Western America disturbance August 10, 1996

- WSCC system (Western Interconnection)
- Split into 4 islands
- Loss of 30 GW load
- 7,5 Million customers without supply for a time between a few minutes and 9 hours

7.5 million customers
30 GW
Western America disturbance August 10, 1996

What happened?

3.42 pm

3.47 pm

3.48 pm

Malin - Round Mountain MW Flow

Time in Seconds
Western America disturbance August 10, 1996

What happened?

• A warm summer afternoon: large amounts of air conditioning in service
  • high North to South flows from Oregon to California
• Initial system state
  • north of the PDCI (Pacific DC intertie): two forced outages of lines
  • a transformer was in maintenance: reduced voltage control
• Sequence of events
  • 3.42pm Allston Keeler 500 kV sagged close to a tree and flashed over
  • Parallel lines got loaded at 115% thermal rating & voltages were slightly depressed (to 504-510 kV)
• 5 min later:
  • Relay failure in 115 kV and an overloaded 230 kV line sagged to a tree
  • Sequential tripping of 13 units (McNary) due to exciter protection malfunction at high field voltage → power and voltage oscillations
  • 40 seconds of sustained oscillations at zero damping
  • Frequency dropped and export from BPA decreased → AGC tried to restore the scheduled exchanges
  • Lack of voltage control was not compensated by converters, and oscillations increased
• System splitting happened at 3.48 (6 minutes after begin) because of low voltage high current conditions (relay trip)
Western America disturbance August 10, 1996

- **Model issue**
  - The event was beyond the N-k security criterion for short-term planning
    - number of failures (protection relays, generator protection) was beyond expectations
  - Nevertheless, the system model was not able to reproduce the event: Dynamic Security Analysis (DSA) was not able to warn about the cascading

Source: D. Kosterev
Western America disturbance August 10, 1996

How synchrophasors could have helped?

Real-time Information → Increased awareness → Possible Solutions

Recorded data → Better models → Better tools

effective use of the data to generate useful information

1. (online use) Visualization of the sequence of events more apparent
2. (offline use) Better modeling of the system oscillatory behavior
   Could have allowed the system operator to identify the problem and take appropriate actions before the cascading was too advanced to be stopped
   The first 5 minutes could have been used to perform preventive or corrective actions
3. Pacific DC intertie:
   ability to damp out oscillations if a well-designed control is in place
Contents

- About Elia and your trainer
- Measurement in power systems
- History of phasor measurement
- Principles of phasor measurement
- Standards for synchrophasors
- Power system applications of synchrophasors
- Conclusions
About Elia Group and your trainer

Power System Wide Area Measurement, Protection & Control
The Transmission System: key component in the European Energy Policy

The European power system (ENTSO-e):

- 34 interconnected countries
  - 532 Million consumers
  - 880 GW installed generation capacity
  - 3.200 TWh/year consumption
  - 380 TWh/year cross-border exchanges
  - 305,000 km lines and cables

→ One of the technological marvels of the 20th century!
Elia Group: High Voltage network ownership

- **Elia**
  - 380-150kV network
  - Most of the high voltage network (70-30kV)

- **50Hertz**
  - 380-220kV network
  - 34% of the German 380kV network
  - 19% of the German 220kV network

Elia Group: High Voltage network ownership

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The Transmission System Operator (TSO): central role as a *de facto* monopoly

The TSO operates, maintains and develops a network consisting of lines, underground cables, transformers and substations linking producers and consumers of electricity.

Elia & 50Hertz

380-220kV

Electricity generation

150-30kV

Elia

<30kV

Distribution System Operators (DSO)

International exports

Large & medium clients

Small industry & domestic clients
Elia Group activities

System Operation

- Capacity allocation
- Network operation
- Balancing generation and demand

Infrastructure Management

- Ownership
- Maintenance
- Development

Related Activities

- Market facilitator
- Services & technical expertise
- Telecom services
- Power Exchange Hubs
- EU Integration: CASC, Coreso
- Activities for third parties (consulting)

More on www.eliagroup.eu
About your trainer: Jacques Warichet

2004  MSc Electromechanical Engineering, Université Libre de Bruxelles (ULB), Belgium

2004-2008  Research and teaching assistant, ULB
Research on PMUs Financed by Siemens AG
PhD about synchrophasor measurements (completed February 2013)

Since 2008  Power Grid Security Expert, Elia, Belgium

Dynamic Security Assessment
Grid Connection requirements for generating units and HVDC links

EU FP7 Project Twenties (2010-2013):
  in charge of the WAMS setup to monitor inter-area oscillations
Measurements in power systems

Power System Wide Area Measurement, Protection & Control
The control room

- The system is supervised 24 hours / day and 7 days / week by system operators
- Computational tools and visual interfaces help
  - assess the system conditions, through alarms and cyclic computations
  - make forecasts
  - take the best decisions
  - perform preventive or corrective actions
- System operator reaction time
  - About 10 minutes
  - Faster actions (if needed), are automated

- SCADA – EMS
  - Supervisory Control and Data Acquisition system (SCADA) collects real-time data and generates alerts, and provide remote controls
  - Energy Management System (EMS) allows performing calculations based on real-time data
Classical measurements

- Currents and Voltages are measured in rms value (magnitude)
- Typically, data is sent to the data acquisition system if
  - the magnitude varies by more than 0.5 - 1% from the last data sent
  - the time elapsed since last data sent exceeds 10 to 30 seconds
- Sampling rate of the data is low and not constant
Classical measurements

- Remote Terminal Units (RTUs) transmit the data through modems, microwave, or internet.
- The data from different locations are not captured at exactly the same time.
- Under the assumption that V and P, Q do not change abruptly, this data can be used in a **static state estimator** to validate the measured data and compute non-metered voltages and power flows.
Why Phasor Measurement Units (PMUs) ?

• Phasor measurement data is synchronized with GPS signals
  • all voltage and current phasors measured across a wide geographical region will be synchronized

• High sampling rate (10-50 samples per second)
  • Extended visibility through phasor data exchange: across different operating regions (beyond the eye of a single TSO)
  • Dynamic responses and steady state responses also: better monitoring.
  • Exposes system dynamics, e.g. inter-area oscillations.
  • Aids in validating the system performance, model parameters, and controller settings
  • Assists protective systems with new information
  • Aid in restoration (e.g. synchronization of islands)

• Can help existing EMS functions and provide new ones
  • Supplement/Assist static state estimators with additional data
  • Precise angle measurement allows the calculation of power transfer between buses: improves static state estimator performance and accuracy
Phasor representation of an AC signal

- Any sinusoidal signal with constant frequency and constant amplitude can be represented by a phasor.

- The phasor is a vectorial representation of:
  - the magnitude
  - phase angle with respect to a (arbitrarily) chosen reference

- Phasor is a steady-state concept

Source: Wikipedia, the free encyclopedia
Synchronized phasors or “synchrophasors”

- if we are interested in the phasor at a specific time, then we simply set a reference time
  - Reference time defines the phase angle
  - Reference time is arbitrary
  - Difference between phase angles is independent of the reference time

Source: A. Phadke
Using synchrophasors

- By synchronizing the phasor measurements for different signals - which may be taken hundreds of km apart - ,
  - it is possible to put their phasors on the same phasor diagram and to obtain a “photograph” of the system at a specific instant of time
  - Voltage phase angle measurement has a high added value
- And this information is available immediately at a high rate!
  - synchrophasors are measured 10 - 50 times per second, at regular time intervals
  - However, it requires more telecom infrastructure
SCADA vs. synchrophasors

Source: Terna
Wide Area Measurement Systems (WAMS)

Wide Area Monitoring, Protection and Control

Substation automation
Samples - Phasors

Protection
Samples

SCADA
EMS
Control Center

Dynamic
Static
History of phasor measurement

Power System Wide Area Measurement, Protection & Control
History of WAMS & PMUs

• **Wide area measurement systems**
  • Wide area measurements in power systems have been used in EMS (Energy Management System) functions for a long time
    • Ex: State Estimation, Economic Dispatch, tie line bias control and Automatic Generation Control (AGC)
  • Modern wide area measurement systems can be traced back to 1965, after the first North Eastern Blackout → synchronization
    • But GPS fully deployed in the 1980s

• **Phasor Measurement Units**
  • Computer/Numerical Relaying developments in 1960-70s
    • Computational speed limited the ability to supervise all type of faults
    • 1977: symmetrical components allowed reducing the number of equations
  • Application of symmetrical components to power system applications
    • Development of first PMUs at Virginia Tech (USA) ~ 1982-1992 led by Arun Phadke
    • Leads to the first commercial PMU “Macodyne” in 1992
North Eastern Blackout 2003

August 14, 2003
North Eastern Blackout

Affected Region
- 55 Million People
- 4 Billion Lost in Economic Activity
- 61,000 MW interrupted
North Eastern Blackout 2003: causes


In addition to physical roots, an informational root was identified:

2.a. A utility’s control room alarm system stalled
   → Lack of system state awareness

2.b. This failure deprived them of alerts for monitoring important changes in system state
   → Lack of early warnings

2.c. Back-up server failures slowed the screen refresh rate of the operators’ consoles from 1-3 seconds to 59 seconds per screen
   → Lack of dynamic visibility

3.c. The loss of alarms led operators to dismiss a call from a neighbor utility about the tripping and re-closure of a major line
   → Lack of corrective measures
Triggers towards synchrophasors technology

- While synchrophasors already existed prior 1996, the major disturbances in the USA (1996, 2003) and the Italian blackout of 2003, were the trigger towards practical implementation of synchrophasors.

- Why wait so long?
  - Despite these events, the Security of Supply is very high (99,995%).
  - Power industry is known to be “conservative”: new tools, new processes need a thorough validation and a good business case.

- Recent developments put extra pressure on the power industry to use their assets better, closer to the limits of the system:
  - Market liberalization and penetration of “intermittent” renewable energy sources lead to more changing flows patterns.
  - Developing the grid takes time and is more and more difficult due to environmental constraints.
Milestones in wide area measurement systems

1893
- Introduction of “Phasor” concept

1960s
- Start of Numerical Relays Development

1965
- North Eastern Blackout
- Birth of Modern Wide Area Measurement Systems

1980s
- GPS technology

1988
- 1st PMU Prototype Virginia Tech

1992
- 1st commercial PMU Macrodyne

1995
- 1st PMU Standard (IEEE 1344)

2005
- New PMU Standard (IEEE C37.118-2005)

2011
- Latest version of IEEE Std. C37.118-2011

2011-2012
- Massive deployment program Financed by the DoE (USA)

2013
- 28/08/2013 Summer School for Smart Energy Systems 2013 - WAMS
The first PMU at Virginia Tech (Arun Phadke)

Source: A. Phadke
Some commercial Phasor Measurement Units

Macodyne Model 1690

ABB PMU RES 521

Mehta Tech TRANSCAN IED

Arbiter Power Sentinel 1133A

GE N60 Stability and Synchrophasor Measurement System

Schweitzer Eng. Labs. SEL-421

Source: L. Vanfretti (KTH)
Principles of phasor measurement

Power System Wide Area Measurement, Protection & Control
Anatomy of a Phasor Measurement Unit

- Analog inputs obtained from secondary winding of measurement transformers
- Filtered with anti-aliasing filters and converted into digital samples at the analog-to-digital (A/D) converter
- The sampler works in phase-locked with the GPS pulses (coming once per second)
- Device sampling rate is usually high (10 kHz) for accuracy reasons, but a decimation filter converts it to a lower rate, leading to a more stable response
- µ-processor receives the sampled data and the GPS time-tags and computes the positive sequence components of voltages and currents
Phasor definition

⇒ A sinusoidal quantity can be written as: \( x(t) = X_m \cos(\omega t + \phi) \):

- \( \omega \) is the signal’s freq. (rad/sec), and \( \phi \) the phase angle (rad).
- \( X_m \) is the peak amplitude and its RMS value is \( X_m/\sqrt{2} \)

⇒ We can write \( x(t) \) as

\[
    x(t) = \Re \left\{ X_m e^{j\omega t} e^{j\phi} \right\}
\]

⇒ Dropping the \( e^{j\omega t} \) term \( x(t) \) can be represented as

\[
    X = \frac{X_m}{\sqrt{2}} e^{j\phi} = \frac{X_m}{\sqrt{2}} (\cos \phi + j \sin \phi)
\]

→ Only possible for pure sinusoids.
→ In practice signals contain additional freqs, the fundamental component is extracted using signal processing (FFT).

Source: L. Vanfretti (KTH)
Phasor estimation from sampled data

- The voltage and current continuous signals are sampled. Here we use 12 points per cycle → sampling rate: 12 x 50 Hz = 600 Hz

- Discrete Fourier Series (DFT) are used to compute the magnitude and phase of the signal.

Source: A. Phadke
Non-recursive phasor estimation

Input signal

- $\theta_1$
- $\theta_2$

New sample, window 2

$\theta_2 = \theta_1 + k\phi$

sin and cos functions, window 1

sin and cos functions, window 2 (shifted)
Recursive phasor estimation

Input signal

\[ \theta_1 \]

\[ \theta_2 = \theta_1 \]

New sample, window 2

New samples, sine and cosine
## Non-recursive vs. recursive phasor estimation

<table>
<thead>
<tr>
<th>Non-recursive</th>
<th>Recursive</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{X}^{N-1} = \frac{\sqrt{2}}{N} \sum_{k=0}^{N-1} x_k e^{-j k \varphi}$</td>
<td>$\hat{X}^{N+r} = \hat{X}^{N+r-1} + \frac{\sqrt{2}}{N} (x_{N+r} - x_r) e^{-j r \varphi}$</td>
</tr>
</tbody>
</table>

For a constant sinusoid, the phasor rotates in the counterclockwise direction as the window advances sample by sample.

For a constant sinusoid, the phasor does not move.

Computationally intensive. DFT computation is re-made at each phasor.

Computationally more efficient. Only two components in the sum (first and last sample) are computed.

Numerically stable.

Numerically unstable. Round-off errors remain in the phasor and propagate.
Noise in phasor estimation

- Harmonics are eliminated correctly if Nyquist criterion is satisfied: $f_s > 2f_{max}$
- Using a complete cycle reduces the effect of random noise (mostly, measurement noise) on the resulting phasor.
- DFT over multiple cycles is also possible

Source: A. Phadke
System frequency

The frequency of the system is related to the balance between generation and consumption and varies continuously.
Operating Frequency in Continental Europe

CE system frequency statistics based on 10s sampling frequency

[Graph showing frequency ranges and percentage of time spent in each range]

Daily Average Network Frequency 2010

[Graph showing frequency deviations due to 1h energy products and frequency deviations due to 15min and 30min energy products]

Time of Day (Berlin)
Off-nominal frequency, fixed clock DFT estimation

Input signal at off-nominal frequency

Sampling clock based on nominal frequency

DFT property: spectral leakage introduces error if the window length is not a multiple of the fundamental frequency

Source: A. Phadke
Off-nominal frequency, fixed clock DFT estimation

• Using the normal phasor estimation formula with ‘\(x_r\)’ being the first sample, the estimated phasor is:

\[
\hat{X}_r = P \, X \, e^{jr(\omega-\omega_0)\Delta t} + Q \, X^* \, e^{-jr(\omega+\omega_0)\Delta t}
\]

• where \(\Delta t\) is the sampling interval, \(\omega\) is the actual signal frequency, and \(\omega_0\) is the nominal frequency. \(P\) and \(Q\) are independent of ‘\(r\)’, and are given below:

\[
P = \frac{\sin \frac{N(\omega-\omega_0)\Delta t}{2}}{N \sin \frac{(\omega-\omega_0)\Delta t}{2}}
\]

\[
Q = \frac{\sin \frac{N(\omega+\omega_0)\Delta t}{2}}{N \sin \frac{(\omega+\omega_0)\Delta t}{2}}
\]

\[
P = e^{j(N-1)\frac{N(\omega-\omega_0)\Delta t}{2}}
\]

\[
Q = e^{-j(N-1)\frac{N(\omega-\omega_0)\Delta t}{2}}
\]

Source: A. Phadke
Off-nominal frequency, fixed clock DFT estimation

\[ \hat{X}_r = PX e^{jr(\omega-\omega_0)\Delta t} + QX^* e^{-jr(\omega+\omega_0)\Delta t} \]

- True phasor = \( X \)
- At off-nominal frequency constant input, the phasor estimate is no longer constant, but depends upon sample number ‘r’
- The principal effect is summarized in the ‘P’ term. It shows that the estimated phasor turns at the difference frequency
- The ‘Q’ term is a minor effect, and has a rotation at the sum frequency.

Source: A. Phadke
Off-nominal frequency, fixed clock DFT estimation

- For small deviations in frequency, P is almost 1 and Q is almost 0

Source: A. Phadke
Off-nominal frequency, fixed clock DFT estimation

- If a cycle by cycle phasor is estimated at off-nominal frequency,
  - the magnitude and angle will show a ripple at \((\omega + \omega_0)\),
  - the average angle will show a constant slope corresponding to \((\omega - \omega_0)\)

Source: A. Phadke
Off-nominal frequency, fixed clock DFT estimation

- 3-phase signals

Positive sequence voltage at $\omega$

Balanced 3-phase voltages at $\omega$

- The ripple components of the three phase voltages are equal and 120° apart, and thus cancel in the positive sequence estimate.

Source: A. Phadke
Off-nominal frequency, fixed clock DFT estimation

• Summary
  • For small frequency deviations, a single phase input with constant magnitude and phase will lead to an estimate having minor error terms.
  • The principal effect is the rotation of the phasor estimate at difference frequency \((\omega - \omega_0)\), and a small ripple component at the sum frequency \((\omega + \omega_0)\).
  • A pure positive sequence input at off-nominal frequency produces a pure positive sequence estimate without the ripple. The positive sequence estimate rotates at the difference frequency.

• Performance of the DFT estimator can be improved by adapting the length of the measurement window to the actual frequency of the signal.
Phasor estimation process with resampling

Performance of the DFT estimator can be improved by adapting the length of the measurement window to the actual frequency of the signal.
Filtering to improve performance

- **Frequency response of the DFT**
  - Noise rejection depends on the rejection capability for high frequency deviations. Ex. Hamming filter over 2 cycles.
  - Performance at off-nominal frequency can be improved by using filters with a response which is more flat for the frequency range of interest. Ex. Raised-Cosine filter over 4 cycles.

- **There are drawbacks to longer windows**
  - The sensitivity to frequency variations within the window is reduced.
  - Latency in phasor estimation.

- Immunity to frequency deviations.
- Immunity to random noise.
Sources of errors

Phasor estimation algorithms: error sources

1. Aliasing

2. Long range leakage

3. Short range leakage
Sources of errors

Phasor estimation algorithms: mitigation approaches

1. Aliasing
   - Anti-aliasing filters
   - Increase sampling frequency

2. Long range leakage
   - Windowing function

2. Short range leakage
   - Interpolated DFT methods
Latency of phasor estimation

- **Latency**
  - time delay between the phasor and the time instant it represents

- **Increasing the length of the window involves a higher latency in the phasor estimation**

- **There is a tradeoff between accuracy and latency**
## Latency and data requirements

Different applications have different requirements on the data and their latency.

<table>
<thead>
<tr>
<th>Main Application</th>
<th>Applications based on it</th>
<th>Origin of Data/Place where we need the data</th>
<th>Data</th>
<th>Latency requirement</th>
<th>Number of PMUs we may need to optimally run the application</th>
<th>Data time window</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State Estimation</strong></td>
<td>Contingency analysis, Power flow, AGC, AVC, Energy markets, Dynamic/Voltage security assessment</td>
<td>All substations/Control center</td>
<td>P, Q, V, theta, I</td>
<td>1 second</td>
<td>Number of buses in the system</td>
<td>Instant</td>
</tr>
<tr>
<td><strong>Transient Stability</strong></td>
<td>Load trip, Generation trip, Islanding</td>
<td>Generating substations/Application servers</td>
<td>Generator internal angle, df/dt, f</td>
<td>100 milliseconds</td>
<td>Number of generation buses (1/20 buses)</td>
<td>10-50 cycles</td>
</tr>
<tr>
<td><strong>Small Signal Stability</strong></td>
<td>Modes, Modes shape, Damping, Online update of PSS, Decreasing tie-line flows</td>
<td>Some key locations/Application server</td>
<td>V phasor</td>
<td>1 second</td>
<td>1/10 buses</td>
<td>Minutes</td>
</tr>
<tr>
<td><strong>Voltage Stability</strong></td>
<td>Capacitor switching, Load shedding, Islanding</td>
<td>Some key location/Application server</td>
<td>V phasor</td>
<td>1-5 seconds</td>
<td>1/10 buses</td>
<td>Minutes</td>
</tr>
<tr>
<td><strong>Postmortem analysis</strong></td>
<td>Model validation, Engineering settings for future</td>
<td>All PMU and DFR data/Historian. This data base can be distributed to avoid network congestion</td>
<td>All measurements</td>
<td>NA</td>
<td>Number of buses in the system</td>
<td>Instant and Event files from DFRs</td>
</tr>
</tbody>
</table>

Source: P. Kansal and A. Bose
Accuracy of phasor estimation

• **Accuracy of the phasor estimation depends on the input signal**
  • In steady-state, accuracy is very high (<< 0.1 degrees of error)
  • If the frequency varies (dynamic system conditions), then the error can be substantial
  • During transients, especially with discontinuities, phasors meaning are questionable
• Each manufacturer implement its own algorithm for phasor estimation
  • Performance can be very different in different conditions
• Compared to other sources of errors in the measurement chain, the phasor estimation algorithm is of the same order of magnitude

| Error cause                        | Requirement source            | Error in degrees | Error in $\mu s$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time synchronization</td>
<td>IEEE Std. C37.118</td>
<td>0.018</td>
<td>1</td>
</tr>
<tr>
<td>(accuracy requirement in $\mu s$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instrument transformers</td>
<td>IEC Std. 60044</td>
<td>0.167</td>
<td>9</td>
</tr>
<tr>
<td>(metering transformers - class 0.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phasor estimation device</td>
<td>IEEE Std. C37.118</td>
<td>0.1 - 0.3</td>
<td>5.6 - 17</td>
</tr>
<tr>
<td>(accuracy requirement in degrees)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Time Synchronization

- **Satellite broadcasts**
  - GPS (US Dept of Defence), GOES (NASA), GLONASS, GALILEO (future)

- **At the substation level**
  - Synchronization of IEDs within a substation
  - IRIG-B pulses

- **Global Positioning System (GPS)**
  - 24 Satellites with 12 hour orbit time
  - 5 to 8 Units are visible from any point at any time
  - GPS signal can be used, when you know the position, to have an accurate time
  - Accuracy of synchronization: commercial PMUs <100 ns required by standard < 1 μs
Sub-second time tagging

- GPS clock signal is received once every second (1 PPS), on the second.
- Inside the PMU, a **phase-locked oscillator** is used to generate the time tags within the second.
- The time tag is sent out with the phasors (time tagging). If a phasor information packet arrives out of order to a PDC (phasor data concentrator), the phasor time response can still be assembled correctly (with the cost of latency).
- If the GPS pulse is not received for a while, errors in the time tag can result in phase angle errors (considerable).

![Diagram showing GPS pulses and time tagging](source: L. Vanfretti (KTH))
Wide Area Measurement System (WAMS)

- The Phasor Data Concentrator (PDC)
  - gathers data from several PMUs
  - rejects bad data
  - aligns time-stamps
  - creates coherent sets of simultaneously recorded data from part or the whole system

- The data sets are then sent to the applications and to storage facilities
Inside a Phasor Data Concentrator (PDC)

Source: J. Chow (RPI)
WAMS architectures

• Choice between centralized and decentralized architecture
  • Considerations are reliability (improved by redundancy) and latency (depends on length of media, number of routers)
  • Decentralized architecture has the potential, for equivalent cost, to decrease latency and improve reliability
• Hierarchical structure: Super-PDC (SPDC)

Source: L. Vanfretti (KTH)
# Measurement chain: sources of inaccuracy, delay & unavailability

<table>
<thead>
<tr>
<th>Element in the chain</th>
<th>source of inaccuracy</th>
<th>source of delay</th>
<th>source of unavailability</th>
<th>responsible party</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument transformers</td>
<td>X</td>
<td></td>
<td></td>
<td>user</td>
</tr>
<tr>
<td>A/D converter and input filtering</td>
<td>(X)</td>
<td>(X)</td>
<td></td>
<td>PMU manufacturer</td>
</tr>
<tr>
<td>Phasor estimation algorithm</td>
<td>X</td>
<td>X</td>
<td></td>
<td>PMU manufacturer</td>
</tr>
<tr>
<td>Internal clock synchronization</td>
<td>(X)</td>
<td></td>
<td></td>
<td>PMU manufacturer</td>
</tr>
<tr>
<td>GPS emission and reception</td>
<td>X</td>
<td></td>
<td></td>
<td>GPS owner</td>
</tr>
<tr>
<td>GPS signal substation distribution</td>
<td>X</td>
<td></td>
<td></td>
<td>user</td>
</tr>
<tr>
<td>Telecommunication links and routers</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>user</td>
</tr>
<tr>
<td>Data concentration and alignment</td>
<td>X</td>
<td>X</td>
<td></td>
<td>PDC developer</td>
</tr>
<tr>
<td>Computation and applications</td>
<td>X</td>
<td></td>
<td></td>
<td>user and PDC developer</td>
</tr>
</tbody>
</table>
Standards for synchrophasors

Power System Wide Area Measurement, Protection & Control

28/08/2013  Summer School for Smart Energy Systems 2013 - WAMS
Interoperability

- **Interoperability is the primary scope of industry standards**
  - Goal = two PMUs from different vendors measure the *same* phasor
  - It is very common to have PMUs from different vendors at two substations (even within a same utility)
  - It is usually fine during normal operation, when signals are close to stationary – scope of the standard 2005
  - However, during oscillations or disturbances, significant differences can appear
Accuracy information

- **Total Vector Error (TVE)**
  - The IEEE standard defines an indicator of the measurement accuracy: the TVE
  - It compares the theoretical phasor with the measured phasor
  - Assessment of the TVE is only possible in a laboratory, where the theoretical phasor is the output of the signal generator
  - $X_f = \text{measured values (real and imaginary)}$, $X = \text{corresponding theoretical values}$
  - The TVE should be $< 1\%$ for a range of influence quantities (signal frequency, signal magnitude, THD, out-of-band interfering signal)

- Unfortunately, the standard does not define any indicator of the actual accuracy on the field

The TVE is defined as:

$$\text{TVE} = \sqrt{\frac{(X_{rf} - X_r)^2 + (X_{if} - X_i)^2}{X_r^2 + X_i^2}}$$
Total Vector Error (TVE) < 1%

- 1% TVE corresponds to
  - a magnitude error of 1% (no phase error)
  - a phase angle error of 0.6 degree (no amplitude error)
  - the combination of a magnitude error of 0.5% and a phase error of 0.5 degrees
- The TVE does not include errors from synchronization and transformers
Chronology of the standards for synchrophasors

- **IEEE 1344 (1995)**
  - Limited to steady-state conditions
  - Data format inspired by COMTRADE and not fully compatible to network communications

- **IEEE C37.118 (2005)**
  - Introduced TVE for quantifying phasor measurement errors
  - Recommended steady-state performance compliance test requirement
  - Defined data format compatible with other standards (e.g. IEC 61850)
- **IEEE C37.118.1 and C37.118.2 (2011)**
  - Standard is split in two: (1) synchrophasor measurement and (2) data transfers
  - Beside the TVE, errors on frequency and df/dt are quantified and limited in order to avoid TVE variations within a window
  - Introduces dynamic performance compliance tests
  - Two performance classes (user-selectable) taking into account the trade-off between accuracy and latency: P-class (fast, no explicit filtering required) and M-class (slower but more accurate)
Assessing the maturity of the synchrophasor technology

Today, “a PMU is a basic equipment”

(Damir Novosel, 2012)

- Costs mostly in engineering
- Interoperability in dynamics?

However, the full maturity is dependent on the

“capability of measuring electrical quantities accurately with measurement lags compatible with closed-loop control and special protection requirements”

(Innocent Kamwa, 2005)
Power system applications of synchrophasors

Power System Wide Area Measurement, Protection & Control
Applications

• Most widespread applications in Transmission
  – Improved state estimation (or state measurement)
  – Phase angle monitoring
  – Inter-area oscillations monitoring (online modal analysis)
  – Online voltage stability assessment
  – Early warnings
  – Post-disturbance event analysis
  – Model validation
  – Backup protection (as a substitute for zone 3 protection)
  – Load shedding control
  – Islanding control
  – Angular stability control
  – Interface with Control and Defense System (WAPS-WACS)
North American Synchrophasor Initiative (NASPi) roadmap 2011 (26 applications)

- Angle/ Frequency/Voltage/Flow Monitoring, Trending & Alarming
- Mode Meter and Mode Shape Identification
- Steady-state System Baseline (e.g., based on angle separation)
- Dynamic Nomograms
- Power System Restoration
- Voltage Stability Monitoring
- Frequency Response Monitoring
- Control and Islanding for Renewables & DG
- Event & Performance Analysis
- Improved State Estimation
- System Inertia Monitoring
- Advanced Remedial Action Schemes
- Dynamic State Estimation
- Planned Power System Separation
- Adaptive Protection
- Real Time Transient Stability Margin
- Wind Site Voltage Control
- System Dynamic Model Validation
- Congestion Management
- Linear State Estimation
- Transient Stability Control
- Voltage Stability Control
- Oscillations Damping
- Interconnection Wide State Estimation
- Wide Area Frequency Response
- Wide Area PSS Stabilization
- Detection of imminent cascading

Deployment Challenge:
- LOW
- MED
- HI

Source: D. Novosel (Quanta technology)
State estimation

• The state estimation is the core of the EMS: online computations (e.g. security analysis) are performed on the output of this important tool
  • The state ($x$) is defined as the complex voltage magnitude and angle at each bus:
    \[ \tilde{V}_i = V_i e^{j\delta_i} \]
    \[ x = [\delta_1 \  \delta_2 \ \cdots \ \delta_n \  V_1 \ V_2 \ \cdots \ V_n]^T \]
  • All variables of interest can be calculated from the state and the measurement model:
    \[ z = h(x) \]
  • Classical state estimation

• There is a non-linear relationship between the measured data and unknown parameters (e.g. see load flow equation):
  \[ P_{i,j} = G_{ii}^{L} U_{i}^{2} - U_{i} U_{j} \left( G_{ij}^{L} \cos \Theta_{ij} + B_{ij}^{L} \sin \Theta_{ij} \right) \]
  • Solution is given through an iterative procedure (heavy computation).
State measurement: state estimation using synchrophasors

- Unlike the classical state estimator, the (matrix) equations to solve are LINEAR, and hence no iterations are needed.
  - As soon as the measurements are obtained, the estimate is obtained by matrix multiplication.
- It is also possible to mix phasor measurements with traditional measurements to obtain a Hybrid state estimator.
Using phasors: increasing visibility

Assume you have one PMU, measuring $\tilde{V}_i = V_i \angle \theta_i$ and $\tilde{I}_{ij} = $, but there is no PMU at Bus $j$.

$\tilde{V}_j = V_j \angle \theta_j$ can be calculated from

$$\tilde{V}_2 = \tilde{V}_1 - j X_l \tilde{I}_{12}$$

This is a **direct calculation** which does not require a state estimator solution.

Measuring voltage and current phasor data on one bus, it is possible to directly calculate the voltage phasors from all adjacent buses and the transmission line parameters.
Power-angle relationship

The power-angle characteristics represents the active power across a transmission line or corridor as a function of the voltage phase angle differences.

It relies on the following assumptions:
- The two areas are represented by ideal voltage sources,
- The transmission line is purely inductive (R=0, C=0).

\[ P_{A \rightarrow B} = \frac{E_A \cdot E_B}{X_L/2} \sin(\delta_A - \delta_B) \]
Power-angle relationship

- Impact of an incident on the phase angle difference

\[ P_{A\rightarrow B} = \frac{E_A \cdot E_B}{X} \sin(\delta_A - \delta_B) \]

Source: SEL
Using phasors: power flow calculation

\[ \tilde{I}_{12} = \frac{\tilde{V}_1 - \tilde{V}_2}{jX_l}, \quad S_{12} = \tilde{V}_1 \tilde{I}_{12} = P_{12} + jQ_{12}, \quad P_{12} = \frac{V_1 V_2}{X_l} \sin(\theta_1 - \theta_2) \]

- Assume you have two PMUs, each at one adjacent bus measuring \( \tilde{V}_i = V_i \angle \theta_i \), the \( P_{ij} \) and \( Q_{ij} \) can be by knowledge of the transmission line parameters computed as follows:

- The two voltage phasors must be synchronized, i.e. measured at the same instants in time.

- Angle separation between major transmission corridors provide a good mean to asses the stress of the network.

Source: L. Vanfretti (KTH)
Power-angle relationship

- Angle separation between two areas / across major transmission corridors is a good mean to assess the stress of the system

Source: D. Novosel (Quanta technology)
Visualizing voltage phase angles

- Red = exporting area
- Blue = importing area
- Patterns of flows across the system can be easily observed
- Note: simplified, theoretical scenario
Visualizing voltage phase angles

- Red = exporting area
- Blue = importing area

- Increased transfer across the “Switzerland corridor”

- Note: simplified, theoretical scenario
Visualizing voltage phase angles

- Red = exporting area
- Blue = importing area
- Loss of the direct line between Switzerland and Italy
- Note: simplified, theoretical scenario
Online modal estimation (oscillations monitoring)

- The high rate and synchronization allow to observe “small signals”, in particular, inter-area oscillations in the range 0.1 – 2 Hz
Small-signal stability

- Conventional studies are performed during planning studies
  - These are based on a detailed model of the system
  - There are uncertainties: how good is the model? Are all scenarios investigated?
  - The oscillation modes are associated to the eigenvalues of the state matrix $A$

- State equation:
  $$\dot{x} = Ax$$

- Eigenvalue:
  $$\lambda = \sigma + j\omega$$

- Damping ratio:
  $$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$
Online modal estimation (oscillations monitoring)

August 10, 1996 Western Power System Breakup
California-Oregon Intertie

Power (MW)
1600
1500
1400
1300
1200
1100

15:42:03
15:47:36
15:48:51

Damping
~ 8.4%

< ~3.5%

Early Warning
~6 minutes

~ -3.1%

Pacific Northwest
NATIONAL LABORATORY
Imagine Buses 1 and 2 are thousands of miles apart in different regions of the pan-European system. From the synchronized measurements of their voltage angles, $\theta_1$ and $\theta_2$, the bus frequencies are derived.

It is possible then to compute frequency differences as

$$\Delta f_{1-2} = f_1 - f_2$$

If interarea oscillations exist between the machines near Bus 1 going against the machines at Bus 2, they will be reflected in $\Delta f$. The interarea component can be extracted for that oscillation mode can be extracted from $\Delta f$.

This kind of interarea mode oscillation monitoring is possible thanks to the high sampling rates of PMUs (30-50 sps).
The NETFLEX Demonstration (2010-2013)
The challenge of integrating large scale renewable energy sources

- Assumption: install renewable energy sources where the potential is the highest
- Transmission system is the bottleneck
- Transmission system development challenges: time, investment, environment, NIMBY
- Can we make the current system more flexible with little investment?

www.twenties-project.eu
Network Enhanced Flexibility (Netflex): increasing Transmission capacities

- Control: To respect reliability margins
- Monitor: More accurately
- Plan: More aggressively
- Higher Transmission Capacities
- Dynamic Line Rating devices
- Power Flow Controllers (Phase Shifting transformers, FACTS)

Same level of reliability
Estimated gain for the EU

Plan
More aggressively

Monitor
More accurately

Control
To respect reliability margins

Same level of reliability

Up to 250M€/y of savings
Thermal vs. stability limits

- In highly meshed systems (e.g. Continental Europe)
  - Electrical distances between nodes / between generators are small
  - Voltage phase angle differences between nodes are small

- Flows transfers are limited by thermal constraints and not by stability constraints

- What happens if thermal constraints are moved away?
Impact on Stability of increasing capacities

Plan
More aggressively

Monitor
More accurately

Control
To respect reliability margins

Closer to the damping limit

WAMS to monitor the damping level

Same level of reliability

Yet to be constructed
Setup of a Wide Area Measurement System (WAMS) within Twenties

= Twenties PMU
= exchange of PMU data
= post-Twenties agreement with TSO to exchange PMU data
Forecasting the system damping

- Forecast performed based on DACF files
  - Day-ahead congestion forecasts (DACF) are the best estimate of the flows for the next day
  - Real-time deviates from day-ahead forecasts
- Probability levels (P50, P90)
  - Indicate the level of confidence that the damping will not be lower than the forecast
  - Related to risk policy
The Italian WAMS and its modal estimator

Source: Terna
Wide Area Power System Stabilizer (WAPSS)

- **Power system stabilizers (PSS)**
  - Control loop in the large generators voltage control system
  - Local modulation of the voltage to damp oscillations

- **Wide Area PSS**
  - Improve the damping capability by increasing the observability and controllability
  - Observability increased by measuring at the place where modes are the best “visible”
  - Controllability increase by injecting the feedback signal at a place where the modes are the best controllable
Gaps between requirements and achieved performance

- Performance of WAMS should be improved for some applications requiring a high accuracy and a very short time delay

<table>
<thead>
<tr>
<th>Application</th>
<th>Phasor used</th>
<th>Latency requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>State estimation</td>
<td>stationary positive-sequence phasor</td>
<td>1 second</td>
</tr>
<tr>
<td>Voltage stability</td>
<td>stationary and dynamic positive-sequence phasor</td>
<td>1-5 seconds</td>
</tr>
<tr>
<td>Oscillations monitoring</td>
<td>dynamic positive-sequence phasor</td>
<td>10 seconds</td>
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<tr>
<td>Oscillations closed-loop</td>
<td>dynamic positive-sequence phasor</td>
<td>1 second</td>
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<tr>
<td>control</td>
<td></td>
<td></td>
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<tr>
<td>Transient stability</td>
<td>dynamic positive-sequence phasor</td>
<td>100 milliseconds</td>
</tr>
<tr>
<td>Postmortem analysis</td>
<td>dynamic and transient single-phase phasor</td>
<td>NA</td>
</tr>
</tbody>
</table>

Measurement conditions (accuracy) vs. Time constraints
Conclusions, lessons learned and items for further research

Power System Wide Area Measurement, Protection & Control
2 things to remember

• Thanks to synchronization, PMUs enable the measurement at a high rate of the voltage phase angle:
  • a great value for power system applications
  • Allows to simplify computations and speed up understanding of the system dynamics

• The PMU technology is not fully mature:
  • interoperability during dynamics is not ensured, and
  • there is still a gap between what is available and what is required for some applications (in terms, for example, of accuracy & latency)
  • → there is a large margin for research and experimentations
Smart Operation and Control

- The Holy Grail = Automatic feedback control for a self-healing system
- Measure → Communicate → Analyze (System Assessment and Real Limits) → Determine Preventive/Corrective Actions → Communicate → Control and Protect
- A cycle to be completed in some milliseconds for the most demanding applications

beyond WAMS

- phasor data have the potential to deliver a higher potential for smart grid applications;
- WAMS rely on the careful design and implementation of supporting communication networks and computer systems
Looking for a bit of reading?

- **An introductory book on PMUs:**
  (downloadable for free)

- **More specialised documentation:**
  IEEE Xplore
  Ask me and I will be pleased to help you
jacques.warichet@elia.be