Ultra-Large Scale Distributed Control for Electric Power Grids

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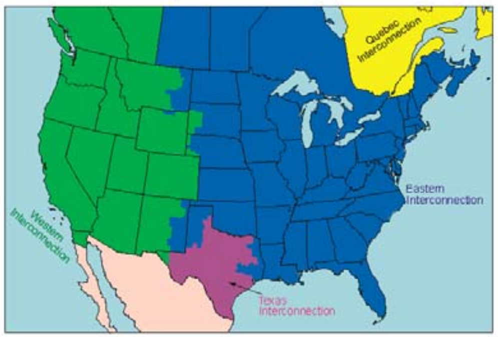
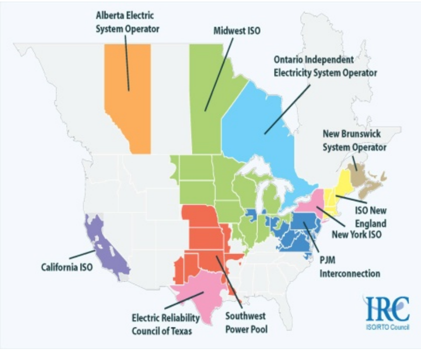
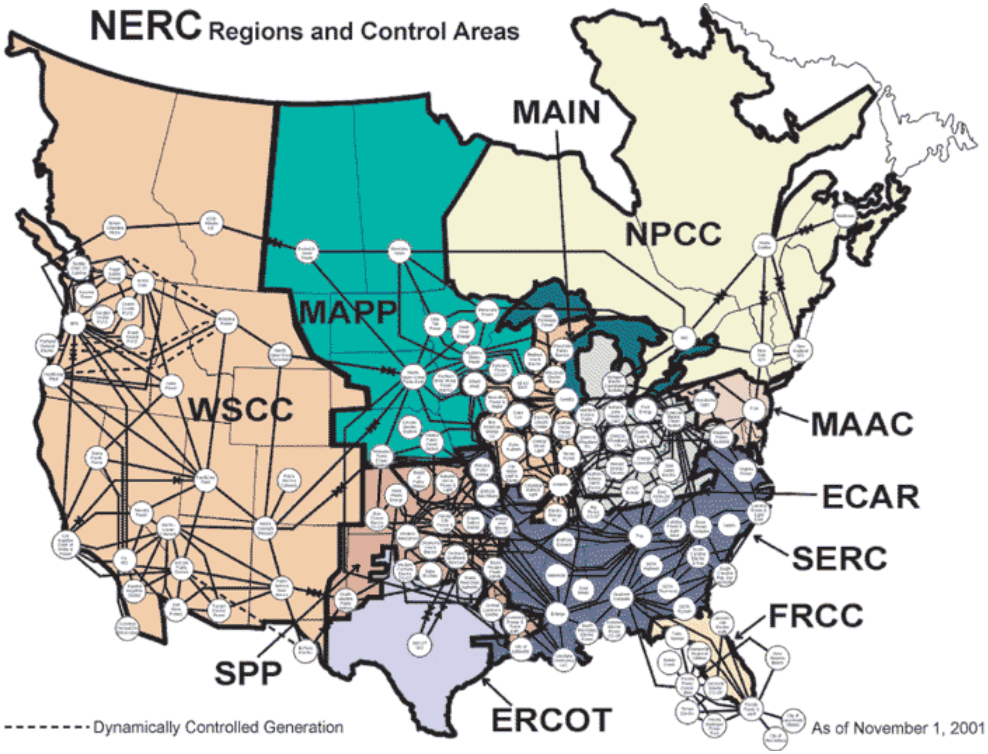
Electric Grid Background

- Highly complex interaction of devices, systems, and organizations
- Low observability
- Thousands of siloed control systems
- Based on load-following and balancing as key control principles
- Some meshing at transmission level
- Distribution treated as floating on transmission
- Distribution power flows presumed unidirectional

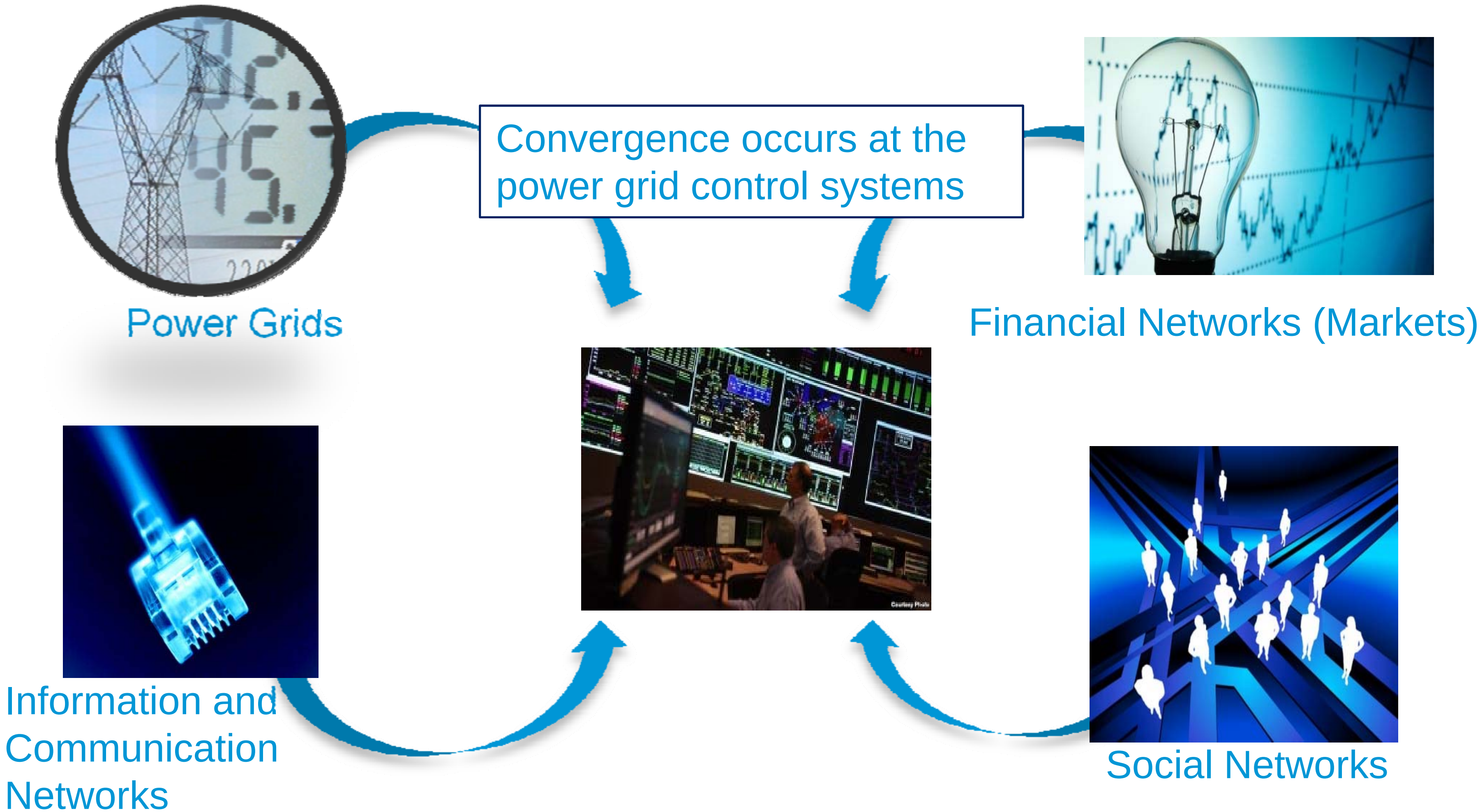
Interconnections of the North American Electric Reliability Council in the Contiguous United States, 1998







Grid Integration Turns Out To Be About Something Much Larger than Meters or “Smart Objects”



It is the decision and control systems and processes that cause business outcomes

emerging power grid issues

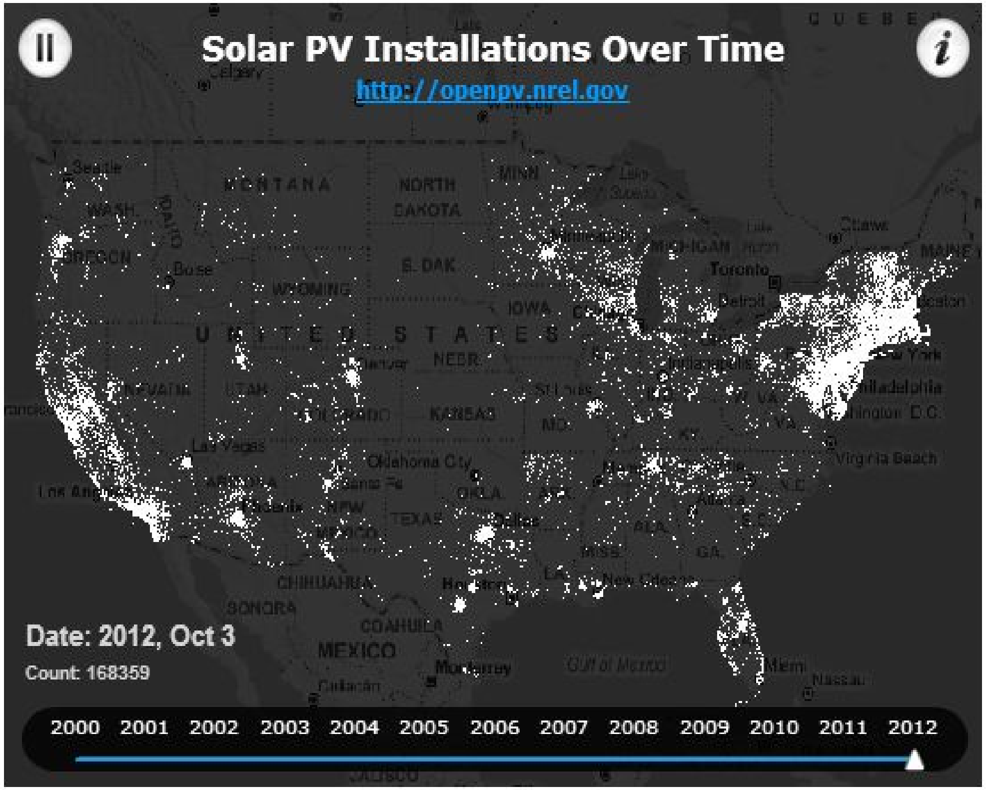
Advanced Grid Management Issues

- Grid stabilized by inherent rotational inertia
- Dispatchable generation
- Passive loads
- Moderate digital control is adequate

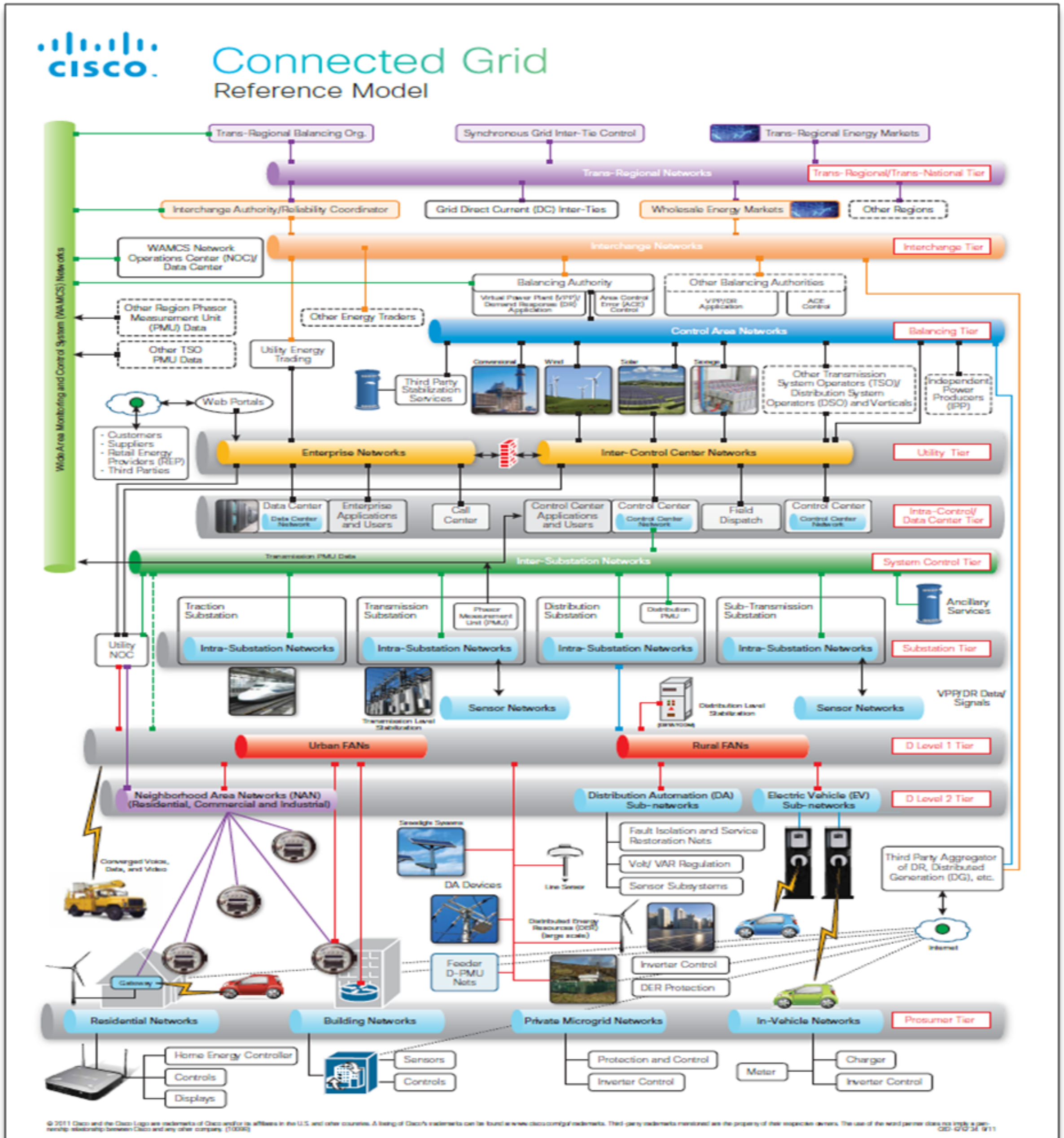
- Reduced rotational inertia due to change in energy source mix
- Stochastic generation (DER/VER)
- Transactive loads and markets
- Grid control as we know it is not adequate

US Key Utility Transitions

- Extensive connectivity with greatly increased security
- Centralized to distributed control and intelligence
  - Destabilizing effects are accumulating rapidly and irreversibly
  - “Human in the Loop” is not sustainable or scalable



Increasing Scope of Networking



Issue: Faster System Dynamics

Standard Grid Management	Advanced Grid Management
Distribution Voltage/Reactive Power control Response times: 5 minutes to hours	Distribution V/VAr (DG/DS/Load Modulation) Response times: msec to sub-second
Transmission Level Stabilization (Ancillary Services) Response times 6-30 minutes	Transmission Level Stabilization Response times < 1 second
Distribution Level Stabilization Not typically done	Distribution Level Stabilization Response times 32-300 msec
Distribution Fault Isolation (Manual Control) Response times: minutes to hours	Distribution Fault Isolation/Service Restoration Response times: sub-second to sub-minute

Response times, sample rates, latencies all are shortening by two or more orders of magnitude.

"Human-in-the-loop" is not sustainable going forward.

Issue: Hidden Coupling via the Grid

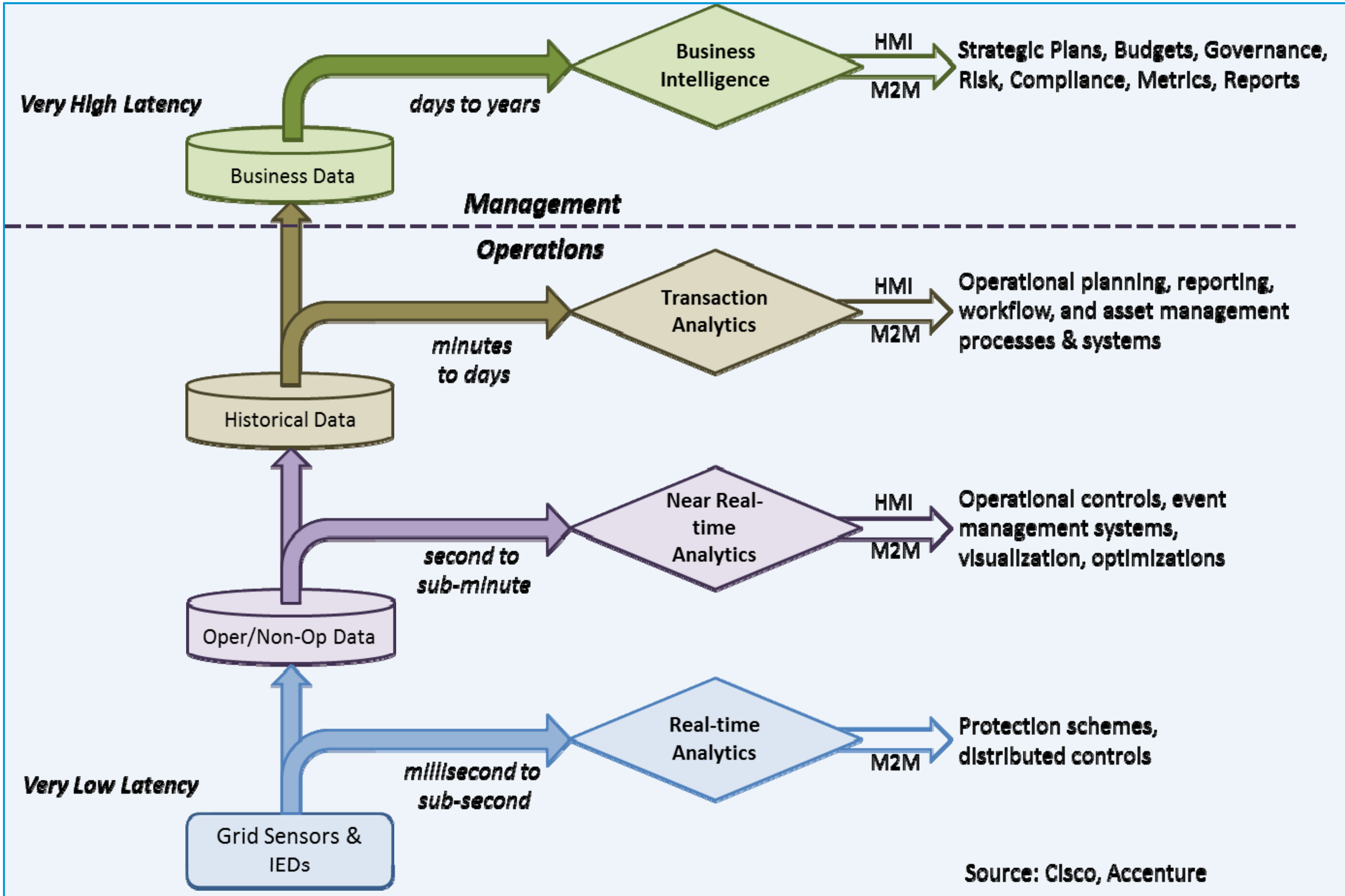
- Electrical physics rules the grid – shaped by grid connectivity
- Business models and software cannot change this
- Must be taken into account in control design to avoid unintended consequences
  - IVVR/DR example
  - CVR/PV example
  - market/responsive load example
- Becomes important as new rollouts of smart devices scale to full deployment
- Implications for architecture, design, and control

Jose Medina, Nelson Muller, and Ilya Roytelman, "Demand Response and Distribution Grid Operations: Opportunities and Challenges," **IEEE Trans. On Smart Grid**, vol. 1, pp. 193-198, Sept. 2010.

Issue: Synchronized Measurement

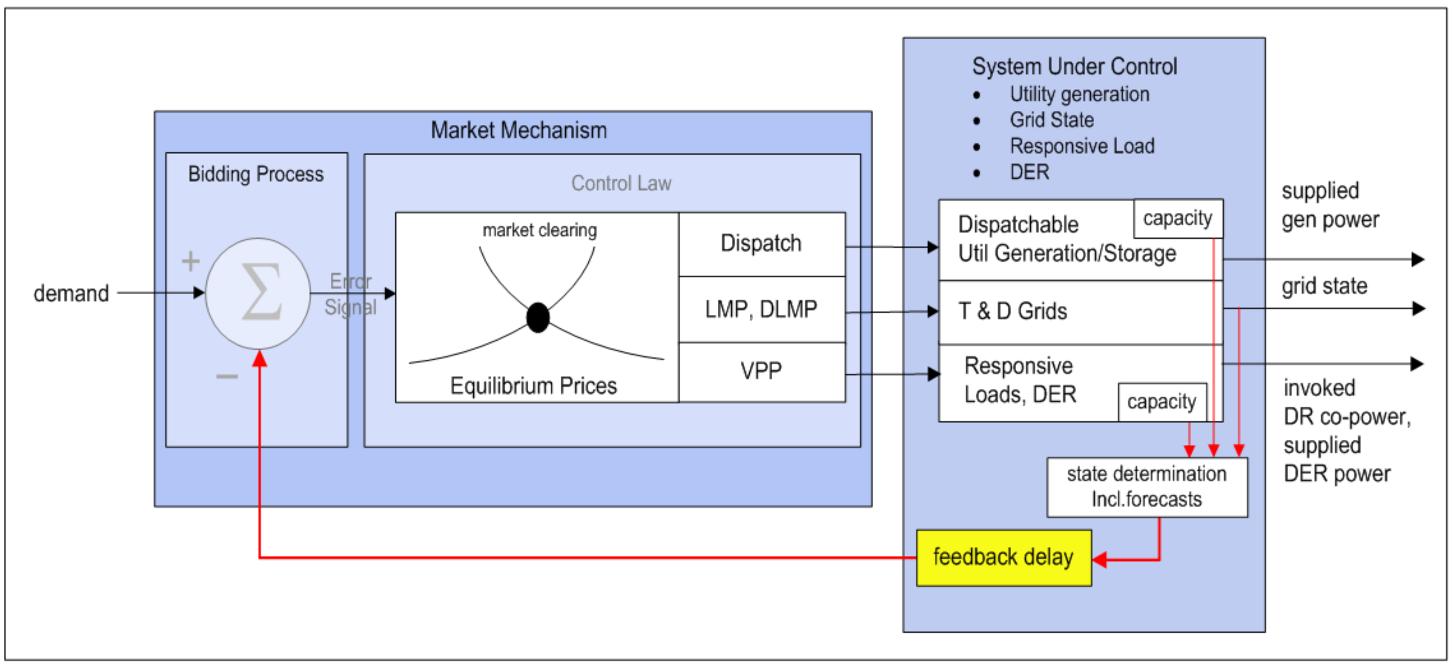
- Traditional Distribution SCADA does round-robin polling of endpoints
  - 4 second cycle to collect all points is common today, no synchronization
- Measures RMS voltage, RMS current, real and reactive power
  - Optionally, a few harmonics for power quality
  - No phasor measurement; data is time skewed
- All this is changing for advanced DA:
  - Need for phase measurements
  - Therefore, need synchronized measurement (synchrophasors)
  - Some can be done in substation, but this is not adequate for many functions
  - Need distributed, synchronized SCADA

Data Latency Hierarchy



Issue: New Instability Sources

- Variable Energy Resources; reduction in rotational inertia in grid
- Some elements may reside outside of the utility: responsive loads, DG/DER
- Energy Services Organizations operating outside grid control regime
- Inter-tier control loops
- Active load interactions with grid control systems can be unstable; volatility of grid with price sensitive loads; markets as control elements: flash crashes

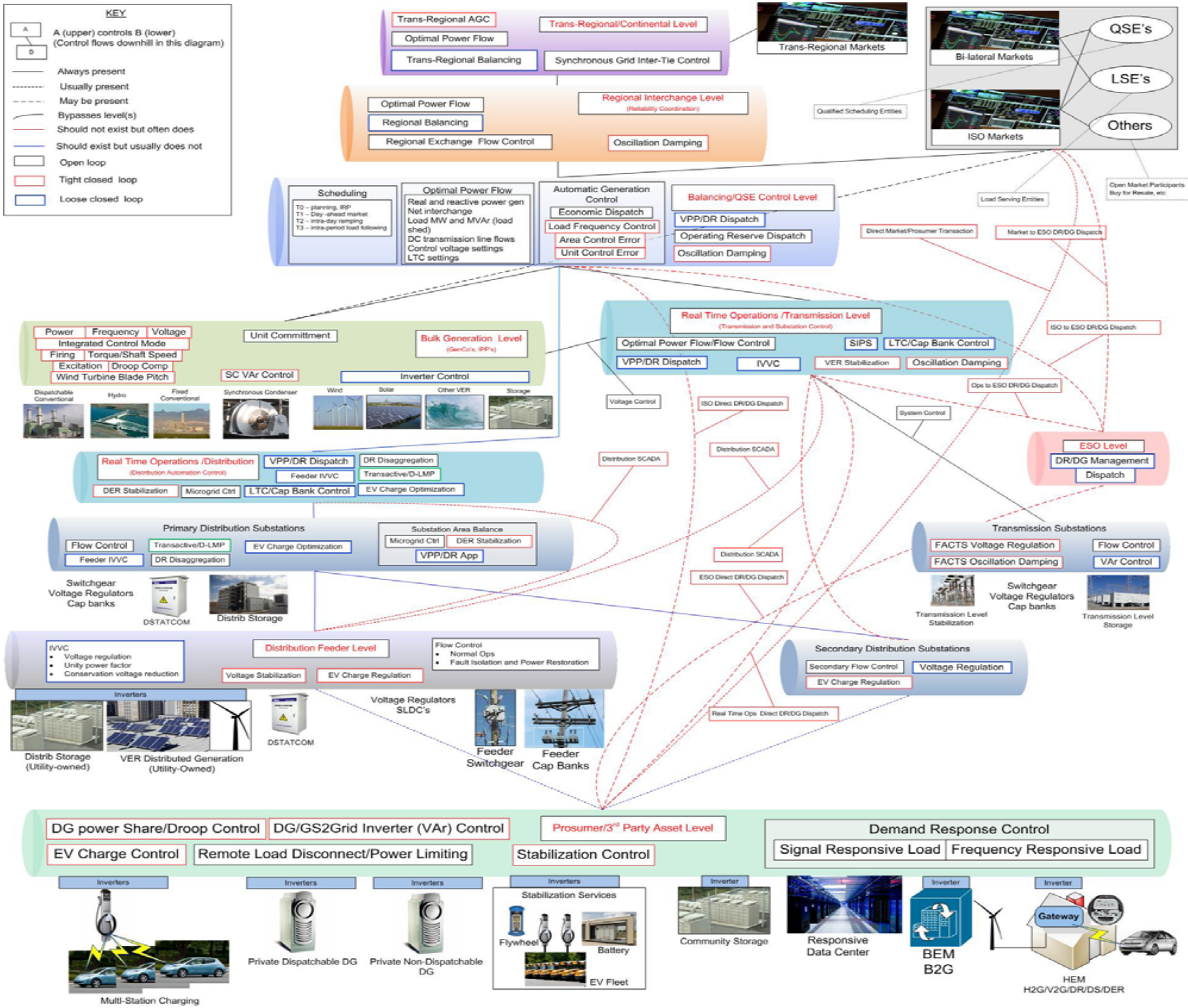


"Volatility of Power Grids Under Real Time Pricing", [www.mit.edu/~mardavij/publications_files/**Volatility**.pdf](www.mit.edu/~mardavij/publications_files/Volatility.pdf)

Issue: Lack of Observability and Coordination

- Observability improving now
  - PMU networks for transmission
  - SCADA for distribution; DER/responsive load forecasting
  - Distribution PMU’s are coming
  - Networked grid devices (IED’s)
- Network and data management implications
  - Low latency
  - Multiple data classes, including streaming
- Need to coordinate hierarchical control over wide areas
  - Federation and disaggregation
  - Constraint fusion
  - Boundary deference
  - 3rd party connectivity

Issue: Emerging Structural Chaos

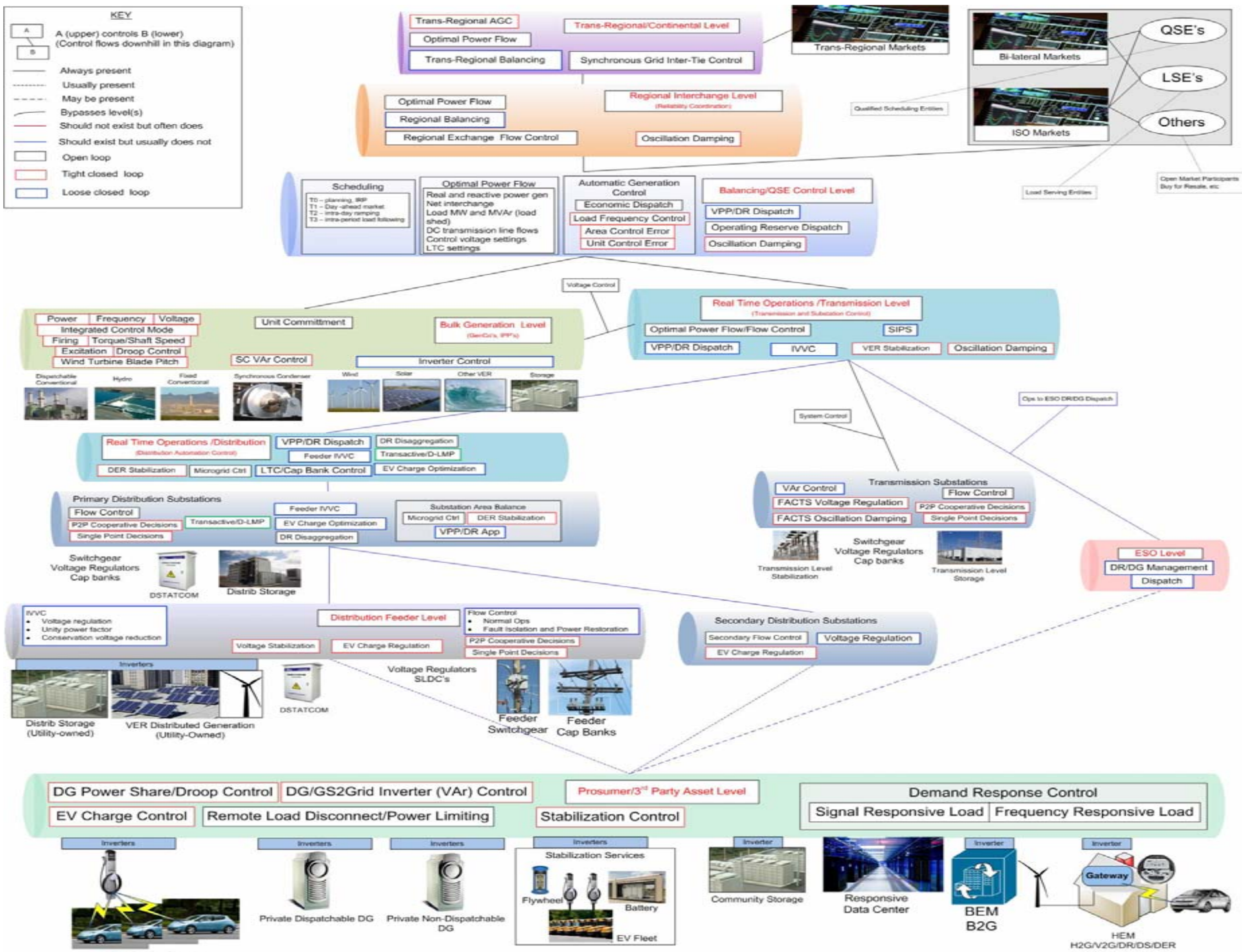


ultra large scale control

What to Do

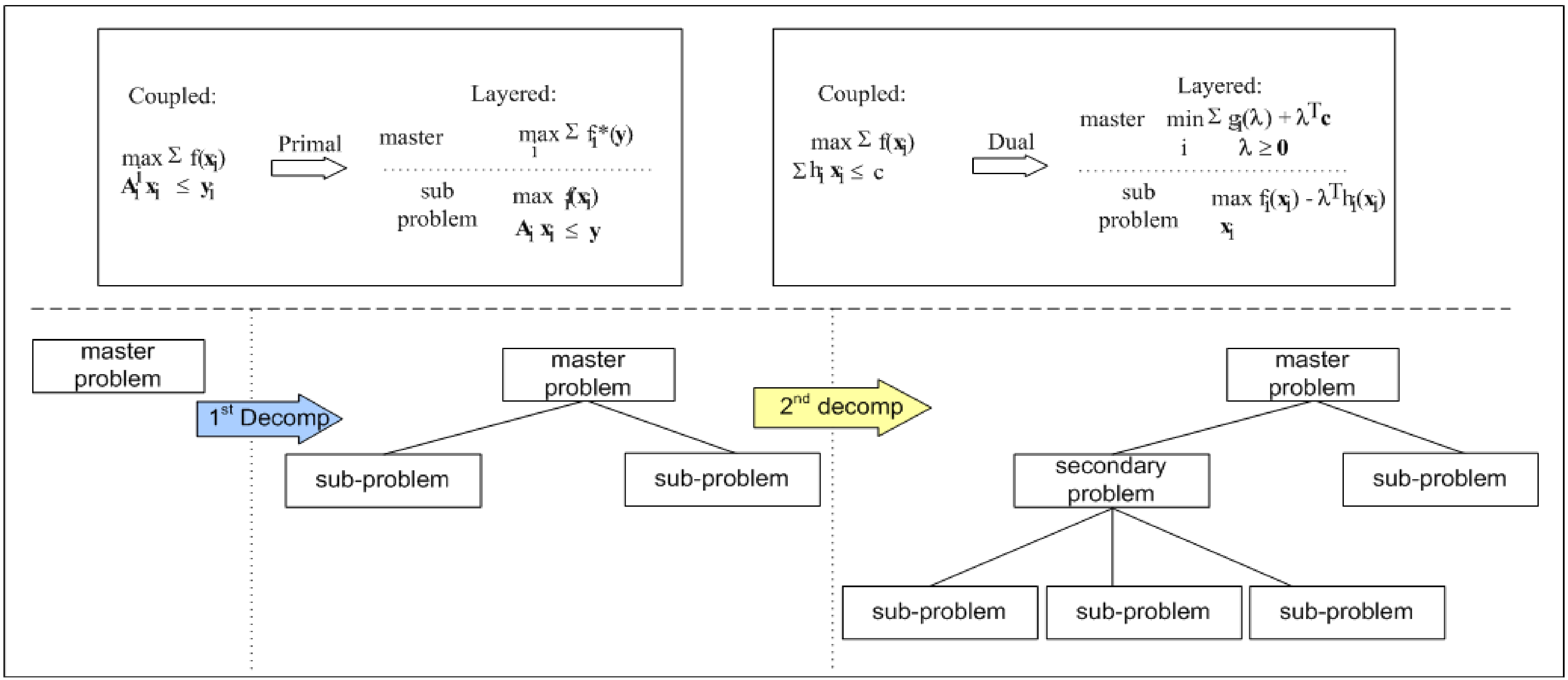
- Regularize the structure
    - Eliminate “tier hopping” control
    - Avoid closing loops around multiple tiers
    - Use the layer architectural paradigm
- Introduce layered optimization
    - Can match inherent grid hierarchy
    - Can match functional boundaries
- Distribute the control
    - Flows logically from the first two steps
    - Preserves much traditional control
    - Addresses new control needs

1. Regularize the Structure

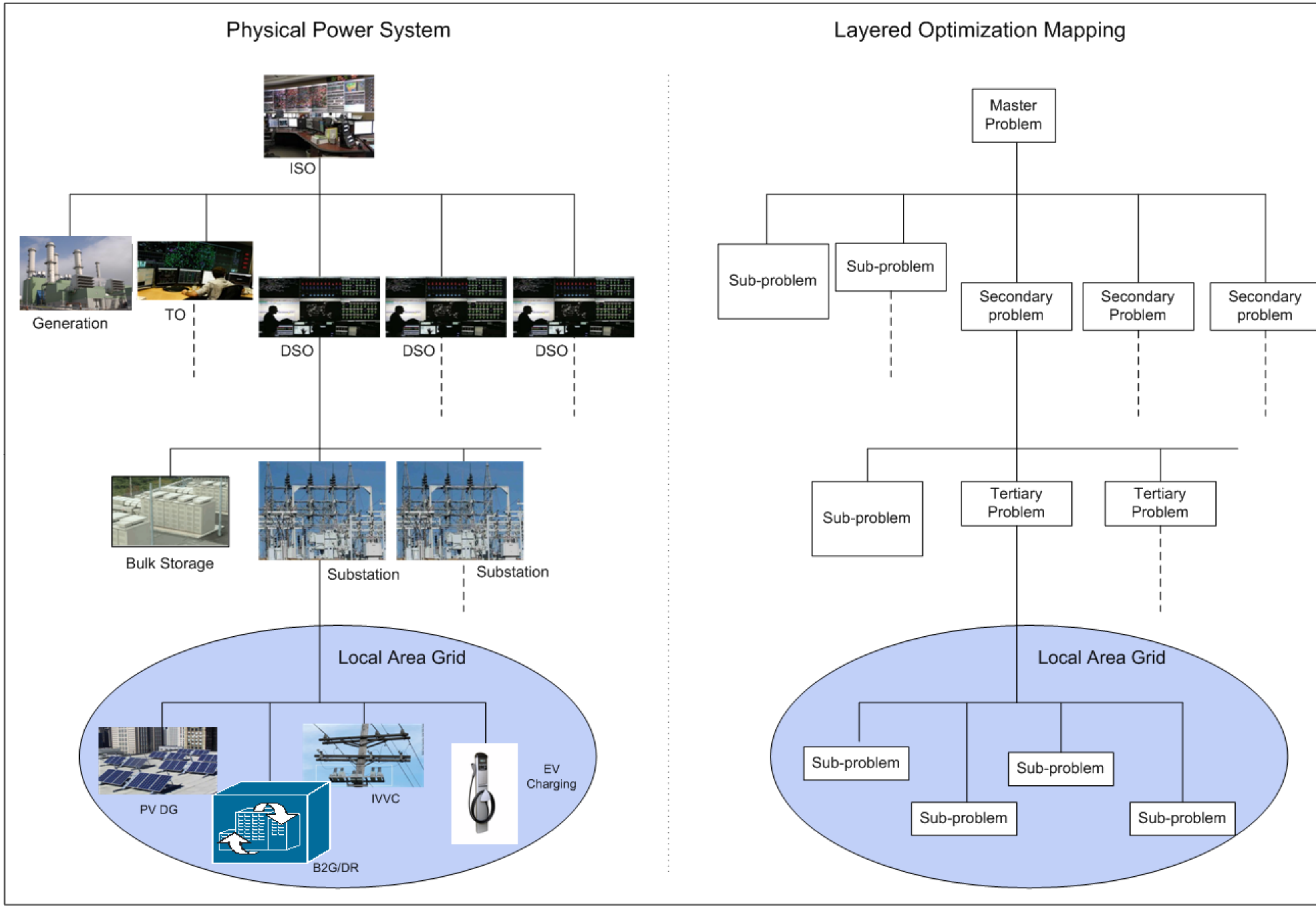


2. Introduce NUM-based Layered Optimization for Hierarchical Coordination

- Can use optimization techniques to design complex controls
- Benefits from layered architectural paradigm

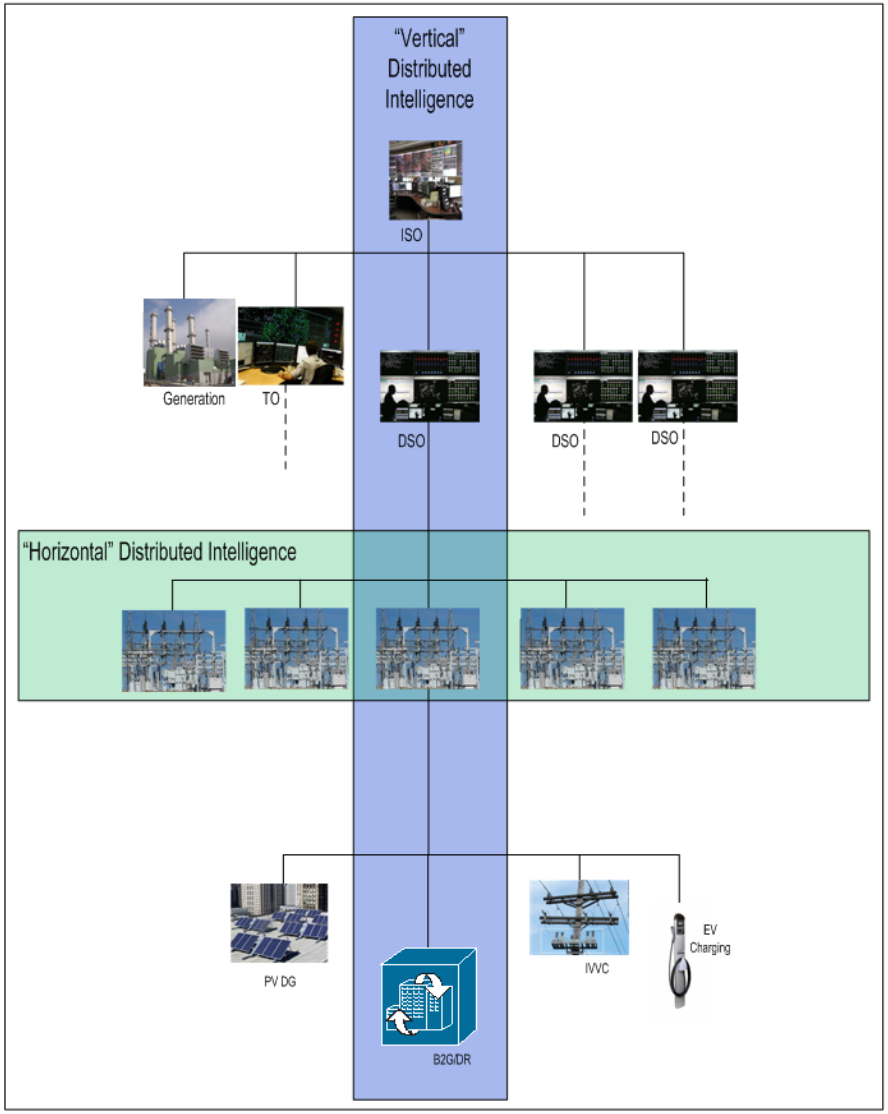


Mapping Optimization Layers to the Grid



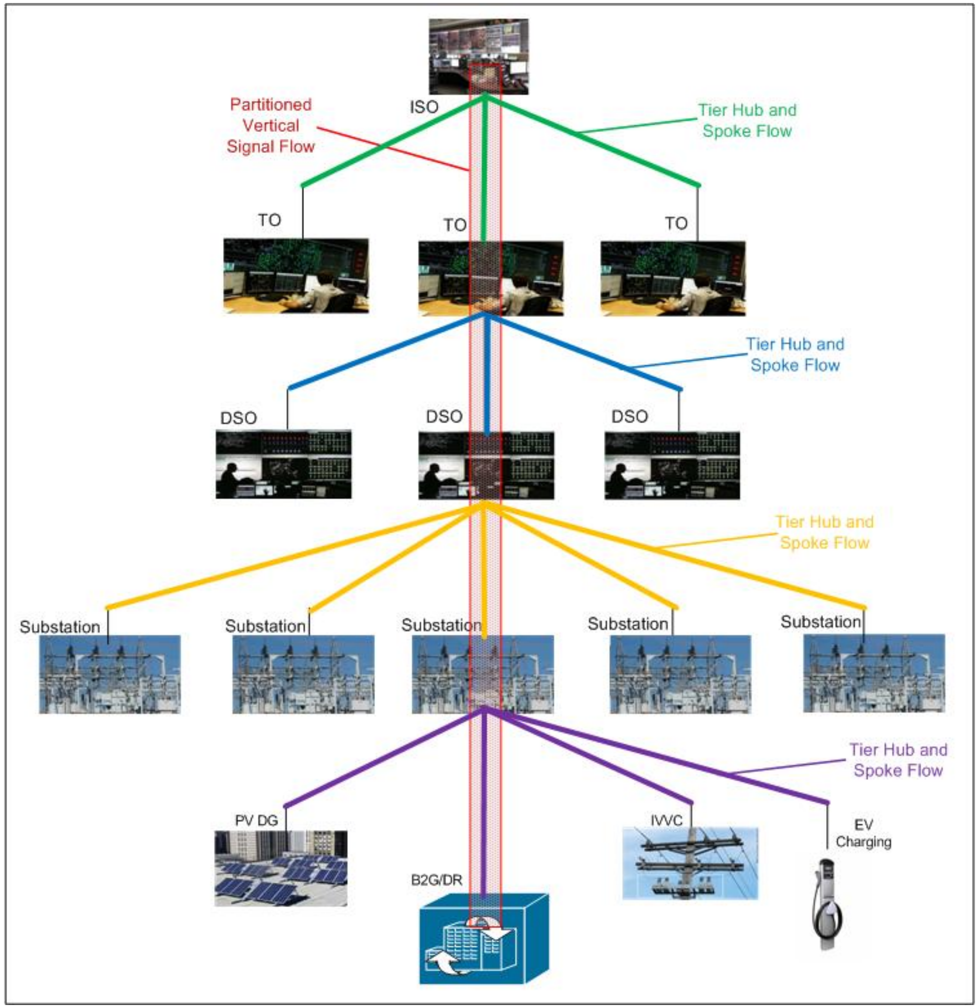
3. Distribute the Control

- Layered Optimization Decomposition leads directly to distributed control
- Layers can be matched to grid tiers
- May be more than one horizontal control tier
- Scalable and robust structure
- Sub-problems may be “selfish”
  - Local goals
  - Local constraints and states
  - Bounded local autonomy



Scalability and Resilience via NUM-based Structure

- Multi-tier hub and spoke flow patterns
- Scalability of data flows
- Auto-abstraction of grid state
- Computational burden limiting via domain specification
- Adaptation to grid structural changes



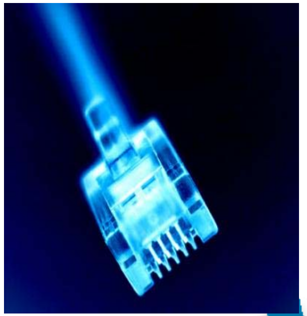
More Than Just Power Grids

Inland waterways
Logistics systems
Oil & Gas pipelines
Railroads
Irrigation systems
Whole cities…

Any Cyber-Physical System

Convergence occurs at the decision & control systems

Financial Networks (Markets)



Information and Communication Networks

Social Networks

thank you