System-Wide Centrally Coordinated Power System Operation and Control
Challenges & Future Directions

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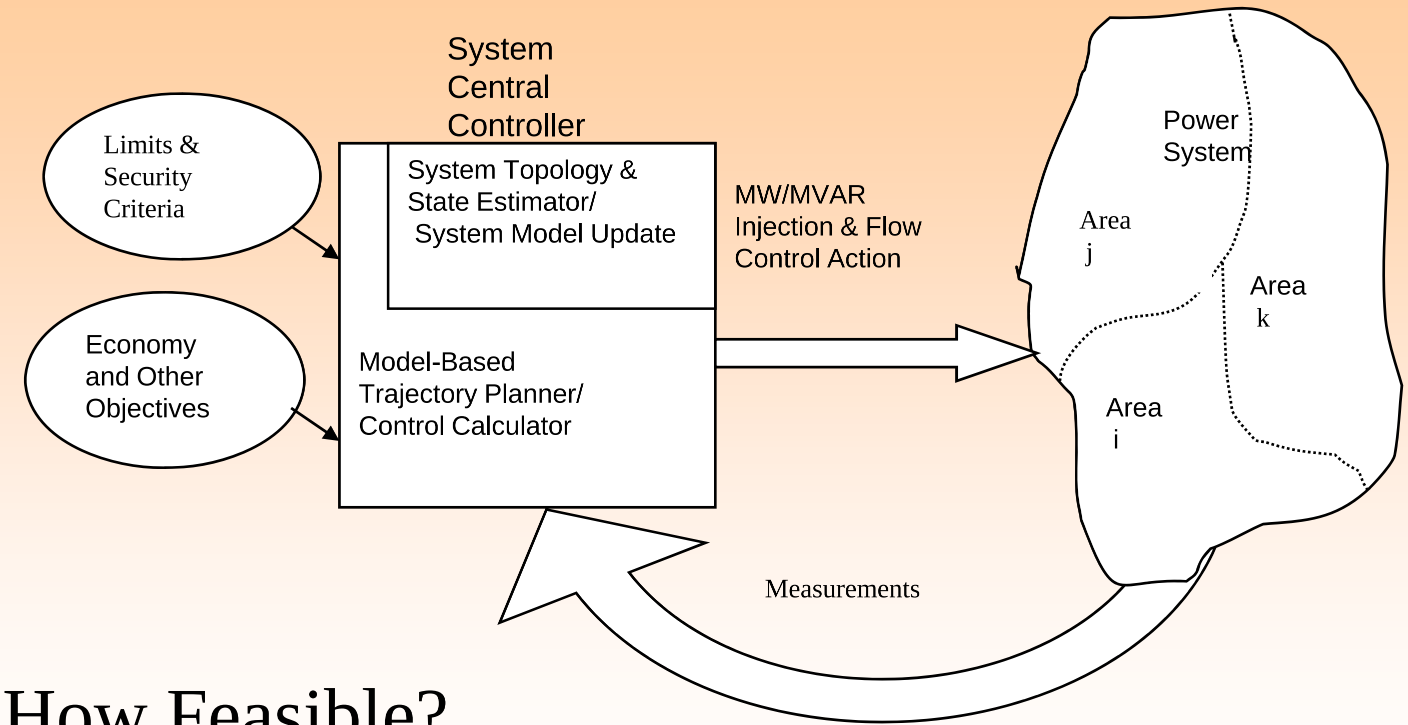
The Ideal Control Scenario- Centrality



How Feasible?

Limitations:

- Structural: Geographically Distributed Nature ⇒ Communications
- Computational Speed ⇒ Control Bandwidth
- Existence of Controllers ⇒ Infrastructure

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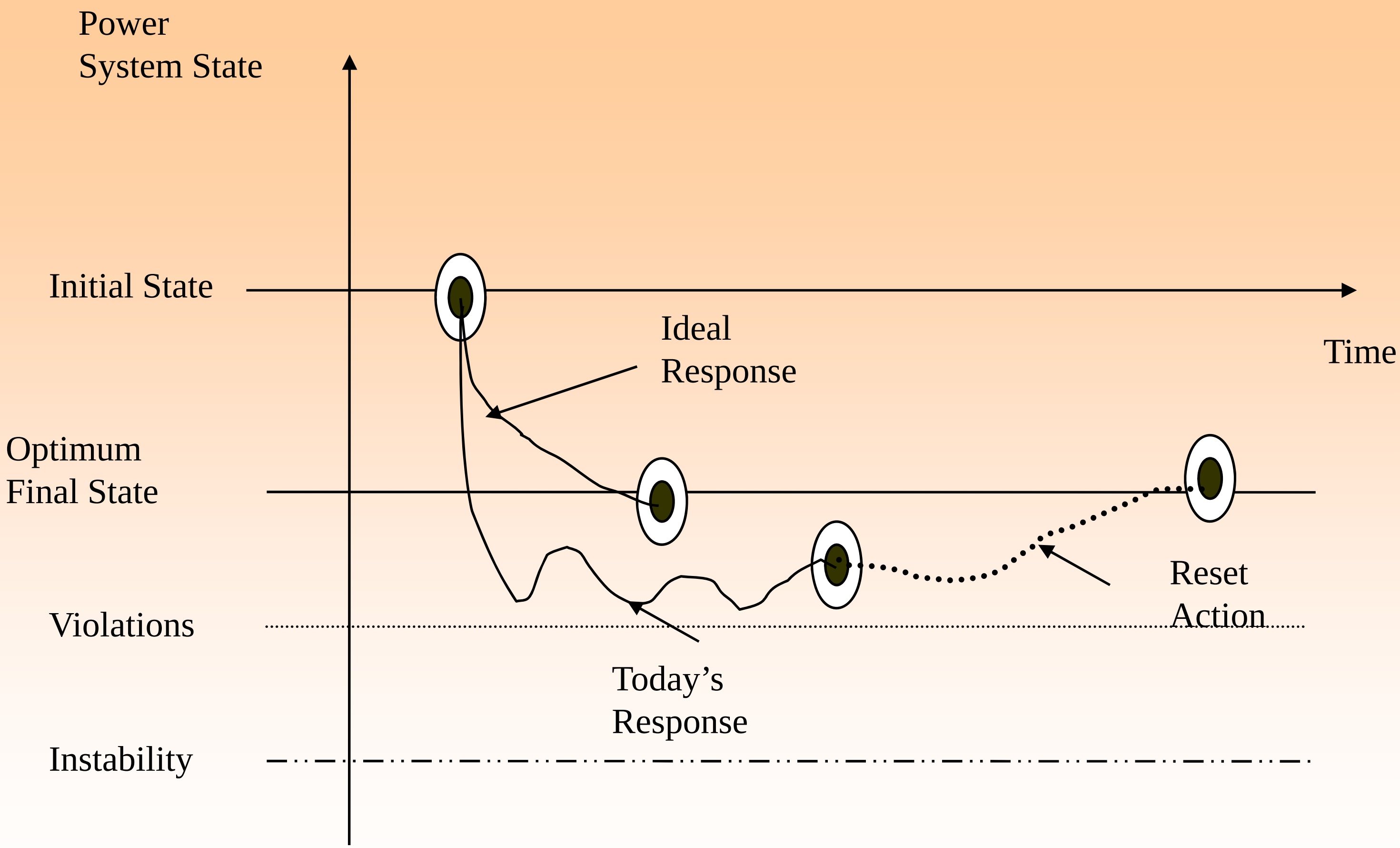
Relying on Margin- No Coordinated Active Steering
Price Paid in Performance & Cost



Solution- A Way Out

- Can still exert Centrality and Coordinated Control via Hierarchical (Multi-Level) Control
- Offers a Divide and Conquer Capability
- Complex in its True Form

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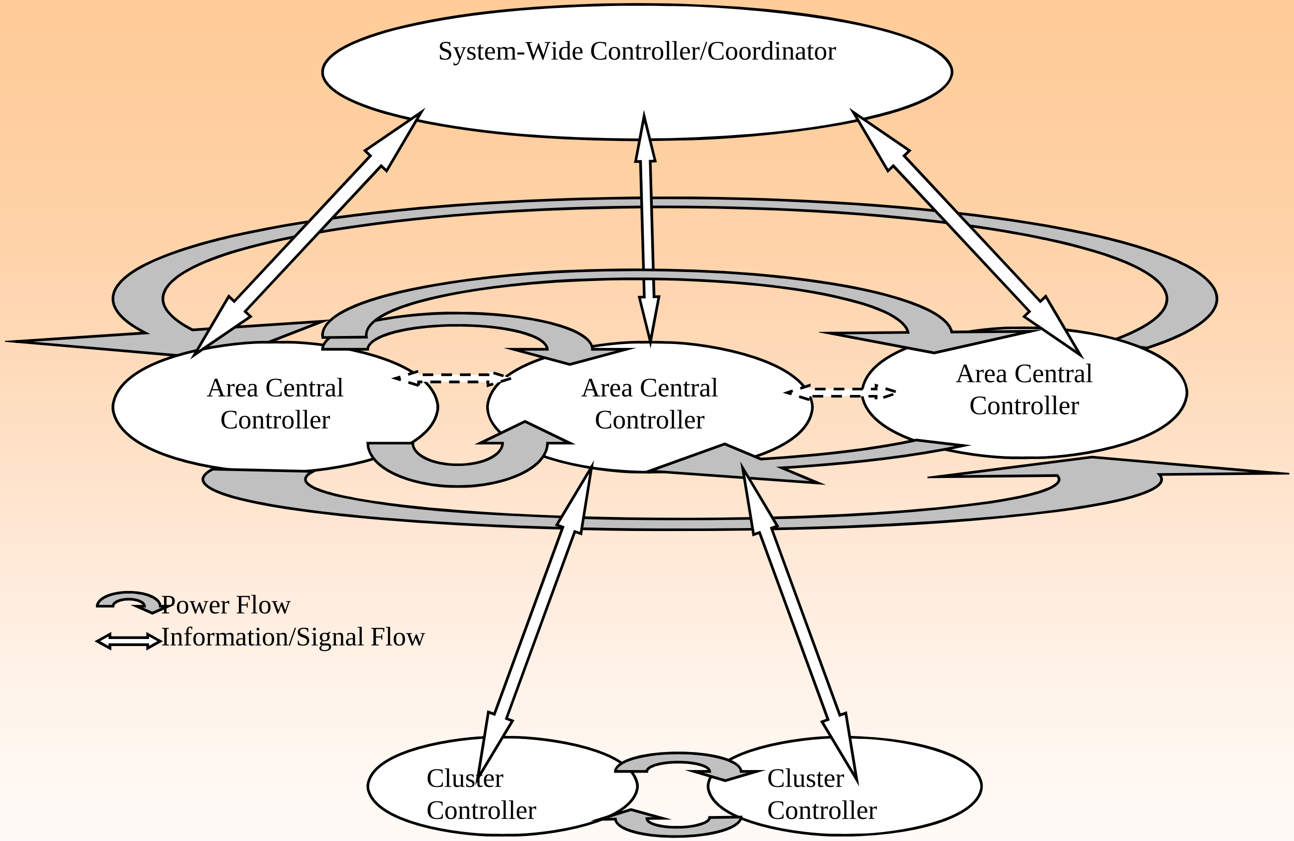
Hierarchical (Multi-Level) Control Structure



The Main Premise:

Minimization of operating margins or maximum utilization of existing transmission assets with heavier reliance on traditional as well as new control equipment, taking full advantage of high-bandwidth integrated and centrally-coordinated control of power injections and flows, with increased system security and reliability.

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Power System Operating Limits

- Transient and Small-Signal Stability
- Voltage Stability
- Thermal

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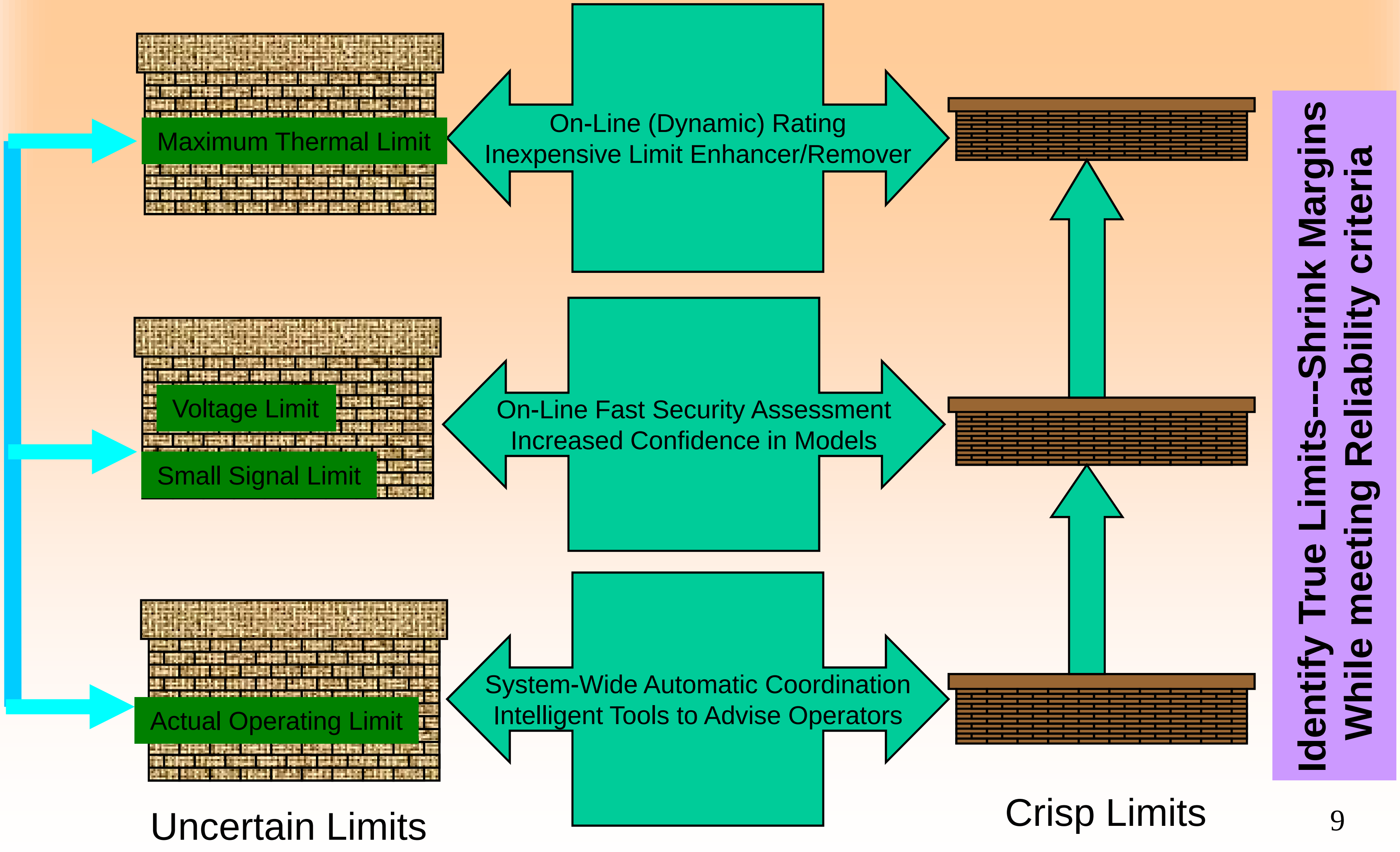
Uncertainty in Computed Limits



Power System Control Mechanisms

- Injection (Shunt) Controllers
  - Generator/AVR/PSS; Fixed Shunt Capacitors/Reactors(no fine control); Shunt FACTS Devices
- Routing (Series) Controllers
  - Fixed Series Capacitors/Reactors(no fine control) ; Phase-Shifters, Tap Changing Under Load Transformers (step-wise slow control); Series FACTS Devices

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Centralized Coordination

- A simpler form of Hierarchical Control:

  Centralized Set-Point Coordination
- Separate P and Q - Further Decomposition
- System-wide Automatic (Closed-Loop) Real Power Control Existing for Years
- System-wide Closed-Loop Reactive Power Control--Not Quite Yet!
- Sacrifices Made:

  Degraded Performance

  Large Margin Requirements

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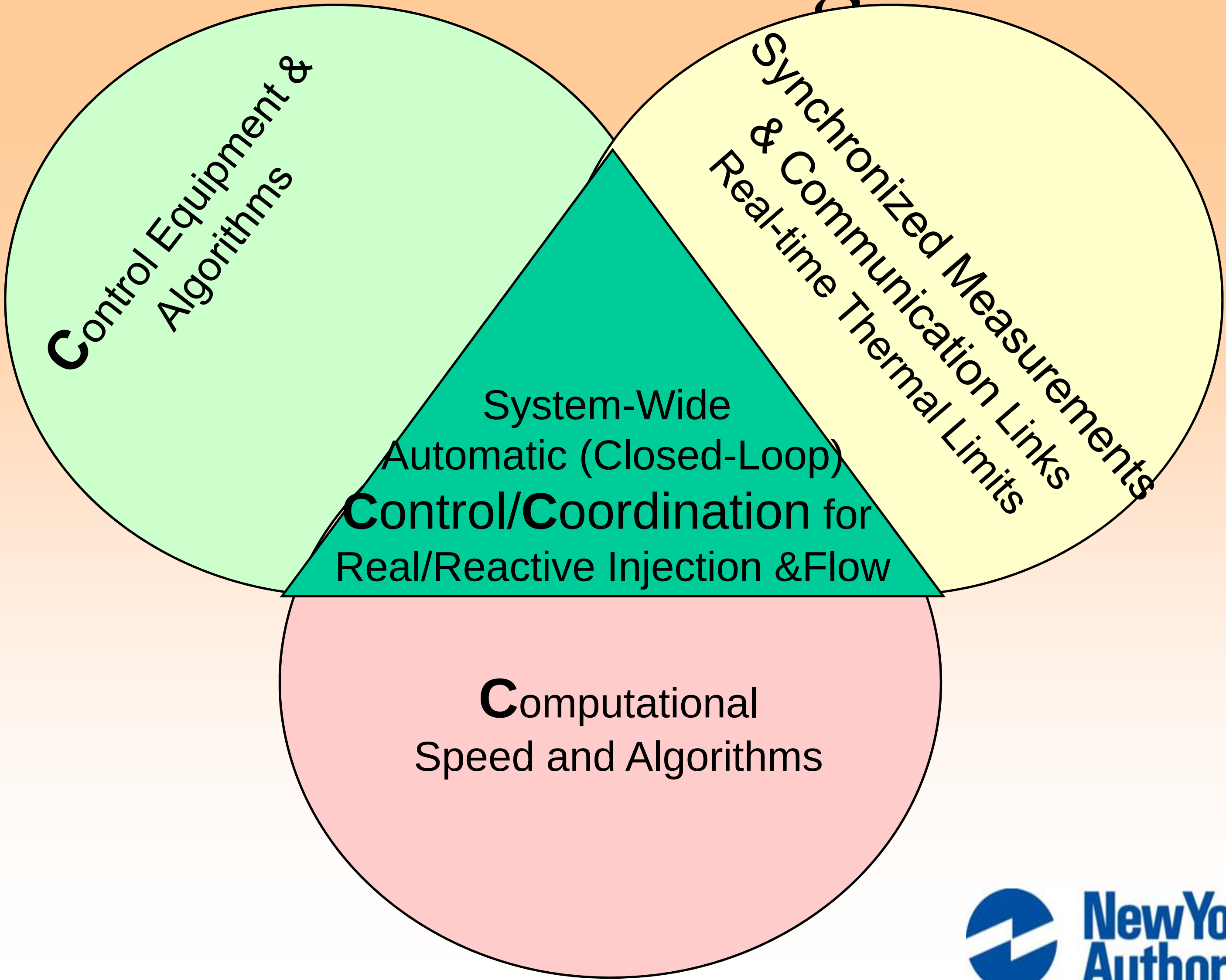
To Reduce Margins



Making a Case for Additional and Faster Coordinated Controls:

Then we will have to:

- Squeeze more of the existing margins on the power system
- Expand the transmission capability via compensation both fixed and variable
- Build only in new or existing substations and/or underground to deal with NIMBY or BNANA
- Rely on additional and Faster Coordinated Controls

Operating with Less Margin Means More Reliance on Controls

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Compensation and Control Solutions

- Usually a Hybrid of Switched Fixed and Vernier Control

Controller Requirements:

- Reliability/Redundancy
- Adaptability
- Flexibility

Voltage-Sourced Converter (VSC) Based Controllers offer such Potential

System-wide Automatic Power Control (SAPC)

- Centrally-Coordinated Hierarchical Real Power Control to achieve Maximum Utilization closer to Thermal Capacity of Transmission System
  - Stabilization
  - Frequency Control
  - Coordinated MW Injection and Flow Control
  - Phase-Angle Equalization and Reduction across the system
  - Reduce (Delay) the need for Transmission Expansion

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System-wide Automatic Voltage Control (SAVC)

- Centrally-Coordinated Hierarchical Voltage Control to achieve:
  - Voltage Stability
  - Voltage Profile Control
  - Coordinated MVAr Injection and Flow Control
  - Maximum Distance to Voltage Collapse
  - Reduced or Minimized Losses

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What is Needed?

Hardware:

- Fast-acting MW/MVAr injection/absorption and flow controllers including fast-dynamics generators and/or energy storage devices
- Adequate highly reliable less expensive VSC-based controllers
- Abundant highly reliable high-bandwidth communication networks
- EHV level solid-state or power electronics based breakers to for increased stability
- System-wide synchronous measurements for robust and fast state and parameter feedback

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What is Needed?

Algorithms and Faster Computing:

- Criteria for selection of feedback quantities for coordinated closed-loop power injection/flow control
- Determination of appropriate response rates of closed control loops
- Robust, adaptive, high-bandwidth control algorithms for large-scale structurally decentralized dynamic systems
- Faster computation capability to approach real-time optimization, coordination and control
- Proven robust hierarchical control algorithms to overcome the limitations in achieving wide-area integrated centralized controller performance
- System/equipment model identification and validation tools
- Faster algorithms for system topology and state estimation
- Parallel algorithms and faster computers

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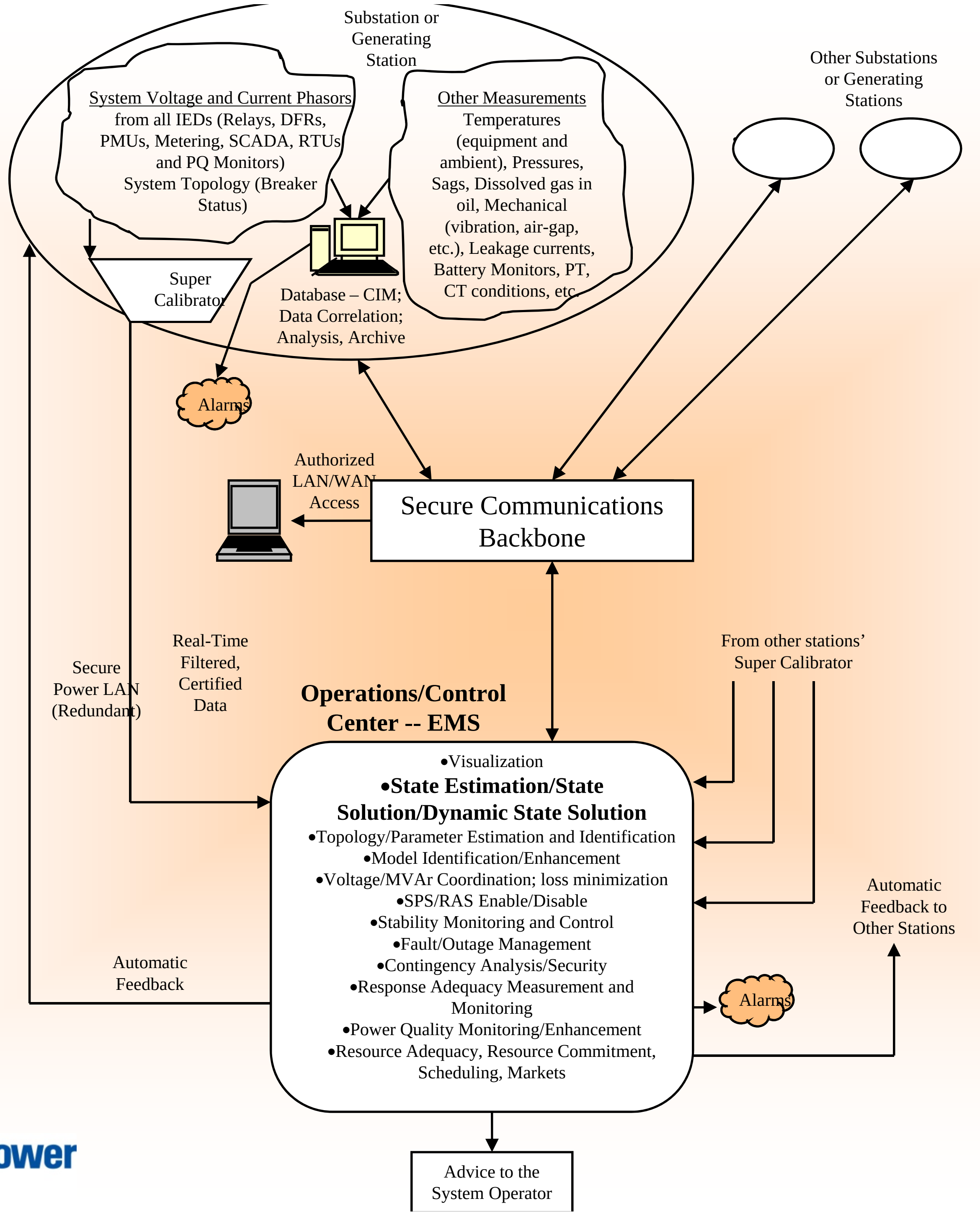
A Future Architecture for Power Systems Operations and Control



Intelligent Use of Sensing and Communications

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Direct Non-Iterative State Estimation: A New Paradigm

- A direct one-shot solution for the state of a power system is now possible
- Full AC solution
- No more iterations
- No reliance on the “goodness” of the initial guess
- An envisioned faster more robust solution

$$\begin{bmatrix} -241.5 & 2849 & 0 & 60 & 337 & 0 & 7.5 & 0 & -85 & 0 & -14.25 & -1989 & -1 & 0 \\ 64 & 0 & 260 & 156 & -17 & -10 & -6 & 0 & 0 & -30 & 0.5 & 0 & -25 & -9 \\ -163.5 & 1667 & -120 & -12 & 321 & -15 & -1.5 & 175 & 20 & 0 & -15 & -1700 & 0 & 0 \\ -13.5 & 97 & -26 & 0 & 10 & 1 & 0 & 0 & 0 & 3 & -0.75 & -17 & 5 & 0 \\ -90 & 10 & 0 & 0 & 118 & 0 & 5 & 0 & 0 & 0 & -9.75 & -1 & 0 & 0 \\ 0 & -85 & 0 & 0 & -9.5 & 0 & 0 & 0 & 5 & -1 & 0 & 117 & 0 & 0 \\ 0 & 0 & 29 & 26 & 0 & 10 & -1 & -100 & 0 & -4 & 0 & 0 & 10 & -3 \\ 0 & 5 & 0 & 26 & 0.5 & 0 & -1 & 0 & 0 & -5 & 0 & -1 & 0 & -3 \\ -162 & 3042 & 430 & 385 & -117 & 48 & 23.5 & -586 & -351 & -25 & 9.5 & 0 & 0 & -15 \\ 1125.5 & -11893 & 850 & -55 & -2120 & 95 & -40 & -1170 & 382 & -50 & 95 & 11700 & 0 & -5 \\ 231 & -2600 & 115 & -61 & 101 & -60 & -31 & 500 & 300 & -35 & -10 & 0 & -50 & -3 \\ 8 & -26 & -25 & -15 & 1 & -1.5 & -1.5 & 5 & 3 & 0 & -0.5 & 0 & 0 & 0 \\ -64.5 & 529 & -50 & -5 & 60 & -5 & 0.5 & 10 & 1 & 0 & -5 & -100 & 0 & 0 \\ 0 & 0 & 0 & -12 & 0 & 0 & -1.5 & 1 & 17 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \\ t_9 \\ t_{10} \\ t_{11} \\ t_{12} \\ t_{13} \\ t_{14} \end{bmatrix} = \begin{bmatrix} 1020 \\ 676 \\ 348 \\ 60 \\ 25 \\ 0 \\ 0 \\ 0 \\ 2210 \\ -2465 \\ -754 \\ -130 \\ 145 \\ 0 \end{bmatrix}$$

A Simple Example

$$\begin{bmatrix} -241.5 & 2849 & 0 & 60 & 337 & 0 & 7.5 & 0 & -85 & 0 & -14.25 & -1989 & -1 & 0 \\ 64 & 0 & 260 & 156 & -17 & -10 & -6 & 0 & 0 & -30 & 0.5 & 0 & -25 & -9 \\ -163.5 & 1667 & -120 & -12 & 321 & -15 & -1.5 & 175 & 20 & 0 & -15 & -1700 & 0 & 0 \\ -13.5 & 97 & -26 & 0 & 10 & 1 & 0 & 0 & 0 & 3 & -0.75 & -17 & 5 & 0 \\ -90 & 10 & 0 & 0 & 118 & 0 & 5 & 0 & 0 & 0 & -9.75 & -1 & 0 & 0 \\ 0 & -85 & 0 & 0 & -9.5 & 0 & 0 & 0 & 5 & -1 & 0 & 117 & 0 & 0 \\ 0 & 0 & 29 & 26 & 0 & 10 & -1 & -100 & 0 & -4 & 0 & 0 & 10 & -3 \\ 0 & 5 & 0 & 26 & 0.5 & 0 & -1 & 0 & 0 & -5 & 0 & -1 & 0 & -3 \\ -162 & 3042 & 430 & 385 & -117 & 48 & 23.5 & -586 & -351 & -25 & 9.5 & 0 & 0 & -15 \\ 1125.5 & -11893 & 850 & -55 & -2120 & 95 & -40 & -1170 & 382 & -50 & 95 & 11700 & 0 & -5 \\ 231 & -2600 & 115 & -61 & 101 & -60 & -31 & 500 & 300 & -35 & -10 & 0 & -50 & -3 \\ 8 & -26 & -25 & -15 & 1 & -1.5 & -1.5 & 5 & 3 & 0 & -0.5 & 0 & 0 & 0 \\ -64.5 & 529 & -50 & -5 & 60 & -5 & 0.5 & 10 & 1 & 0 & -5 & -100 & 0 & 0 \\ 0 & 0 & 0 & -12 & 0 & 0 & -1.5 & 1 & 17 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \\ t_9 \\ t_{10} \\ t_{11} \\ t_{12} \\ t_{13} \\ t_{14} \end{bmatrix} = \begin{bmatrix} 1020 \\ 676 \\ 348 \\ 60 \\ 25 \\ 0 \\ 0 \\ 0 \\ 2210 \\ -2465 \\ -754 \\ -130 \\ 145 \\ 0 \end{bmatrix}$$

- Redundant Polynomial Equations

$$x_1^2 - 2x_1x_2 + x_3^2 + x_2 = 8$$

$$2x_2x_3 - x_2^2 + 2x_1 = 10$$

$$5x_1x_3 - x_1x_2 + 3x_3 + x_2^2 = 26$$

$$7x_1^2 - 2x_2x_3 + x_3^2 - 5x_3 = -11$$

$$x_1^2 - x_2^2 - 5x_2x_3 + 12x_1 = -13$$

$$\begin{bmatrix} -241.5 & 2849 & 0 & 60 & 337 & 0 & 7.5 & 0 & -85 & 0 & -14.25 & -1989 & -1 & 0 \\ 64 & 0 & 260 & 156 & -17 & -10 & -6 & 0 & 0 & -30 & 0.5 & 0 & -25 & -9 \\ -163.5 & 1667 & -120 & -12 & 321 & -15 & -1.5 & 175 & 20 & 0 & -15 & -1700 & 0 & 0 \\ -13.5 & 97 & -26 & 0 & 10 & 1 & 0 & 0 & 0 & 3 & -0.75 & -17 & 5 & 0 \\ -90 & 10 & 0 & 0 & 118 & 0 & 5 & 0 & 0 & 0 & -9.75 & -1 & 0 & 0 \\ 0 & -85 & 0 & 0 & -9.5 & 0 & 0 & 0 & 5 & -1 & 0 & 117 & 0 & 0 \\ 0 & 0 & 29 & 26 & 0 & 10 & -1 & -100 & 0 & -4 & 0 & 0 & 10 & -3 \\ 0 & 5 & 0 & 26 & 0.5 & 0 & -1 & 0 & 0 & -5 & 0 & -1 & 0 & -3 \\ -162 & 3042 & 430 & 385 & -117 & 48 & 23.5 & -586 & -351 & -25 & 9.5 & 0 & 0 & -15 \\ 1125.5 & -11893 & 850 & -55 & -2120 & 95 & -40 & -1170 & 382 & -50 & 95 & 11700 & 0 & -5 \\ 231 & -2600 & 115 & -61 & 101 & -60 & -31 & 500 & 300 & -35 & -10 & 0 & -50 & -3 \\ 8 & -26 & -25 & -15 & 1 & -1.5 & -1.5 & 5 & 3 & 0 & -0.5 & 0 & 0 & 0 \\ -64.5 & 529 & -50 & -5 & 60 & -5 & 0.5 & 10 & 1 & 0 & -5 & -100 & 0 & 0 \\ 0 & 0 & 0 & -12 & 0 & 0 & -1.5 & 1 & 17 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \\ t_9 \\ t_{10} \\ t_{11} \\ t_{12} \\ t_{13} \\ t_{14} \end{bmatrix} = \begin{bmatrix} 1020 \\ 676 \\ 348 \\ 60 \\ 25 \\ 0 \\ 0 \\ 0 \\ 2210 \\ -2465 \\ -754 \\ -130 \\ 145 \\ 0 \end{bmatrix}$$

- Dual Transformation and Direct One-Shot Solution

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A Power System State Estimator/Solver

- Bus power injection equations in Rectangular from
- Naturally in the desired form:

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

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

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

- Other Measurement equations have similar form

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Envisioned Benefits

$$\begin{bmatrix} -241.5 & 2849 & 0 & 60 & 337 & 0 & 7.5 & 0 & -85 & 0 & -14.25 & -1989 & -1 & 0 \\ 64 & 0 & 260 & 156 & -17 & -10 & -6 & 0 & 0 & -30 & 0.5 & 0 & -25 & -9 \\ -163.5 & 1667 & -120 & -12 & 321 & -15 & -1.5 & 175 & 20 & 0 & -15 & -1700 & 0 & 0 \\ -13.5 & 97 & -26 & 0 & 10 & 1 & 0 & 0 & 0 & 3 & -0.75 & -17 & 5 & 0 \\ -90 & 10 & 0 & 0 & 118 & 0 & 5 & 0 & 0 & 0 & -9.75 & -1 & 0 & 0 \\ 0 & -85 & 0 & 0 & -9.5 & 0 & 0 & 0 & 5 & -1 & 0 & 117 & 0 & 0 \\ 0 & 0 & 29 & 26 & 0 & 10 & -1 & -100 & 0 & -4 & 0 & 0 & 10 & -3 \\ 0 & 5 & 0 & 26 & 0.5 & 0 & -1 & 0 & 0 & -5 & 0 & -1 & 0 & -3 \\ -162 & 3042 & 430 & 385 & -117 & 48 & 23.5 & -586 & -351 & -25 & 9.5 & 0 & 0 & -15 \\ 1125.5 & -11893 & 850 & -55 & -2120 & 95 & -40 & -1170 & 382 & -50 & 95 & 11700 & 0 & -5 \\ 231 & -2600 & 115 & -61 & 101 & -60 & -31 & 500 & 300 & -35 & -10 & 0 & -50 & -3 \\ 8 & -26 & -25 & -15 & 1 & -1.5 & -1.5 & 5 & 3 & 0 & -0.5 & 0 & 0 & 0 \\ -64.5 & 529 & -50 & -5 & 60 & -5 & 0.5 & 10 & 1 & 0 & -5 & -100 & 0 & 0 \\ 0 & 0 & 0 & -12 & 0 & 0 & -1.5 & 1 & 17 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \\ t_9 \\ t_{10} \\ t_{11} \\ t_{12} \\ t_{13} \\ t_{14} \end{bmatrix} = \begin{bmatrix} 1020 \\ 676 \\ 348 \\ 60 \\ 25 \\ 0 \\ 0 \\ 0 \\ 2210 \\ -2465 \\ -754 \\ -130 \\ 145 \\ 0 \end{bmatrix}$$

- Direct State Estimation
- More robust– No more iterations
- No reliance on the initial guess
- Faster– 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

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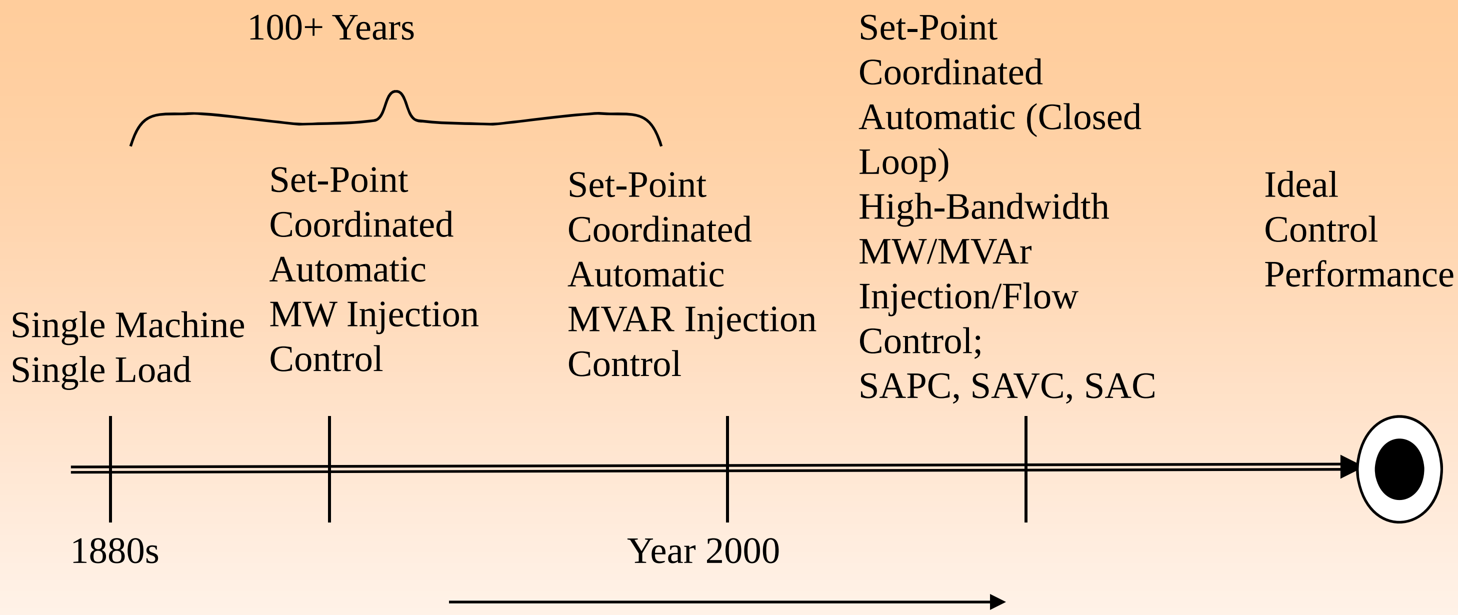
A Historic Perspective



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