balance
Overview of protection systems and practices

1. Equipment Protection (Primary)

   Example: Lines, Transformers, Generators, Buses

   Fairly straight forward: Protect against faults to avoid damage to the equipment, to get the fault off the system as quickly as possible to avoid cascading failures of the network.

   Modern relays are autonomous, fast acting, and often duplicated or even triplicated to avoid failure to clear a fault.

   Relay times may be as short as a cycle, and circuit breaker times may be 2-3 cycles.

   These are primary protection systems.
Overview of protection systems and practices

1. Equipment Protection (Primary)

   Contest between security and dependability
   Biases

2. Equipment Protection (Back-up)

   Back-up operation is more damaging
   Of necessity it is slower
   It trips larger part of the system
   It is more difficult to set, depends too much on conditions of the network.
Overview of protection systems and practices

3. System Protection
   The aim is to protect the power system from hurtful faults
     Load shedding and restoration
     Loss of field
     Out-of-step
     Islanding

   It has the same performance characteristics as the Back-up systems:
     Of necessity it is slower
     It trips larger part of the system
     It is more difficult to set, depends too much on conditions of the network.

4. Remedial Action Schemes
   More complex, a start on wide area measurement based protections
Preliminary Remarks

- Wide area measurements: PMU data
- High-speed protections not affected
- Slow speed protections – Back-up, Stability, Loss-of-field, RAS
- Adequate communication facilities implied: within substation, with neighboring substations, with remote substations, system-wide
Topics for WAMS based protection

(1) Adjusting balance of security-dependability

Balance to be shifted when the power system is in emergency state as determined from wide area measurements.

(2) Alarming for relay characteristic penetration

Wide area measurements to determine trajectories and trends of relaying parameters.

(3) Adaptive out-of-step relaying

Wide area measurements to determine trajectories and predict outcome of stability swings in real-time.
Topics for WAMS based protection

Other possibilities:

(4) Supervision of back-up zones

(5) Intelligent load shedding using load-generation imbalance estimate in real time

(6) Adaptive loss-of-field relay

(7) System-wide integration of Remedial Action Schemes (RAS or SIPS)
Protection system bias:
High dependability
Corresponding
best possible security

(1) Adjusting balance of security-dependability

(Dealing with Hidden Failures)

Adjustment of Dependability-Security balance under stressed system conditions.
(2) Alarming for relay characteristic penetration

Critical Relay locations

Static: Load encroachment

Dynamic: Swings

How close? Revise settings?
(3) Adaptive Out-of-Step Relays

Inadequacies in present systems

Impedance relays and timers are used to detect and protect against unstable oscillations.

Setting are determined from results of a large number of simulations under different conditions.

Traditional out-of-step relay parameters using reactance type relays and timers.
Previous Experience

System behaving as a 2-machine system

Georgia

Out of step condition

1993-1994
Swing Prediction for Florida-Georgia Interconnection

Equal Area Criterion

Equivalents Angle Difference, September 8, 1994

Pre-disturbance power-angle curve

Decelerating area $A_2$

Accelerating area $A_1$

$A_{max}$

Post-disturbance power-angle curve

Swing Prediction for Florida-Georgia Interconnection
Out-of-step relaying for complex networks

(1) Identify critical PMU placement sites
(2) Real-time coherency determination

(3-a) Two machine equivalent
(4-a) Extended Equal Area Criterion application

(3-b) Two machine equivalent
(4-b) Time-series of swing curves and prediction
Out-of-step relaying for complex networks

(2) Real-time coherency determination

Observation window

PMU data
Out-of-step relaying for complex networks

(3-a) Two machine equivalent

(4-a) Extended Equal Area Criterion application
Out-of-step relaying for complex networks

(3-b) Two machine equivalent

(4-b) Time-series of swing curves and prediction
(4) Supervision of back-up zones

Balanced Conditions?
Any Zone-1 picked up?

Yes. If not Block Zone-3
(5) Intelligent load shedding using load-generation imbalance estimate in real time

\[ \text{ACE} = \Delta T - B\Delta F \]

Dynamic ACE measures
Load needed to be shed
To return to pre-disturbance state
(6) Adaptive loss-of-field relay

System Thevenin Z Determined In real time

Strong system

Weak system

R

X
Are RAS 1 and RAS 2 in conflict with each other?

Make one RAS which will combine the Objectives of the two RAS schemes and create a unified response.
Concluding remarks on protection system improvements

- Protection systems can be improved with the help of wide-area measurements
- Only slow-responding protections are appropriate candidates for such improvements
- Many improvements occur as steps to improve response to next contingencies, and are not intended to operate when a fault has occurred.

With careful implementation, frequency and intensity of blackouts can be reduced, and service restoration can be more rapid.
SYSTEM CONTROL WITH PHASORS
This lecture is theoretical in nature. A number of studies have been reported in literature, although as yet there is no field implementation of these ideas.

- **We will consider control of**
  
  - HVDC systems
  - Excitation Control
  - Power System Stabilizer
  - FACTS control
Control with phasor feed-back.
Phasor feed-back

• Expect to be less dependent on model of the system being controlled.

• Processes being controlled are relatively slow.

• Process frequencies in the range of 0.2-2.0 Hz. These are representative of electromechanical oscillations, transient stability, and certain overload phenomena.

• The frequency of phasor measurements is expected to be of the order of 15-30 Hz, which is certainly sufficient to handle the control task.
Example of control with phasor feed-back

Power demand Controller

System A

System B

\[ \delta_A - \delta_B \]

Desired performance

Performance with constant power control law

Time
Example 1: HVDC Controller

- G1: 1640 MW
- G2: 820 MW
- 3 phase fault cleared in 3 cycles
- 680 MVAR
- 590 MVAR
- (200+j20) MVA
Example 1: HVDC Controller

Control law 1: Constant current, constant voltage on HVDC

Control law 2: Optimal controller

\[ \delta_1 \]

\[ \delta_2 \]
Example 2: Excitation Controller
Example 2: Excitation Controller

Centralized optimal controller

Network real-time phasor data

Optimal Controller

Control vector for all generator excitation and governor systems
Example 2: Excitation Controller

All generator angles plotted with $G_{10}$ angle as reference.

Control law 1: Without optimal feed-back vector

Control law 2: Optimal controller vector feed-back
Example 3: Power System Stabilizer

Control modes:

1. AVR alone
2. PSS on one machine
3. Phasor feed-back on one machine
## Example 3: Power System Stabilizer

Small signal analysis for tie flows of 158 MW

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
<th>Damping ratio</th>
<th>Mode shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5977±j7.0365</td>
<td>1.1199</td>
<td>0.0849</td>
<td>local area 1</td>
</tr>
<tr>
<td>-0.6060±j7.2470</td>
<td>1.1534</td>
<td>0.0833</td>
<td>local area 2</td>
</tr>
<tr>
<td>+0.0296±j4.1784</td>
<td>0.665</td>
<td>-0.0071</td>
<td>inter-area</td>
</tr>
</tbody>
</table>

![Diagram showing eigenvalues with 50 MW and 158 MW](image)
Example 3: Power System Stabilizer

1. AVR alone
2. PSS on one machine
3. Phasor feed-back on one machine
Example 4: FACTS controller

Simulation scenario:
- Determine loading levels which are dynamically unstable
- Use phasor feedback to stabilize that operating condition
References:


Multi-infeed HVDC Systems in China

11.4% annual growth in GDP – doubling time 6.42 years
16 times bigger in less than 26 years
WAMS Based Wide-area Coordinated Modulation Control of Multi-infeed HVDC

Increase the damping of inter-area oscillation in CSG
Wide-area Coordinated HVDC Control System – Control Unit in Converter Substation

- GPS
- PMU
- Control Unit
- Communication Interface
Wide-area Coordinated HVDC Control System – Centralized Control Server

Real-time Control Server

Event Archives
7. CONCLUSIONS

- PMUs have introduced a game-changing technology in power system engineering.
- Power grids throughout the world have launched ambitious programs to introduce WAMS on their systems.
- State Estimation will see the first applications.
- Instrument transformer calibration, network parameter estimation will likely be the next steps.
- Protection and control are likely to be tried on an experimental basis, before they are integrated in the normal power system EMS applications.