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
West European Power Grid
Communication for Power System

- Analog measurements
- Digital states

Control Center

Third Party

RTU

RTU

RTU
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

Super PDC

- PDC
  - PMU
  - PMU

- PDC
  - PMU
  - PMU

- PMU
  - PMU
  - PMU
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)
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

QoS Meta-Data

Generator

PMU

Area Controller

Wide Area Computer Network (Data Plane)

QoS Control

Area Controller

Load Following

ISO

US/EU-Wide Monitoring? (future??)

QoS Requirements

Publishers

Subscribers
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

RC SE

BA SE

BA SE

BA SE

BA EMS

BA EMS

BA EMS

BA EMS

RC EMS
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
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: $Z_{inj}$
    - Currents on Circuit Breakers: $Z_{cb}$
  - Measurement Functions
    - Kirchhoff’s Current Law
    - Identity Matrix
  - Formula:

$$z = \begin{pmatrix} Z_{inj} \\ Z_{cb} \end{pmatrix} = \begin{pmatrix} A_{KCL} \\ I \end{pmatrix} x + \begin{pmatrix} r_{inj} \\ r_{cb} \end{pmatrix} = Hx + r$$
Substation Level LSE

• Zero-Impedance Voltage State Estimator
  ▪ State:
    • Complex Bus Voltages
  ▪ Measurements:
    • Voltage from PMUs
  ▪ Measurement Functions
    \[ \tilde{z} = \tilde{H} \tilde{x} + \tilde{r} = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \tilde{x} + \tilde{r} \]
  ▪ Solutions:
    \[ x_{\text{real}} = \frac{\sum_{i=1}^{m} W_{2i-1,2i-1} \tilde{z}_{i,\text{real}}}{\sum_{i=1}^{m} W_{2i-1,2i-1}} \]
    \[ x_{\text{imag}} = \frac{\sum_{i=1}^{m} W_{2i,2i} \tilde{z}_{i,\text{imag}}}{\sum_{i=1}^{m} W_{2i,2i}} \]
Control Center Level LSE

• Topology Processor
  ▪ Merging Substation Topologies (STDFs)
Control Center Level LSE

• State Estimation
  ■ States
    • Complex Bus Voltages
  ■ Measurements (Phasor)
    • Bus Voltages $\tilde{V}_{bus}$
    • Two Direction Branch Currents $\tilde{I}_{b1}$, $\tilde{I}_{b2}$
    • Injection Currents $\tilde{I}_{inj}$
  ■ Measurement Functions

\[ \tilde{z} = \begin{pmatrix} \tilde{V}_{bus} \\ \tilde{I}_{b1} \\ \tilde{I}_{b2} \\ \tilde{I}_{inj} \end{pmatrix} = \tilde{H}\tilde{x} + \tilde{r} = \begin{pmatrix} I \\ \tilde{Y}_{1} \\ \tilde{Y}_{2} \\ \tilde{Y} \end{pmatrix} \begin{pmatrix} \tilde{x} + \tilde{r} \end{pmatrix} \]
Transitional Multi-Area State Estimator

- State Estimation - Whole System

\[
\text{Min} \left( \sum_{i=1}^{p} \tilde{r}_i^T \tilde{W}_i \tilde{r}_i + \sum_{j=1}^{q} r_j W_j r_j \right)
\]

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

\[
z_j = h_j(x_j) + r_j = h_j \left( [x_{j,\text{int}}, x_{j,b}]^T \right) + r_j
\]

- 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