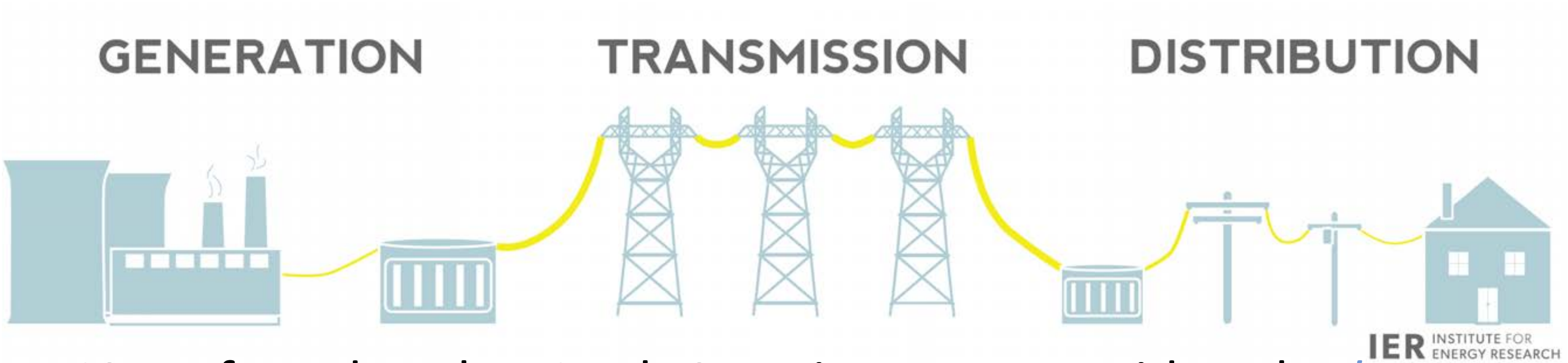
Optimal Portfolio of Power Flow Control Technologies: Topology and Impedance Control



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

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Outline

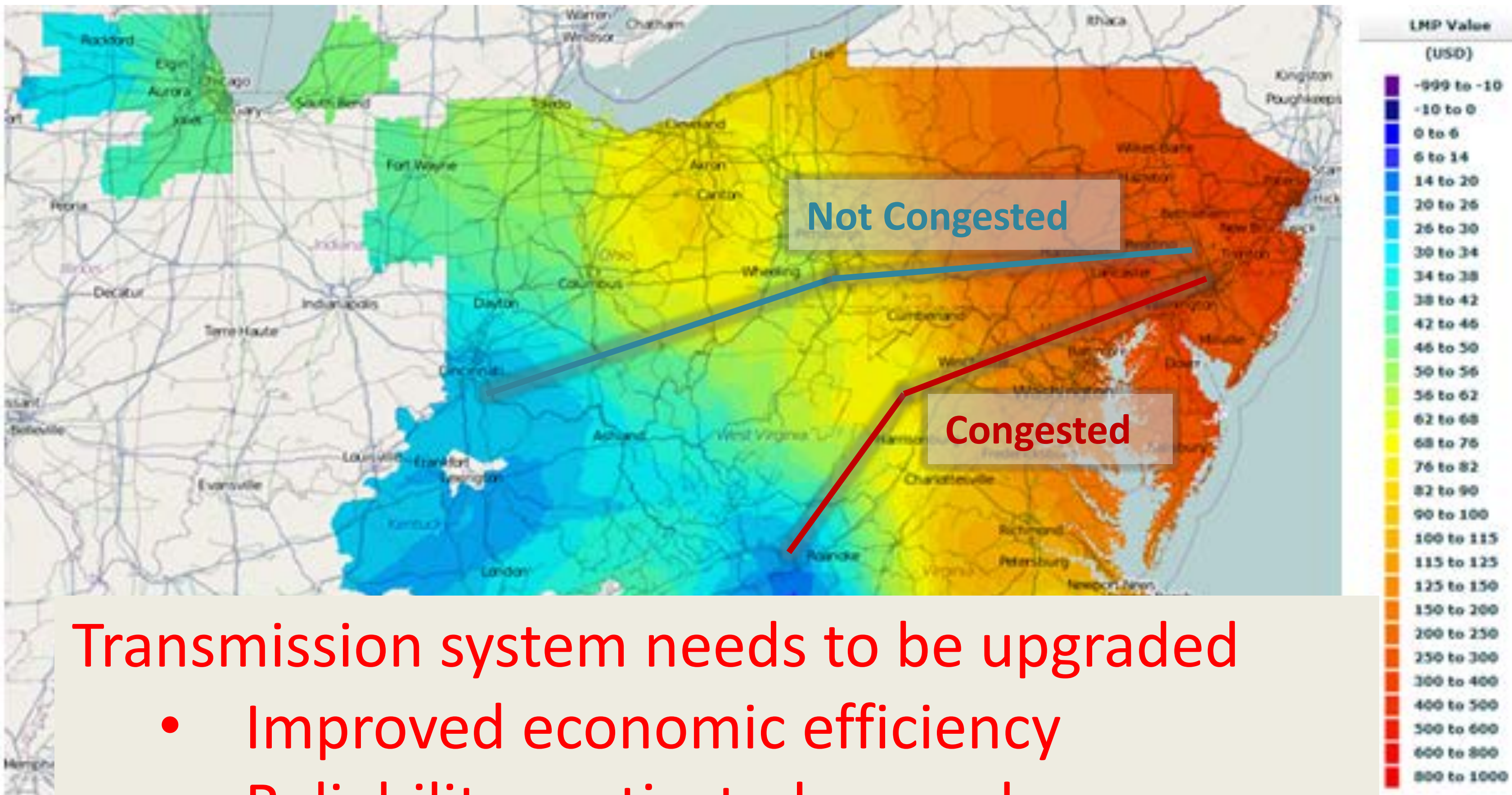
- Flexible Transmission
- Modeling Challenges
- Potential Solutions
  - Transmission Switching
  - Variable Impedance Flexible AC Transmission Systems (FACTS)
- Interdependence of the two Technologies

Large Economic Size

More than 350 Billion Dollars!

Even Little Efficiency Matters!

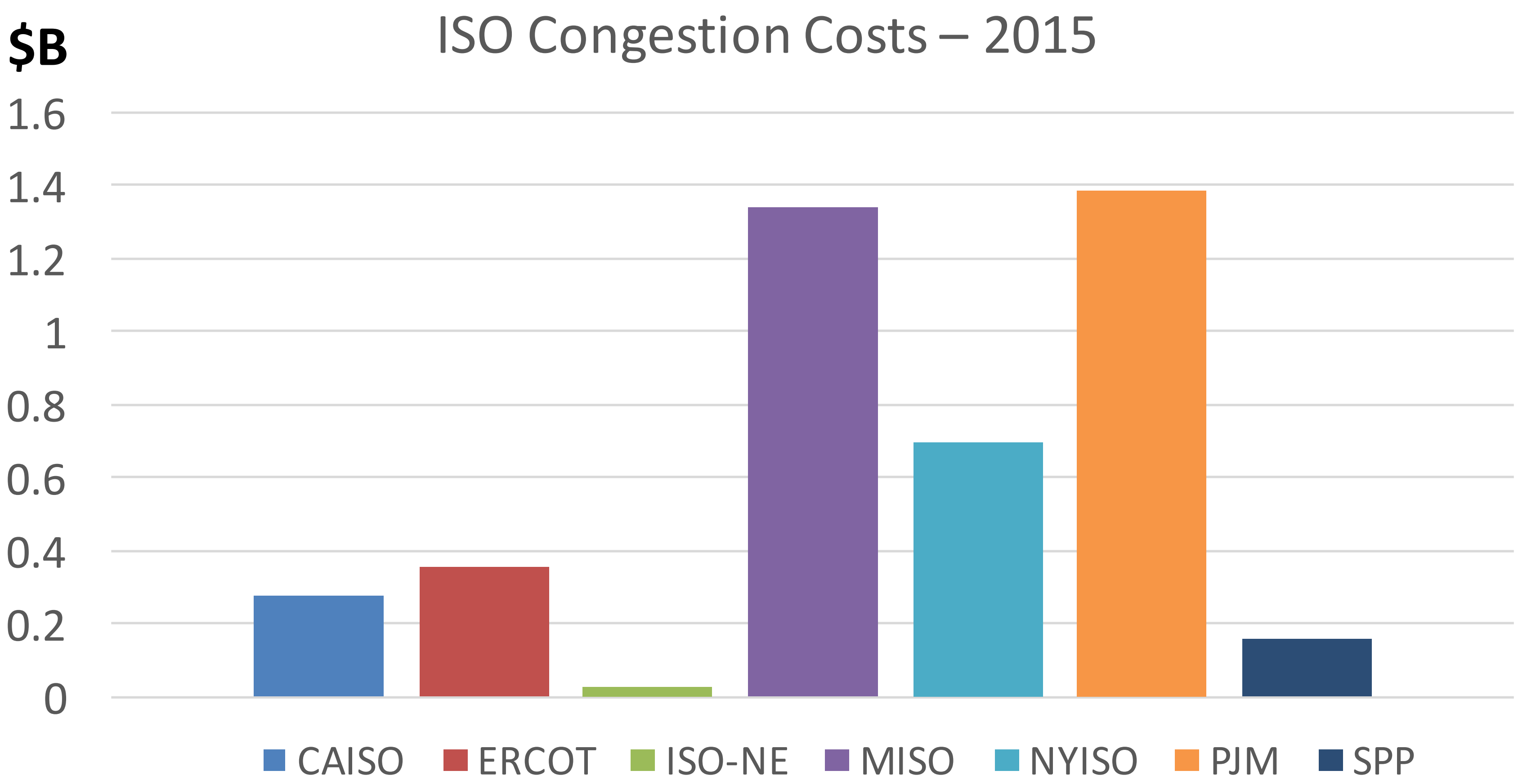
Transmission Bottlenecks



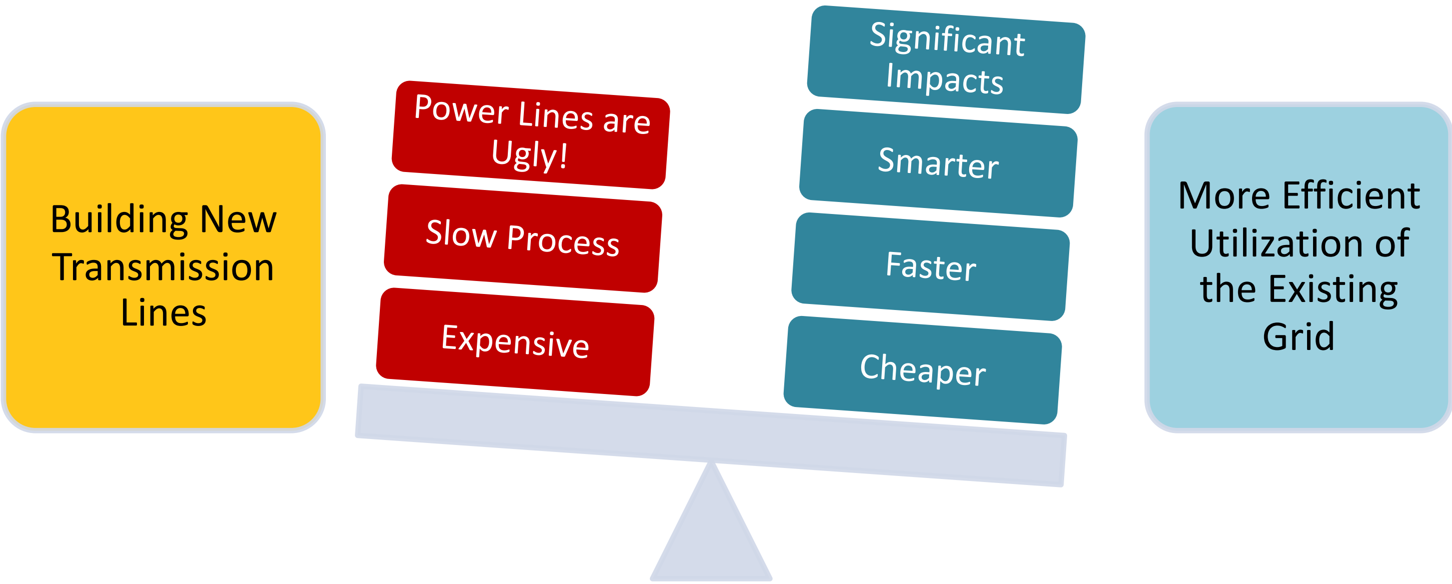
Transmission system needs to be upgraded

- Improved economic efficiency
- Reliability-motivated upgrades

Congestion Cost in US ISO/RTOs



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

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Transmission switching does not require additional hardware.

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

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

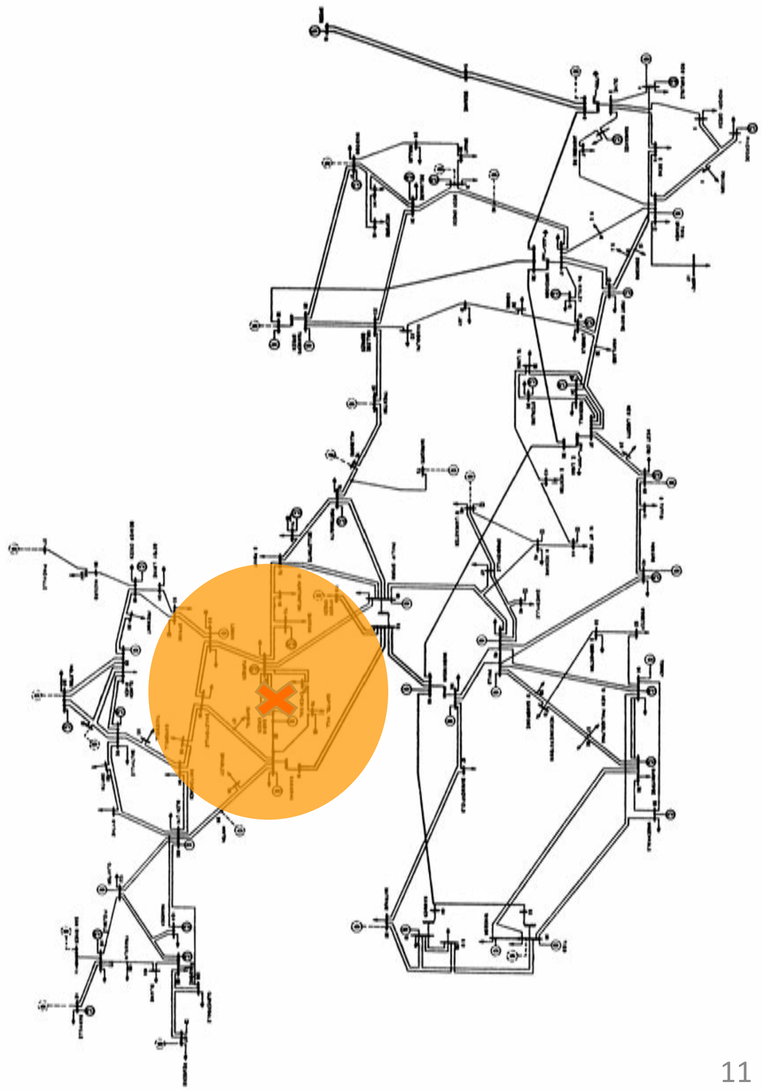
Solution for Transmission Switching

- Challenge: $F_k = Z_k B_k(\theta_j - \theta_i) \qquad Z_k \in \{0,1\}$
  - 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

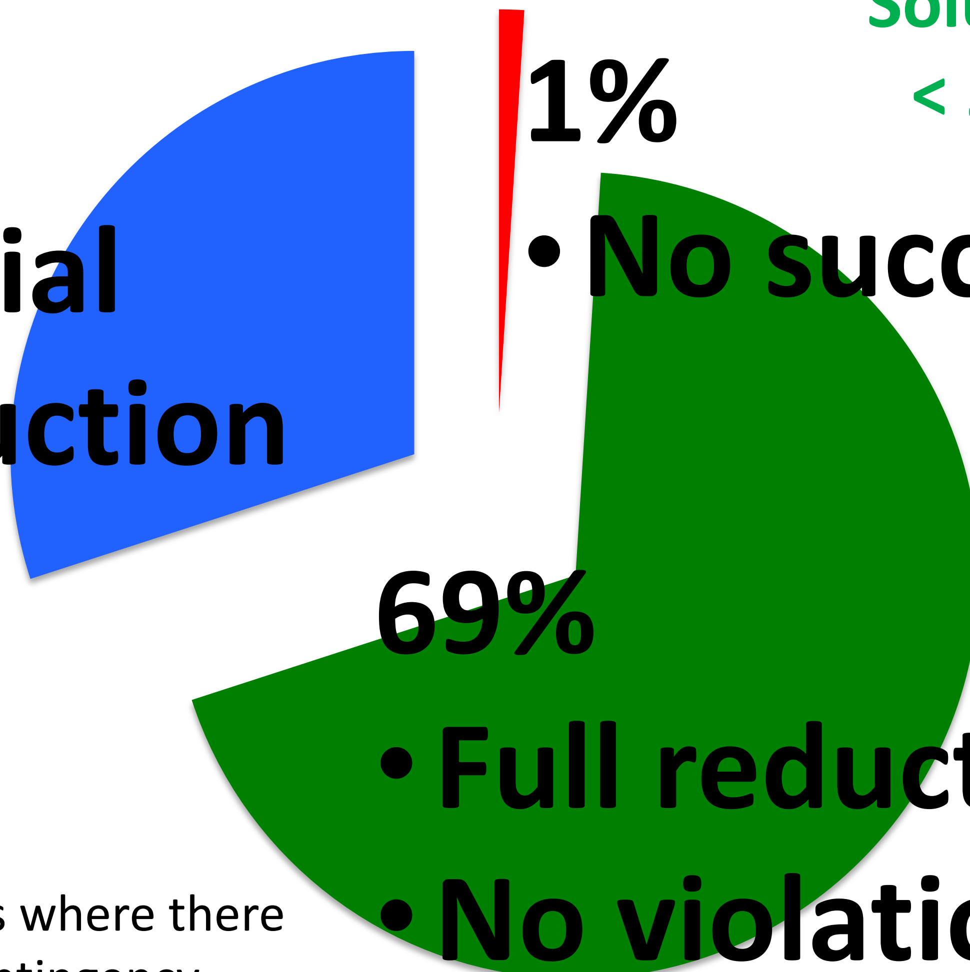
- Post-contingency violations are local:
  - A priority list is created: **100** lines closest to the contingency
- All lines in the priority list are evaluated
  - Each evaluation is an independent **AC power flow (in parallel)**
- **5** best candidates are reported to the operator (based on total improvement)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



IEEE 118 Bus System – University of Washington

CTS Benefit: PJM

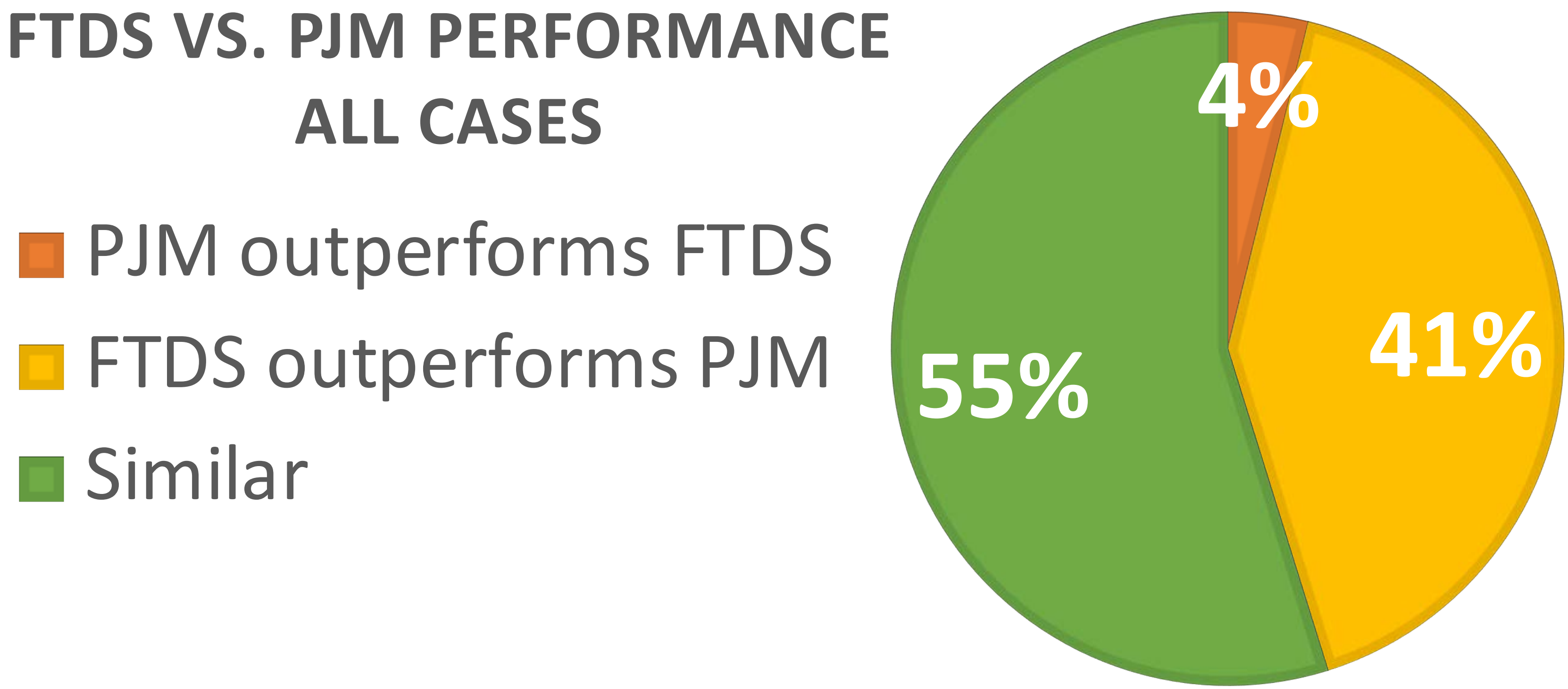
Solution Time:
< 5 minutes



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
- Relevant work by Pablo Ruiz, et al.

FACTS and Modular-FACTS

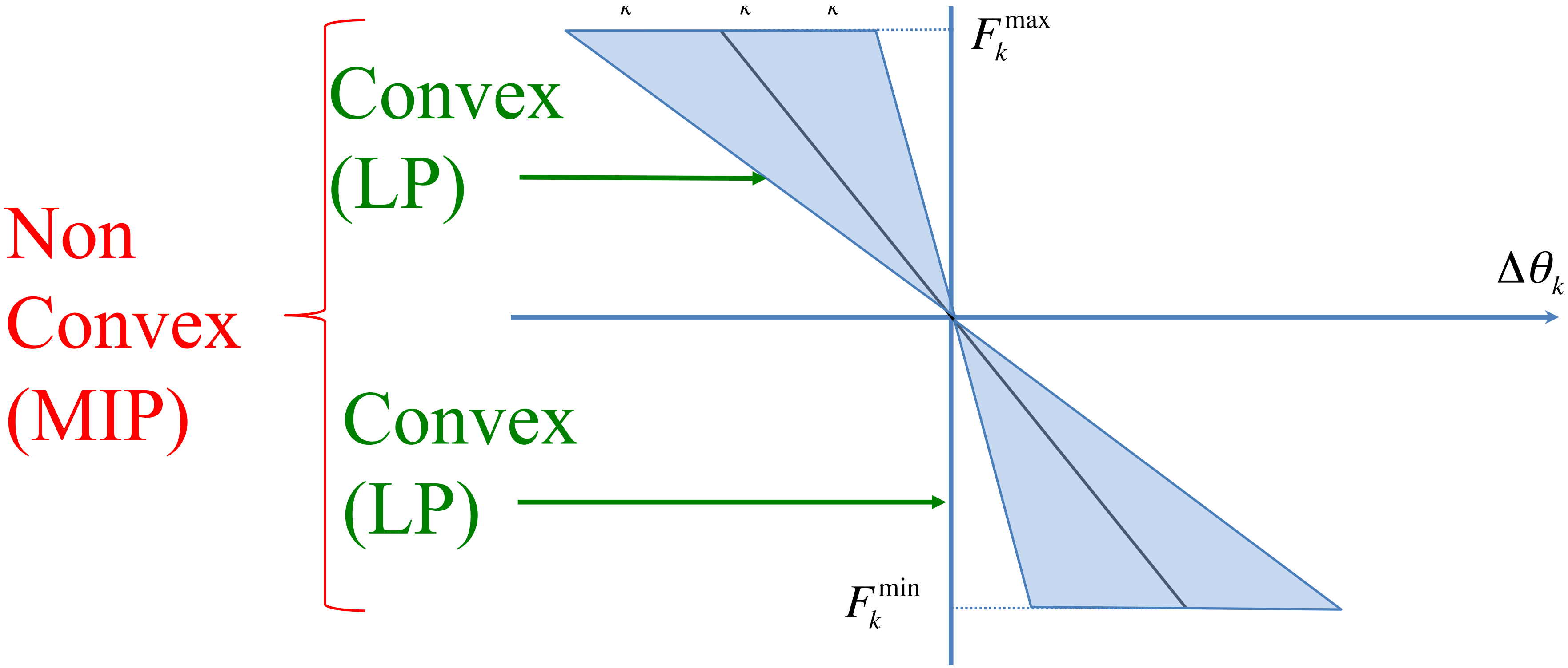
- Conventional FACTS:
  - Expensive
  - Large
- Modular FACTS:
  - Relatively cheaper
  - Smaller and **modular**
  - Can be installed rather quickly
  - Can be redeployed
  - *Additional binary variables in planning (how many on a line)*

Modular FACTS

Conventional FACTS

Computational Complexity of FACTS: NLP/MIP

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

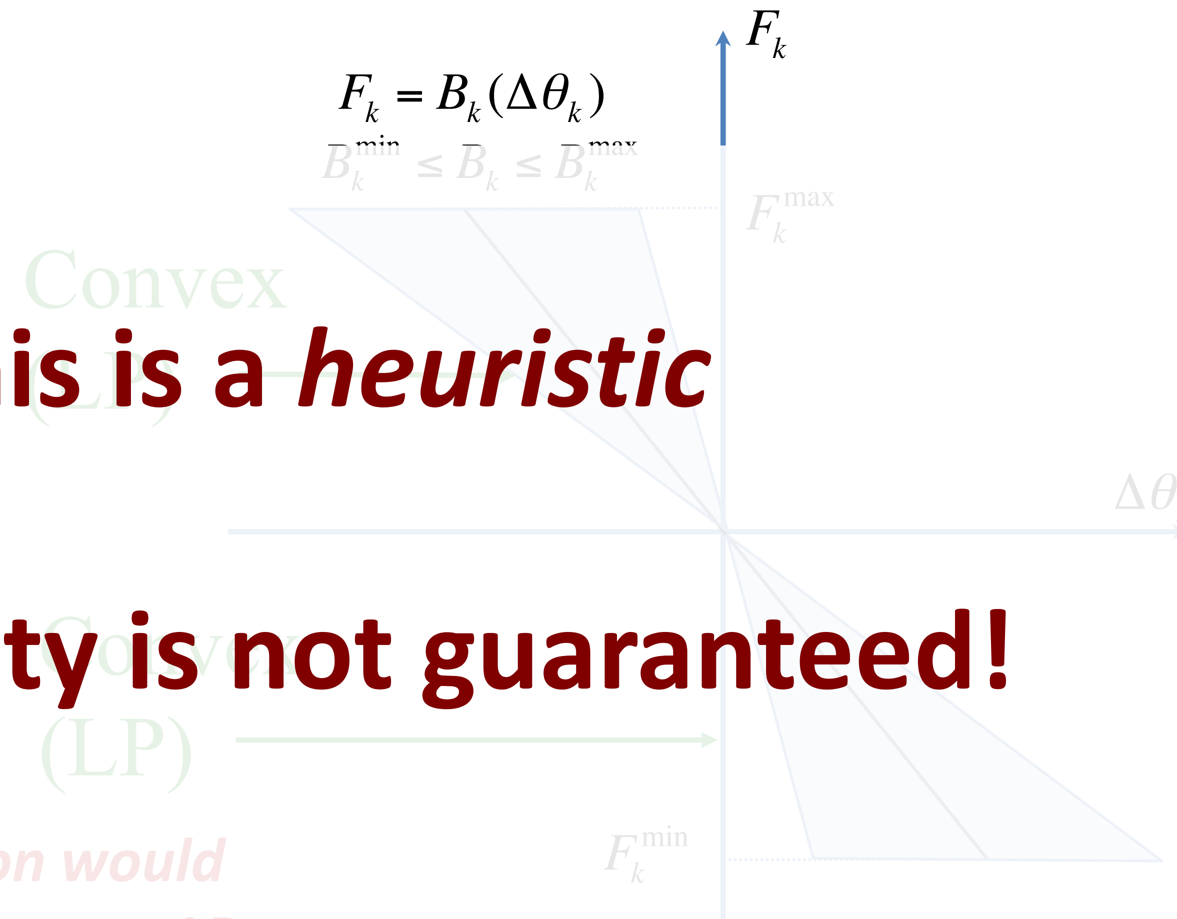


Engineering Insight

- 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*

$$F_k = B_k(\Delta\theta_k)$$

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



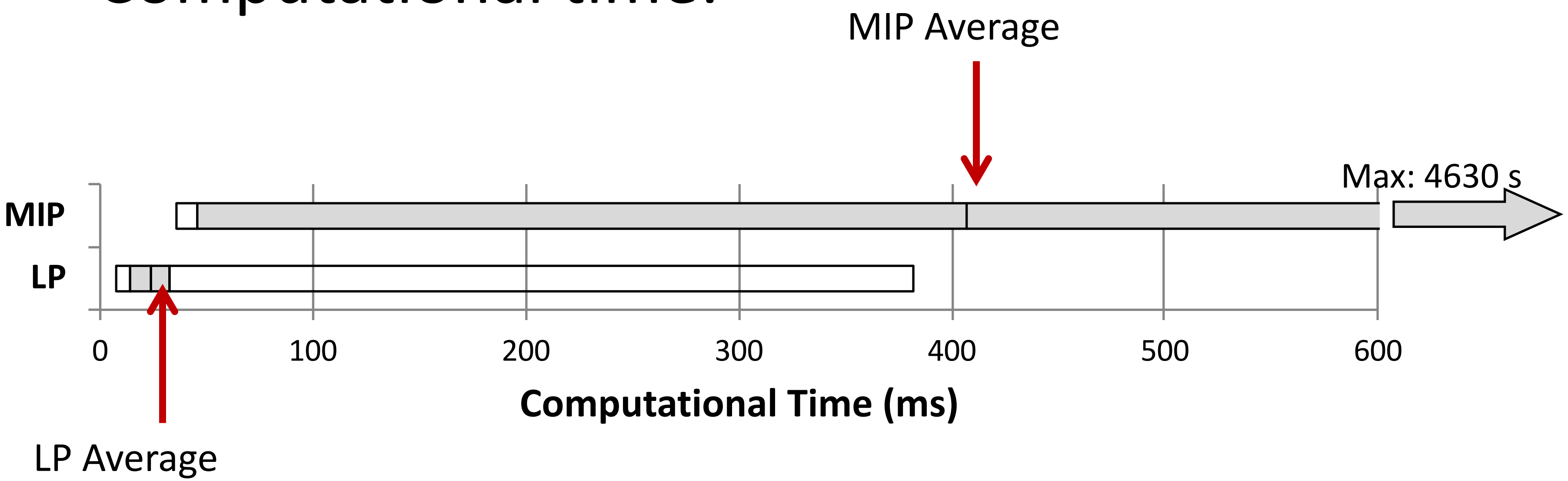
This is a *heuristic*

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

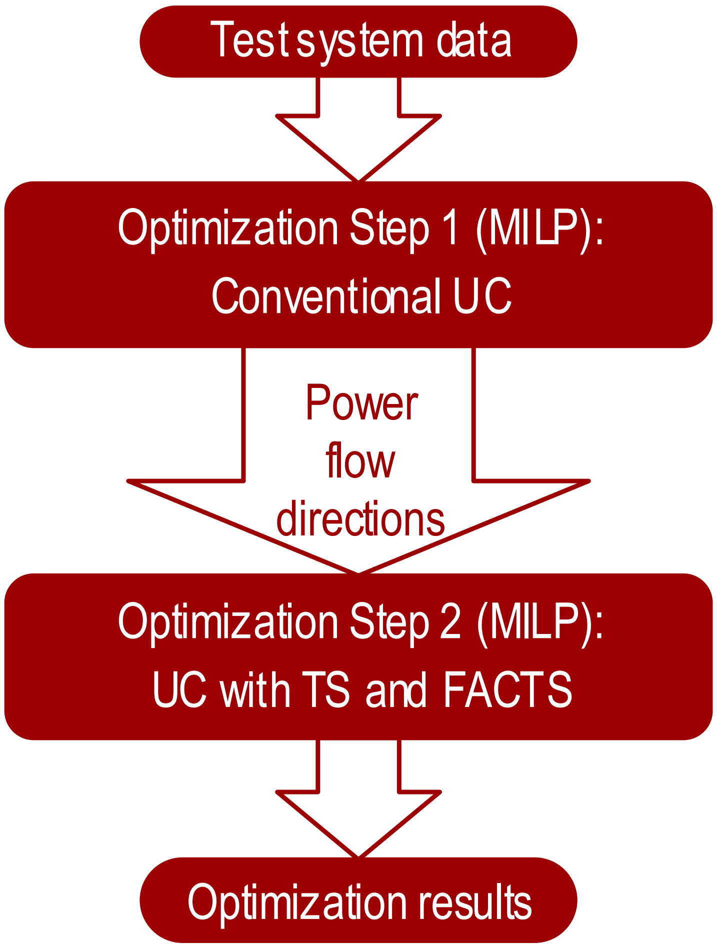
- Estimate the direction of power flow on lines with FACTS
  - If estimation is not available, run a DCOPF and find the direction
- Fix the direction to achieve an LP
- Outcomes:
  - Computational efficiency
  - Near optimal performance
  - Optimality is not guaranteed

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

Summer

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

Winter

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

72-Hour Results (% Savings)

Season	Number of FACTS	Type	Switching Actions: 0	1	2
Spring	0	NA	0	10.4	11.6
		Low Cap.	5.6	13.2	

A combination of the two technologies achieves larger savings!

Season	Number of FACTS	Type	Switching Actions: 0	1	2
Winter	1	High Cap.	5.4	12.1	
		Low Cap.	5.2	11.4	
	2	High Cap.	9.4	14.3	

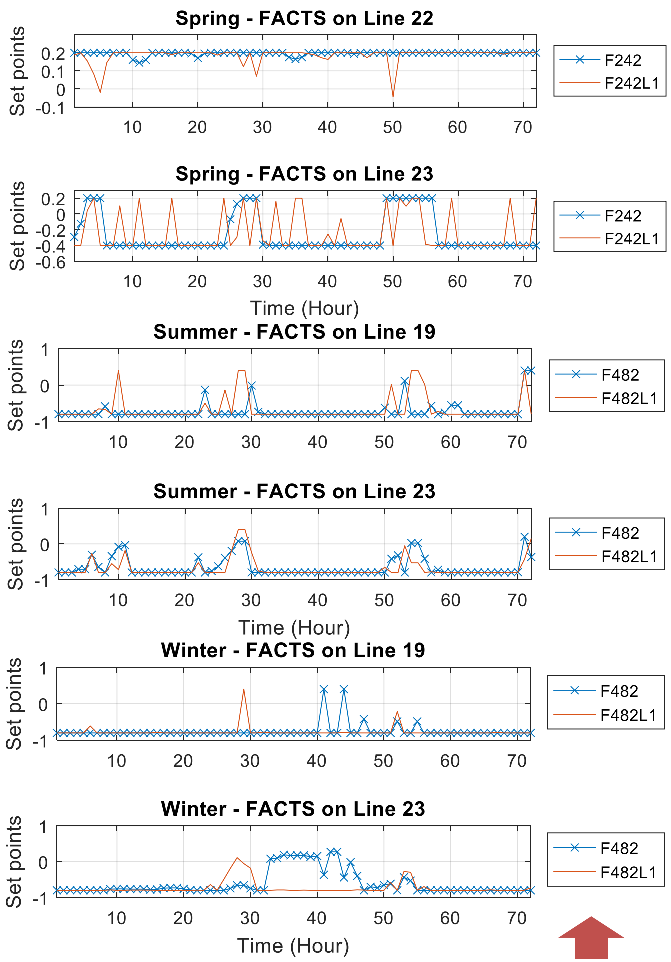
72-Hour Results (FACTS Location)

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

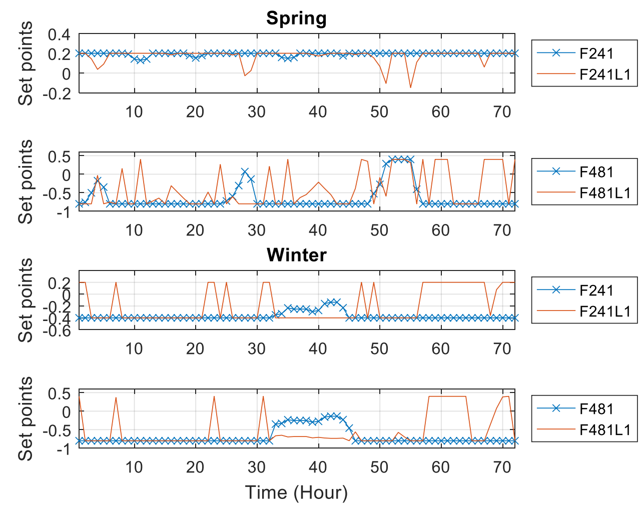
72-Hour Results (FACTS Location)

Transmission switching affects the optimal location of FACTS devices!

72-Hour Co-optimization Analysis



FACTS set points in the cases with two FACTS



FACTS set points in the cases with only one FACTS

72-Hour Co-optimization Analysis

Spring - FACTS on Line 22

Spring

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

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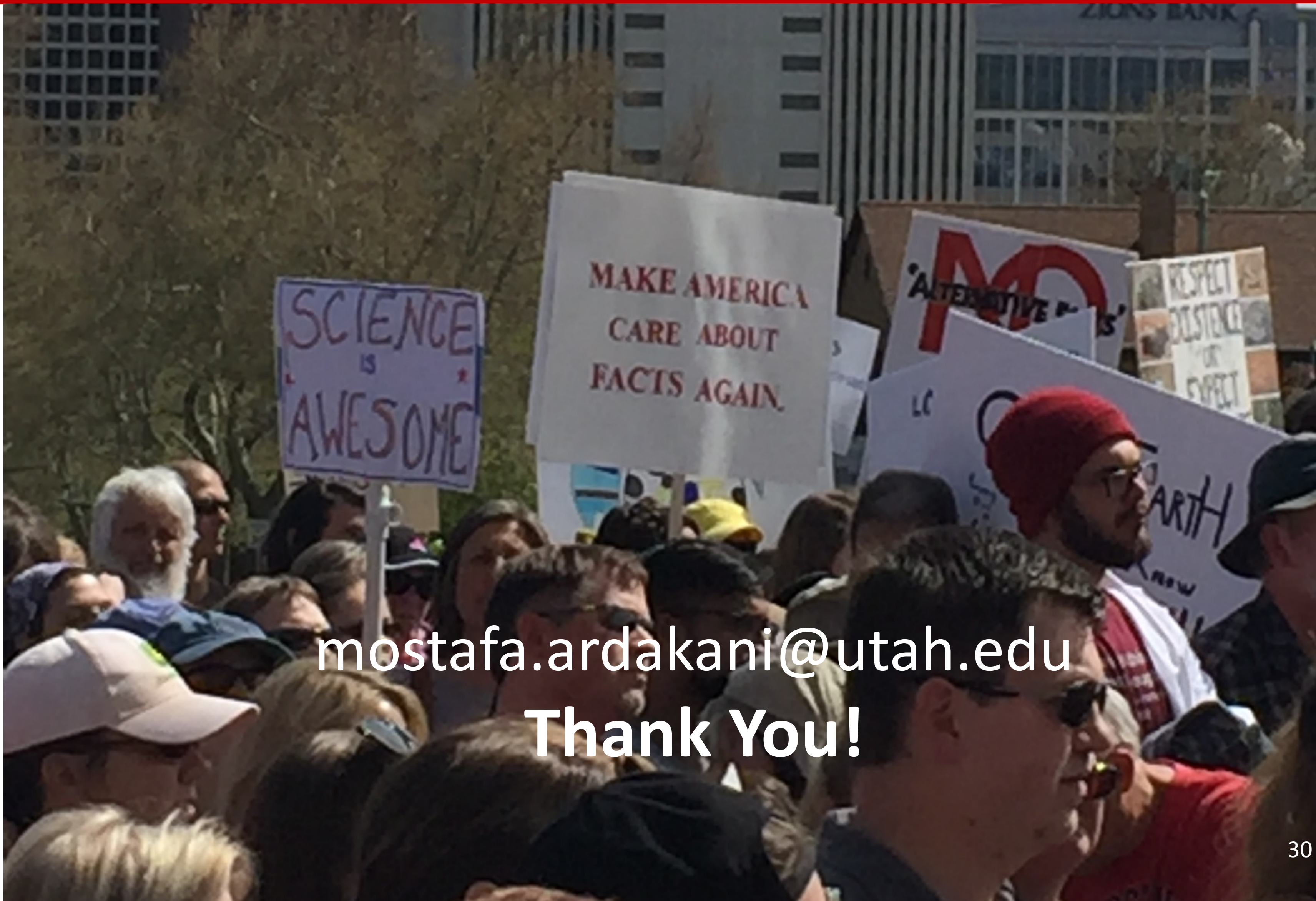
Time (Hour)

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.

Make America Care about FACTS Again!



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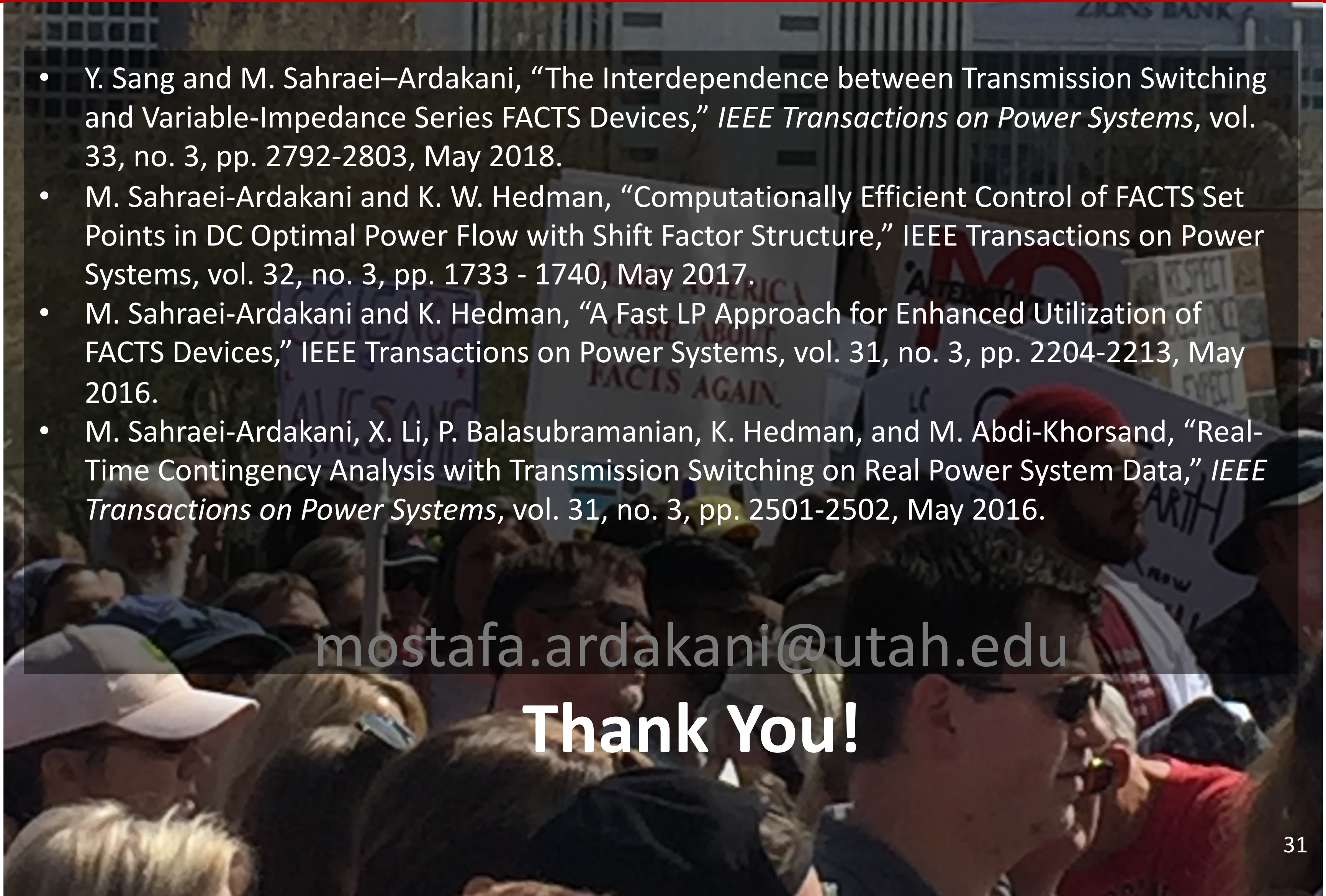
Thank You!

References and Further Reading



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Thank You!