Valuating Infrastructure For a Self-Healing Grid

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Presented by: Khosrow Moslehi
Overview

- Vision
- Background
  - Architectural Framework
  - Analytical Framework
- Valuating
  - Cost Models
  - Benefit Models
  - Business Cases
  - Costs-Benefits Analysis
- Conclusion
Background: **Self-Healing Power Grid**

- High reliability
- Non-stop service (or graceful/minimal degradation)
- Fail-proof control actions (no errors of omission or commission)
- Flexible responses to various disturbances and attacks
- Resource deployment to minimize impact of potential problems
- Minimum possible loss of service and time to restore service

Instances of such features already exist

They need to be ubiquitous
Background: Blackout Experiences

Angular Separation 14 August 2003

NERC

Cleveland

West Michigan (lower trajectory)
Background: Off-line Analyses May not Apply in Real-Time

- Transfer study cases vs. Actual Transfers

covered by the study cases
Background: Why Self-Healing?

- Power system is operated much closer to its limits (more often!)
- Qualitatively a different operating environment (more touchy!)
- Larger foot-print (more pressure on the operator!)
- More volatility
- More data, more automation, more control (higher performance data processing!)

Need a higher performance IT infrastructure
Background: **Drivers of Architectural Innovation**

- **Large blackouts involve:**
  - Cascading events within seconds
  - Aggravated by uncoordinated and unintelligent local actions

- **Prevention/Containment requires:**
  - Better monitoring
  - Coordinated response
  - Sub-second response

- **Centralized systems are too slow**

- **Distributed autonomous systems**
  - Existing RAS is an early example of distributed intelligence

- **Any number of operating entities (RTO/ISO, TO, etc.)**
Background: Distributed Intelligent Agents

Distributed Agents afford:
- Fast response

Flexible framework for various strategies
- Distributed applications
- Coordination
  - Hierarchical
  - Temporal

Reusable plug and play components

Greater level of reliability
Distributed Agents - State Estimation Example

- Grid
- Region 1
  - CA SE Agent
  - C Area 11
    - SS SE Agent
    - SS SE Agent
    - SS SE Agent
    - SS1
    - SS2
    - SSm
    - SSm
- Region i
  - CA SE Agent
  - C Area 12
    - SS SE Agent
    - SS SE Agent
    - SS SE Agent
    - SS
    - SS
    - SS
  - C Area ik
    - SS SE Agent
    - SS SE Agent
    - SS SE Agent
    - SS...
    - SS...
    - SS...
Background: Distributed Autonomous System

Function F1
(e.g. Voltage Stability)

Intelligent Functional Agent for F1

Region R1

Intelligent Functional Agent for F1

Region Ri

Intelligent Functional Agent for F1

Control Area C1

Intelligent Functional Agent for F1

Control Area Ck

Intelligent Functional Agent F1

Substation S1

Actuator

Substation Sn

Actuator

Actuator
Background: Execution Cycles and Temporal Coordination

Power System

Including control, measurement and protection devices

Slower cycles – 2 sec & over
- Hour-Ahead cycle
- 5 min cycle
- 1 min cycle
- 2 sec cycle

Faster cycles - under 2 sec
- 1 sec cycle
- 100 m-sec cycle
- 10 m-sec cycle

monitoring
control

Forward plans, schedules, guidelines controls, messages
Feedback data, violations, alerts, messages
Valuation of Self-Healing Grid

- Is the IT infrastructure financially feasible?
Challenges of Valuation

- **Framework is broad and flexible**
  - Entire grid - All control levels, geographical areas, etc.
  - All analytical functions
  - All time scales - Milliseconds to hour

- **General systematic methodology**
  - Too many context dependent parameters
  - Subjectivity of size, existing infrastructure & solutions, costs, benefits
  - Too many cost factors - R&D, SW, devices, etc.

- **Meaningful business cases**
  - Too narrow - Not of interest
  - Too broad - Provides no specific guidelines
Approach to Valuation

- No specific assumptions regarding power system
- Focus on IT - all cycles and all hierarchical levels
- Plug-and-play intelligent agents
  - Functionally generic and encompassing
  - Configurable to existing measurement and control capabilities
- Reasonable “upper bounds” on costs
- Reasonable “lower bounds” on Benefits

Consider:
- Incremental implementation
- Shared benefits and costs
- Existing SW & HW products
What are we costing?

- Software components/intelligent agents
- IT hardware
- System deployment and integration
- Control equipment (if absolutely needed)

- Not costed - Communication Connectivity
Cost Models: Software Components/Intelligent Agents

- **R&D / Prototype Costs**
  - Investigate/demonstrate innovative concepts and algorithms
  - One-time cost

- **Productization Costs**
  - Robustness, models, solutions, performance, visualization
  - Integration of R&D results to standardized modules

- **Shakedown Costs**
  - Database development, system configuration & integration
  - Maturity through multiple implementations for “plug-and-play” status:
    - Substation: 10 implementations
    - Zone/vicinity: 5 implementations
    - Control Area: 2 implementations
## Cost Models: Software Components/Intelligent Agents

<table>
<thead>
<tr>
<th>#</th>
<th>Level</th>
<th>Prototype / Productization (Person-Yrs)</th>
<th>Field Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Shake-down</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Later implementations</td>
</tr>
<tr>
<td>1</td>
<td>Substation</td>
<td>3 / 11</td>
<td>- 10% for the first 10 substations (13 person-months each)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- 0.5% later (3 person-weeks each)</td>
</tr>
<tr>
<td>2</td>
<td>Zone/Vicinity</td>
<td>4 / 13</td>
<td>- 15% for the first 5 zones/vicinities (23 person-months each)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- 3% later (5 person-months each)</td>
</tr>
<tr>
<td>3</td>
<td>Control Area</td>
<td>10 / 30</td>
<td>- 25% for the first 2 control areas (90 person-months each)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- 15% later (54 person-months each)</td>
</tr>
<tr>
<td>4</td>
<td>Region</td>
<td>2 / 8</td>
<td>- 25% for the first 2 regions (24 person-months each)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- 15% later (14 person-months each)</td>
</tr>
<tr>
<td>5</td>
<td>Grid</td>
<td>2 / 5</td>
<td>- 25% for the first 2 grids (15 person-months each)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- 15% later (9 person-months each)</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>21 / 67</strong></td>
<td>Use above formulae for various systems</td>
</tr>
</tbody>
</table>
Cost Models: IT hardware

- Measurements
  - PMUs as representative

- Communications
  - Consider routers at all locations of the hierarchy

- Computing
  - Standard computing modules each with:
    - 2 CPUs (3.6 GHz or higher)
## Costs Model – Typical HW Requirements and Costs

<table>
<thead>
<tr>
<th>#</th>
<th>Level</th>
<th>PMU/PDC</th>
<th>Routers</th>
<th>SCM</th>
<th>Cost/Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Substation</td>
<td>2 PMUs</td>
<td>3</td>
<td>3</td>
<td>$83 k</td>
</tr>
<tr>
<td>2</td>
<td>Zone/ Vicinity</td>
<td>2 PDCs</td>
<td>6</td>
<td>4</td>
<td>$135 k</td>
</tr>
<tr>
<td>3</td>
<td>Control Area</td>
<td>0</td>
<td>4</td>
<td>8</td>
<td>$100 k</td>
</tr>
<tr>
<td>4</td>
<td>Region</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>$33 k</td>
</tr>
<tr>
<td>5</td>
<td>Grid</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>$50 k</td>
</tr>
</tbody>
</table>

- 200 Substations, 20 Vicinity/Zones – per CA
- 20 Control Areas/ Region, 10 Regions/Grid
- Communications connectivity already exists
- Assume $15k/PMU, $22.5k/router and $7.5k/computer
Costs Model – System deployment and integration

- Efforts for different levels and stages include:
  - DB development
  - Configuration
  - Integration
  - Field verification
  - etc.

- Cost roughly proportional to the number of substations

- Integration cost – system dependent
  - Typically 30% of total cost of SW deployment & HW
Cost Models: Control Equipment

- Where absolutely necessary
- Consider shunt FACTS devices as representative
- Potentially about 10% of transmission system supplied reactive requirements through FACTS
  - Translates to 4 MVAr per 100 MW peak load
  - Costed at $50k/MVAr
Benefits Model – Which benefits?

- **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 Prices/Production Costs
- Reduced Unserved Energy

Potential Benefits:

- Reduced Emergency Maintenance

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Benefits Models - Limit Improvements

Ideal limit order

- Stability Limit
- Voltage Limit
- Thermal Limit
- Actual Operation

Thermal being the binding limit

- Stability Limit
- Thermal Limit
- Voltage Limit
- Actual Operation

- Voltage Limit
- Stability Limit
- Thermal Limit
- Actual Operation

- Thermal Limit
- Stability Limit
- Voltage Limit
- Actual Operation

- Thermal Limit
- Voltage Limit
- Stability Limit
- Actual Operation

Limit Improvements – Less Expensive MWh

- Estimated price differential
  - Gas CC vs Coal
  - Typically $20/MWh

- Estimated effective hours/year
  - Capacity factor of CC
  - Typically 45%

- Possible Limit Improvement
  - Transfer limit
  - 1% of base load
  - Analytically justified

Weighted Average LMPs for PJM Market - 2004
## Limit Improvements - Industry Statistics for Parameters

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Range in Industry Statistics</th>
<th>Sources</th>
<th>Value used in this project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LMP Differentials</td>
<td>$0-$438/MWh</td>
<td>Delmarva Study, NYISO real-time LMP’s PJM State of the Market</td>
<td>$20/MWh</td>
</tr>
<tr>
<td>2</td>
<td>Hours with high LMP’s (&gt;=$45/MWh)</td>
<td>45% = 3942hrs/Yr</td>
<td>PJM State of the Market Report</td>
<td>3942 hrs/Yr</td>
</tr>
<tr>
<td>3</td>
<td>Base load MW at Low LMP’s ($0-$25)/MWh</td>
<td>80% of average load</td>
<td>PJM State of the Market Report</td>
<td>80% of average load</td>
</tr>
<tr>
<td>4</td>
<td>Average MW affected</td>
<td>0-1136 MW 1888 MW/TLR Event</td>
<td>Delmarva study, TLR report</td>
<td>1% of base load for 45% of the hours = ~ 31.5 Sys.Hrs/Yr</td>
</tr>
</tbody>
</table>
## Limit Improvement - Validation of Model

### Model: Entire US

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective congested hours (45%)</td>
<td>3942 hr/Yr</td>
</tr>
<tr>
<td>1% of base load for entire U.S.</td>
<td>3,560 MW</td>
</tr>
<tr>
<td>Potential Impact</td>
<td>14,034 GWh/Yr</td>
</tr>
</tbody>
</table>

### Industry:

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>GWh/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Congested GWh in Top 20 paths in Eastern Grid</td>
<td>107,470</td>
</tr>
<tr>
<td></td>
<td>(National Transmission Grid Study Report)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Congested GWh in Top 20 paths in Western Grid</td>
<td>38,548</td>
</tr>
<tr>
<td></td>
<td>(National Transmission Grid Study Report)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Energy schedules cut by TLR’s (Eastern Grid - actual)</td>
<td>3,468</td>
</tr>
<tr>
<td></td>
<td>(NERC TLR data)</td>
<td></td>
</tr>
</tbody>
</table>
Benefits Models - Unserved Energy

Published Information

Average Unserved Mwh due to Transmission Outages

Reduction in Unserved Energy (Mwh)

Benefit: Reduction in Unserved Energy ($)

Residential Cust. ($/kwh)

Commercial Cust. ($/kwh)

Industrial Cust. ($/kwh)

Weighted Average Value $/kwh
## Unserved Energy - Parameters for Valuating

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Range</th>
<th>Sources</th>
<th>Value used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Service interruptions due to transmission problems ignoring major disturbances</td>
<td>4-22</td>
<td>- PG&amp;E, Reliability Indices Report submitted to CPUC (10 year history)</td>
<td>10 sys.min. per year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System-minutes per year</td>
<td>- TVA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- NERC/DAWG Database (Year 2002)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Interruptions due to major disturbances due to transmission problems</td>
<td>0-133</td>
<td>- PG&amp;E, Reliability Indices Report submitted to CPUC (10 year history).</td>
<td>20 sys.min. per year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System-minutes per year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fraction of the above that could be avoided</td>
<td>-----------</td>
<td>- Analytically justified</td>
<td>10%</td>
</tr>
<tr>
<td>4</td>
<td>Value of unserved energy</td>
<td>$1,000-$361,000/MWh</td>
<td>PG&amp;E, Ontario Hydro, SCE and other studies – adjusted for inflation</td>
<td>$24,000/MWh</td>
</tr>
</tbody>
</table>
## Benefit Models: Unserved Energy Value ($/MWh)

<table>
<thead>
<tr>
<th>Sector</th>
<th>PG&amp;E 1990 $/MWh</th>
<th>PJM Inflation Factor</th>
<th>2004 $/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>4,640</td>
<td>1.42</td>
<td>6,590</td>
</tr>
<tr>
<td>Commercial</td>
<td>31,630</td>
<td>1.42</td>
<td>44,910</td>
</tr>
<tr>
<td>Industrial</td>
<td>10,770</td>
<td>1.42</td>
<td>15,290</td>
</tr>
<tr>
<td>Agricultural</td>
<td>3,670</td>
<td>1.42</td>
<td>5,210</td>
</tr>
<tr>
<td>Weighted</td>
<td>16,930</td>
<td>1.42</td>
<td>24,040</td>
</tr>
</tbody>
</table>

Source:
Business Case – Model for Full Scale Implementation

- A reasonably large control area embedded in an interconnection

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peak load</td>
<td>20,000 MW</td>
</tr>
<tr>
<td>2</td>
<td>Average load</td>
<td>12,500 MW</td>
</tr>
<tr>
<td>3</td>
<td>Base load</td>
<td>10,000 MW</td>
</tr>
<tr>
<td>5</td>
<td>Substations</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>Vicinities/zones</td>
<td>20</td>
</tr>
</tbody>
</table>
# Full Scale Implementation – Total Deployment Cost

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Cost ($K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SW Deployment Subtotal</td>
<td>11,400</td>
</tr>
<tr>
<td>2</td>
<td>IT Hardware</td>
<td>19,400</td>
</tr>
<tr>
<td>3</td>
<td>System Integration</td>
<td>9,240</td>
</tr>
<tr>
<td></td>
<td>(30% of SW &amp; HW)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deployment Total</td>
<td>40,040</td>
</tr>
</tbody>
</table>
Full Scale Implementation – Costs and Benefits Summary

<table>
<thead>
<tr>
<th>Item</th>
<th>K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW + HW + Integration</td>
<td>40,040</td>
</tr>
<tr>
<td>Control Equipment</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total Costs</strong></td>
<td>40,040</td>
</tr>
<tr>
<td>Limit improvement benefit</td>
<td>39,420</td>
</tr>
<tr>
<td>Avoided unserved energy benefit</td>
<td>75,000</td>
</tr>
<tr>
<td><strong>Total Benefits</strong></td>
<td>114,420</td>
</tr>
</tbody>
</table>

- SW implementation cost includes deployment at 200 substations, 20 vicinities, and the control area as well as interfaces with region and grid.
- The SW development cost of $34 M to be distributed/licensed.
Partial Implementation Problem 1 - EHV Outage Stresses HV System

When one of the EHV lines is out for maintenance, the contingent outage of another EHV line places severe stress on the underlying HV system.
Partial Implementation Problem 2 - Voltage Collapse

When one line is down due to maintenance or forced outage, the (N-1) reliability criterion is not met. The underlying sub-transmission system will be subject to voltage collapse if another line fails.
## Partial Implementation Problems - Costs and Benefits

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Amount ($K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Problem 1</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Cost (at 3 substations)</td>
<td>~400</td>
</tr>
<tr>
<td>1.2</td>
<td>Total Benefits</td>
<td>~60,000</td>
</tr>
<tr>
<td>1.3</td>
<td>Benefit / Cost</td>
<td>~149</td>
</tr>
<tr>
<td>2</td>
<td>Problem 2</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Cost (at 3 substations)</td>
<td>~400</td>
</tr>
<tr>
<td>2.2</td>
<td>Total Benefits</td>
<td>2,660</td>
</tr>
<tr>
<td>2.3</td>
<td>Benefit / Cost</td>
<td>~6.67</td>
</tr>
</tbody>
</table>

- All software and hardware has matured in prior implementations.
- Only interfaces necessary for the two specific problems are included.
Empirical Models – Costs and Benefits
Conclusions

- Systematic and general methodology to translate broad scope into quantifiable costs and benefits
  - Identification of significant cost components
  - Identification of financially significant benefits
  - Scalable framework of models to assess reasonable “upper bounds” on costs and “lower bounds” on benefits for localized or system-wide implementations
  - Validation of the models against industry statistics.
  - Analytical justification of model parameters.
  - Development of an empirical model to facilitate feasibility analysis
Conclusions

- Inevitable grid-wide penetration of self-healing capabilities:
  - First implementation would substantially bring down the “entry barrier” for the remaining utilities to a level comparable to traditional control centers
  - Steady decline of cost of computing power
  - Value of benefits continue to increase as the economy and quality of life become more dependent on a reliable power grid
  - For the entire U.S., benefits (billions of $) would far exceed initial R&D costs of $65M
- The above conclusion remains valid and unaffected by any reasonable changes in the specific values of the parameters used in the calculations.