

The Smart Transmission Grid

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What is a SMART Grid?

- **Self-heals**
- **Motivates and includes the consumer**
- **Resists attack**
- **Provides power quality for 21st century needs**
- **Accommodates all generation and storage options**
- **Enables markets**
- **Optimizes assets and operates efficiently**

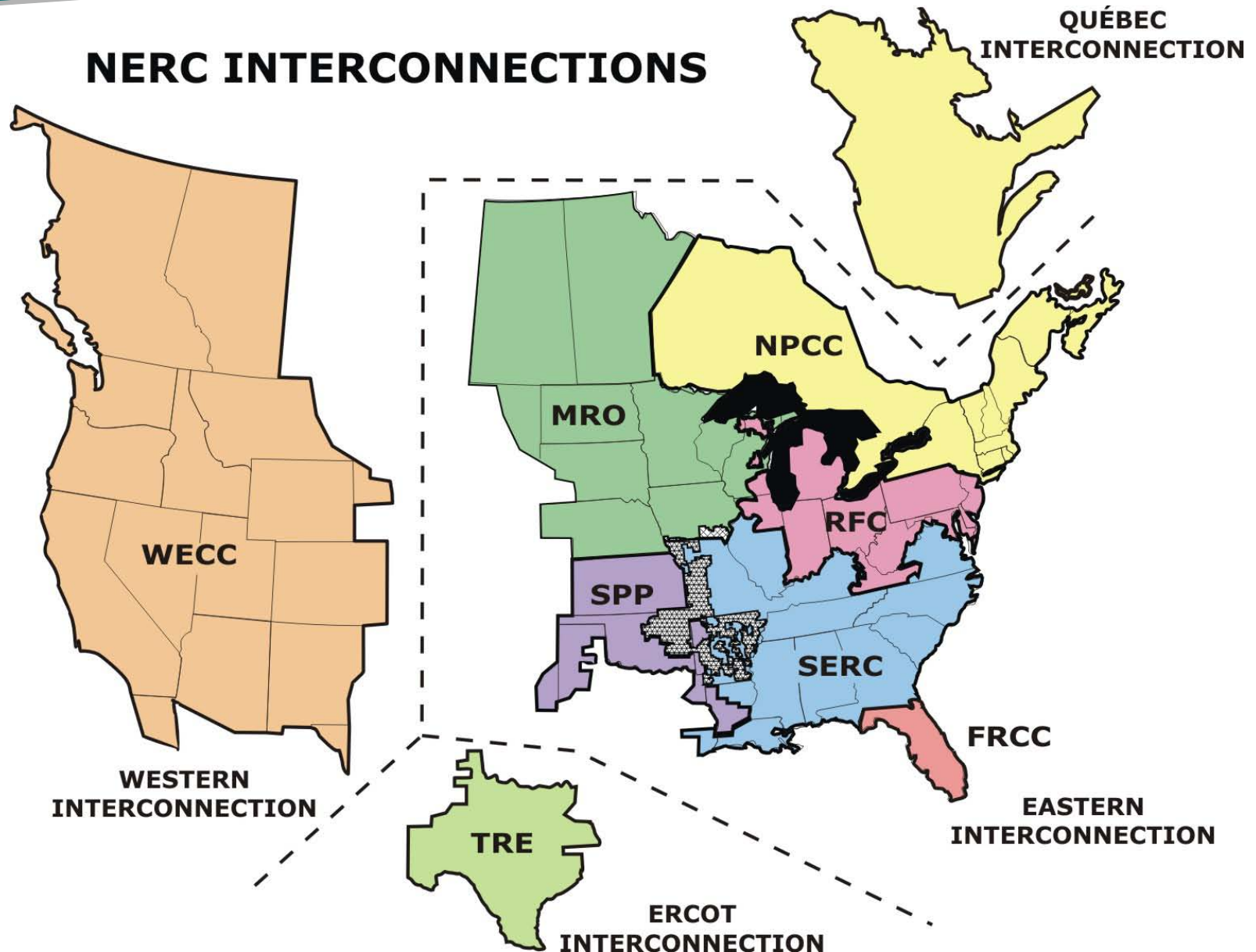


Transmission vs Distribution

- Smart Meters
- Demand side load control
- Distribution automation (including two-way flow)
- Micro-grids
- Real-time pricing

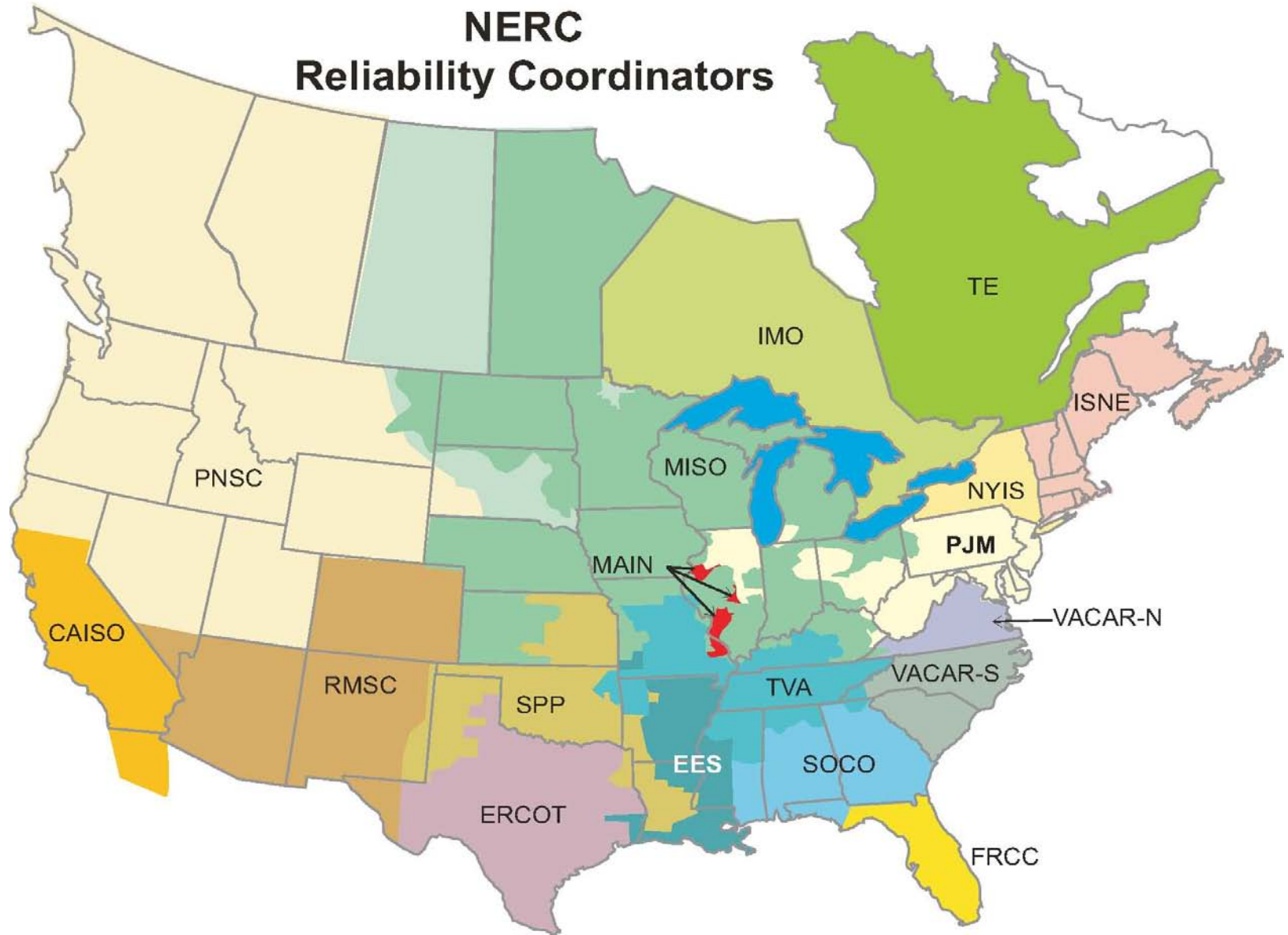
Will talk mainly about Transmission

- Prevent cascading blackouts
- Wide-area control



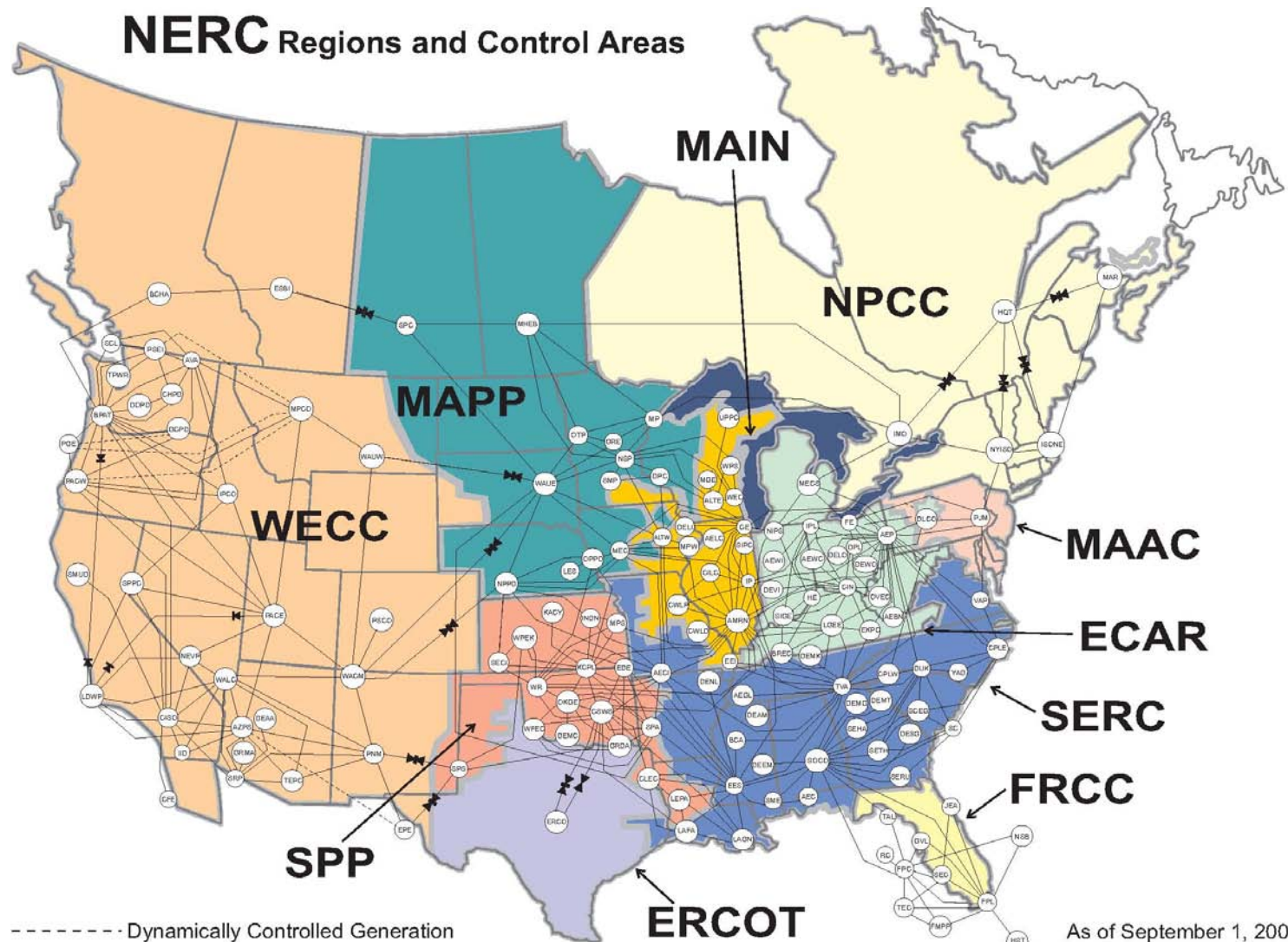


NERC Reliability Coordinators





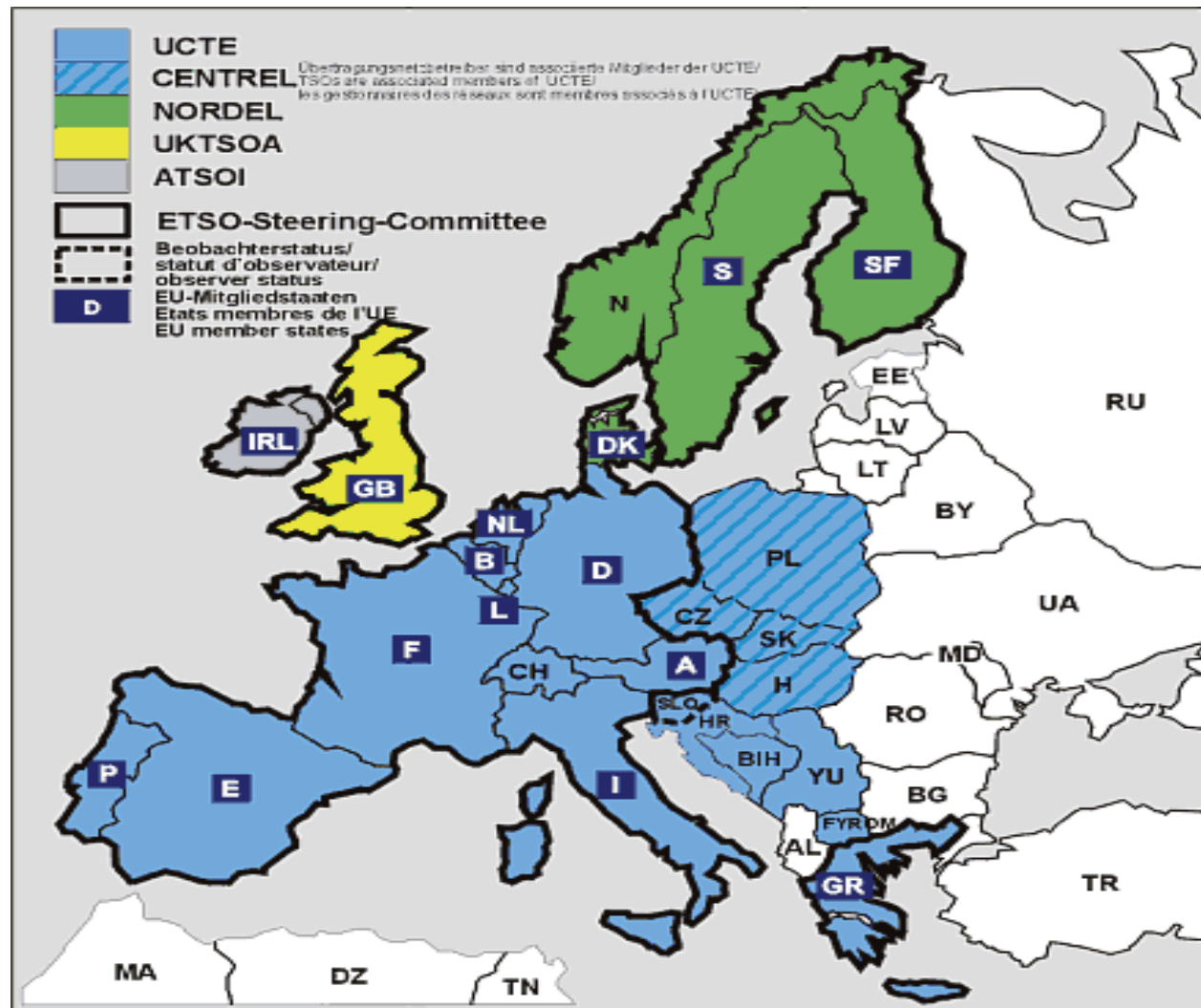
NERC Regions and Control Areas



As of September 1, 2003:



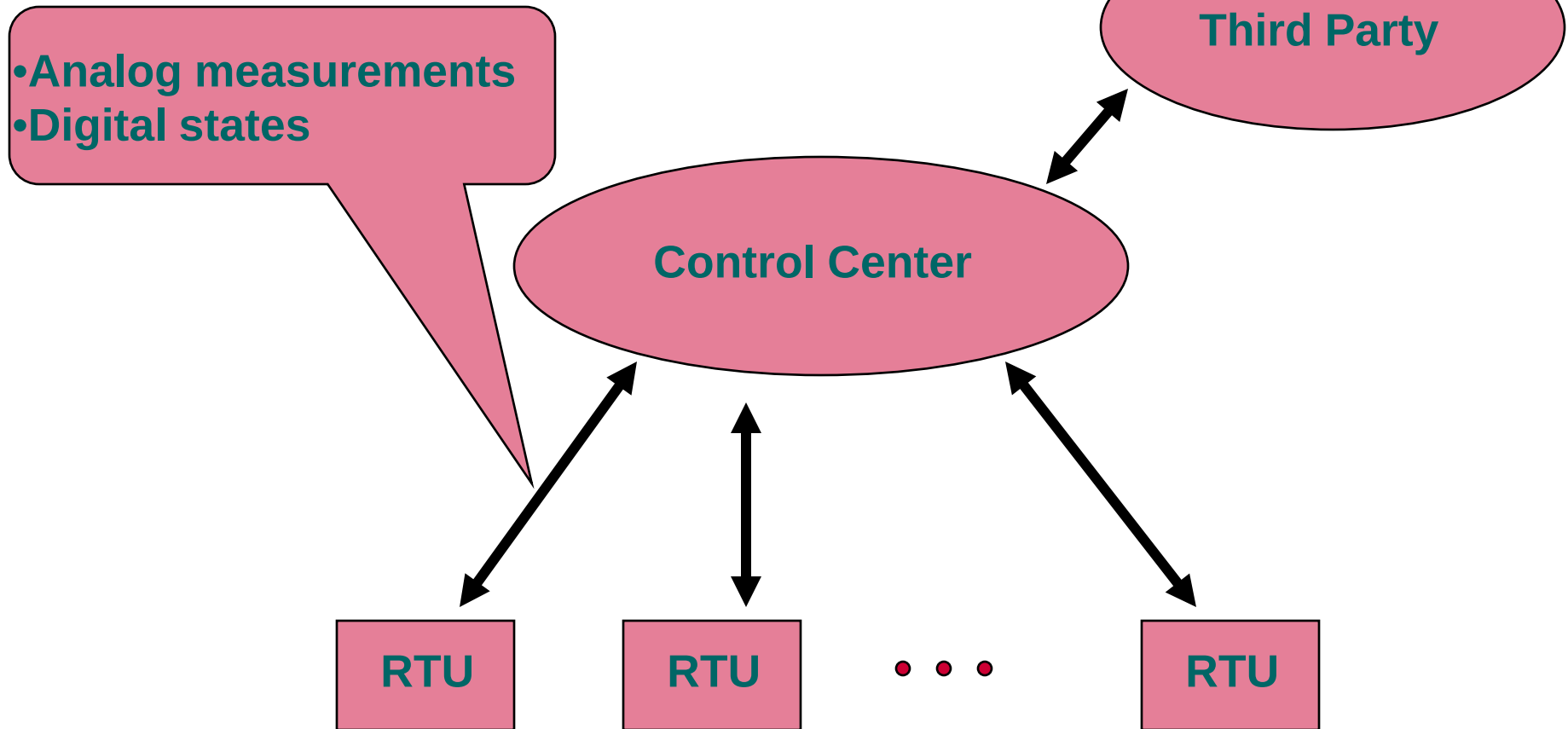
West European Power Grid







Communication for Power System



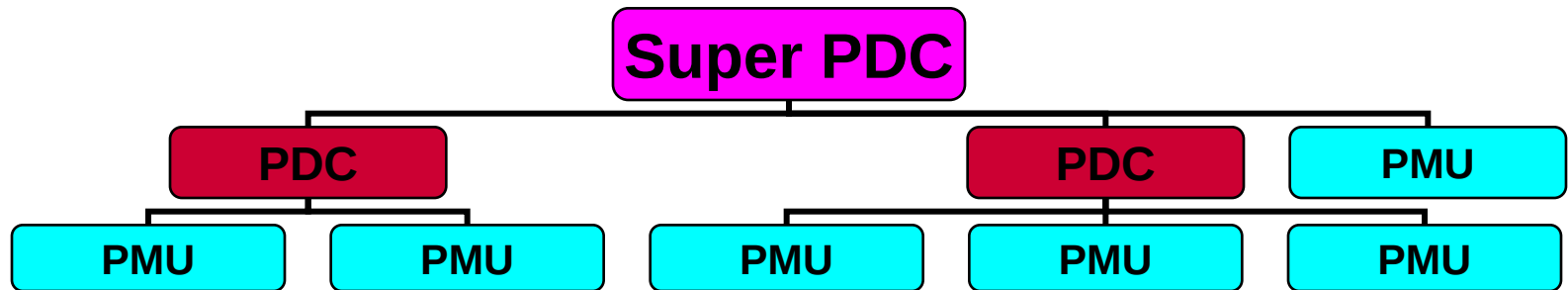


Substation Automation

- Many substations have
 - Data acquisition systems at faster rates
 - Intelligent electronic devices (IED)
 - Coordinated protection and control systems
 - Remote setting capabilities
- Data can be time-stamped by satellite



Phasor Measurements





Monitoring the Power Grid

- **Alarms**
 - Check for overloaded lines
 - Check for out-of-limit voltages
 - Loss of equipment (lines, generators, feeders)
 - Loss of communication channels
- **State estimator**
- **Security alerts**
 - Contingencies (loading, voltage, dynamic limits)
 - Corrective or preventive actions

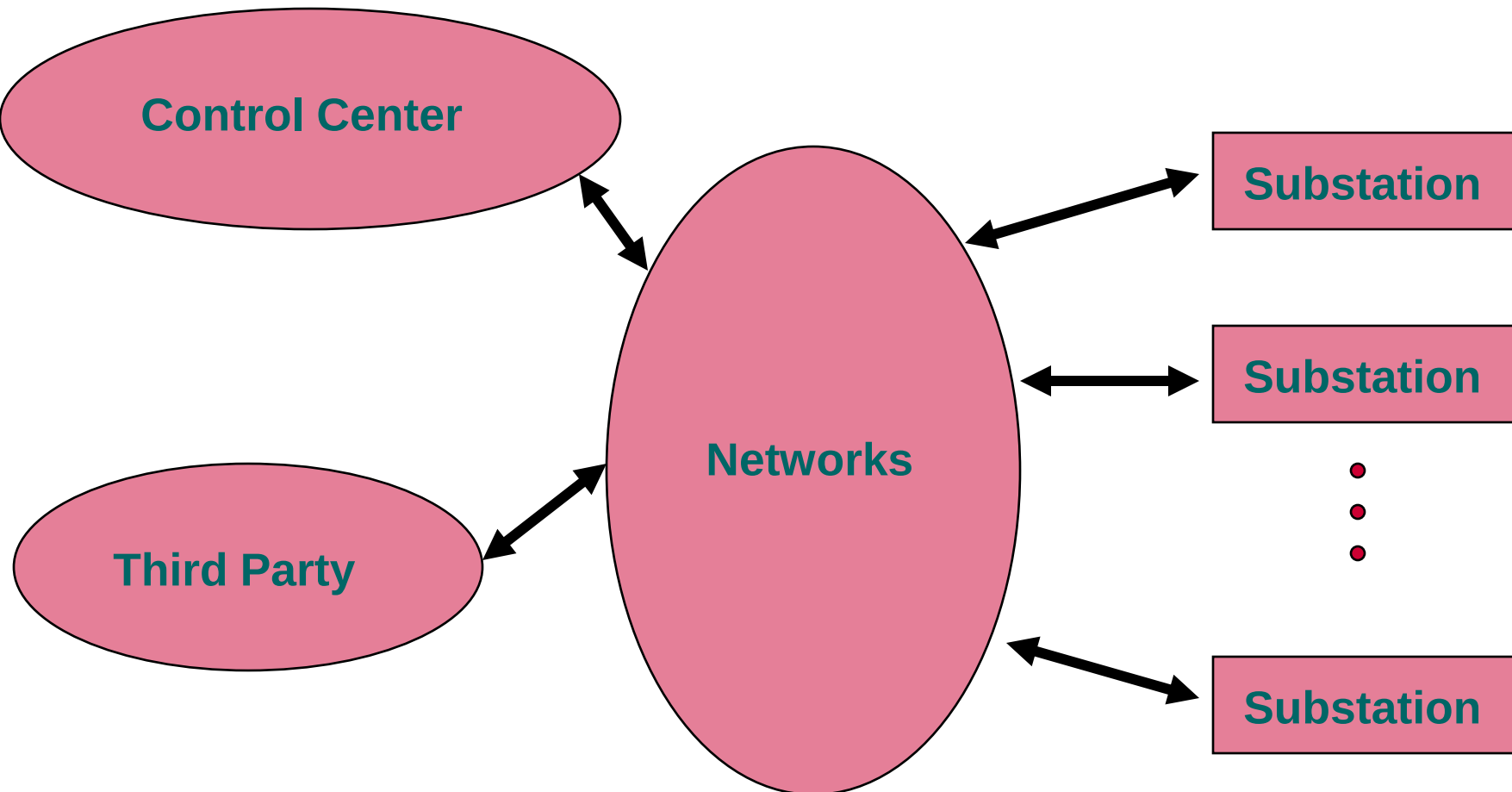


Control of the Power Grid

- **Load Following – Frequency Control**
 - Area-wise
 - Slow (secs)
- **Voltage Control**
 - Local
 - Slow to fast
- **Protection**
 - Local (but remote tripping possible)
 - Fast
- **Stability Control**
 - Local machine stabilizers
 - Remote special protection schemes
 - Fast

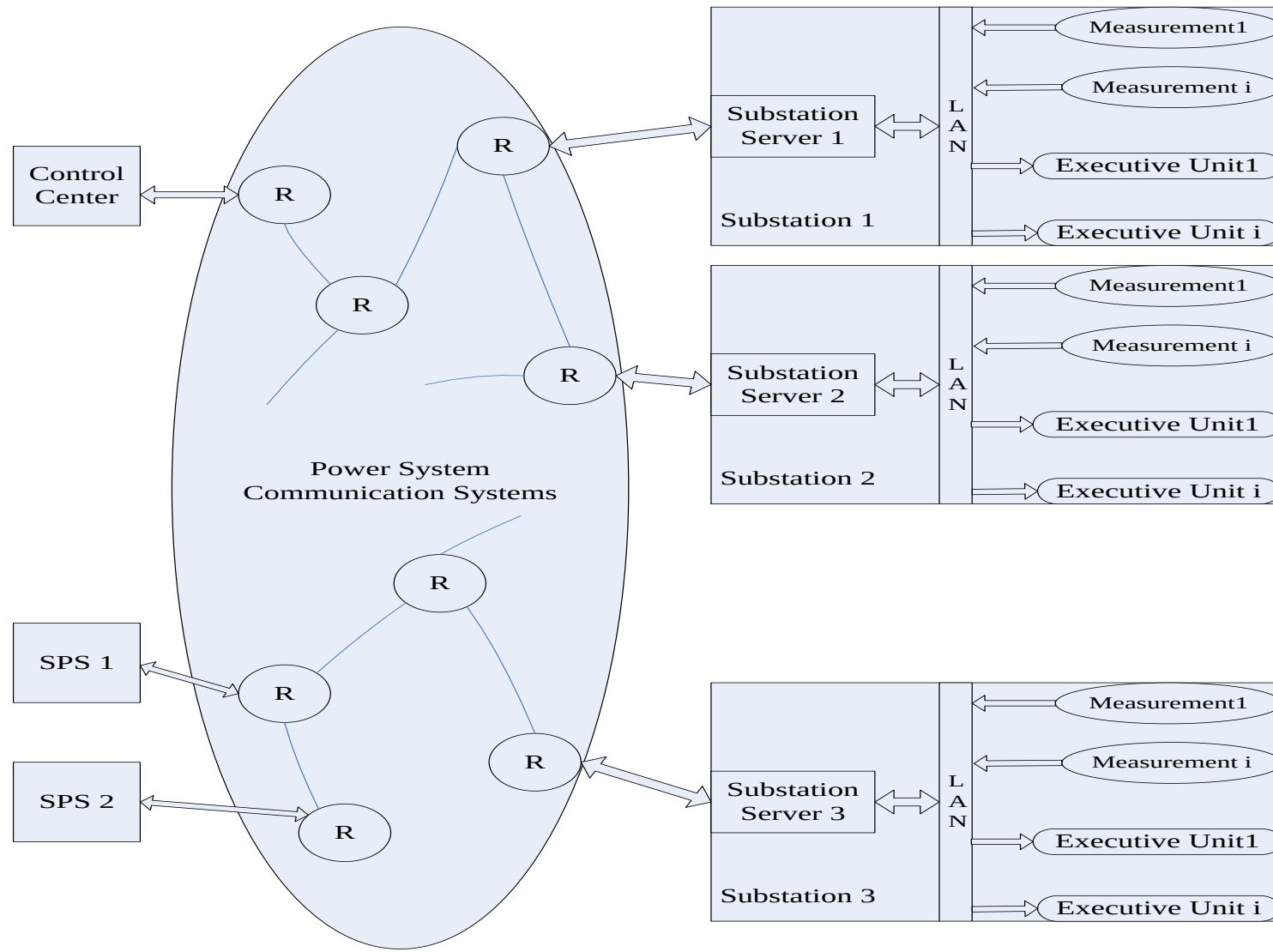


Communication for Power System (proposed)





Proposed Communications



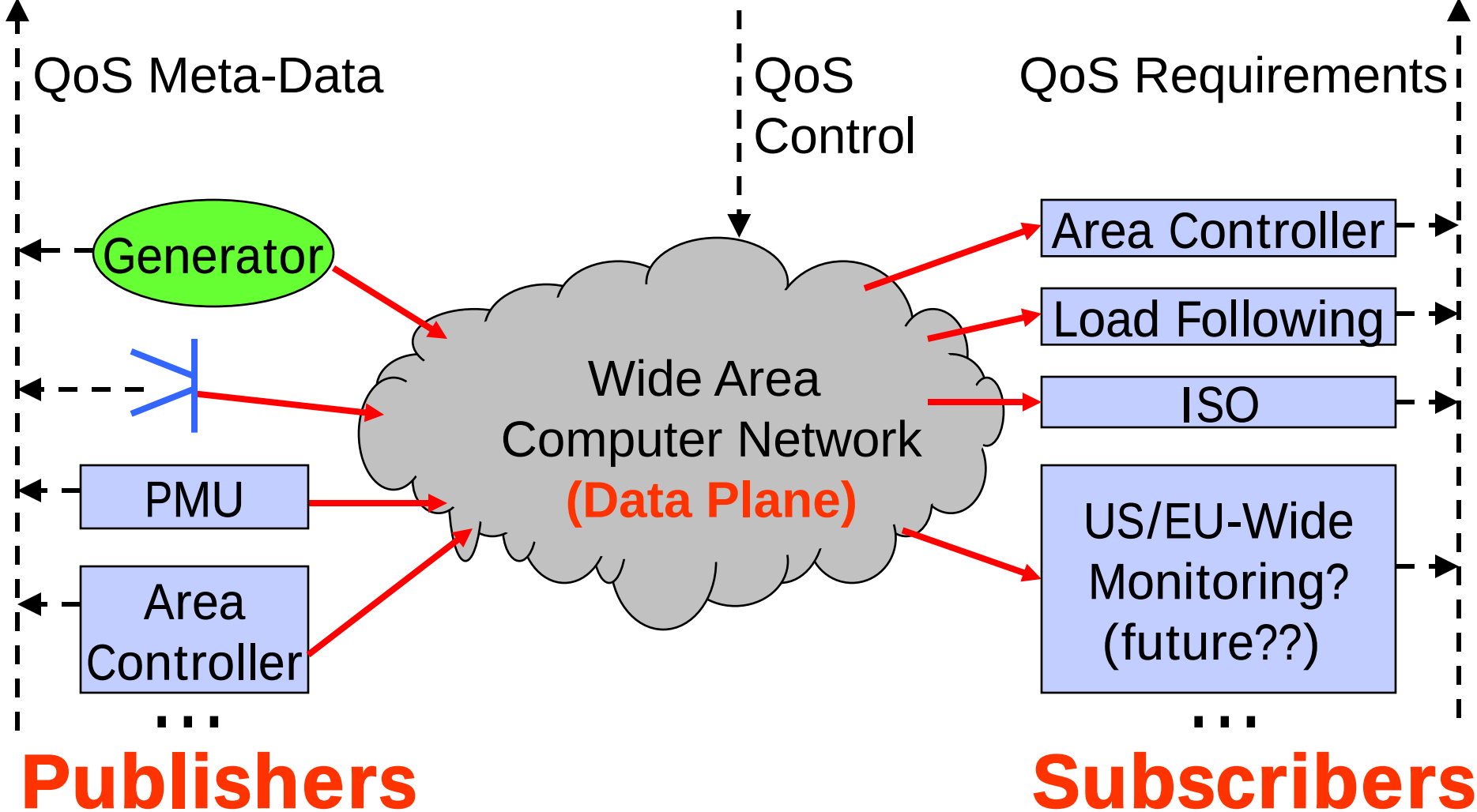


Each Application – Different Data

- **Monitoring at the control center**
 - Needs all data points
 - But at slow rates (every few seconds)
- **Special Protection Schemes**
 - Needs few data points
 - But at fast rates (many times a second)
- **Each application must access this data in a different way**
 - Moving real time data from source to application is a complex optimization task

Basic GridStat Functionality

Management Plane





Data Base Issues

- Real time data base must be distributed
 - Large amounts of calculated data must be part of this data base
- Static data base must be distributed
- Historical data base will require still another design
- Substation data bases and system level data bases have to be coordinated
- All data bases in the same interconnection will have to be coordinated
- Standards will be key



What is Wide Area Control?

- **Wide area implies ‘not local’ i.e. input-output signals not confined to one substation**
- **Control implies a controller that uses measurements as input signals to compute output signals for control equipment**
- **Input signals: frequency, currents, voltages, phase angles, watts, vars, switch status, etc.**
- **Output signals: generator output, transformer taps, HVDC, SVC, UPFC, switch status**



What is Wide Area Control?

- Control also implies **computation**
 - Detection of emergencies
 - Identification of emergencies
 - Calculation of controls
- ‘Wide area’ also implies **communication**
 - Signals are sampled (digital)
 - Signals have time delays (latency)



What WACs are feasible?

- **Slow control (10-seconds)**
 - **AGC**
 - **Regional voltage control**
 - **Phasor measurements not needed**
- **Oscillation control (seconds)**
- **Transient stability control (sub-seconds)**



What have we learnt?

Technology is available for ad hoc development and demonstration of WACs

- Have a good idea
- Test on simulations
- Design the prototype
 - Measurements needed
 - Point-to-point communications needed
 - Controls needed
- Install and test on real time data
- Close the loop



What have we learnt?

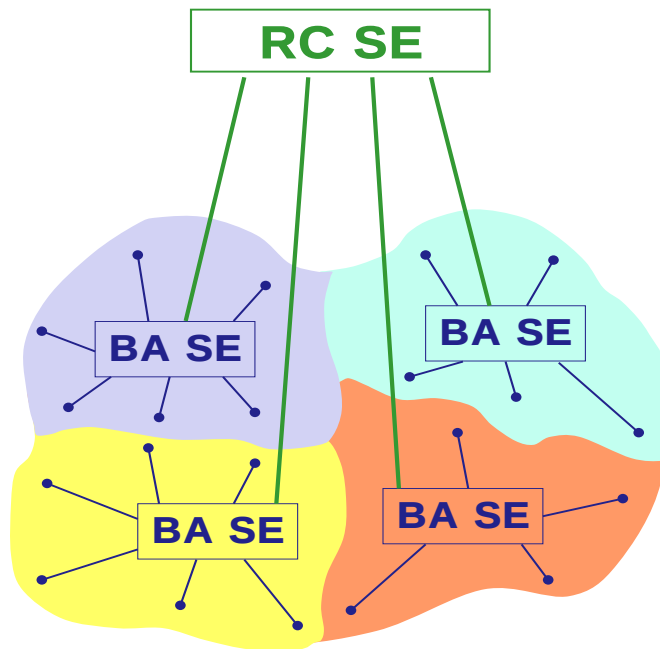
Systematic development of WACs will require

- **Communications infrastructure**
 - Networked, high-bandwidth
 - User-friendly applications level middleware
- **Detection/identification algorithm development**
- **Controller design process**
 - Determining best inputs, outputs
 - Developing output calculations
- **Off-line testing methods**
 - Nonlinear, digital simulations

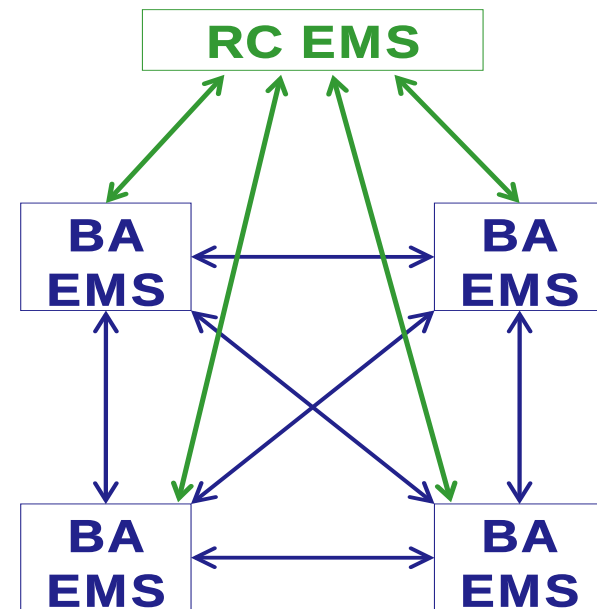


State Estimator

HIERARCHICAL STATE ESTIMATOR



COMMUNICATION NETWORK



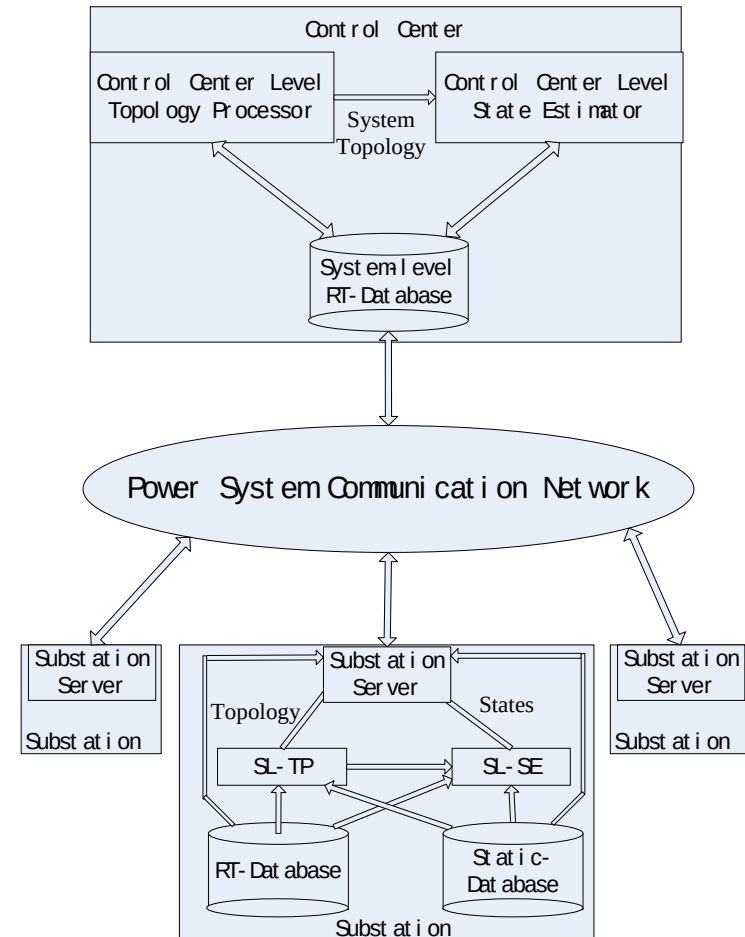
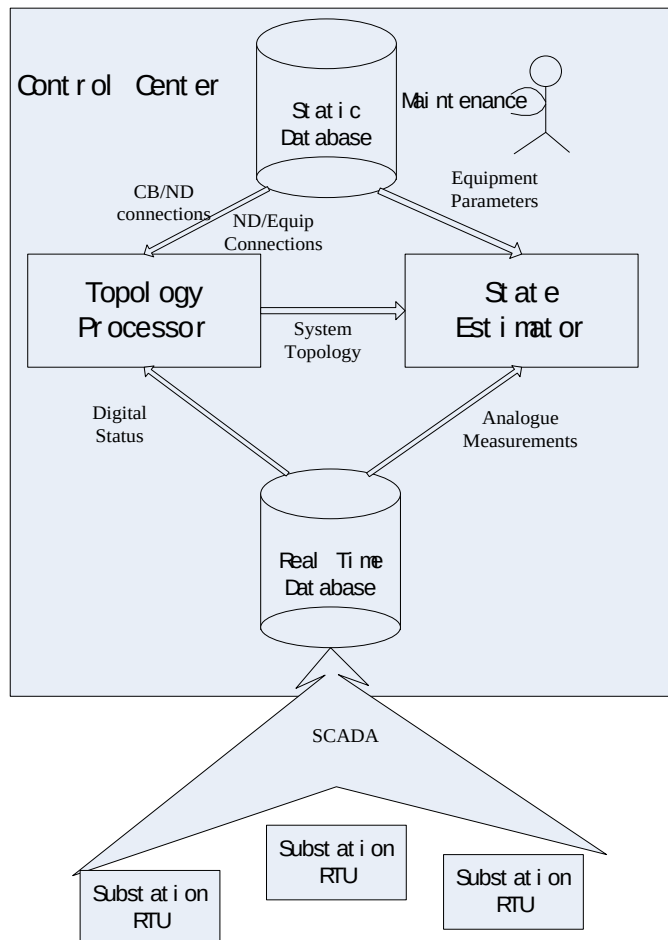


Two-Level Linear State Estimator

- **Substation Level**
 - **Substation Model**
 - **Circuit Breaker State Estimator**
 - **Bus Voltage State Estimator**
 - **Bad Data Detection & Identification**
- **Control Center Level**
 - **System Model**
 - **Topology Processor (system level)**
 - **State Estimator**
 - **Bad Data Detection & Identification**



Database & Communication Architecture



SL-TP: Subst at i on Level Topol ogy Processor

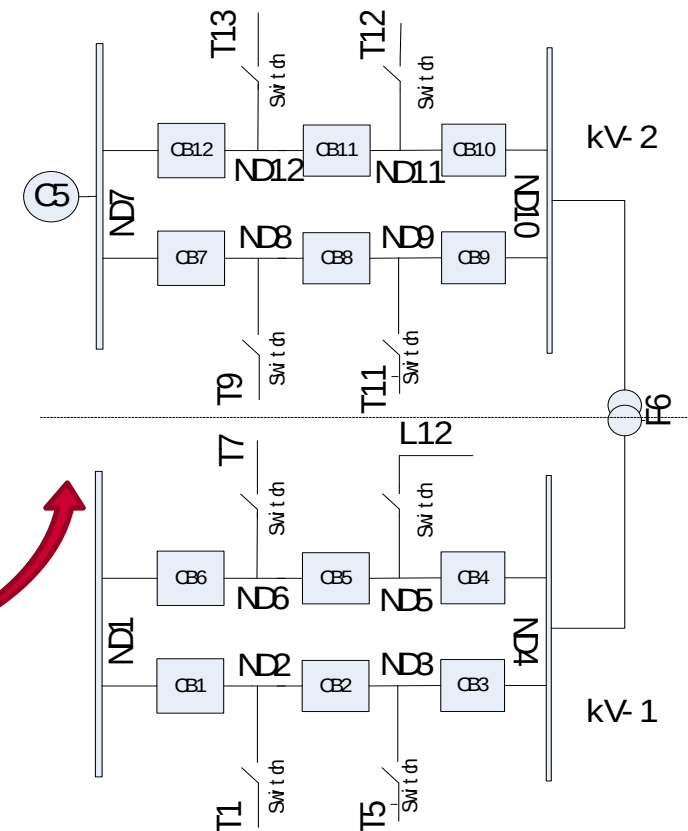
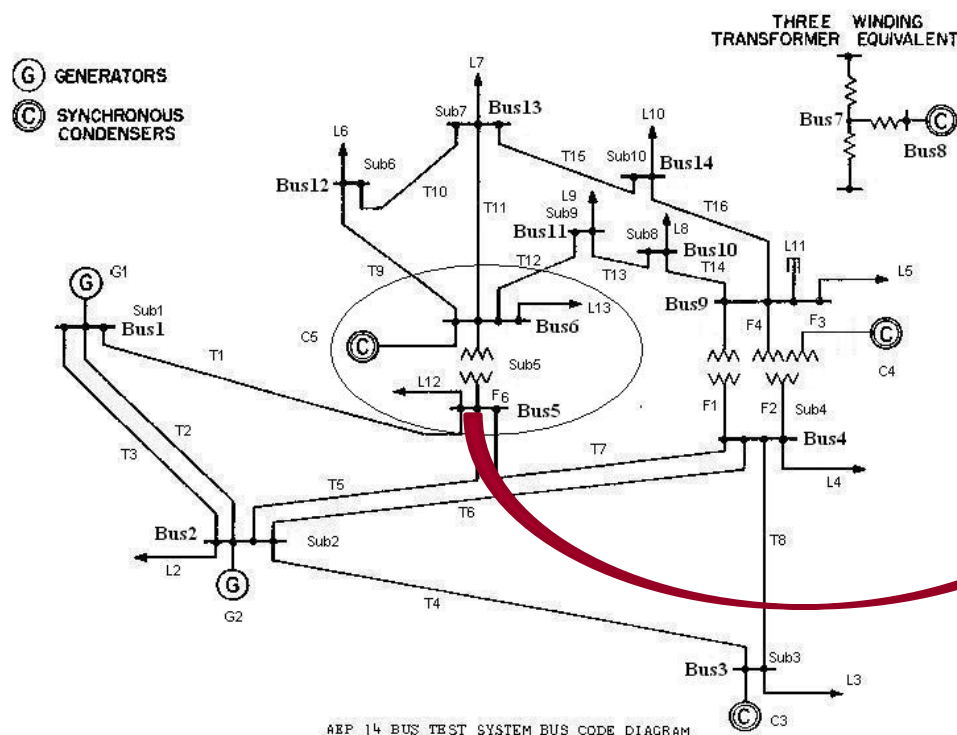
SL-SE: Subst at i on Level St at e Est i nat or

RT: Real Ti ne



Substation Level LSE

- Zero-Impedance Current State Estimator
 - Circuit Breaker Oriented Substation Model





Substation Level LSE

- **Analog State Estimation**

- **State:**

- **Currents on Circuit Breakers**

- **Measurements:**

- **Injection Currents to Nodes:** $\mathbf{z}_{inj}$

- **Currents on Circuit Breakers:** $\mathbf{z}_{cb}$

- **Measurement Functions**

- **Kirchhoff's Current Law**

- **Identity Matrix**

- **Formula:**

$$\mathbf{z} = \begin{pmatrix} \mathbf{z}_{inj} \\ \mathbf{z}_{cb} \end{pmatrix} = \begin{pmatrix} \mathbf{A}_{KCL} \\ \mathbf{I} \end{pmatrix} \mathbf{x} + \begin{pmatrix} \mathbf{r}_{inj} \\ \mathbf{r}_{cb} \end{pmatrix} = \mathbf{H}\mathbf{x} + \mathbf{r}$$



Substation Level LSE

- Zero-Impedance Voltage State Estimator

- State:

- Complex Bus Voltages

- Measurements:

- Voltage from PMUs

- Measurement Functions

$$\tilde{\mathbf{z}} = \tilde{\mathbf{H}} \tilde{\mathbf{x}} + \tilde{\mathbf{r}} = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \tilde{\mathbf{x}} + \tilde{\mathbf{r}}$$

- Solutions:

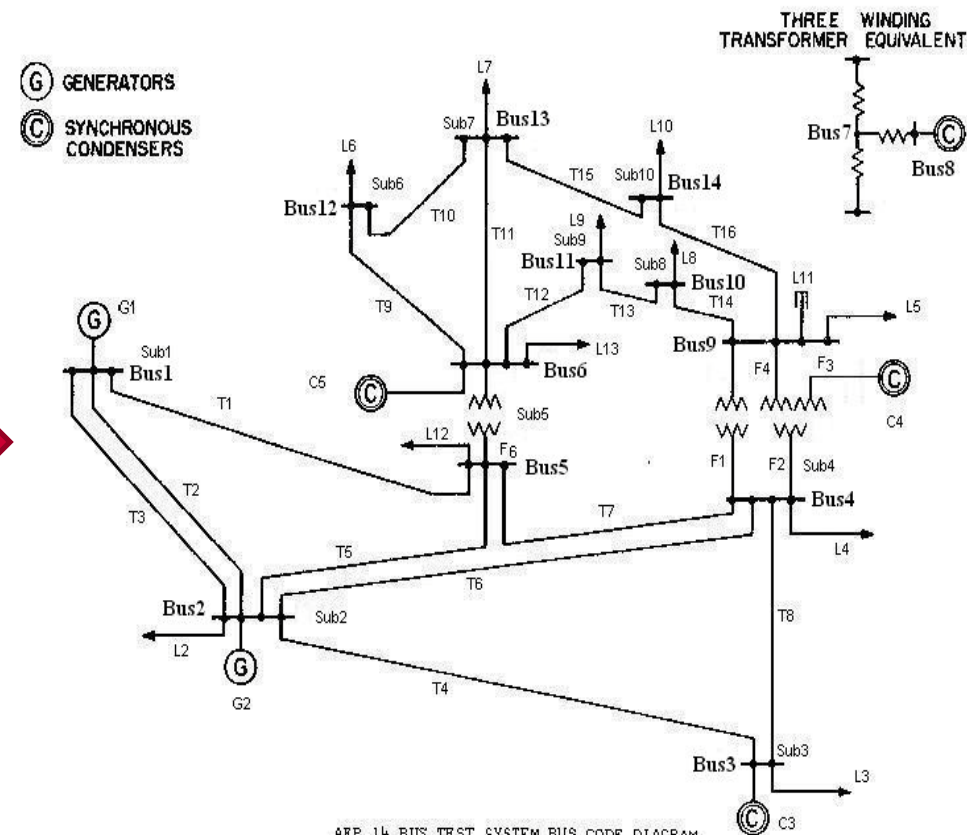
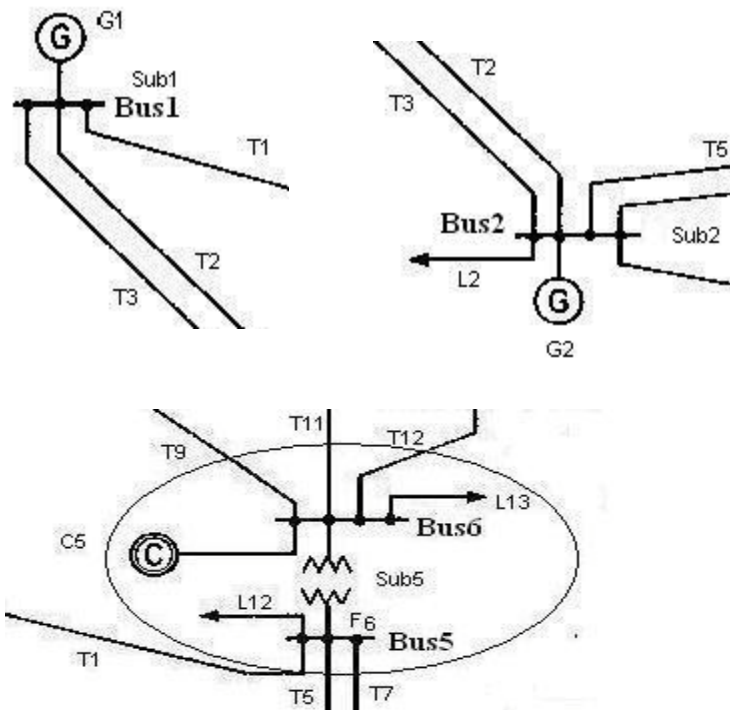
$$x_{real} = \frac{\sum_{i=1}^m w_{2i-1,2i-1} z_{i,real}}{\sum_{i=1}^m w_{2i-1,2i-1}}$$

$$x_{imag} = \frac{\sum_{i=1}^m w_{2i,2i} z_{i,imag}}{\sum_{i=1}^m w_{2i,2i}}$$



Control Center Level LSE

- Topology Processor
 - Merging Substation Topologies (STDFs)





Control Center Level LSE

- **State Estimation**

- **States**

- **Complex Bus Voltages**

- **Measurements (Phasor)**

- **Bus Voltages** $\tilde{\mathbf{V}}_{bus}$
 - **Two Direction Branch Currents** $\tilde{\mathbf{I}}_{b1} \quad \tilde{\mathbf{I}}_{b2}$
 - **Injection Currents** $\tilde{\mathbf{I}}_{inj}$

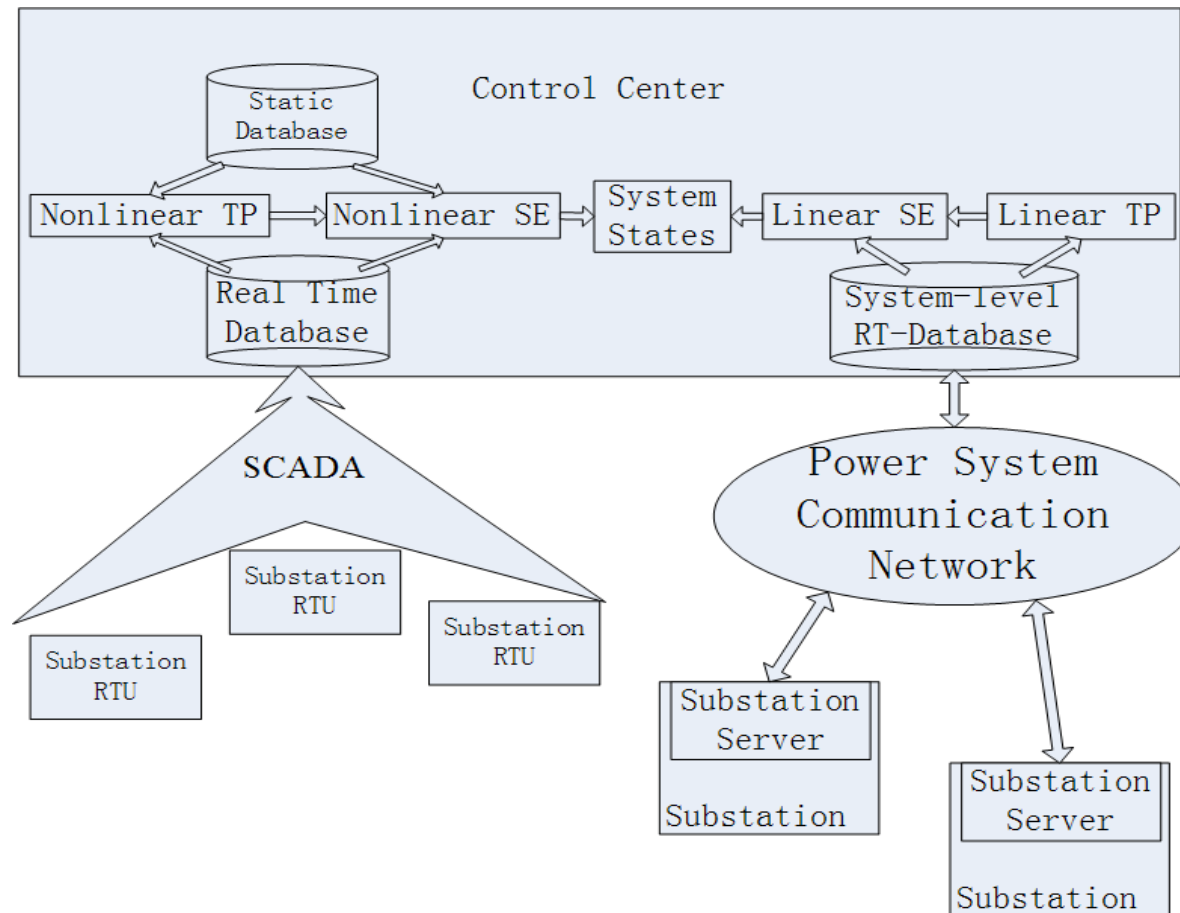
- **Measurement Functions**

$$\tilde{\mathbf{z}} = \begin{pmatrix} \tilde{\mathbf{V}}_{bus} \\ \tilde{\mathbf{I}}_{b1} \\ \tilde{\mathbf{I}}_{b2} \\ \tilde{\mathbf{I}}_{inj} \end{pmatrix} = \tilde{\mathbf{H}}\tilde{\mathbf{x}} + \tilde{\mathbf{r}} = \begin{pmatrix} \mathbf{I} \\ \tilde{\mathbf{Y}}_1^b \\ \tilde{\mathbf{Y}}_2^b \\ \tilde{\mathbf{Y}} \end{pmatrix} \tilde{\mathbf{x}} + \tilde{\mathbf{r}}$$



Transitional Multi-Area State Estimator

Database & Communication Architecture





Transitional Multi-Area State Estimator

- **State Estimation - Whole System**

$$\text{Min } \left(\sum_{i=1}^p \tilde{\mathbf{r}}_i^T \tilde{\mathbf{W}}_i \tilde{\mathbf{r}}_i + \sum_{j=1}^q \mathbf{r}_j^T \mathbf{W}_j \mathbf{r}_j \right)$$

$$\text{s.t. } \tilde{\mathbf{z}}_i = \tilde{\mathbf{H}}_i \tilde{\mathbf{x}}_i + \tilde{\mathbf{r}}_i = \tilde{\mathbf{H}}_i [\tilde{\mathbf{x}}_{i,\text{int}}^T, \tilde{\mathbf{x}}_{i,\text{b}}^T]^T + \tilde{\mathbf{r}}_i$$

$$\mathbf{z}_j = \mathbf{h}_j(\mathbf{x}_j) + \mathbf{r}_j = \mathbf{h}_j([\mathbf{x}_{j,\text{int}}^T, \mathbf{x}_{j,\text{b}}^T]^T) + \mathbf{r}_j$$

- **Linear Area**
- **Non-linear Area**
- **Boundary Buses**



Conclusions

- Controls at the substation level get more sophisticated every day
- Real time data collection increases at the subs
- Utilizing these measurements and controls at the system level remains difficult
- The communication infrastructure to move this data has to be built
- The software infrastructure to handle the data has to be built
- Only then can the smart grid applications be implemented