PJM On-Line Stability Applications:
--- Voltage Stability & Transient Stability

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PJM Interconnection
• Overview of PJM System
• On-Line Stability Applications
  – Voltage Stability
  – Transient Stability
  – Impacts of System Topology Changes
• Discussions
PJMs as Part of the Eastern Interconnection

- 27% of generation in Eastern Interconnection
- 28% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection

KEY STATISTICS

<table>
<thead>
<tr>
<th>Metric</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>PJM member companies</td>
<td>800+</td>
</tr>
<tr>
<td>Millions of people served</td>
<td>61</td>
</tr>
<tr>
<td>Peak load in megawatts</td>
<td>165,492</td>
</tr>
<tr>
<td>MWs of generating capacity</td>
<td>183,604</td>
</tr>
<tr>
<td>Miles of transmission lines</td>
<td>62,556</td>
</tr>
<tr>
<td>2012 GWh of annual energy</td>
<td>793,679</td>
</tr>
<tr>
<td>Generation sources</td>
<td>1,376</td>
</tr>
<tr>
<td>Square miles of territory</td>
<td>243,417</td>
</tr>
<tr>
<td>Area served</td>
<td>13 states + DC</td>
</tr>
<tr>
<td>Externally facing tie lines</td>
<td>191</td>
</tr>
</tbody>
</table>

21% of U.S. GDP produced in PJM

As of 6/1/2013
Voltage levels of modeling

- 765 kV
- 500 kV
- 345 kV
- 230 kV
- 138 kV
- 115 kV
- 69 kV & below - depending on detail required

Network Model Summary

- Node: 87,674
- Bus: 14,000
- Unit: 3370 / 1900
- CB: 77335
- XF: 6587
- Line: 13486
- Shunt: 3008
System Operations Tool – Real-Time Analysis

- Telemetry updates every 10 seconds
- State Estimation (SE) executes (full AC) every 60 seconds
- Security Analysis (SA)* executes (full AC) every 60 seconds
- **TLC (Transfer Limit Calculator) executes every 3-5 minutes, identify voltage collapse points related and calculates voltage stability limits, based on pre/post-contingency, for each interface,**
- **VSA (Voltage Stability Analysis) follows TLC to provide supplemental control recommendations for potential collapse area**
- **TSA* (Transient Stability Analysis) executes every 7 minutes and recalculates transient stability limits for each stability interface and critical n-1 conditions**
- Forecasting: Load, Net Interchange Schedules and Wind Generations
- Network Model Validation (developing)
- Optimal Voltage Control (evaluation)
Voltage Stability Analysis and Control (VSA)

--- A Real Time Tool for PJM System Operations
PJM Real-time Voltage Stability Analysis

- Model Update (MU)
- State Estimator (SE)
- Security Analysis (SA)
- Transfer Limit Calculation (TLC)
- VSA Control

SCADA

EMS NA

Monitors the actual voltage violations

Evaluates more than 2000 contingencies
Monitors the post-contingency voltage limit / voltage drop violations

Monitors the pre-/post-contingency voltage stability margin in terms of the load increase margin and interface increase margin

Full Feature online voltage stability analysis
- Fast contingency screen
- Contingency analysis
- Security Enhancement (Preventive and Corrective Control Calculation)
1. TLC Application
Determines the maximum pre- and post-contingency MW transfer interface flow under the constraints of

- Voltage stability (collapse)
- Voltage drop limits
- Voltage low limits
2. Control/Sensitivity Calculations

<table>
<thead>
<tr>
<th>Preventive control &amp; corrective control</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Adjusting LTC and PAR tap positions</td>
<td>➢ Stability margin increase vs. Bus injections</td>
</tr>
<tr>
<td>➢ Switching of capacitors and reactors</td>
<td>➢ Bus voltage increase vs. Bus injections at collapse point</td>
</tr>
<tr>
<td>➢ Rescheduling the generator output</td>
<td>➢ Loading shedding (where and how much)</td>
</tr>
<tr>
<td>➢ Loading shedding (where and how much)</td>
<td></td>
</tr>
</tbody>
</table>
Transient Stability Analysis and Control (TSA&C)

--- A On-line Tool for PJM System Operations
Overview - Main functions of TSA&C

• Monitor and Control **transient stability** of the PJM system subject to 3000 contingencies pre-defined. (Officially started on June 1, 2013)

• Compute **stability limits** for PJM Outage Study 2 or 3 day ahead. (Officially started on Jan. 1, 2013)

• Provide recommend **transient stability control measures** required to prevent the system from losing transient stability for potentially unstable system condition and/or contingencies
Overview - TSA&C models, systems and technologies

Three systems:
• Production TSA&C system
• Test TSA&C system
• OTS TSA&C system

Real time models:
• Real time network model (14,500 bus) and State Estimation solution
• On-line forming Negative and Zero Sequence models for unbalanced faults.
• Operation dynamic generator models (2600 generators)
• Contingency models (Each contingency contains common fault and switching events (circuit tripping, generator tripping, shunt switching, etc.))

Technologies:
• Advanced non-linear system technology
• Parallel computation
Overview – TSA

• Assessment cycle
  ➢ 7 minutes

• System size
  ➢ 14,500 buses
  ➢ 2,500 generators
  ➢ Must accommodate planned system expansion
Impacts of System Topology Changes

• An Example

<table>
<thead>
<tr>
<th>Op</th>
<th>Cog Name</th>
<th>Security</th>
<th>Margins</th>
<th>Dump</th>
<th>POM Recommendation</th>
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<tbody>
<tr>
<td>542</td>
<td>1 L765 Glenn-Mountaineer</td>
<td>Insecure</td>
<td>-100.00</td>
<td>93.00</td>
<td>MV Reduction at ANVRAEP 29 A</td>
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</table>

![DSA Monitor](image)
Stability & System Topology

• An Example
— Different Stability Limits if the system topology changes.
— On-line stability applications is the validations tools for system topology changes (topology controls)
— The topology control optimization needs to include stability constraints.
— The topology control optimization is applied to the area of outage study in days/weeks ahead.
Alex M. Stankovic’s Small-Signal Stability
Application to the List of TC changes

<table>
<thead>
<tr>
<th>(k)th line opening</th>
<th># of generators in $N_g$</th>
<th>(k)th line opening</th>
<th># of generators in $N_g$</th>
<th>(k)th line opening</th>
<th># of generators in $N_g$</th>
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<tr>
<td>45–729</td>
<td>11 (C)</td>
<td>9662–9723</td>
<td>12</td>
<td>12262–12263</td>
<td>X</td>
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<tr>
<td>45–12366</td>
<td>9 (C)</td>
<td>9662–9763</td>
<td>12</td>
<td>12352–12428</td>
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<td>273–2528</td>
<td>9 (C)</td>
<td>10077–10580</td>
<td>X</td>
<td>12446–12453</td>
<td>10 (C)</td>
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<td>729–948</td>
<td>11 (C)</td>
<td>10078–10080</td>
<td>11</td>
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<td>944–948</td>
<td>11 (C)</td>
<td>10189–10233</td>
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<td>10419–10562</td>
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<td>12487–12543</td>
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<td>1844–1952</td>
<td>9 (C)</td>
<td>10567–13587</td>
<td>11</td>
<td>12490–12721</td>
<td>11 (C)</td>
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<td>1845–12243</td>
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<td>12150–12190</td>
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<td>9 (C)</td>
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<td>9635–9723</td>
<td>12</td>
<td>12216–12226</td>
<td>X</td>
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<td></td>
</tr>
</tbody>
</table>

21 line openings are candidates for optimal generator’s re-dispatch.
Step 6a: Optimization of eigenvalues movement - Results

Critical Disconnected Line 10567–13587

Before re-dispatch

After re-dispatch

Basic Case
TC Case (Simplified model)
TC Case (Detailed model)

σ, [1/s]

f, [Hz]

lb_ub=7; % Lower/Upper bound in [%]
Bus = 813 ; Generator = G 4; Pg0 = 16.7100 p.u.; DePg = -1.296811 p.u.
Bus = 13004 ; Generator = G 1; Pg0 = 42.0500 p.u.; DePg = 3.070611 p.u.
Bus = 11154 ; Generator = G 1; Pg0 = 79.5800 p.u.; DePg = 5.697711 p.u.
Bus = 11152 ; Generator = G 1; Pg0 = 79.5700 p.u.; DePg = 5.697011 p.u.
Bus = 9775 ; Generator = G12; Pg0 = 86.7500 p.u.; DePg = -6.199611 p.u.
Bus = 12181 ; Generator = G 1; Pg0 = 197.1200 p.u.; DePg = 13.925511 p.u.
Bus = 12149 ; Generator = G 1; Pg0 = 674.8600 p.u.; DePg = -47.367311 p.u.
Bus = 12226 ; Generator = G 1; Pg0 = 427.3700 p.u.; DePg = 15.618156 p.u.
Bus = 12604 ; Generator = G 1; Pg0 = 45.9500 p.u.; DePg = 3.343611 p.u.
Bus = 12838 ; Generator = G 1; Pg0 = 74.7900 p.u.; DePg = 5.362411 p.u.
Bus = 12800 ; Generator = G 4; Pg0 = 28.8800 p.u.; DePg = 2.148711 p.u.

Sum of DePg = 7.9936e-015 p.u.
Step 6a: Optimization of eigenvalues movement - Results

Before re-dispatch

Very small perturbations
(as expected)

After re-dispatch

Bus = 813; Generator = G 4; Pg0 = 16.7100 p.u.; DePg = 0.028912 p.u.
Bus = 13004; Generator = G 1; Pg0 = 42.0500 p.u.; DePg = 0.043858 p.u.
Bus = 11154; Generator = G 1; Pg0 = 79.5800 p.u.; DePg = 0.039769 p.u.
Bus = 11152; Generator = G 1; Pg0 = 79.5700 p.u.; DePg = 0.041438 p.u.
Bus = 9775; Generator = G12; Pg0 = 86.7500 p.u.; DePg = -0.378609 p.u.
Bus = 12181; Generator = G12; Pg0 = 197.1200 p.u.; DePg = 0.033793 p.u.
Bus = 12149; Generator = G 1; Pg0 = 674.8600 p.u.; DePg = 0.033759 p.u.
Bus = 12226; Generator = G 1; Pg0 = 427.3700 p.u.; DePg = 0.033628 p.u.
Bus = 12604; Generator = G 1; Pg0 = 45.9500 p.u.; DePg = 0.044094 p.u.
Bus = 12838; Generator = G 1; Pg0 = 74.7900 p.u.; DePg = 0.041790 p.u.
Bus = 12800; Generator = G 4; Pg0 = 28.8800 p.u.; DePg = 0.037568 p.u.

Sum of DePg = 7.1136e-015 p.u.
STEP 0: SSS Analysis environment (temporary static and dynamic files, variables mapping and renumeration...) \(\approx 0 \text{ sec}\)

STEP 1: Calculation of eigenvalues for Base Case (in Damping Ratio (0 to 3.5 %) and Frequency (0 to 10 Hz) ranges) \(\approx 0.05 \text{ sec}\)

STEP 2: Calculation of SSS constraints (participation generators and calculation of eigenvalue sensitivities to generation perturbations) \(\approx 0.05 \text{ sec} \times \# \text{ of Crit. Eigs.}\)

STEP 2a: Number of critical eigenvalues

STEP 2b: Participation generators for critical eigenvalues

STEP 2c: Generation perturbations (static (raw) file)

STEP 2d: Calculation of eigenvalues and participation generators

STEP 2e: Calculation of sensitivities and constraints

STEP 3: Export SSS to TCO \(\approx 0 \text{ sec}\)

STEP 4: SSS-based optimization \(\approx 0.05 \text{ sec}\)