Coordinated Planning and Operation of M-FACTS and Transmission Switching

NAE referred to the North American power grid as the largest and most complex machine ever built.

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Outline

• Flexible Transmission
• Modeling Challenges
• Potential Solutions
  – Transmission Switching
  – Variable Impedance Flexible AC Transmission Systems (FACTS)
• Modular FACTS
• Interdependence of the Technologies
Large Economic Size

More than 350 Billion Dollars!

Even Little Efficiency Matters!
Transmission Bottlenecks

Transmission system needs to be upgraded
- Improved economic efficiency
- Reliability-motivated upgrades
Congestion Cost in US ISO/RTOs

ISO Congestion Costs – 2015

$B

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More efficient utilization of the existing network is cheaper and paramount!
Transmission Flexibility

\[ F = B(\theta_j - \theta_i) \]

Transmission Switching

\[ F_k = Z_k B_k (\theta_j - \theta_i) \]

\[ Z_k \in \{0, 1\} \]

Non-Linear Program

Transmission switching does not require additional hardware.

\[ F_k = B_k (\theta_j - \theta_i) \]

\[ B_{\text{min}} \leq B \leq B_{\text{max}} \]

Variable Impedance FACTS

Mixed Integer Program

Non-Linear Program

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Transmission Flexibility

\[ F = B(\theta_j - \theta_i) \]

Power Flow Equations

Flexible transmission

\[ F_k = Z_k B_k (\theta_j - \theta_i) \]
\[ Z_k \in \{0, 1\} \]

Transmission switching does not require additional hardware.

\[ F_k = B_k (\theta_j - \theta_i) \]

Variable Impedance FACTS

Power flow control

Mixed Integer Program

Non Linear Program
Challenge:

- Computational complexity of modeling Transmission Switching and FACTS

Existing EMS & MMS neglect transmission asset flexibility (lines, transformers, FACTS)

- Handled outside optimization/power flow engines (e.g., SCUC, SCED, RTCA) on an ad-hoc basis

Goal: Optimal utilization of flexible transmission assets (transmission switching & FACTS) within the EMS and MMS
Solution for Transmission Switching

• Challenge: 
  \[ F_k = Z_k B_k (\theta_j - \theta_i) \quad Z_k \in \{0,1\} \]
  – Each switchable line/transformer: a binary variable
  – Large number of binary variables
  – Heavy computational burden

• Engineering insight: switching impacts are local
• Solution:
  – only a limited subset of all the switchable elements will be beneficial
Corrective Switching Algorithm

- Post-contingency violations are local:
  - A priority list is created: 100 lines closest to the contingency
  - All lines in the priority list are evaluated
  - Each evaluation is an independent AC power flow (in parallel)
  - 5 best candidates are reported to the operator (based on total improvement)
  - Each is a single corrective switching action
For the 4,000 cases where there is a critical post-contingency violation

CTS Benefit: PJM

- 30% Partial reduction
- 69% Full reduction
- 1% No success

Solution Time: < 5 minutes

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Comparison with PJM’s Own Switching Solutions

Flexible Transmission Decision Support (FTDS): An implementation of our CTS algorithm

FTDS VS. PJM PERFORMANCE
ALL CASES

- 41% FTDS outperforms PJM
- 55% Similar
- 4% PJM outperforms FTDS
Comparison with PJM’s Own Switching Solutions

Flexible Transmission Decision Support (FTDS): An implementation of our CTS algorithm

96% of the time: FTDS does the same or better than PJM’s identified switching solution
Computationally-Efficient Transmission Switching

• Generate a switching candidate list
  – Orders of magnitude smaller than the list of all switchable assets (100 compared to 20K: 0.5%)
• Only allow those lines to be switched
• Limit the number of switching actions:
  – Stability and reliability concerns
• Outcomes:
  – Computational efficiency
  – Near optimal performance
  – Optimality is not guaranteed
Computational Complexity of FACTS: NLP/MIP

What if we knew which B&B tree node is the optimal node?

Non Convex (MIP)

Convex (LP)

Convex (LP)

\[ F_k^{\text{max}} \]

\[ F_k^{\text{min}} \]
We only need to know the direction of the power flow.

We know this direction for major lines (COI).

Even if we do not know the direction, we can run a two-stage DCOPF and identify it.

Knowing the direction would reduce the complexity to a LP.
Engineering Insight

- We only need to know the direction of the power flow.
- We know this direction for major lines (COI).
- Even if we do not know the direction, we can run a two-stage DCOPF and identify it.

This is a heuristic.

Optimality is not guaranteed!

Knowing the direction would reduce the complexity to a LP.
FACTS Results

- Optimality:
  - More than 98% over more than 4000 simulations
  - Suboptimal solutions (<2%): very close to optimal

- Computational time:
• Estimate the direction of power flow on lines with FACTS
  – If estimation is not available, run a DCOPF and find the direction
• Fix the direction to achieve an LP
• Outcomes:
  – Computational efficiency
  – Near optimal performance
  – Optimality is not guaranteed
FACTS vs. Modular-FACTS

- Conventional FACTS:
  - Expensive
  - Large

- Modular FACTS:
  - Relatively cheaper
  - Smaller and modular
  - Can be installed rather quickly
  - Can be redeployed
  - Additional binary variables in planning (how many on a line)
Interdependence between FACTS and Transmission Switching

• Trend in industry practices:
  – Now: Ad hoc implementation of transmission switching and FACTS adjustment
  – Mostly based on operator knowledge and engineering judgment
  – Future: Automated operation of the two technologies

• Is there a strong interdependence between the two technologies?

• If so, what are the implications of this interdependence?
  – Optimal switching actions
  – Optimal location of FACTS (built now)
  – Optimal set point of FACTS (built now)
In order to study the interdependence of TS and FACTS, we co-optimize TS and FACTS

- The system is co-optimized over 72 hours in each season
- We test the algorithm on IEEE RTS test system
### 72-Hour Results (% Savings)

<table>
<thead>
<tr>
<th></th>
<th>Number of FACTS</th>
<th>0</th>
<th>1</th>
<th>2</th>
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</thead>
<tbody>
<tr>
<td><strong>Spring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Low Cap.</strong></td>
<td>0</td>
<td>0</td>
<td>10.4</td>
<td>11.6</td>
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<tr>
<td><strong>High Cap.</strong></td>
<td>1</td>
<td>5.6</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td><strong>Low Cap.</strong></td>
<td>1</td>
<td>7.3</td>
<td>12.6</td>
<td></td>
</tr>
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<td>2</td>
<td>8.4</td>
<td>13.2</td>
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<td>13.3</td>
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<td><strong>High Cap.</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Summer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0</td>
<td>9.7</td>
<td>13.7</td>
</tr>
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<td>3.2</td>
<td>11.7</td>
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</tr>
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<td>7</td>
<td>13</td>
<td></td>
</tr>
<tr>
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<td>5.5</td>
<td>15.1</td>
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<td>12.1</td>
<td>15.1</td>
<td></td>
</tr>
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<td><strong>High Cap.</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Winter</strong></td>
<td></td>
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<td>12.9</td>
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### 72-Hour Results (% Savings)

<table>
<thead>
<tr>
<th>Season</th>
<th>Number of FACTS</th>
<th>Number of Switching Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>0</td>
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<tr>
<td></td>
<td>1</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<tr>
<td>Spring</td>
<td>HA</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Low Cap.</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>High Cap.</td>
<td>7</td>
</tr>
<tr>
<td>Winter</td>
<td>1</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Low Cap.</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>2</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.1</td>
</tr>
</tbody>
</table>

A combination of the two technologies achieves larger savings!
### 72-Hour Results (FACTS Location)

<table>
<thead>
<tr>
<th>Number of Switching Actions</th>
<th>Spring</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Low Cap.</td>
<td>22</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>High Cap.</td>
<td>22</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

| Number of FACTS | | | |
|-----------------| | | |
| 1 Low Cap.      | 22 | 23 | 23 |
| 1 High Cap.     | 23 | 23 | 23 |
| 2 Low Cap.      | 22, 23 | 22, 23 | 22, 23, 25, 26 |
| 2 High Cap.     | 19, 23 | 22, 23 | 19, 23 | 19, 23 |

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Transmission switching affects the optimal location of FACTS devices!
72-Hour Co-optimization Analysis

- FACTS set points in the cases with two FACTS
- Locations of switched lines
- FACTS set points in the cases with only one FACTS
1. FACTS set points are affected by transmission switching.

2. FACTS operation affects switching actions.
Conclusions

• Variable impedance FACTS devices and transmission switching can offer significant levels of power flow control
• Power engineering insight can guide the development of computationally-efficient OPF models
• An optimal portfolio of FACTS and switching can provide savings beyond the capabilities of individual technologies.
• Transmission switching affects the optimal location and set point of FACTS devices.
• FACTS operation influences the switching actions.
• Independent utilization of the two technologies, similar to the existing industry practices, may cause inefficiencies that can be avoided through co-optimization.
References and Further Reading


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Thank You!