Optimal Portfolio of Power Flow Control Technologies: Topology and Impedance Control

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)
• Interdependence of the two 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

- CAISO
- ERCOT
- ISO-NE
- MISO
- NYISO
- PJM
- SPP
More efficient utilization of the existing network is cheaper and paramount!
Transmission Flexibility

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

Power Flow Equations

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

Transmission Switching

Mixed Integer Program

Transmission switching does not require additional hardware.

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

Variable Impedance FACTS

Non-Linear Program

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

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

**Power Flow Equations**

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

**Flexible transmission**

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

Transmission switching does not require additional hardware.

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

**Power flow control**

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

**Variable Impedance FACTS**

\[ \text{Mixed Integer Program} \]

\[ \text{Non-Linear Program} \]
Research Objective

• 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: \( F_k = Z_k B_k (\theta_j - \theta_i) \), \( Z_k \in \{0,1\} \)
  – 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 actions
CTS Benefit: PJM

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

For the 4,000 cases where there is a critical post-contingency violation

Solution Time: < 5 minutes
Flexible Transmission Decision Support (FTDS): An implementation of our CTS algorithm

FTDS VS. PJM PERFORMANCE
ALL CASES

- 55%: PJM outperforms FTDS
- 41%: FTDS outperforms PJM
- 4%: Similar
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
- Relevant work by Pablo Ruiz, et al.
FACTS and 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)
What if we knew which B&B tree node is the optimal node?

- Convex (LP)
- Convex (MIP)
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.

This is a heuristic.

Optimality is not guaranteed!
FACTS Results

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

• Computational time:

```
0  100  200  300  400  500  600
LP Average
MIP Average
Max: 4630 s
```
Computationally-Efficient Modeling of FACTS

• 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
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>Number of FACTS</th>
<th>Number of Switching Actions</th>
<th>Spring</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 NA</td>
<td>0</td>
<td>5.6</td>
<td>3.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Low Cap.</td>
<td></td>
<td>13.2</td>
<td>11.7</td>
<td>9.8</td>
</tr>
<tr>
<td>High Cap.</td>
<td></td>
<td>12.6</td>
<td>13</td>
<td>12.1</td>
</tr>
<tr>
<td>1 High Cap.</td>
<td></td>
<td></td>
<td>15.1</td>
<td>15.1</td>
</tr>
<tr>
<td>2 Low Cap.</td>
<td></td>
<td>11.5</td>
<td>15</td>
<td>11.4</td>
</tr>
<tr>
<td>2 High Cap.</td>
<td></td>
<td>13.3</td>
<td>15.1</td>
<td>14.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Switching Actions</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>0</td>
<td>10.4</td>
<td>11.6</td>
</tr>
<tr>
<td>Summer</td>
<td>0</td>
<td>9.7</td>
<td>13.7</td>
</tr>
<tr>
<td>Winter</td>
<td>0</td>
<td>8.5</td>
<td>12.9</td>
</tr>
</tbody>
</table>
### 72-Hour Results (% Savings)

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<th>Season</th>
<th>Number of FACTS</th>
<th>0</th>
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<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1</td>
<td>5.4</td>
<td>12.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Cap.</td>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td>7.3</td>
<td>12.6</td>
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<td>11.6</td>
<td></td>
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A combination of the two technologies achieves larger savings!
## 72-Hour Results (FACTS Location)

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<th>Number of Switching Actions</th>
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<tbody>
<tr>
<td>Low Cap.</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>22</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>22, 23</td>
<td>22, 23</td>
<td>22, 23</td>
</tr>
<tr>
<td>High Cap.</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>19, 23</td>
<td>19, 23</td>
<td>19, 23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of FACTS</th>
<th>Low Cap.</th>
<th>High Cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22, 23</td>
<td>22, 23</td>
</tr>
<tr>
<td>2</td>
<td>19, 23</td>
<td>22, 23</td>
</tr>
<tr>
<td>1</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>23, 25</td>
<td>25, 26</td>
</tr>
<tr>
<td>1</td>
<td>19, 23</td>
<td>19, 23</td>
</tr>
<tr>
<td>2</td>
<td>19, 23</td>
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<th>Number of FACTS High Cap.</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>1</td>
<td>22, 23</td>
</tr>
<tr>
<td>Summer</td>
<td>1</td>
<td>22, 23</td>
<td>22, 23</td>
</tr>
<tr>
<td>Winter</td>
<td>0</td>
<td>23, 25</td>
<td>19, 23</td>
</tr>
</tbody>
</table>

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

FACTS set points in the cases with two FACTS

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.
Make America Care about FACTS Again!

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Thank You!
References and Further Reading


Thank You!

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