Cyber-Physical Architecture
for the
Power Grid of 2020

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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
distribution automation: old and new
A Wave of Investment in DA is Coming

• North America presently has about $300 B of aging or obsolete distribution assets

• New investment in DA is coming as AMI winds down:
  - EEI: $20 B-$23 B /year through 2030
  - EPRI: $335 B - $476 B over 20 years -> $17B - $24B /year
  - GreenTech Media: $3 B /year by 2015

• Comms portion historically about 15% but may go higher for new DA
  - New DA comms more complex
  - Also add in DI platform elements

• Multiple factors driving this investment:
  - Renewed industry focus on operational excellence (“smart grid” is toxic)
  - Regulatory mandates in renewables integration and other functions
  - Response to recent weather events -> renewed focus on resilience
  - Aging and/or obsolete assets
Basic Distribution Automation

• Voltage Regulation
  ▪ OL tap changers and SLDC’s
  ▪ Voltage regulators
  ▪ Cap banks for voltage support

• Flow Control and Sectionalizing
  ▪ Feeder switches and breakers
  ▪ Sectionalizers (remotely operated but manually controlled)
  ▪ Feeder inter-tie switches (remotely operated but manually controlled) or just manual

• Protection
  ▪ Breakers with digital relays
  ▪ Reclosers, Fuses

• Distribution SCADA (if any)
  ▪ V/I line sensors
  ▪ FCI’s
  ▪ Low bandwidth comms

• Outage Management
  ▪ Siloed
  ▪ IVR (maybe)

• FISR (manual/HIL)
Basic Distribution Automation Summary

Many devices are manually controlled or control is based on purely local factors.

Much of the control is merely “on-off” and on very slow time scales.

Networking requirements for basic DA are very modest and low cost tend to dominate.
Advanced Distribution Automation

- All of the basic DA plus…
- Advanced Regulation
  - IVVC: UPF, CVR
  - Load Freq Regulation
  - Inverter Control for fast VAr regulation
- Responsive Loads
- Stabilization and Synchronization
  - DSTATCOM
  - DER PCC Sync
  - D level PMU’s
- Local Balancing
  - DER integration
  - EV charge control
  - LEN power balance
  - Load modulation (DC, EV)
  - Multi-tier VPP/DR
  - Markets and distrib markets
- Microgrids
- Protection and Flow Control
  - N-way power flow incl. loops
  - D level DG teleprotection
emerging grid control issues
### Issue: Faster System Dynamics

<table>
<thead>
<tr>
<th><strong>Standard Grid Management</strong></th>
<th><strong>Advanced Grid Management</strong></th>
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<tbody>
<tr>
<td>Distribution V/VAR Control (LTC/CAP’s)</td>
<td>Distribution V/VAR (DG/DS/Load Modulation)</td>
</tr>
<tr>
<td>Response times: 5 minutes to hours</td>
<td>Response times: msec to sub-second</td>
</tr>
<tr>
<td>Transmission Level Stabilization (Ancillary Services)</td>
<td>Transmission Level Stabilization (PMU/FACTS)</td>
</tr>
<tr>
<td>Response times 6-30 minutes</td>
<td>Response times &lt; 1 second</td>
</tr>
<tr>
<td>Distribution Level Stabilization</td>
<td>Distribution Level Stabilization (DSTATCOM)</td>
</tr>
<tr>
<td>Not typically done</td>
<td>Response times 32-300 msec</td>
</tr>
<tr>
<td>Distribution Fault Isolation (Manual Control)</td>
<td>Distribution Fault Isolation (FLISR)</td>
</tr>
<tr>
<td>Response times: minutes to hours</td>
<td>Response times: sub-second to sub-minute</td>
</tr>
</tbody>
</table>

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

Issue: Synchronized Measurement

• Traditional Distribution SCADA does round-robin polling of endpoints
  o 4 second cycle to collect all points is common today, no synchronization

• Measures RMS voltage, RMS current, real and reactive power
  o Optionally, a few harmonics for power quality
  o No phasor measurement; data is time skewed

• All this is changing for advanced DA:
  o Need for phase measurements
  o Therefore, need synchronized measurement (synchrophasors)
  o Some can be done in substation, but this is not adequate for many functions
  o Need distributed, synchronized SCADA
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

Issue: Emerging Structural Chaos
ultra-large scale power grid control architecture
What to Do

• Regularize the structure
  o Eliminate “tier hopping” control
  o Avoid closing loops around multiple tiers
  o Use the layer architectural paradigm

• Introduce layered optimization
  o Can match inherent grid hierarchy
  o Can match functional boundaries

• Distribute the control
  o Flows logically from the first two steps
  o Preserves much traditional control
  o Addresses new control needs
1. Regularize the Structure
2. Introduce Layered Optimization

- Decompose problem into distributed solvable problems coordinated by a master problem -> **Network Utility Maximization**
  
  - Master and sub-problem solvers communicate across layers via signaling
    - Master: system-wide control solution; sub-problems: “selfish” endpoints
    - Primal decomposition: master directs sub problems by allocating resources
    - Dual decomposition: master directs sub problems by providing pricing

- Solve federation, disaggregation, and complex constraint fusion problems

- Extend to multiple layers to fit the utility hierarchical model

- Append constraints, dynamics at each level

- Modular approach to ultra-large scale control

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
DI Allocation; Dynamic Re-allocation

- Decentralized control
  - Remote apps
- Distributed Control
  - Remote, cooperating apps
- Static DI element allocation
  - Not 1:1 per substation
- Dynamic topology
  - Must change over time
Benefits of Distributed Approach

• Low Latency Response
  - A distributed intelligence architecture can provide the ability to process data and provide it to the end device without a round trip back to a control center.

• Low Sampling Time Skew
  - Multiple data collection elements can minimize first-to-last sample time skew for better system state snapshots

• Scalability
  - No single choke point for data acquisition or processing; analytics at the lower levels of a hierarchical distributed system can be processed and passed on to higher levels in the hierarchy

• Robustness
  - Local autonomous operation
  - Continued operation in the presence of network fragmentation
  - Graceful system performance and functional degradation in the face of failures

• Ease of incremental rollout
Issues Posed by Distributed Approach

- **Device/system/application management** – smart devices residing in substations, on poles, in underground structures represent significant cost to visit. It is impractical to send a person out to any of these devices to install a patch, reset a processor, or upgrade an application. Zero-touch deployment and remote management are necessary.

- **Harder to design, commission, and diagnose** – distributed intelligence systems can inherently involve a larger number of interfaces and interactions than centralized systems, making design, test, and installation more complex than with centralized systems.

- **More complex communications architectures required** – distributed intelligence involves more peer-to-peer interaction than with centralized systems, so that the communication network must support the associated peer-to-peer communications.
Use Case Ensemble

• The “killer app” is grid control. It has many sub-use cases, most well-known and more coming as the utilities are pushed (as in driven) by the regulators to meet renewable portfolio and other goals by 2020.

• The sub-use cases include:

  o VER integration (wind, solar, etc)
  o Wide area measurement, protection, and closed loop control
  o DER integration (distribution level, incl VER DG)
  o Energy storage integration
  o Responsive loads (command, price, and/or system frequency)
  o Integrated Volt/VAr control for V reg, CVR, UPF in the presence of DER and DR
  o Advanced distribution fault isolation/service restoration
  o Electric Vehicle (EV) charge management
  o Third party energy services integration
  o Inverter control for fast VAr regulation
  o Local energy network and microgrid power balance and flow control; load power modulation (EV’s, DC’s)
  o Multi-tier virtual power plants
  o Energy/power market interactions for prosumers; transactive energy and distributed markets
  o Electronic grid stabilization (FACTS for transmission; DSTATCOM for distribution)
Grid Control Macro Requirements

- Increasing need for low latency electronic stabilization in the presence of fast grid dynamics
- Need for wide area measurement; grid state observability; deep situational awareness -> sensing
- Evolving cross tier and vertically integrated control
- Need for:
  - Control federation
  - Control disaggregation
  - Constraint fusion
  - Agility
  - Robustness
  - Stability
thank you