Phasor Measurements

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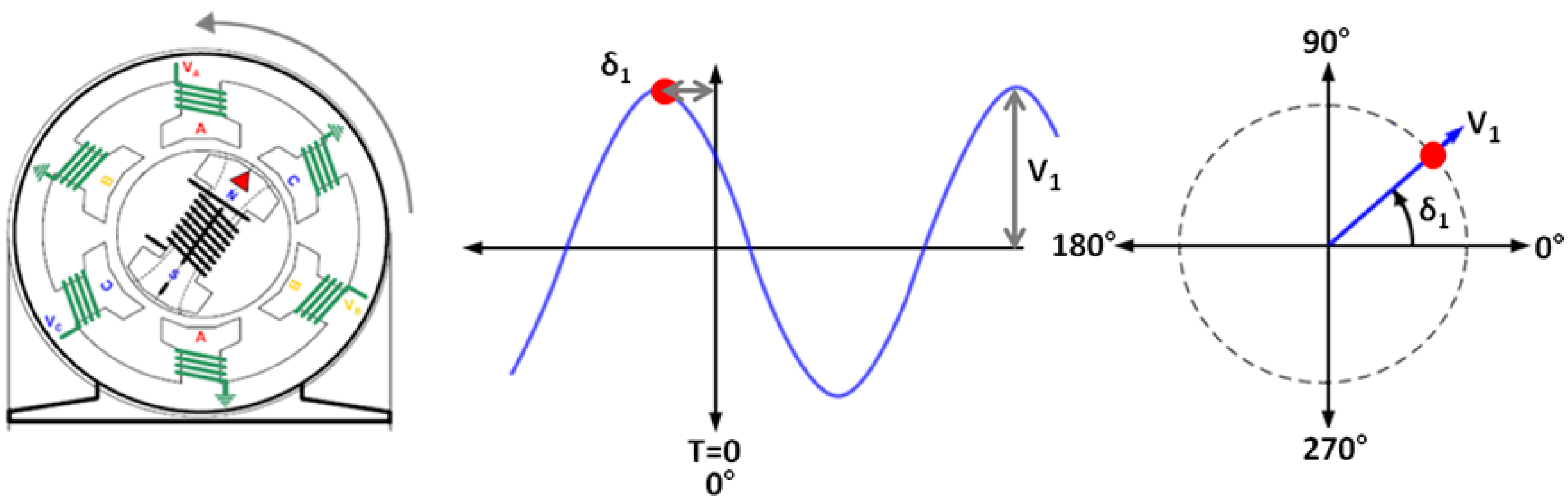
Phasor Measurements

- A **phasor measurement unit** (PMU) is a device used to estimate the magnitude and phase angle of an electrical phasor quantity (such as voltage or current) in the electricity grid using a common time source for synchronization.
- Time synchronization is usually provided by GPS or IEEE 1588 Precision Time Protocol, which allows synchronized real-time measurements of multiple remote points on the grid.
- PMUs are capable of capturing samples from a waveform in quick succession and reconstructing the phasor quantity, made up of an angle measurement and a magnitude measurement. The resulting measurement is known as a **synchrophasor**

Phasor Measurements

WHAT IS A VOLTAGE PHASOR ?

- A Phasor is a rotating vector
- Voltage Phasor is defined by magnitude V_1 and angle δ_1
- Angle is measured with respect to universal time (T=0 top of a second)
- Phasor rotates counter clockwise, similar to rotating magnetic field in a synchronous generator
- A Synchrophasor is a Phasor referenced to 60 Hz with angle referenced to universal time (T=0 top of second)



AC Circuits | Sinusoidal Waveform | Phasor Representation

Phasor Measurements

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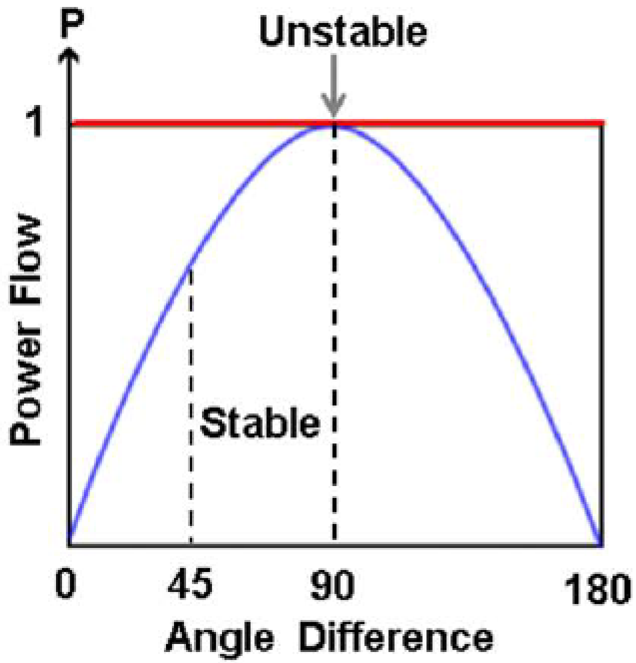
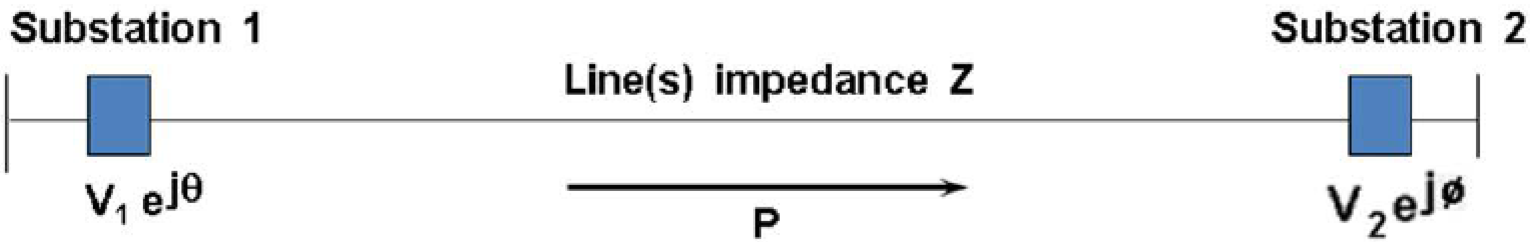
POWER FLOW FUNCTION OF PHASE ANGLE DIFFERENCE



- Power *flows* from high to low voltage in DC systems.
- Power *flows* from high voltage angle to low voltage angle in AC systems.
  - Power flow equation:
    $P = V_1 V_2 \sin(\theta - \phi)/Z$, where θ is greater than ϕ
- Synchrophasor angles are correlated to universal time (UTC) and 60 Hz
  - Allows comparison over wide area
- The voltage angle difference between two substations correlates with the power being transferred across the grid between them
- The current angle paired with voltage angle describes real and reactive power on any line

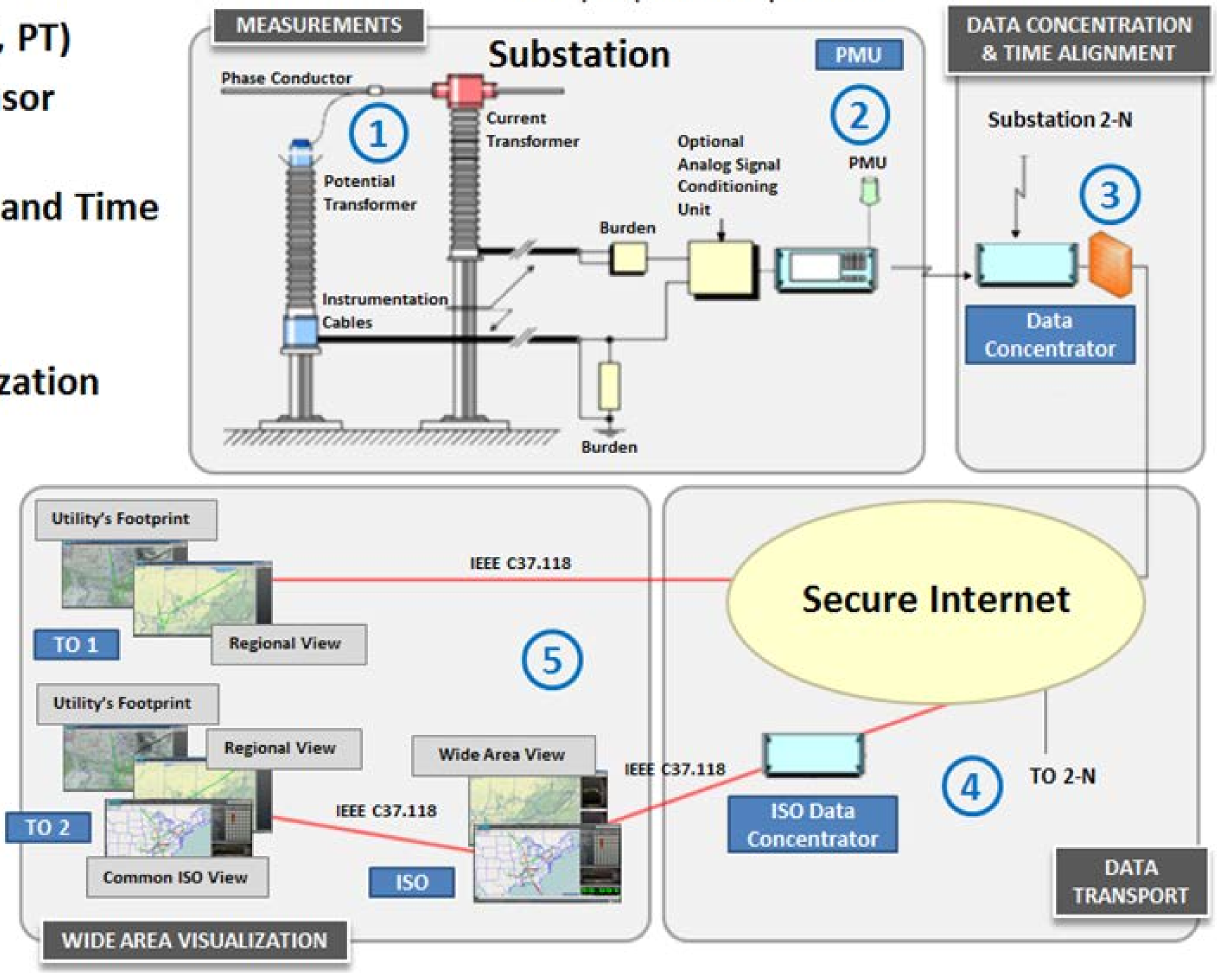


Phasor Measurements

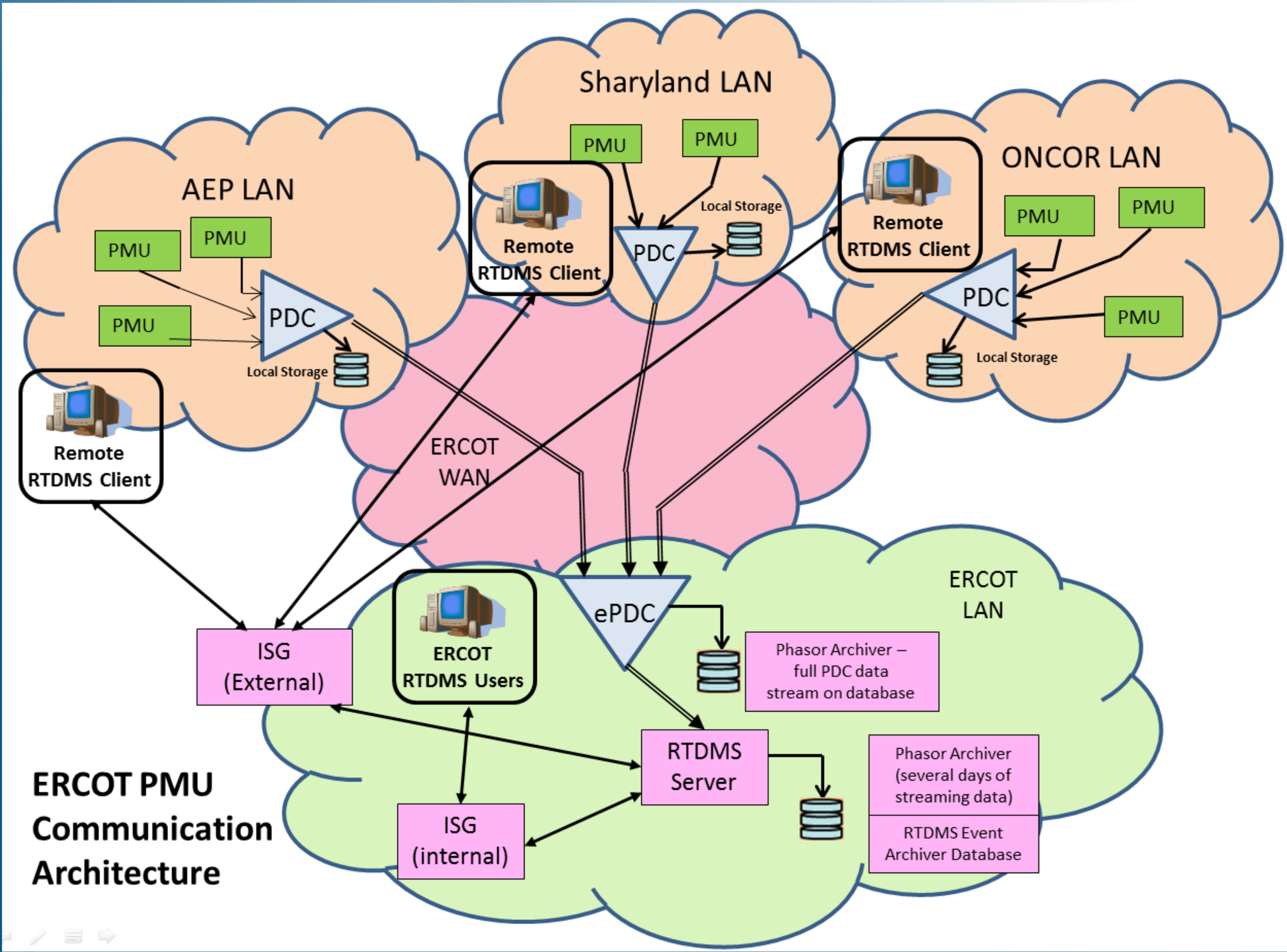
PHASOR TECHNOLOGY INFRASTRUCTURE

1. **Measurement (CT, PT)**
2. **Conversion to Phasor quantities - PMU**
3. **Data Aggregation and Time Alignment**
4. **Data Transport**
5. **Wide Area Visualization**

Courtesy: Adapted from EIPP presentation



Phasor Measurements



Phasor Measurements:
❖ System Monitoring

- ❖ Key feature of a smarter grid: Improved monitoring and control of the transmission system
- ❖ GPS-synchronized Phasor Measurement Units and communication technologies enable advancements in system monitoring
- ❖ This presentation reviews traditional and modern technologies and provides a starting point to the Synchronization Project Proposed for the ERCOT controlled portion of the Grid in Texas

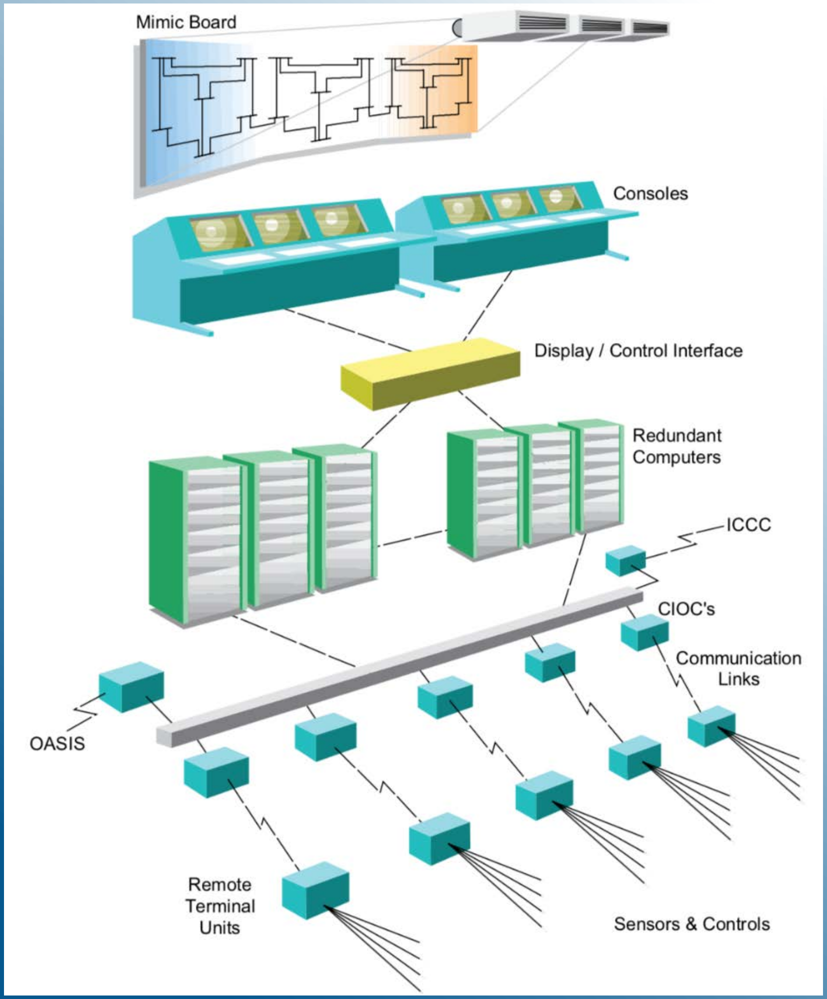
Phasor Measurements

Phasor Measurement systems are made up of the following systems or components

- ❖ Control center and SCADA system
- ❖ State estimation with SCADA measurements
- ❖ Phasor Measurement Units (PMUs)
- ❖ State Estimation with PMU Measurements
- ❖ GPS Timing Control

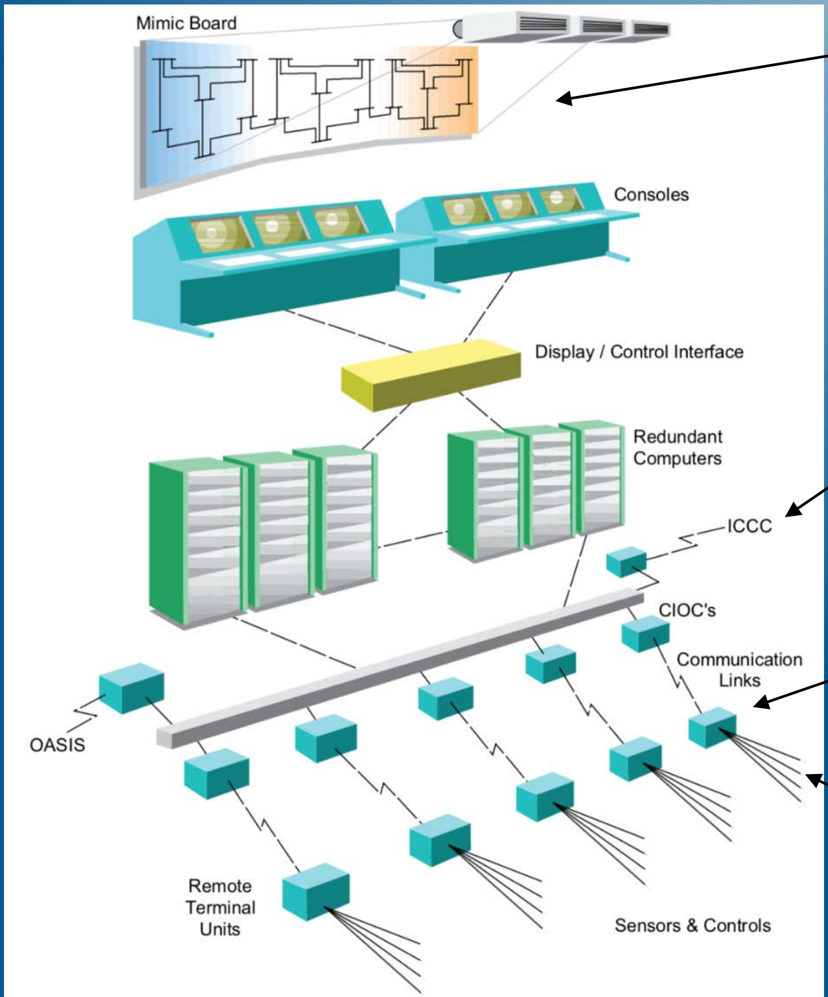
Phasor Measurements:
❖ Control Center

- Computer programs, hardware, and communication infrastructure used to monitor, control, and operate the power grid
- Functions
  - State estimation
  - Economic dispatch
  - Optimal power flow
  - Unit commitment
  - Load forecasting
  - Security assessment



Phasor Measurements:

❖ System Layout



- State estimation, visualization, energy management functions

- Communication input/output controllers (CIOC's) transfer data to computers

- Data collected at Remote Terminal Units (RTUs)

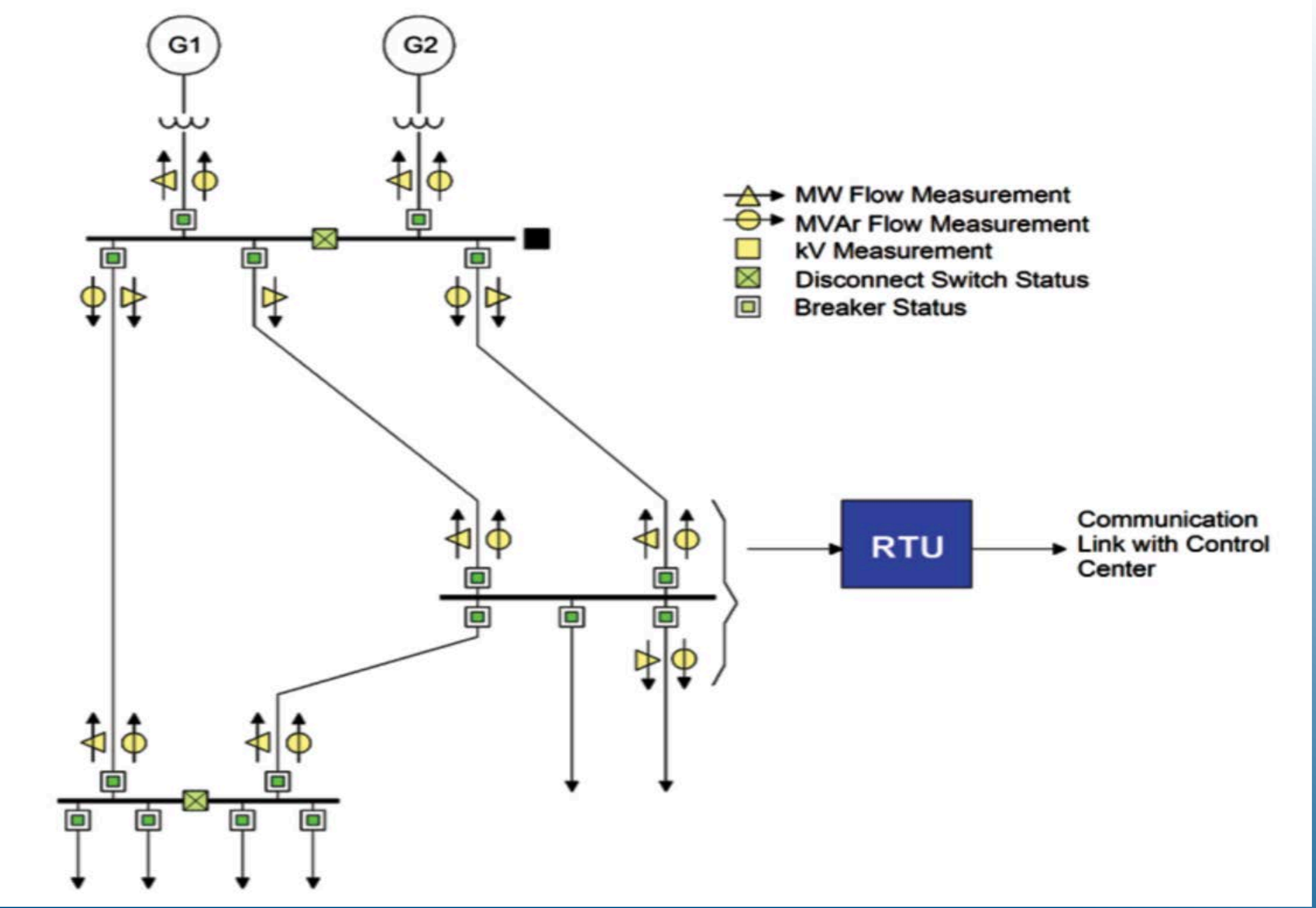
- Sensors located in the field
- Wattmeter, voltmeter, current meter, breaker

Phasor Measurements:
❖ SCADA SYSTEM

- ❖ Supervisory control and data acquisition system
- ❖ Transmits data from the field to a central location and vice versa
- ❖ Data collected **every one to a few seconds**
- ❖ Data typically include
  - ❖ Breaker and switch status
  - ❖ MW flow measurements
  - ❖ MVAR flow measurements
  - ❖ Voltage magnitude measurements
  - ❖ Current magnitude measurements

Phasor Measurements:

❖ SCADA SYSTEM

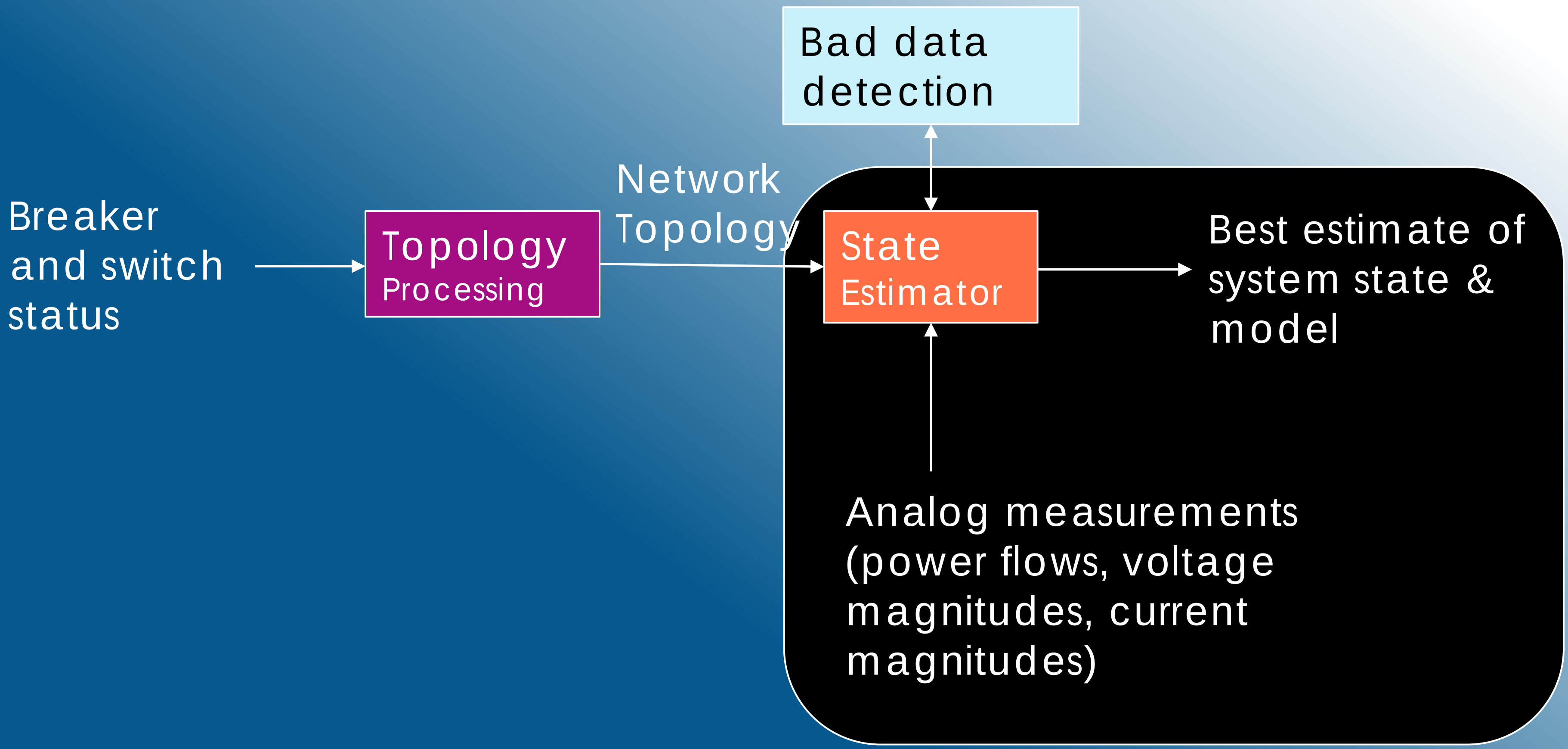


Phasor Measurements:
❖ State Estimation

- ❖ Given measurements, compute an estimate of the system state
- ❖ System state typically considered to include the voltages at all buses
  - ❖ If the network topology is known, then all other electrical quantities can be computed (currents, power flows)
- ❖ Crucial in all other control center functions

Phasor Measurements:

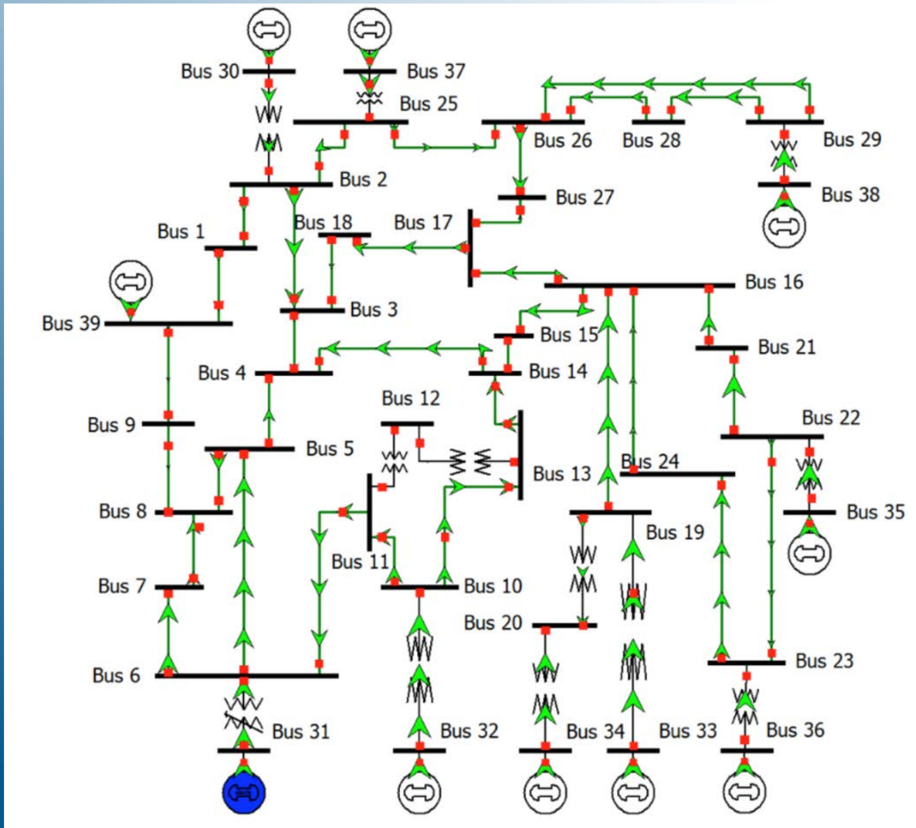
❖ State Estimation Function



Phasor Measurements:
❖ System State Model

- Power grid with N buses
- Complex voltage at bus n

$$\mathcal{V}_n = V_n e^{j\theta_n} = V_{n,r} + jV_{n,i}$$



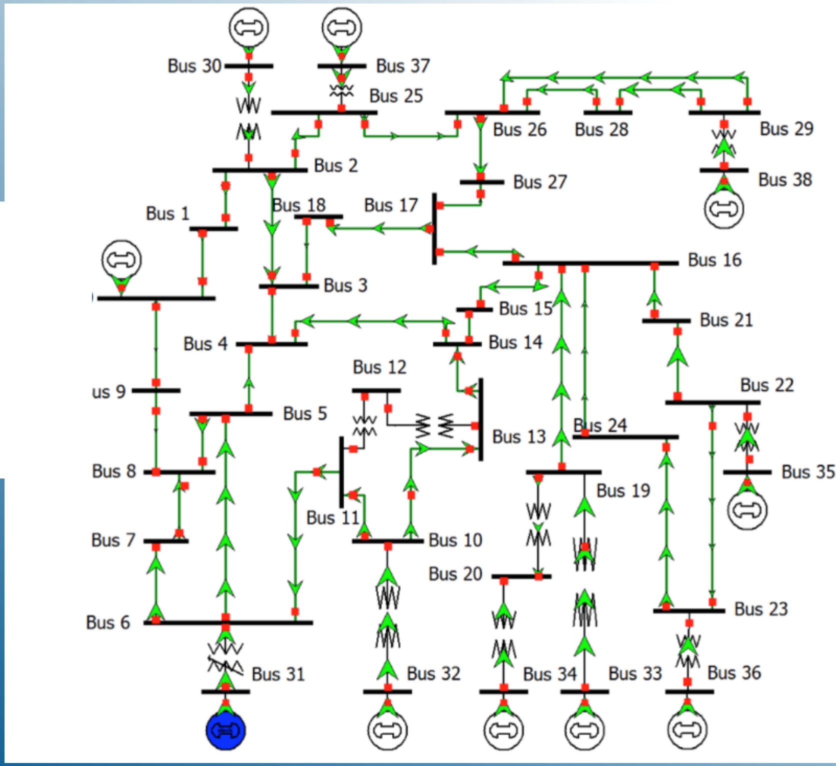
Phasor Measurements:

❖ System State Model

$$\mathbf{x} = [V_1,\ \theta_1,\ V_2,\ \theta_2,\ \ldots,\ V_N,\ \theta_N]$$

$$\text{or}\quad \mathbf{x} = [V_{1,r}, V_{1,i}, V_{2,r}, V_{2,i}, \ldots, V_{N,r}, V_{N,i}]$$

Set to zero to avoid phase ambiguity



- Number of unknown states

$$K = 2N - 1$$

Phasor Measurements:

❖ System State Measurements

M measurements from sensors

1. Flows: MW and MVAR flows on transmission lines or transformers
2. Injections: MW and MVAR injections at system buses
3. Voltage magnitudes at system buses
4. Current magnitudes

Phasor Measurements:

❖ Measurement Model

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \boldsymbol{\epsilon}$$

Measurement vector

Vector function: Nonlinear map from states to measurements

Measurement noise

- **State estimation:** Given measurement vector, find system state
- Overdetermined system: More measurements than unknowns ($M > K$)
- In addition, measurements are perturbed by noise

Phasor Measurements:
❖ Noise Model

- Independent measurements across sensors
- Zero mean
  - It is possible that a sensor introduces gross errors (outliers or bad data) due to e.g., equipment failure
  - Specialized techniques can deal with this situation
- Standard deviation of measurement of sensor i: σ_i
  - Determined by accuracy of meter used

Phasor Measurements:

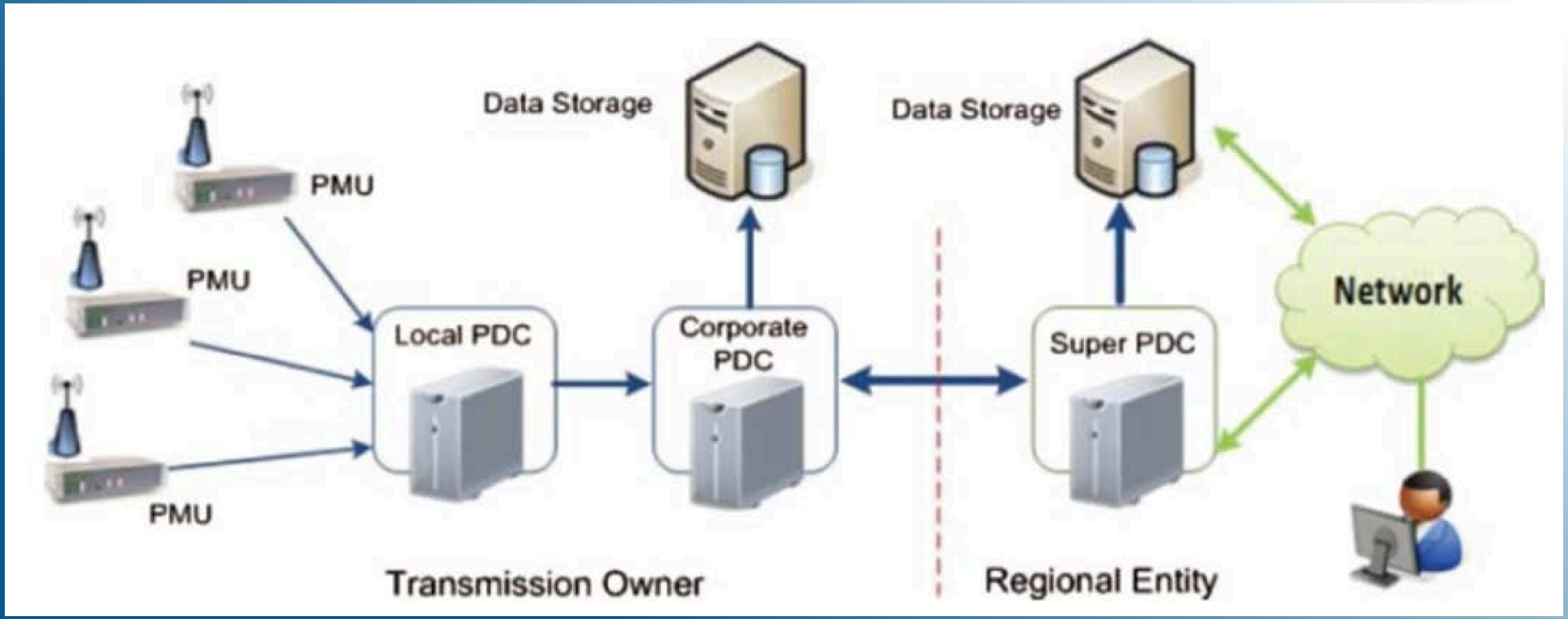
❖ Phasor Measurement Unit

- ❖ Phasor measurement unit (PMU) features
- ❖ PMUs can measure the **voltage phasor** at the bus and **current phasor** at the lines
- ❖ Collect measurements between **10 and 60 times per second for 60 Hz systems** and between 10 to 50 times per second for 50 Hz systems (IEEE C37.118 Standard)
- ❖ Equipped with GPS receivers that provide a very accurate clock signal
- ❖ **GPS time** information is used to timestamp the PMU measurements

Phasor Measurements:
❖ Phasor Data Concentrator

- ❖ Phasor Data Concentrators (PDCs) collect measurements from multiple PMUs
- ❖ Buffer input streams to account for differences between times of delivery from different PMUs
- ❖ Align data according to their time-stamp
- ❖ Provide the data to other PDCs or the control center

Phasor Measurements:
❖ PMU/PDC Networks



Local PDC

- Hardware based device
- Physically close at the PMU (e.g., at the substation)

Corporate PDC

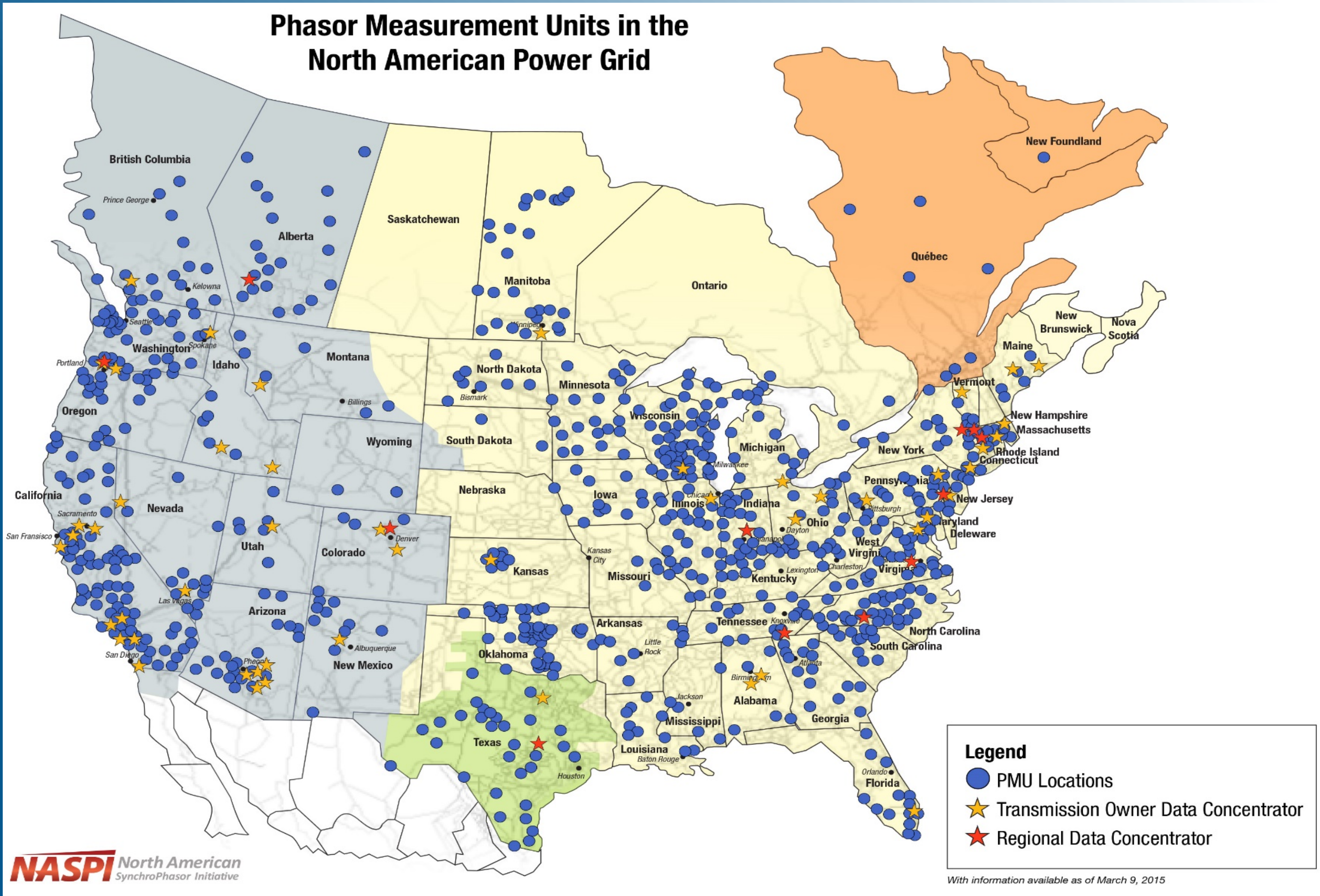
- Collects data from multiple PMUs and PDCs at high speeds

Super PDC

- Operates at regional scale
- Organizes dataset and makes it available for control center functions

Phasor Measurements:

❖ PMUs in North America



Phasor Measurements:

❖ PMU VS. SCADA

PMU VS. SCADA

	SCADA	PMU
Measurements	Power flows and injections, voltage magnitudes, current magnitudes	Voltage and current phasors, frequency
Measurement model for state estimation	Nonlinear	Linear
Solution of state estimation	Iterative	Direct
Measurement rate	One measurement every one to a few seconds	10 – 60 measurements per second
Synchronization between measurements	Poor: Time skewness	Precise: GPS time