# 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.

Mostafa Ardakani and Yuanrui Sang

mostafa.ardakani@utah.edu

# Outline

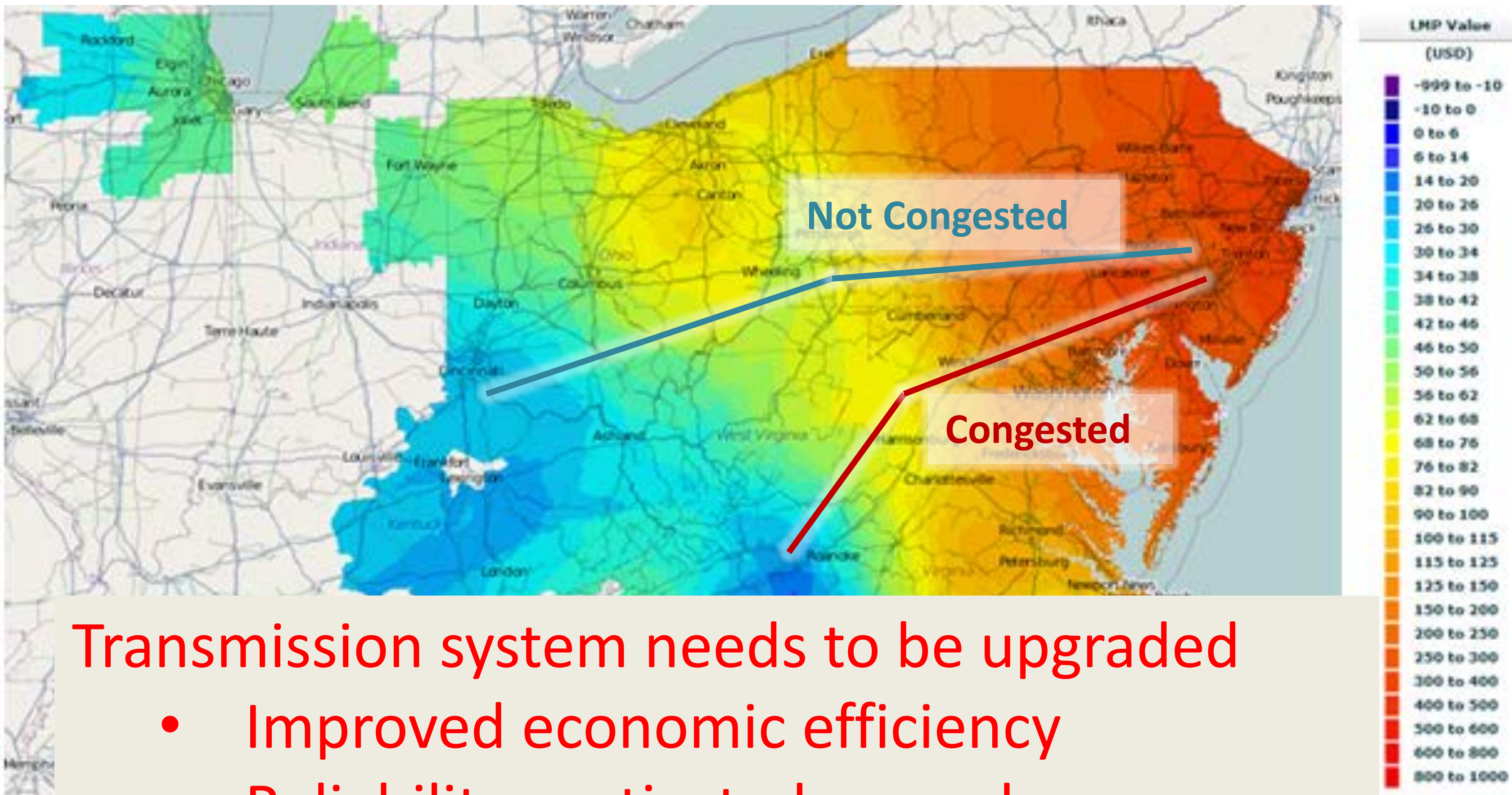
- Flexible Transmission
- Modeling Challenges
- Potential Solutions
  - Transmission Switching
  - Variable Impedance Flexible AC Transmission Systems (FACTS)
- Modular FACTS
- Interdependence of the Technologies

# Large Economic Size

More than 350 Billion Dollars!

Even Little Efficiency Matters!

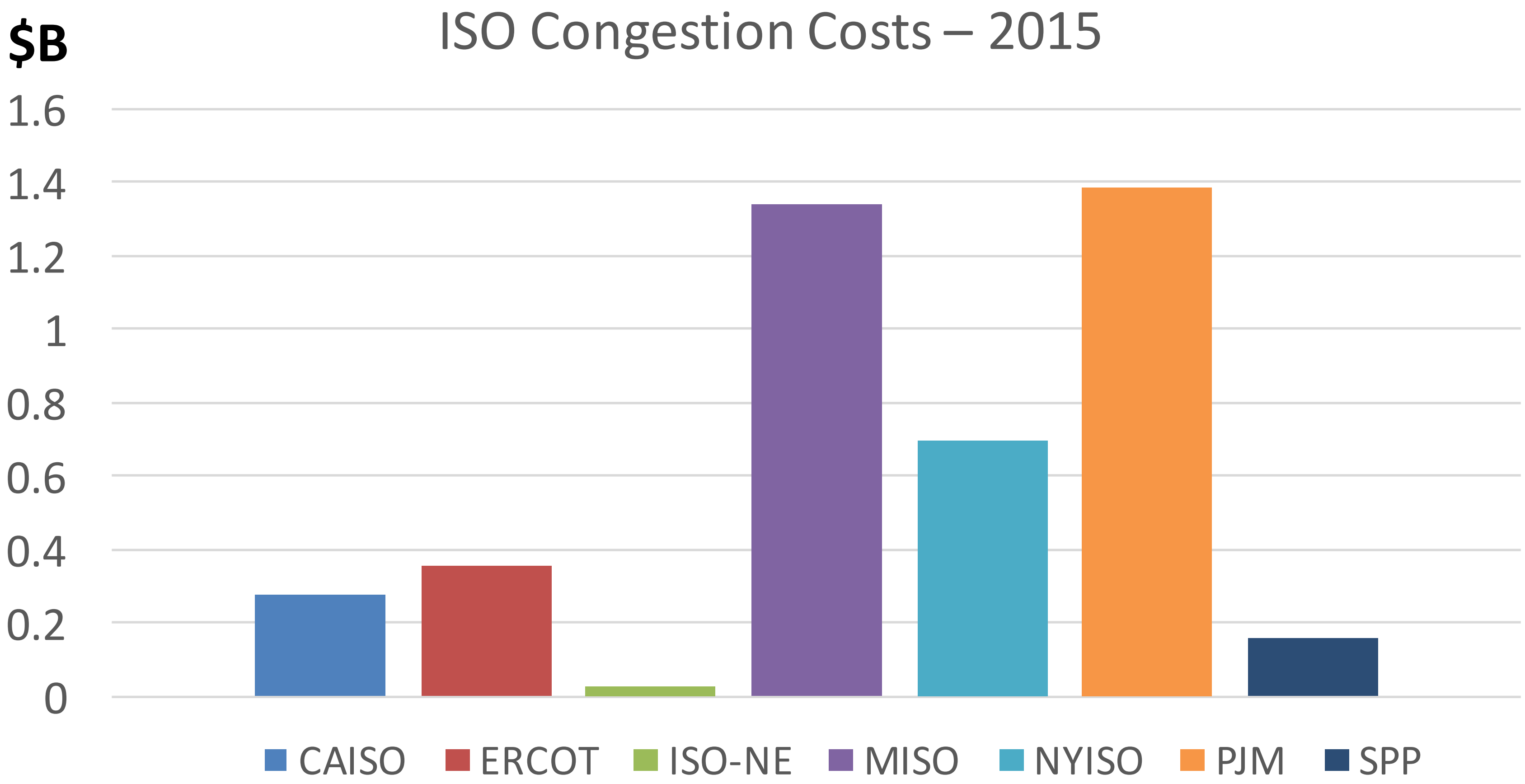
# Transmission Bottlenecks



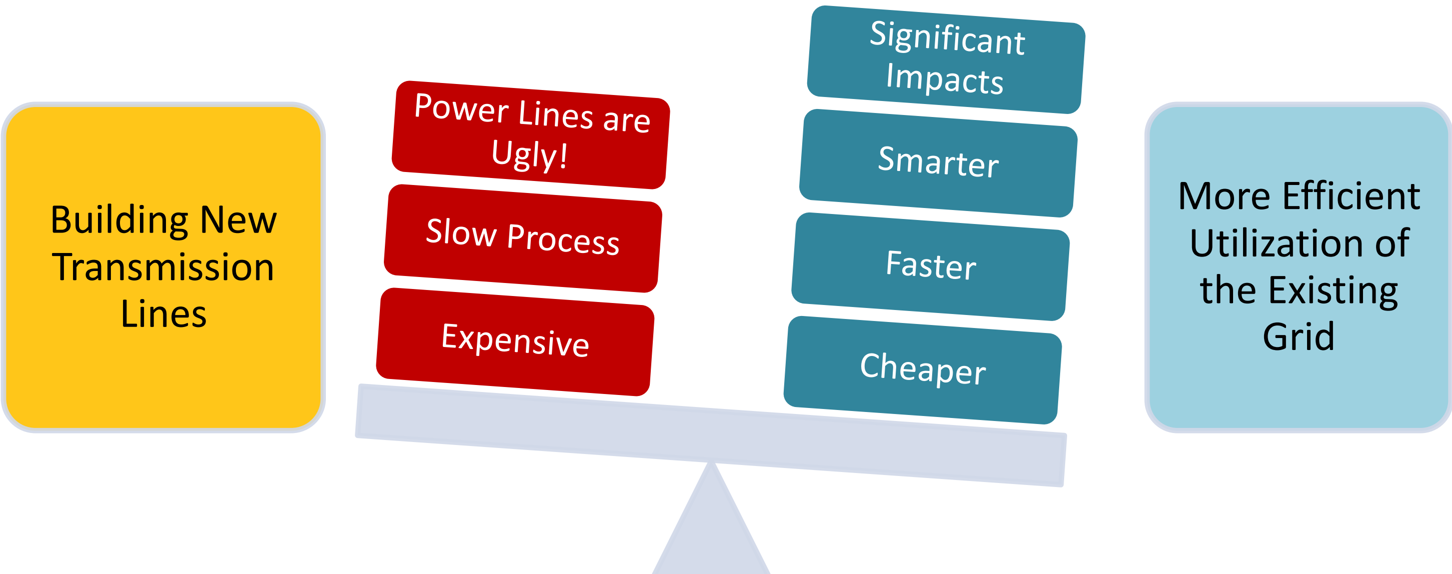

Transmission system needs to be upgraded

- Improved economic efficiency
- Reliability-motivated upgrades

# Congestion Cost in US ISO/RTOs



# Choices




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

# Transmission Flexibility

$$F = B(\theta_j - \theta_i)$$

Power Flow Equations

$$\begin{cases} F_k = Z_k B_k (\theta_j - \theta_i) \\ Z_k \in \{0,1\} \end{cases}$$

**Transmission Switching**

**Mixed Integer Program**

Transmission switching does not require additional hardware.

$$\begin{cases} F_k = B_k (\theta_j - \theta_i) \\ B^{\min} \le B \le B^{\max} \end{cases}$$

**Variable Impedance FACTS**

**Non-Linear Program**

# Transmission Flexibility

$$F = B(\theta_j - \theta_i)$$ Power Flow Equations

**Flexible transmission**

$$\begin{cases} F_k = Z_k B_k(\theta_j - \theta_i) \\ Z_k \in \{0,1\} \end{cases}$$

Transmission Switching

Mixed Integer Program

Transmission switching does not require additional hardware.

**=**

$$\begin{cases} F_k = B_k(\theta_j - \theta_i) \\ B^{\min} \le B \le B^{\max} \end{cases}$$

Variable Impedance FACTS

Non-Linear Program

**Power flow control**

# 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

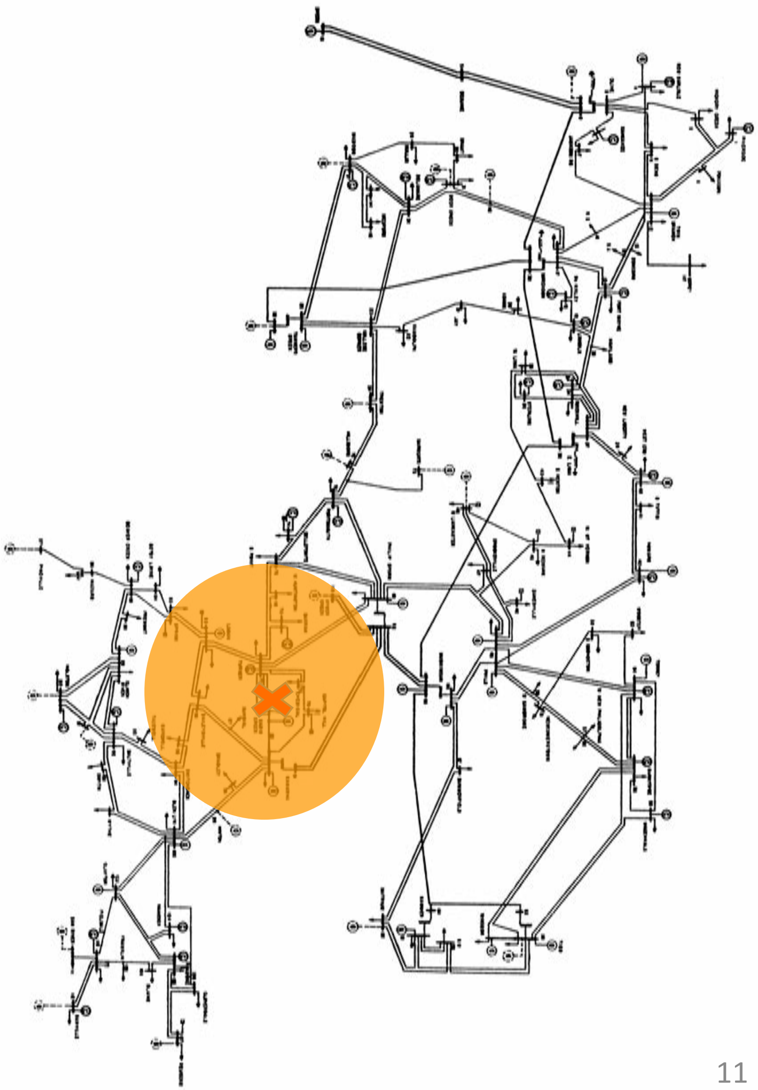
# Solution for Transmission Switching

- 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

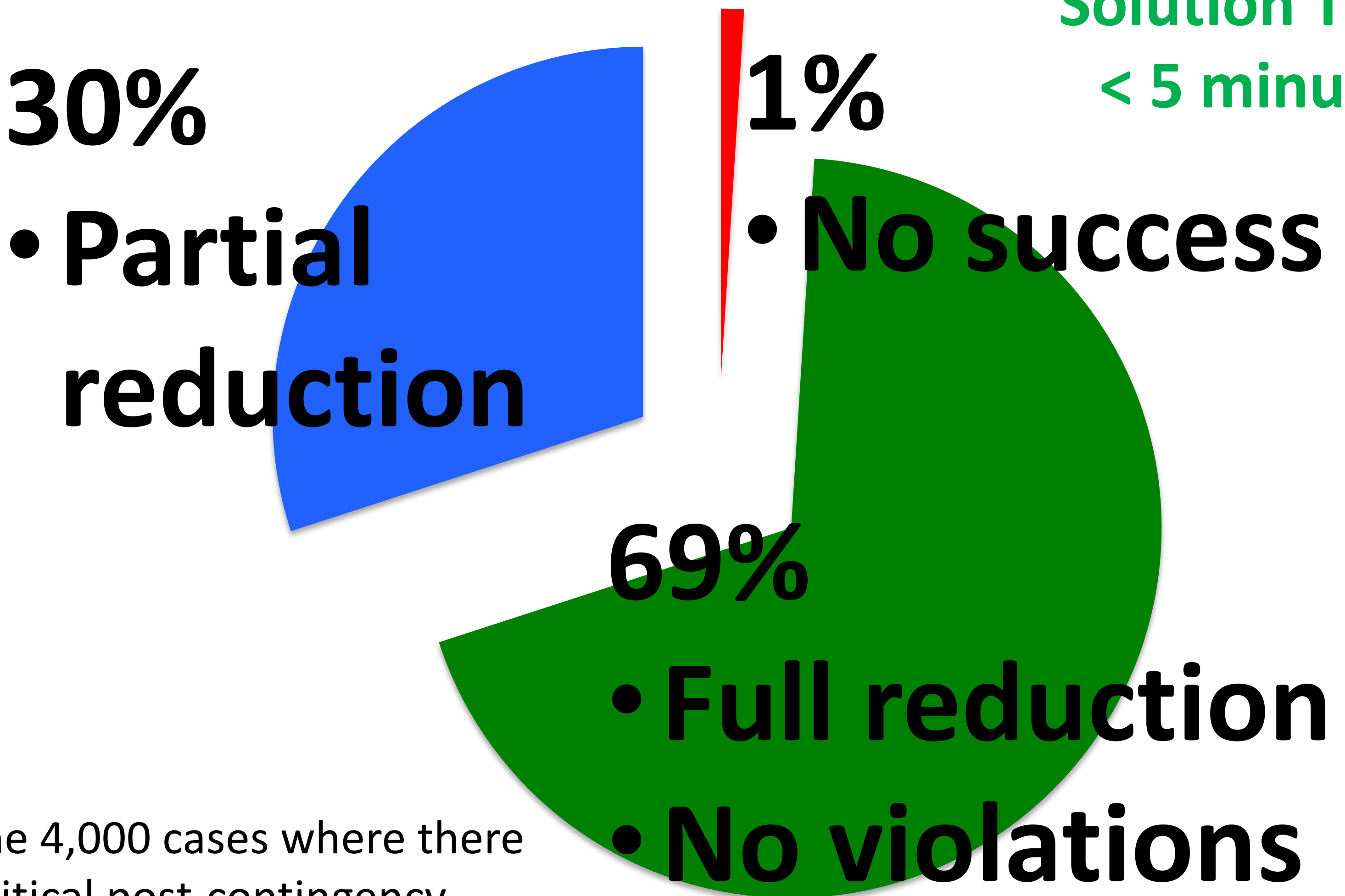
- Post-contingency violations are local:
  - A priority list is created: **100** lines closest to the contingency
- All lines in the priority list are evaluated
  - Each evaluation is an independent **AC power flow (in parallel)**
- **5** best candidates are reported to the operator (based on total improvement)
- Each is a **single** corrective switching actions



IEEE 118 Bus System – University of Washington

# CTS Benefit: PJM

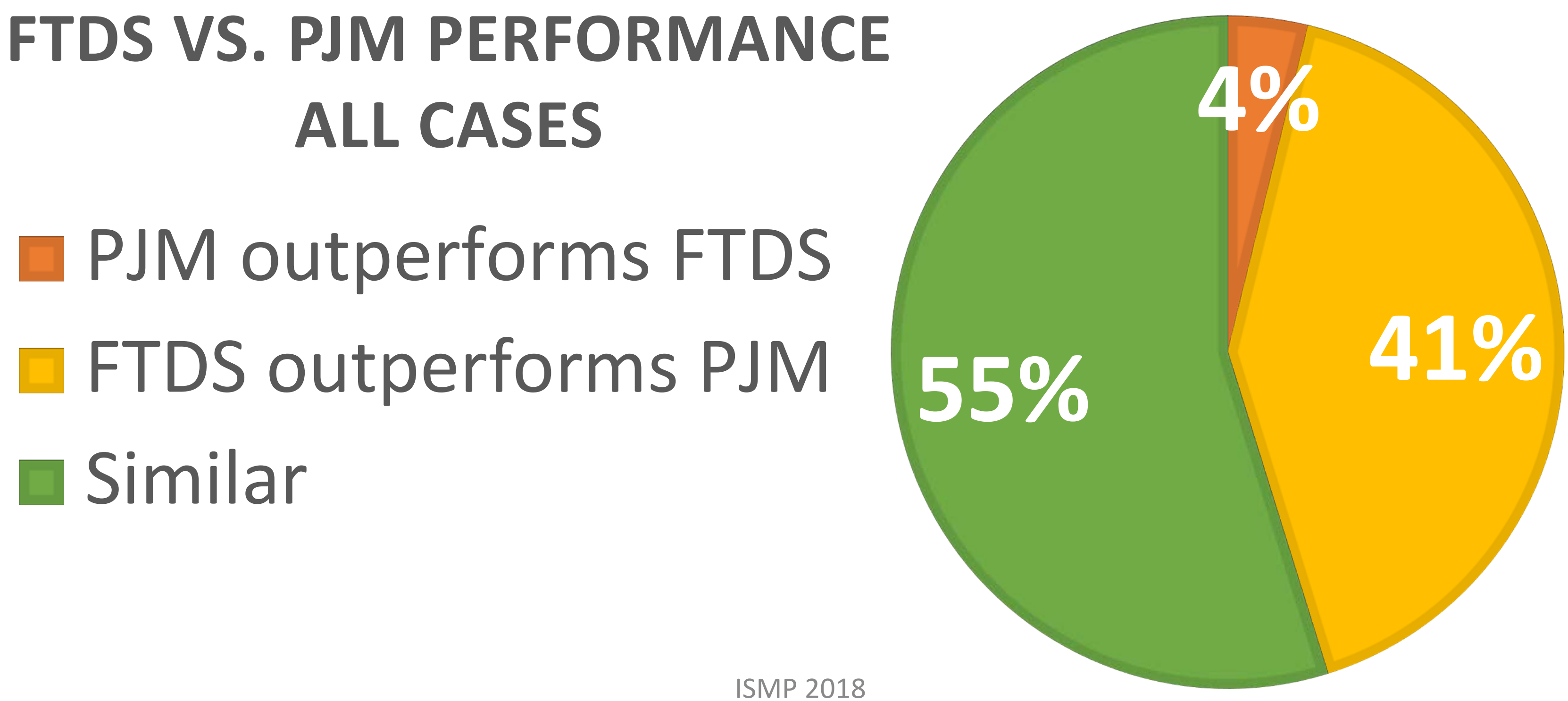
Solution Time:
< 5 minutes




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

# Comparison with PJM's Own Switching Solutions

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



# Comparison with PJM's Own Switching Solutions

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

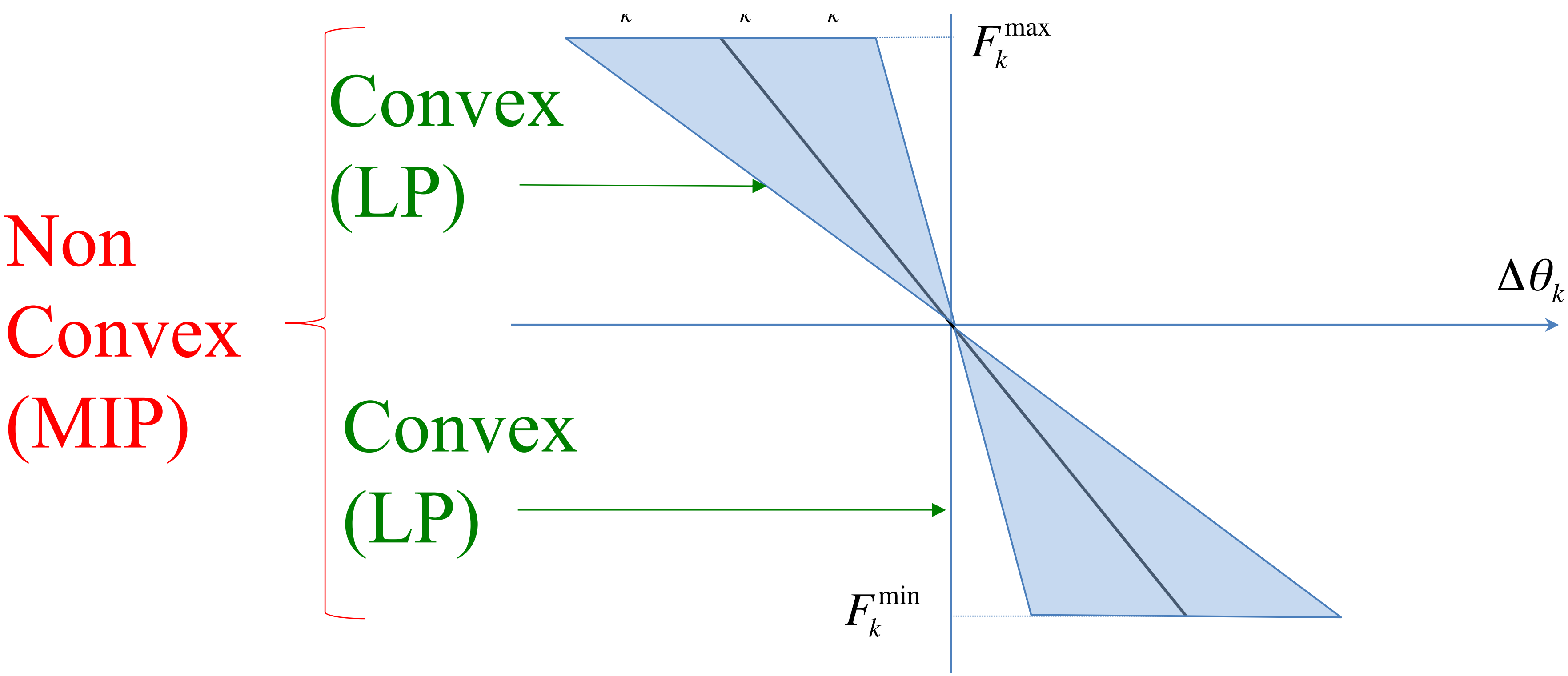
**96% of the time: FTDS does the same or better than PJM's identified switching solution**

# 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

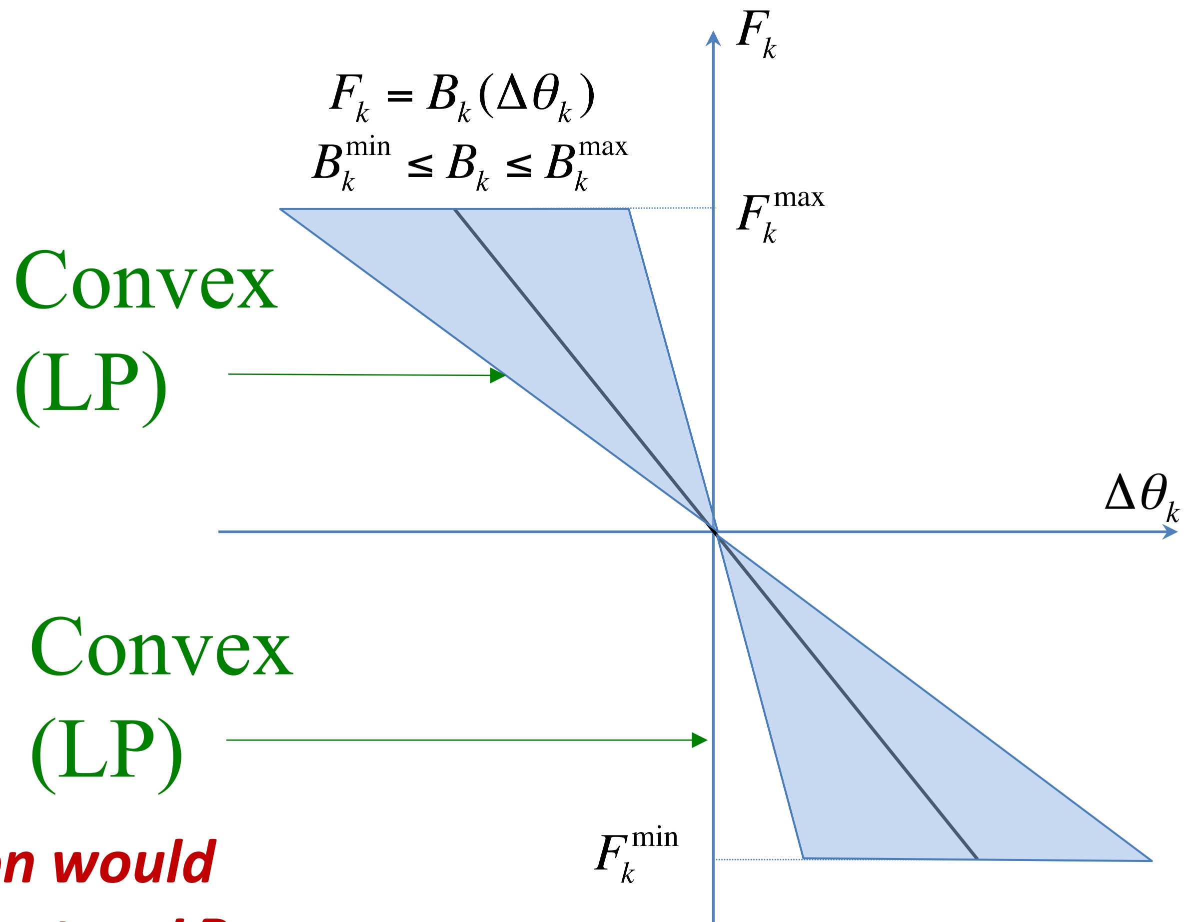
# Computational Complexity of FACTS: NLP/MIP

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



# 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.***



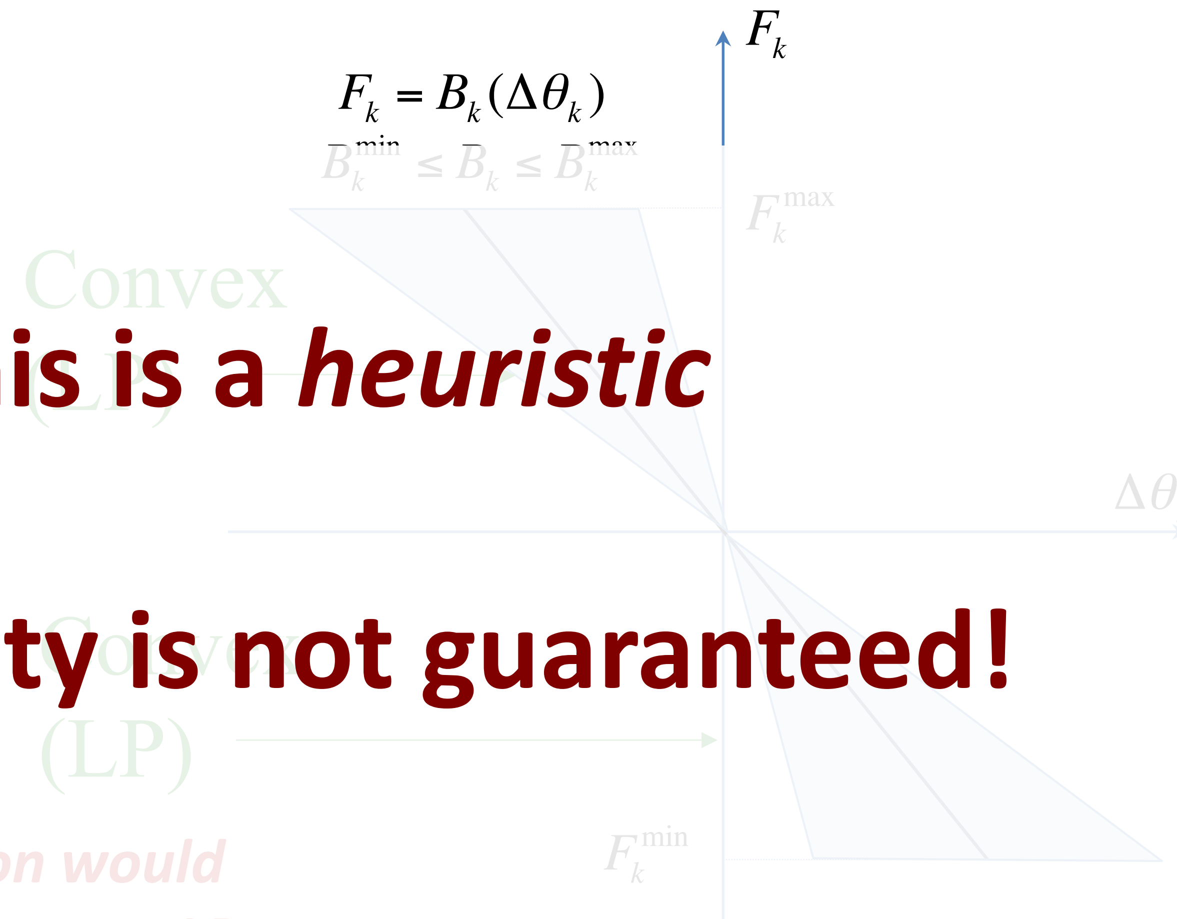

***Knowing the direction would reduce the complexity to a LP***

# 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*

$F_k = B_k(\Delta\theta_k)$

$B_k^{min} \leq B_k \leq B_k^{max}$



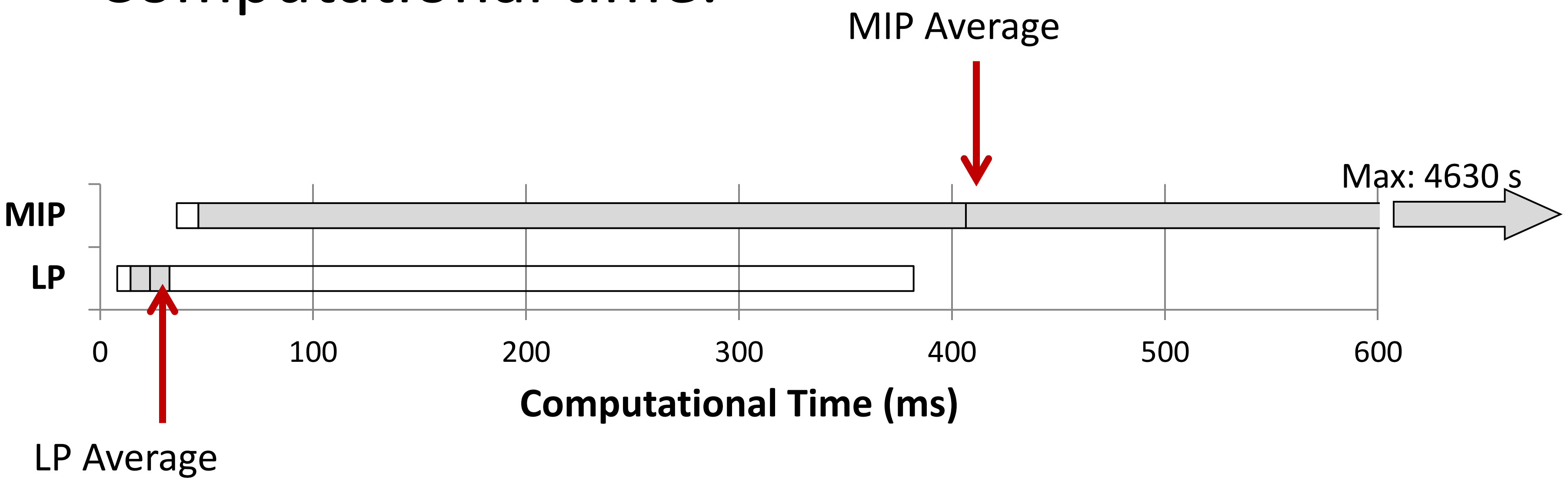

**This is a *heuristic***

**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:



# 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

# 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)*

Modular FACTS

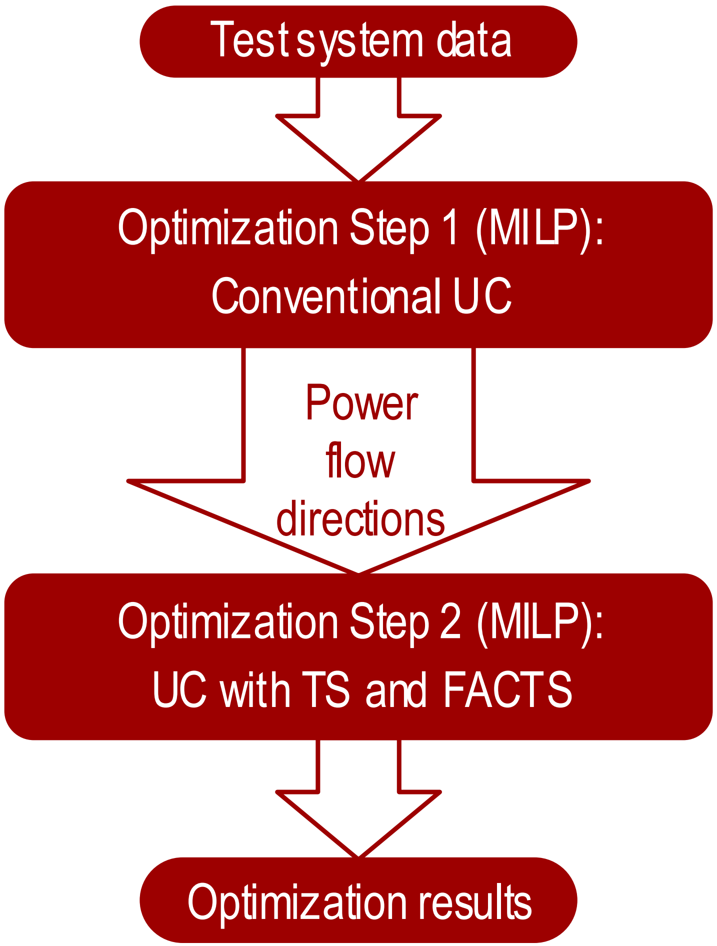
Conventional FACTS

# 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)**

# Co-optimization Model




**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)

**Spring**

| Number of FACTS | | Switching Actions: 0 | 1 | 2 |
|---|---|---|---|---|
| 0 | NA | 0 | 10.4 | 11.6 |
| 1 | Low Cap. | 5.6 | 13.2 | |
| 1 | High Cap. | 7.3 | 12.6 | |
| 2 | Low Cap. | 8.4 | 13.2 | |
| 2 | High Cap. | 11.5 | 13.3 | |

**Summer**

| Number of FACTS | | Switching Actions: 0 | 1 | 2 |
|---|---|---|---|---|
| 0 | NA | 0 | 9.7 | 13.7 |
| 1 | Low Cap. | 3.2 | 11.7 | |
| 1 | High Cap. | 7 | 13 | |
| 2 | Low Cap. | 5.5 | 15.1 | |
| 2 | High Cap. | 12.1 | 15.1 | |

**Winter**

| Number of FACTS | | Switching Actions: 0 | 1 | 2 |
|---|---|---|---|---|
| 0 | NA | 0 | 8.5 | 12.9 |
| 1 | Low Cap. | 2.7 | 9.8 | |
| 1 | High Cap. | 5.4 | 12.1 | |
| 2 | Low Cap. | 5.2 | 11.4 | |
| 2 | High Cap. | 9.4 | 14.3 | |

# 72-Hour Results (% Savings)

| | Number of FACTS | | Number of Switching Actions: 0 | 1 | 2 |
|---|---|---|---|---|---|
| Spring | 0 | NA | 0 | 10.4 | 11.6 |
| | | Low Cap. | 5.6 | 13.2 | |
| Winter | 1 | High Cap. | 5.4 | 12.1 | |
| | | Low Cap. | 5.2 | 11.4 | |
| | 2 | High Cap. | 9.4 | 14.3 | |

**A combination of the two technologies achieves larger savings!**

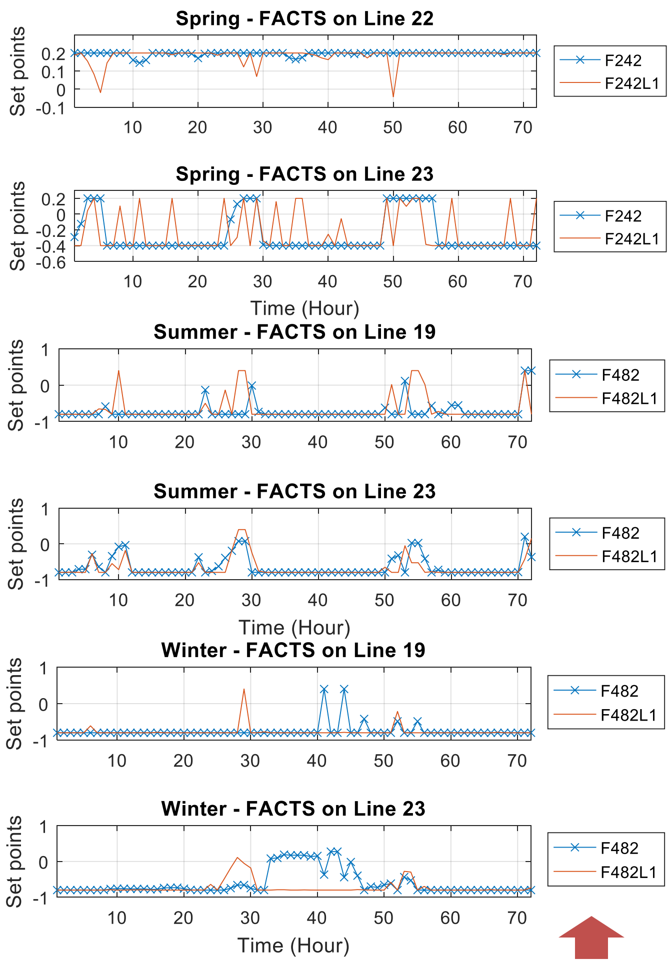
# 72-Hour Results (FACTS Location)

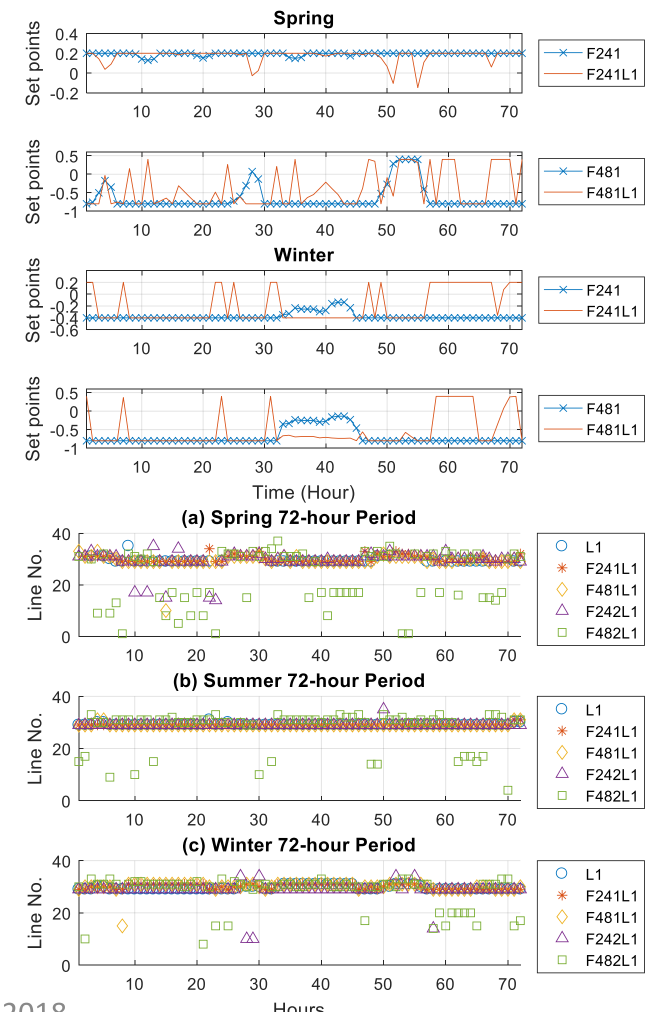
| Number of FACTS | | | Spring | | Summer | | Winter | |
|---|---|---|---|---|---|---|---|---|
| | | **Number of Switching Actions** | 0 | 1 | 0 | 1 | 0 | 1 |
| | 1 | Low Cap. | 22 | 22 | 23 | 25 | 23 | 23 |
| | 1 | High Cap. | 23 | 23 | 23 | 28 | 23 | 23 |
| | 2 | Low Cap. | 22, 23 | 22, 23 | 22, 23 | 25, 26 | 23, 25 | 25, 26 |
| | 2 | High Cap. | 19, 23 | 22, 23 | 19, 23 | 19, 23 | 19, 23 | 19, 23 |

# 72-Hour Results (FACTS Location)

Transmission switching affects the optimal location of FACTS devices!

# 72-Hour Co-optimization Analysis




**FACTS set points in the cases with only one FACTS**

**Locations of switched lines**

**FACTS set points in the cases with two FACTS**

# 72-Hour Co-optimization Analysis

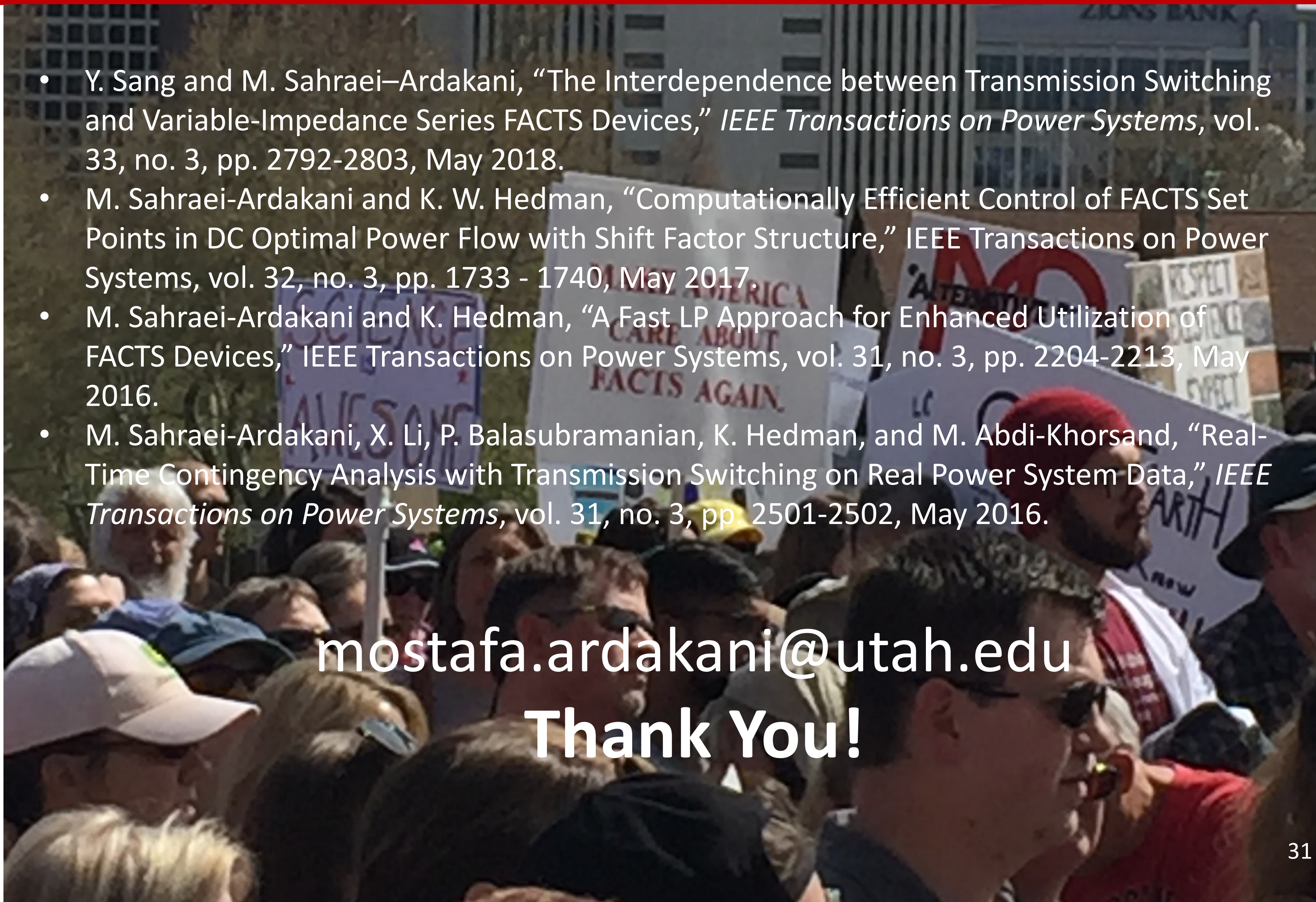
1. FACTS set points are affected by transmission switching
2. FACTS operation affects switching actions

FACTS set points in the cases with two FACTS

# 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




- Y. Sang and M. Sahraei–Ardakani, "The Interdependence between Transmission Switching and Variable-Impedance Series FACTS Devices," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2792-2803, May 2018.
- M. Sahraei-Ardakani and K. W. Hedman, "Computationally Efficient Control of FACTS Set Points in DC Optimal Power Flow with Shift Factor Structure," IEEE Transactions on Power Systems, vol. 32, no. 3, pp. 1733 - 1740, May 2017.
- M. Sahraei-Ardakani and K. Hedman, "A Fast LP Approach for Enhanced Utilization of FACTS Devices," IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 2204-2213, May 2016.
- M. Sahraei-Ardakani, X. Li, P. Balasubramanian, K. Hedman, and M. Abdi-Khorsand, "Real-Time Contingency Analysis with Transmission Switching on Real Power System Data," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2501-2502, May 2016.


mostafa.ardakani@utah.edu

**Thank You!**