Direct Non-Iterative Power System State Estimation & Requirements for the Next Generation EMS

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i-PCGIRD 2015

San Francisco, CA

March 25-27, 2015

New Paradigm

- Historically we have used iterative techniques (Least- Squares) to solve the state estimation problem
- A direct one-shot solution for the state of a power system is now possible
- Full AC solution-No Simplifications
- No more iterations
- No reliance on the “goodness” of the initial guess
- An envisioned faster more robust solution

A Power System State Estimator/Solver

- Power Flow equations in Rectangular from
- Naturally in the desired form:

$$\overline{V}_i = a_i + jb_i$$

$$\sum_{i=l}^{N} \mathrm{Re}(Y_{ij}).(a_j a_i + b_j b_i) + \mathrm{Im}(Y_{ij}).(a_i b_j - a_j b_i) = P_{G_j} - P_{D_j}$$

$$-\sum_{i=l}^{N} \mathrm{Re}(Y_{ij}).(a_j a_i - a_i b_j) + \mathrm{Im}(Y_{ij}).(a_i a_j + b_j b_i) = Q_{G_j} - Q_{D_j} \quad j = 2,\ldots N$$

- Measurement equations have similar form

A Simple Example

- Redundant Polynomial Equations

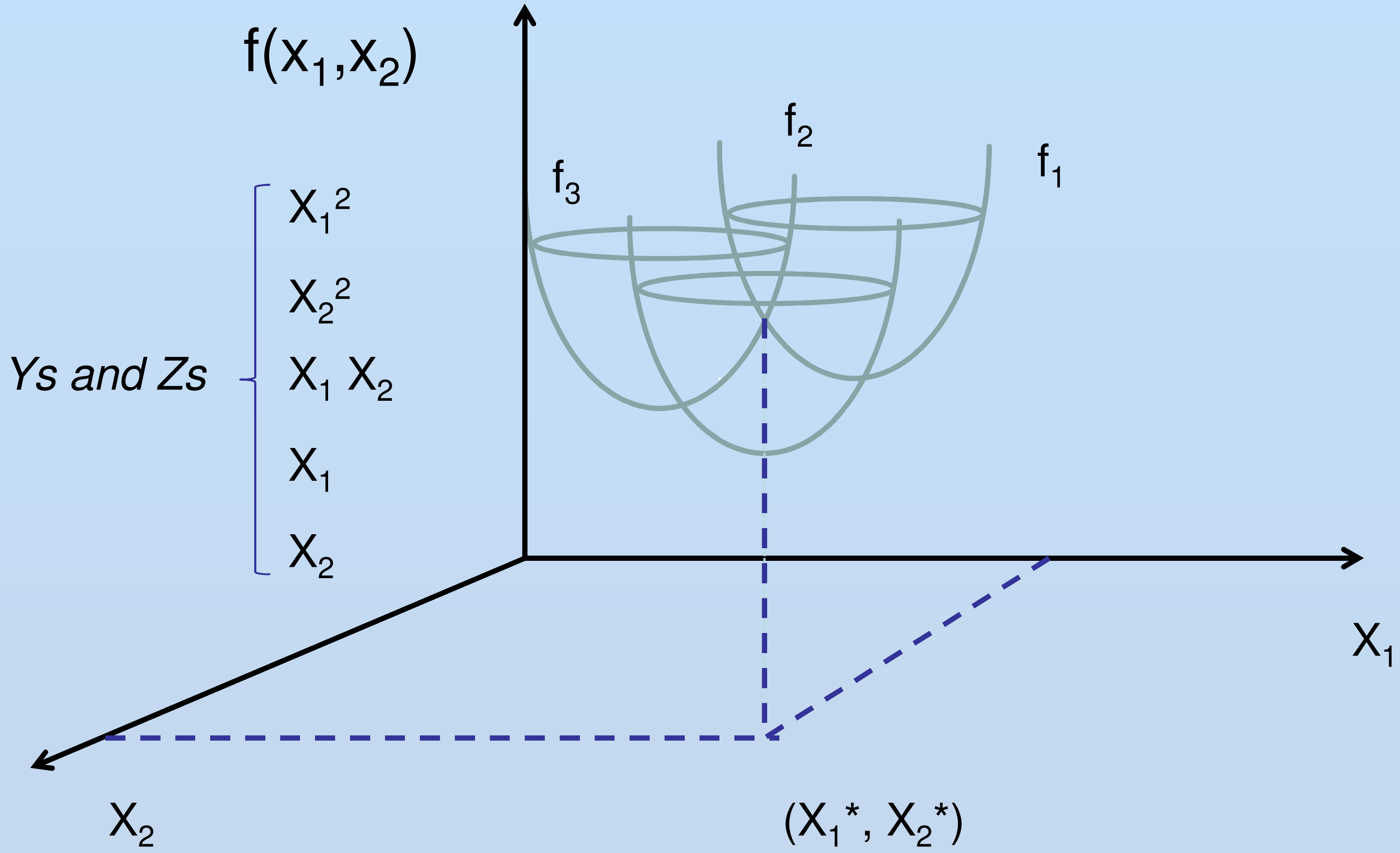
$$
\begin{aligned}
x_1^2 - 2x_1x_2 + x_3^2 + x_2 &= 8 \\
2x_2x_3 - x_2^2 + 2x_1 &= 10 \\
5x_1x_3 - x_1x_2 + 3x_3 + x_2^2 &= 26 \\
7x_1^2 - 2x_2x_3 + x_3^2 - 5x_3 &= -11 \\
x_1^2 - x_2^2 - 5x_2x_3 + 12x_1 &= -13
\end{aligned}
$$

$$
\left[\begin{array}{ccccc|cccc}
1 & -2 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 & -1 & 2 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 1 & 0 & 5 & 3 \\
7 & 0 & 1 & 0 & -2 & 0 & 0 & 0 & -5 \\
1 & 0 & 0 & 0 & -5 & -1 & 12 & 0 & 0
\end{array}\right]
\begin{bmatrix} y_{11} \\ y_{12} \\ y_{33} \\ y_{20} \\ \underline{y_{23}} \\ z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix}
=
\begin{bmatrix} 8 \\ 10 \\ 26 \\ -11 \\ -13 \end{bmatrix}
$$

$$
[M \mid T]\begin{bmatrix} Y \\ \hline Z \end{bmatrix} = [R] \qquad Y = M^{-1}(R - TZ)
$$

Solve for the y_s in terms of the z_s

Basics of the Re-Linearization Method



Basics of the Re-Linearization Method

Form new quadratic Surfaces in term of *Zs* and change variables to t_s:

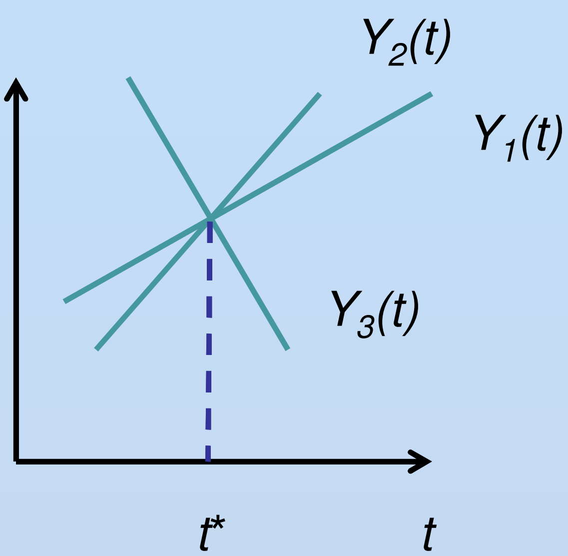
$$y_{ij}\,y_{mn} = y_{im}\,y_{jn} = \ldots = y_{in}\,y_{jm}$$

$$\left[\, z_1 \; z_2 \; z_3 \; z_4 \; z_1z_2 \; z_1z_3 \; z_1z_4 \; z_2z_3 \; z_2z_4 \; z_3z_4 \; z_1^2 \; z_2^2 \; z_3^2 \; z_4^2 \,\right]$$

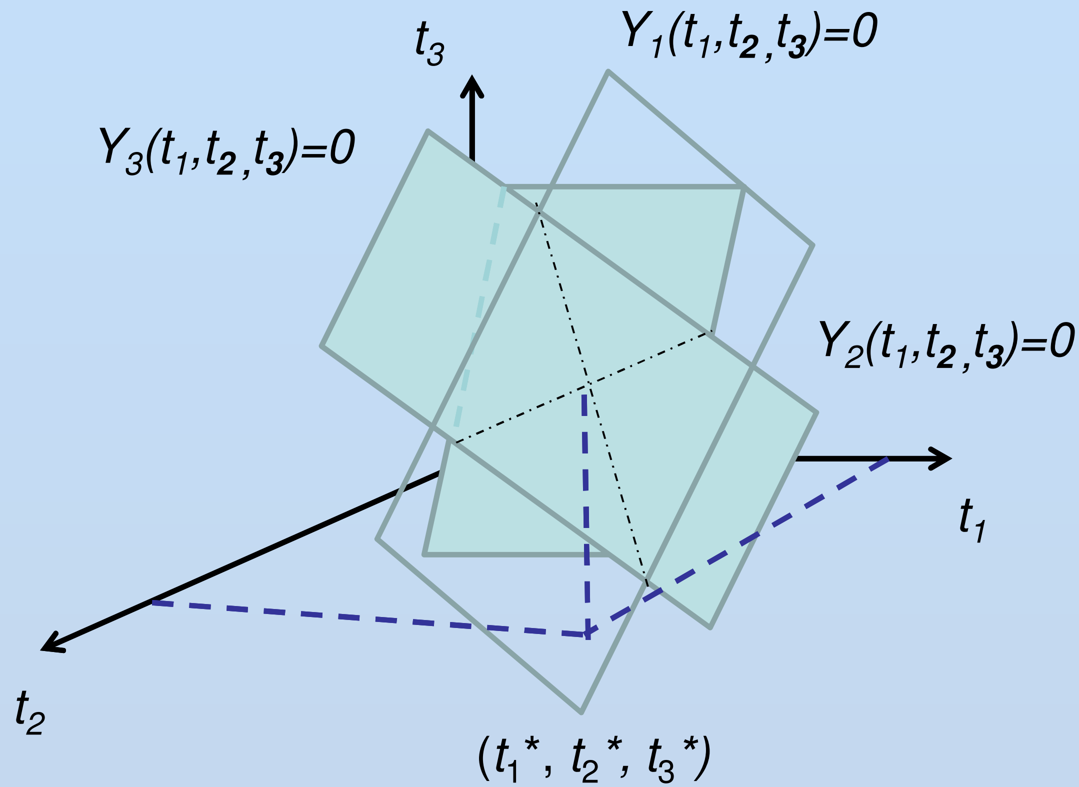
$$\begin{bmatrix}
-241.5 & 2849 & 0 & 60 & 337 & 0 & 7.5 & 0 & -85 & 0 & -142.5 & -1989 & -1 & 0 \\
64 & 0 & 260 & 156 & -17 & -10 & -6 & 0 & 0 & -30 & 0.5 & 0 & -25 & -9 \\
-163.5 & 1667 & -120 & -12 & 321 & -15 & -1.5 & 175 & 20 & 0 & -15 & -1700 & 0 & 0 \\
-13.5 & 97 & -26 & 0 & 10 & 1 & 0 & 0 & 0 & 3 & -0.75 & -17 & 5 & 0 \\
-90 & 10 & 0 & 0 & 118 & 0 & 5 & 0 & 0 & 0 & -9.75 & -1 & 0 & 0 \\
0 & -85 & 0 & 0 & -9.5 & 0 & 0 & 0 & 5 & -1 & 0 & 117 & 0 & 0 \\
0 & 0 & 29 & 26 & 0 & 10 & -1 & -100 & 0 & -4 & 0 & 0 & 10 & -3 \\
0 & 5 & 0 & 26 & 0.5 & 0 & -1 & 0 & 0 & -5 & 0 & -1 & 0 & -3 \\
-162 & 3042 & 430 & 385 & -117 & 48 & 23.5 & -586 & -351 & -25 & 9.5 & 0 & 0 & -15 \\
1125.5 & -11893 & 850 & -55 & -2120 & 95 & -40 & -1170 & 382 & -50 & 95 & 11700 & 0 & -5 \\
231 & -2600 & 115 & -61 & 101 & -60 & -31 & 500 & 300 & -35 & -10 & 0 & -50 & -3 \\
8 & -26 & -25 & -15 & 1 & -1.5 & -1.5 & 5 & 3 & 0 & -0.5 & 0 & 0 & 0 \\
-64.5 & 529 & -50 & -5 & 60 & -5 & 0.5 & 10 & 1 & 0 & -5 & -100 & 0 & 0 \\
0 & 0 & 0 & -12 & 0 & 0 & -1.5 & 1 & 17 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \\ t_9 \\ t_{10} \\ t_{11} \\ t_{12} \\ t_{13} \\ t_{14} \end{bmatrix}
=
\begin{bmatrix} 1020 \\ 676 \\ 348 \\ 60 \\ 25 \\ 0 \\ 0 \\ 0 \\ 2210 \\ -2465 \\ -754 \\ -130 \\ 145 \\ 0 \end{bmatrix}$$

Basics of the Re-Linearization Method

If only one Z

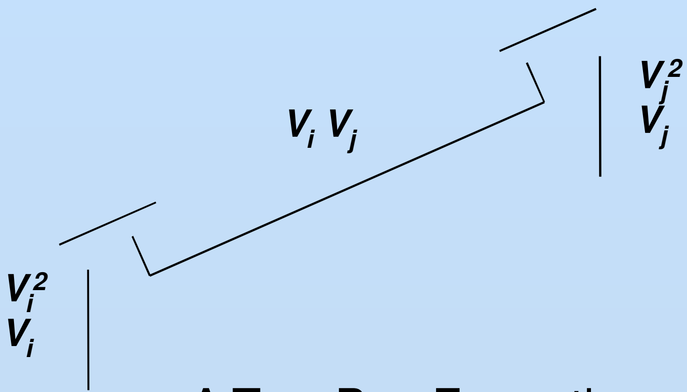


If Z_1 and Z_2 , we will have five *ts;*
Assuming only three ts are present:

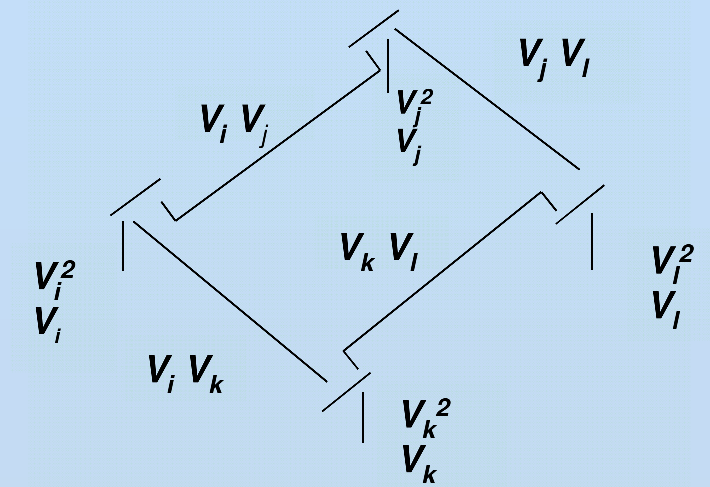


Dual Transformation and Direct One-Shot Solution

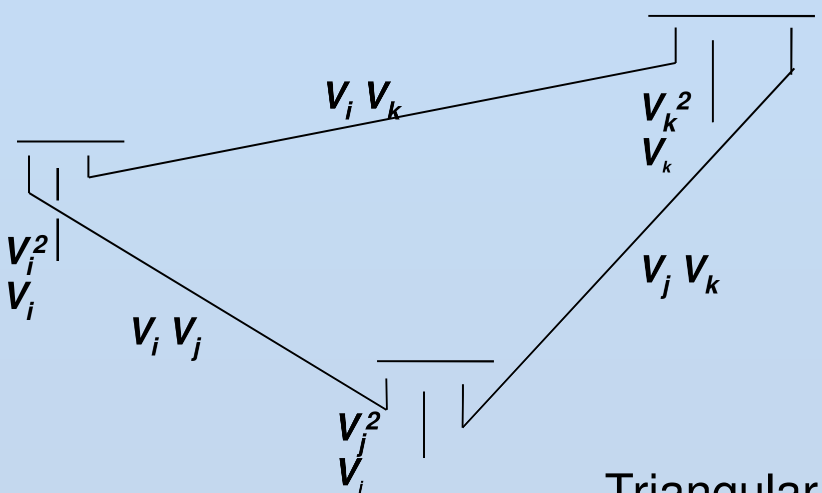
Relation to Network Topology



A Two-Bus Formation



Rectangular Formation



Triangular Formation

Data and Communications

- Can accept both measurement types from the system at the control center—SCADA (type) and PMU
- Bus voltage phasor and line current phasor measurements ONLY—Phasor Only SE
- Locally (at the substation) validated data– “Super-Calibrator “ a plus
- Reliable and redundant communications network

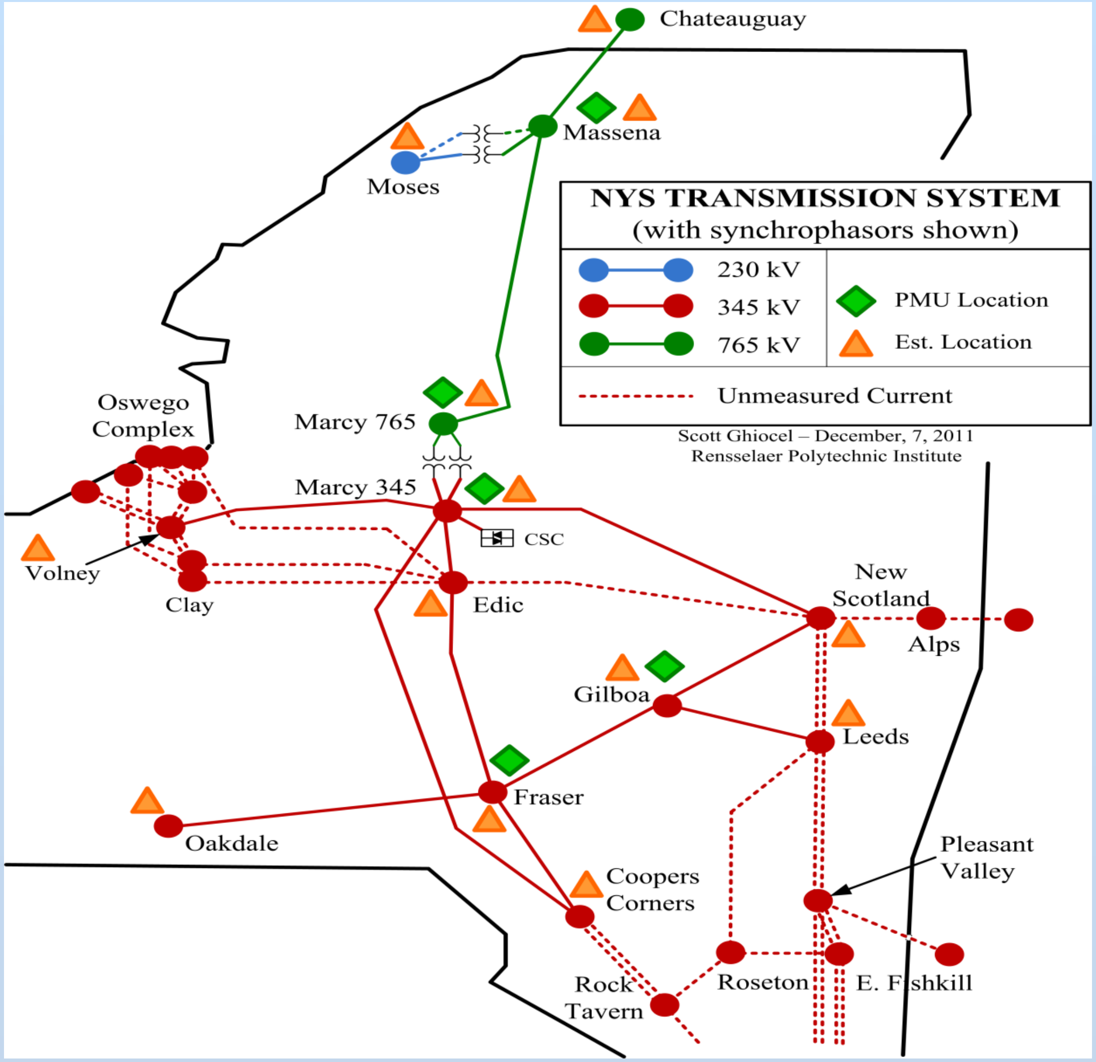
Benefits

- Direct State Estimation/Solution
- More robust– No more iterations
- No reliance on the initial guess
- Fast– Perhaps limited only by the communication links’ latency
- A much more “dynamic” assessment of the system conditions and behavior
- Potential for ultimate use in closed-loop and automatic control of power systems

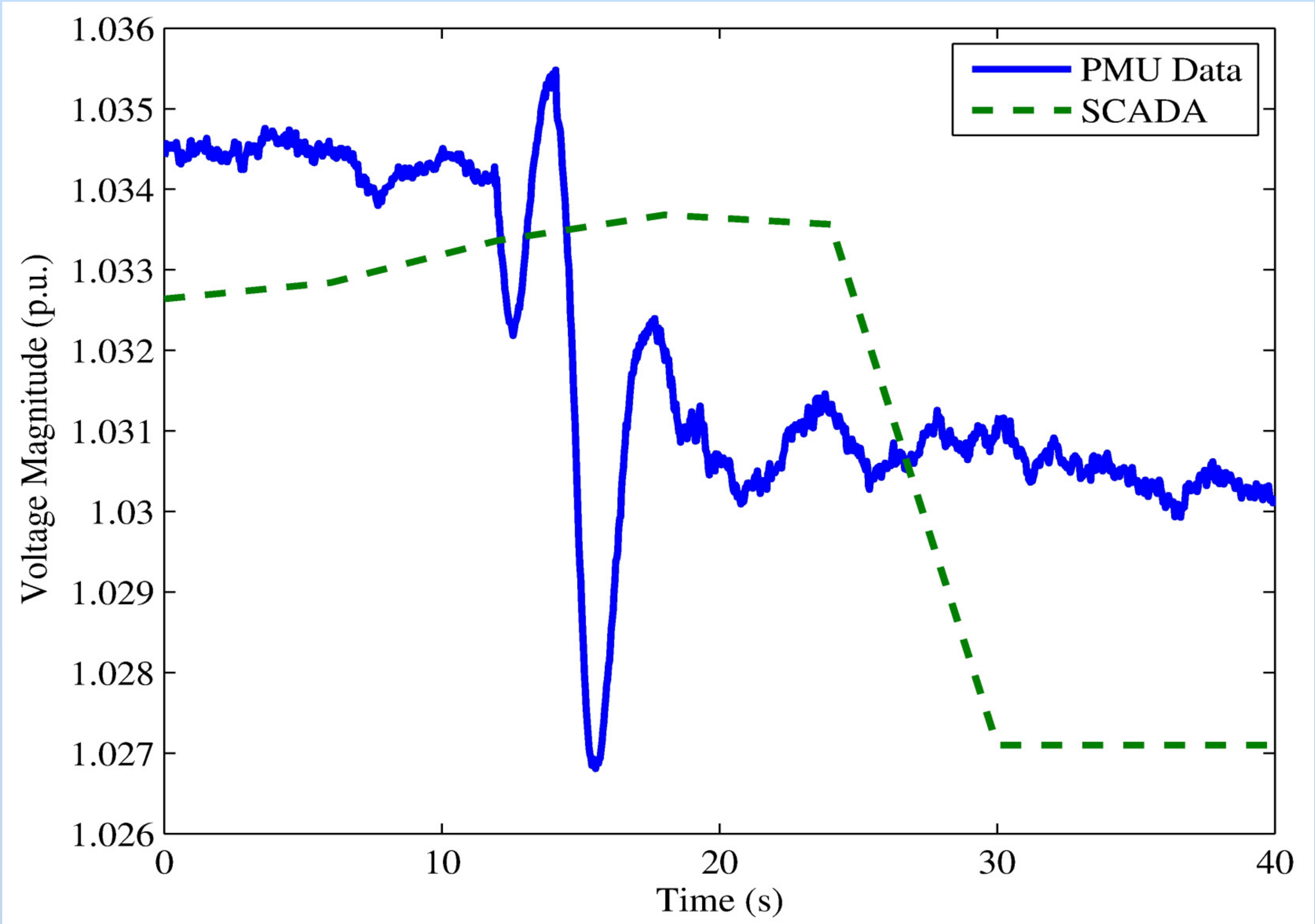
DOE/NYPA/Quanta/EPG Project

- Pre-Commercial Demonstration of Direct Non-Iterative State Estimator for Operational Use of Synchrophasor Management Systems
- Period of Performance – July 30, 2014 – July 29, 2016
- Sub-second performance target for a 1500 Bus Operating Case
- To be installed at NYPA Control Center and hopefully at the NYISO (for side-by-side Comparison with commercial SEs).

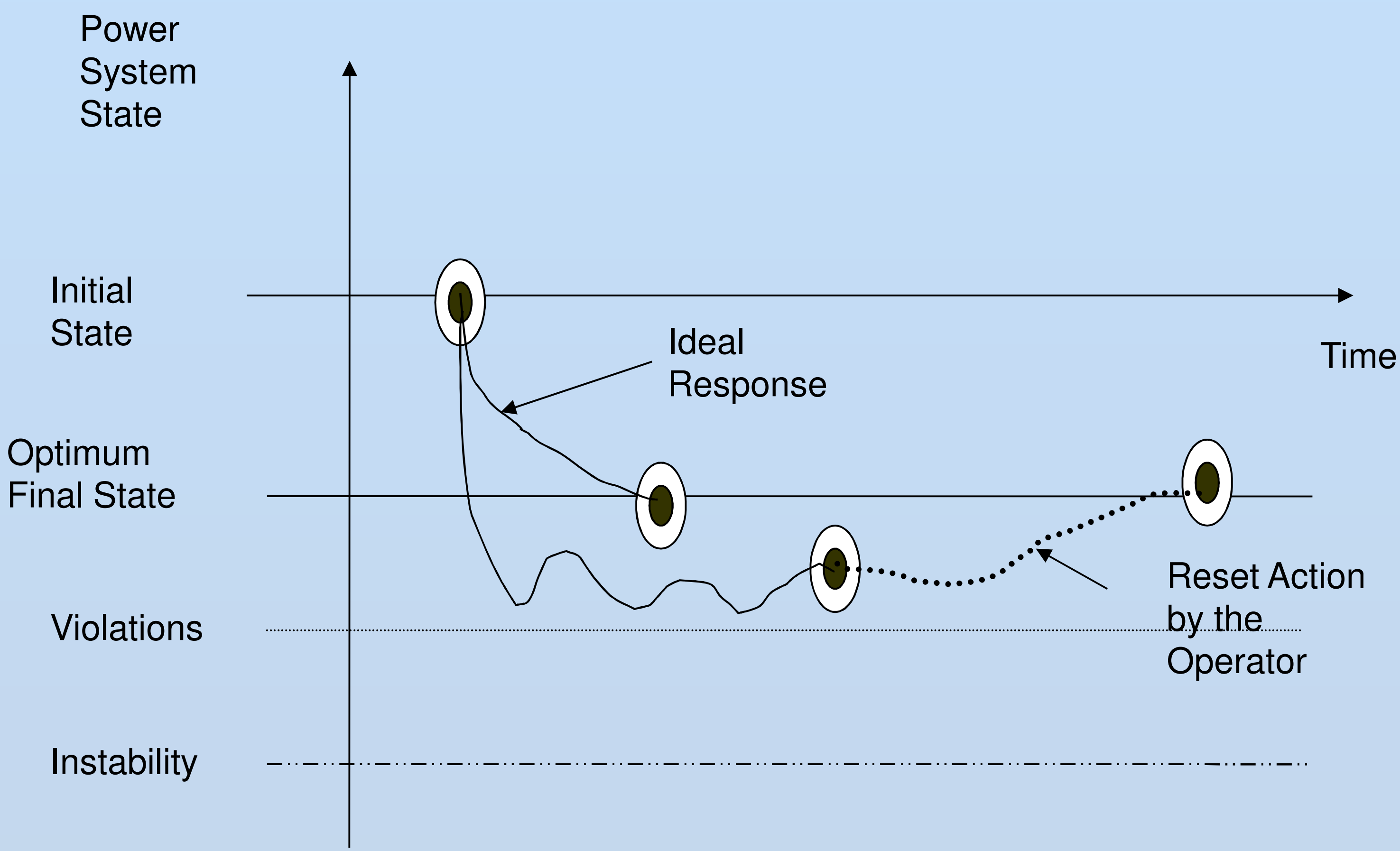
State Estimation-The backbone of the EMS



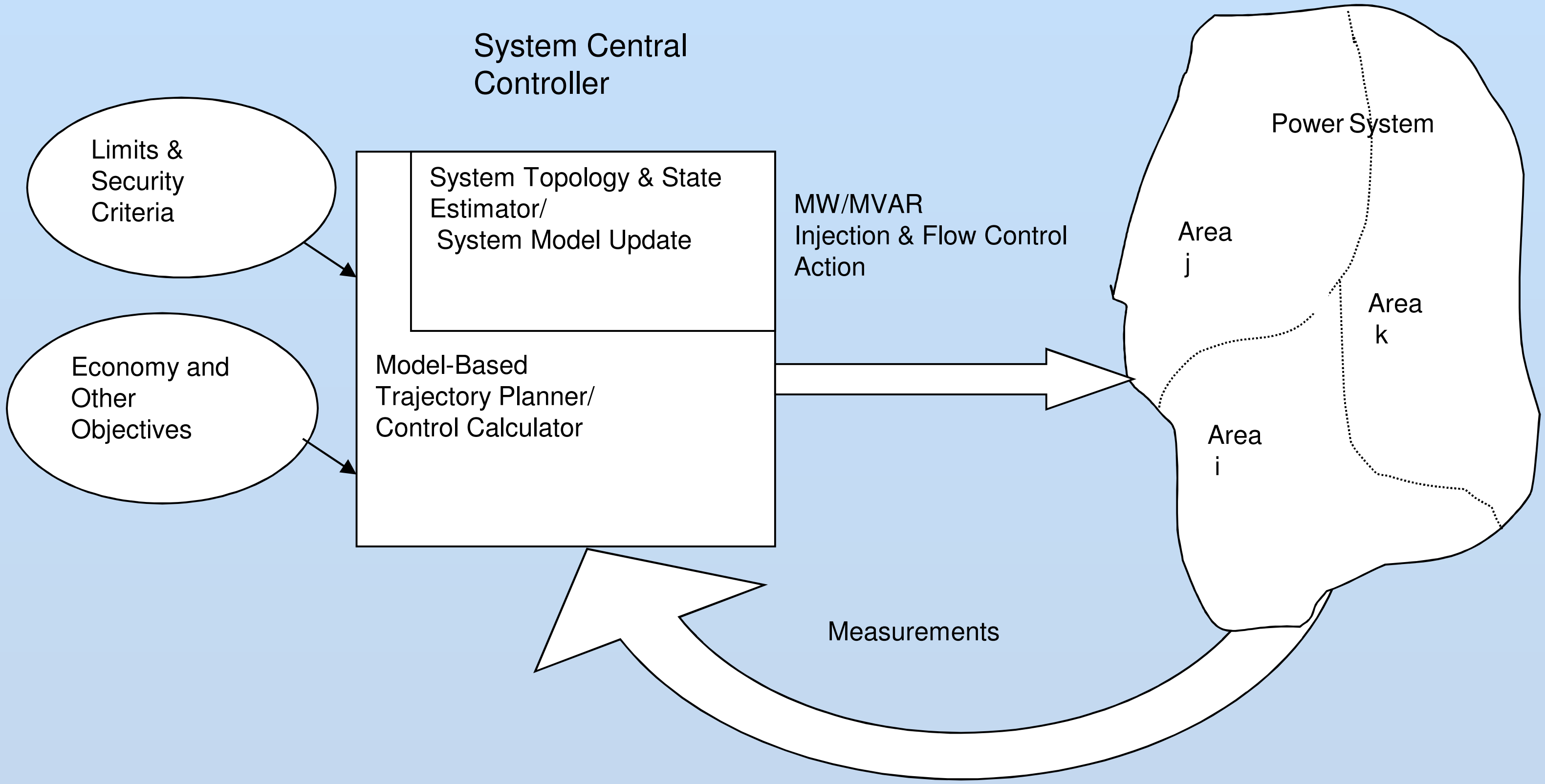
Measurement or information Quality PMU vs SCADA



Today We Rely on Larger Unused Power Transfer Capability Margins
A Price is Paid in Performance & Cost



The Ideal Power Grid Control Scenario- More Centralized Coordination & Automation

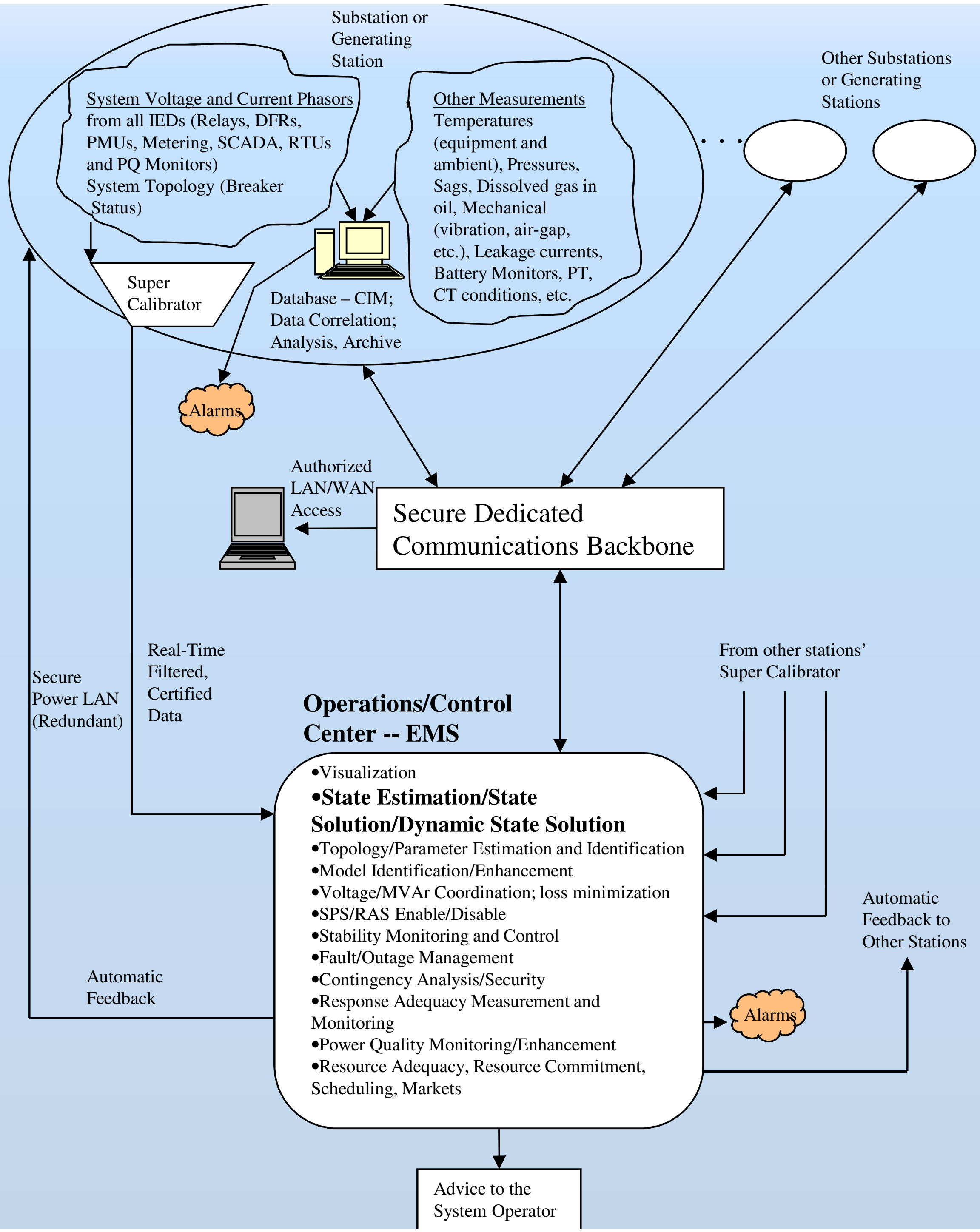


Hallmark of a Smarter Grid: More Centralized Coordination and Automation

- System-wide Automatic (Closed-Loop) Real Power Control Existing for Years – (keep the frequency at 60 Hz)-Can be further improved
- System-wide Closed-Loop Reactive Power Control--Not Quite Yet in the US!
- Sacrifices Made:
  - Less than ideal Performance
  - Large Unused Power Transfer Capability Margin Requirements

The Smarter Grid can get us closer to the ideal control and coordination scenario

A Future Architecture for Power Systems Operations and Control



Intelligent Use of Sensing and Communications

NYPA’s Smarter Grid Activities

Phasors and Analytics

- 20+ years history of PMU installations and data utilization for power grid Advanced Applications-DEO/NYISO SGIG collaboration
- Wide-area disturbance monitoring
- GIC (due to solar storms) monitoring
- Harmonics monitoring
- NYS model validation for dynamic studies-EPRI/NYISO
- Phasor-assisted State Estimation (with Siemens1999)
- The most advanced application being demonstrated at ECC– Direct Non-iterative State Estimation
- Next Generation EMS development and demonstration -- Advanced Grid Innovation Lab for electricity--AGILe

Hierarchical (Multi-Level) Control Structure