Cyber Infrastructure for the Smart Grid

Dr. Anurag K. Srivastava, Dr. Carl Hauser, and Dr. Dave Bakken,

Smart Grid Operational Goals and Measurements
Power System Operation

- Reliably supply the power to customers
- Secure and economic operation under several constraints
Reliable, Economic and Secure Operation

- Predict
- Plan
- Operate
  - Sense
  - Communicate
  - Compute
  - Visualize/Control
- Billing

- Situational Awareness and Decision Support
Reliable, Economic and Secure Operation

- Provide operators with up-to-date information on the condition of the power systems
- Critical quantities are measured
  - Voltages, currents, power flows, and the state of circuit breakers and switches
  - Frequency, generator outputs, and transformer tap positions
- The measurements are sent to the control central
  - Via the telemetry system
Reliable, Economic and Secure Operation

Operator needs information, not data.
Sense

- Potential Transformers
- Current Transformers
- Intelligent Electronic Devices (IEDs)
- Phasor Measurement Units
- Switch Status Monitor
- Fault Indicators
- Smart Meters
Sense: Problems with Analog Sensors Technologies

- Noise
- Variety of transducers with different response rates
- No direct time synchronization, communication bandwidth/response rate differences
- No parts for analog equipment
- RMS rather than phasor values:
  - But both MW and MVAr transducers exist
- Limited flexibility compared to digital world:
  - Example: positive sequence filtering
A Phasor Measurement Unit (PMU) is a device that provides as a minimum, synchrophasor and frequency measurements for one or more ‘three phase AC voltage and/or current’ waveforms.

The synchrophasor and frequency values must meet the general definition and minimum accuracy required in the IEEE Synchrophasor Standard, C37.118-2011.

The device must provide a real-time data output which conforms to C37.118.1 requirements.

“It’s like going from an X-ray to a MRI of the grid.”
Terry Boston, CEO PJM Interconnection
Motivation for Synchronized Measurements: Need for High Resolution Synchronized Data

• The data from different locations are not captured at precisely the same time.

• However, V, P, and Q normally do not change abruptly, unless there is a large disturbance nearby.

• System monitoring is more critical during disturbance and transients

• Faster synchronized data is needed to capture the dynamics

• Fast real time control is possible only with real time situational awareness
• Motivation for synchronization

Substation A

At different locations

Substation B

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.
• Basic building block same as digital relay or digital fault recorder except GPS synchronization

**Instrumentation Including a PMU**

**PMUs can estimate/measure the following:**
- Sequence voltages and currents
- Phase voltages and currents
- Frequency
- Rate of change of frequency (ROCOF)
- Circuit breaker switch status
Sample the continuous voltage or current signal. The figure shows 12 points per cycle (the sampling rate is $12 \times 60 = 720$ Hz).

Use Discrete Fourier Series (DFS/DFT) method to compute the magnitude and phase of the signal (i.e., applying DFS formula).

Calculate magnitude and phase for each phase of the 3-phase quantity.

Using one period of data reduces the effect of measurement noise.
Synchrophasor Fundamentals: Estimation

• Although theoretically one can get a data point on phase \( a \), another data point on phase \( b \), and a third data point on phase \( c \) to compute the positive sequence quantity, the approach is prone to measurement noise.

• There is no standard phasor algorithm used by different PMU manufacturers

• Most phasor calculation in commercial PMUs uses a 1 to 4-cycle window, likely centering in the window

• To reduce noise, some manufacturers use the average value over an even number of windows (2 or maybe 4)

• There is latency in the PMU itself – number of cycles and processing time

• Using the PMU from the same supplier at least provides consistency of the phasor algorithm.
Phasor calculation

Original Phasors

Positive Sequence Phasors

\[
V_{abc} = \begin{bmatrix} V_0 \\ V_0 \\ V_0 \end{bmatrix} + \begin{bmatrix} V_1 \\ \alpha^2 V_1 \\ \alpha V_1 \end{bmatrix} + \begin{bmatrix} V_2 \\ \alpha V_2 \\ \alpha^2 V_2 \end{bmatrix}
= \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}
\]
Phasor calculation with a DFT

- Fourier coefficients from cosine & sine waves
- Multiply with samples from waveform ($x_k$) and compute summation for real and imaginary
- Result is phasor

\[ X = X_r - jX_i \]

\[ X_r = \frac{\sqrt{2}}{N} \sum x_k \cos k\phi \]

\[ X_i = \frac{\sqrt{2}}{N} \sum x_k \sin k\phi \]
Phasor calculation with a DFT

- We cannot measure an instantaneous phasor
- Waveform need to be observed over interval
  - There is no way to recover the phasor value at $t_1$
  - It is estimated over an interval around $t_1$
- Phasor value is instantaneous but estimated over an interval
Synchrophasor Fundamentals: Time Signal

- IRIG-B pulses
- IEEE 1588: distributed by Ethernet
- The GPS clock signal is received once every second on the second.
Synchrophasor Fundamentals: Data Packets

• SOC count starting at midnight 01 Jan-1970
PMU Vendors

- SEL
- GE
- ALSTOM
- ERLphase
- Siemens
- Macrodyne
- Qualitrol
- National Instruments
- Arbiter