Intelligent Infrastructure for Coordinated Control of a Self-Healing Power Grid

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What is “Smart Grid”? 

- **Wide range:** 
  - From a new power application or device 
  - To the Utopian Power Grid!
Smart Grid: A Self-Healing Grid Perspective

- “Electricity transmission and distribution network that uses robust two-way communications, advanced sensors, and distributed computers to improve the efficiency, reliability and safety of power delivery and use.” (Wikipedia)

- A fundamental capability of a self-healing grid is its ability to prevent or contain major disturbances.

- Conceptual design for an IT infrastructure:
  - Realization of self-healing capabilities
  - With focus on transmission
Increasingly Complex Grid

- Diversification of Energy and Storage Resources
  - Aggravating congestion and controllability
- “Active” Demand
- “Insufficient” Investment in Transmission/Load Growth
  - Contention for limited transfer capability
- Market Driven Operations
  - Larger and longer transfers
  - Volatility
- Consolidation of Operating Entities
  - Larger Systems
  - Smaller error margins
  - Shorter decision times
Increasingly Volatile Transfers

Source: TVA
High Cost of Grid Unreliability, Blackouts….

- “August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations…”
- “Overload in Germany's power network triggered outages leaving millions without electricity…”
- “Italian blackout cuts short Rome all-night party…”
- “Millions without power in Denmark, Sweden…”
- ……
Lessons Learned: Need for a Smart IT Infrastructure

- Grid is operated much closer to its limits
  - more often!

- Qualitatively a different operating environment
  - more touchy

- Off-line studies use for real-time decision making
  - less adequate

- More data, more automation, more control

- *Need a higher performance/smart Monitoring and Control Infrastructure*
Fundamentals of a Smart Infrastructure

- **Major disturbances involve:**
  - Cascading events within seconds
  - Aggravated by uncoordinated and unintelligent local actions

- **Prevention requires:**
  - Coordinated response
  - Sub-second response

- **Centralized systems are too slow**

- **Distributed systems afford:**
  - Fast intelligent local actions coordinated with higher level analysis

- **Local intelligent sub-second response is feasible with modern technology**
Realization of Smart Infrastructure

- Better telemetry (time-stamped, faster, etc.)
- Intelligent Devices
- Distributed autonomous architecture
- Virtual hierarchical operation
Dimensions of the Infrastructure

- Geographical/Organizational
  - Grid, Region, …Control Area,…Substation

- Functional
  - Functional areas (control, reliability enhancements, performance & reliability monitoring, and data processing)
  - Functions

- Temporal
  - Scheduling to continuous
Distributed Functional Agents

Grid

Region 1

Agent Fr @R1

C Area 11

Agent Fca @CA11

Agent Fss @SS1

C Area 12

Agent Fss @SS1

Agent Fca @CA12

C Area ik

Agent Fca @CAik

Agent Fss @SS1

Agent Fss @SS1

Agent Fss @SS1

Agent Fss @SS1

Agent Fss @SS1

Agent Fss @SS1

SS1

SS2

SSm

SS...

SS...

SS...

SS...

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Example of a Distributed Functional Agents

SE - Agent n @Substation Z
State Estimator Component
Real-time Data Component
Alarming Component

SE - Agent m @Substation X
State Estimator Component
Real-time Data Component
Alarming Component

SE - Agent j @Control Area H
State Estimator Component
Real-time Data Component
Alarming Component

SE - Agent i @Control Area G
State Estimator Component
Real-time Data Component
Alarming Component

SE - Agent 1 @Region A
State Estimator Component
Real-time Data Component
Alarming Component
Distributed Autonomous System

- Grid
  - Function F1
  - Function F2
  - Function F3
  - (e.g. Voltage Stability, State Estimation)

- Regions
  - Intelligent Functional Agent for F1
  - Region R1
  - Region R2

- Control Areas
  - Intelligent Functional Agent for F1
  - Control Area C1
  - Control Area C2

- Substations
  - Intelligent Functional Agent for F1
  - Actuator
  - Substation S1
  - Substation S2
  - Substation Sn

Integrated Messaging/Data

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Temporal Dimension: Distinct Time Scales

- Hour-ahead
- 5-minute
- 1-minute
- 2-second
- 1-second
- 100-millisecond
- 10-millisecond
- “continuous” - traditional protection systems

Execution Cycles

- ≥ 2 sec
- < 2 sec
Execution Cycles and Temporal Coordination

Legend:
- Data/Feedback
  - Control/Guidelines

- Slower cycles
- Other Control Areas

- Faster cycles
- Other Substations

Power System

Grid: Hourly Cycle, 5 min cycle, 1 min cycle, 2 sec cycle

Region

Control Area: Hourly Cycle, 5 min cycle, 1 min cycle, 2 sec cycle

Zone/Vicinity

Substation: 1 sec cycle, 100 m-sec cycle, 10 m-sec cycle

Protection Systems

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## Typical Execution Cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Objectives</th>
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| 1-hour-ahead       | - Assure adequacy of resources  
                     - Identify system bottlenecks                                                                                   |
| 5-minute           | - Assure reliability, efficiency  
                     - Update control parameters and limits  
                     - Look-ahead (about 10 to 20 minutes)  
                     - Alert system operator and/or hour-ahead cycle                                                        |
| 1-minute           | - Maintain efficiency and reliability, as per the 5-minute cycle.  
                     - Adapt the more recent models                                                                 |
| 2-second           | - Collect/validate data for use by control area or interconnection including data acquired in the 10-millisecond cycle  
                     - Perform closed loop controls (Area Generation Control, etc.)  
                     - Adapt control parameters and limits for faster cycles                                                   |
| 1-second           | - Control extended transients (secondary voltage control, etc.).  
                     - Adapt control parameters and limits for faster cycles                                                      |
| 100-millisecond    | - Control imminent system instabilities including execution of intelligent Special Protection Schemes (iSPS) based on adaptive models or criteria identified by slower cycles. |
| 10-millisecond     | - Perform faster intelligent protection actions (load shedding, generation rejection, system separation) |
Technical Feasibility cont.

- Better telemetry
  - PMU type devices/technology
    - M-sec sampling with microsecond accuracy
    - Accuracy of 0.1% on magnitude and 0.2° on phase angle
    - Information up to the 64th harmonic

- Intelligent Devices
  - Faster controls
  - Better diagnosis
  - More local intelligence (“intelligent” RAS/SPS, etc.)
Technical Feasibility

- **Communications**
  - Latency:
    - Within substations – less than 1 m-sec
    - Others: less than 0.5 sec
  - Time skew: less than 1 m-sec

- **Distributed autonomous architecture**
  - Better algorithms
  - “Internet” technologies
  - Large scale integration

- **Virtual hierarchical operation**
Financial Feasibility - Cost Model

Components:
- Software components/intelligent agents
- Hardware
- System deployment and integration
- Control equipment (if absolutely needed)
- Communication connectivity (not costed)

Intelligent agents/SW
- R&D / Prototype Costs
- Productization Costs
- Shakedown Costs
  - Database development, system configuration & integration
  - Maturity through multiple implementations for “plug-and-play” status: e.g. implementations: 10 SSs, 5 ZNs, 2 CAs
Financial Feasibility - Benefit Model

- **Limit improvement:**
  - Improved market prices/production costs

- **Blackout containment:**
  - Reduced unserved energy

- **Possible others:**
  - Reduction of emergency maintenance costs
  - Deferral of capital expenses
  - Improved power quality
  - Etc.

Selected Benefits:
- Reduced Unserved Energy
- Reduced Prices/Production Costs
- Reduced Emergency Maintenance

Potential Benefits:
- Etc.
Empirical Models – Costs and Benefits

The diagram illustrates the relationship between the number of substations and various costs and benefits. The y-axis represents millions of dollars, and the x-axis represents the number of substations. Key labels include:

- New Control Equipment
- Unserved Energy
- SW & Shake-Down
- Production Cost
- R&D
- Integration
- HW

Lines connecting these points indicate trends and relationships between these costs and benefits.
Thank You