Operation of Power Flow Controllers: Computational Efficiency and Market Participation

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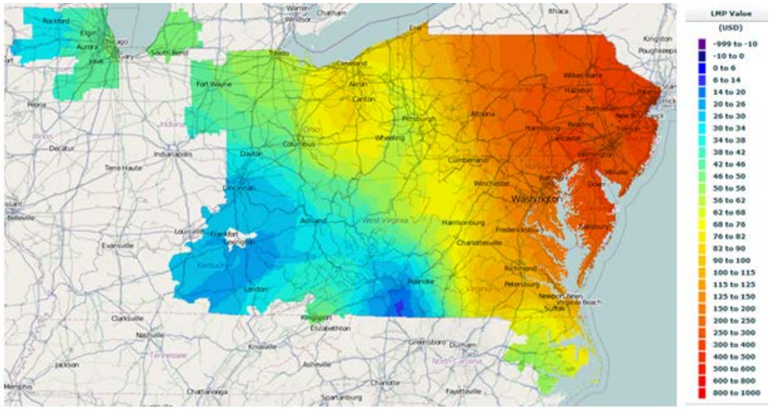
Summary of Research Projects

- Power System Operation During Windstorms
  - Collaborative Research with Department of Civil Engineering
- Computationally-Efficient Algorithm Design for Operation of Power Flow Controllers
  - Transmission Switching (ARPA-E Project)
  - Controllable Reactance (TCSC, Smart Wire Grid)
- Market Design for Flexible Transmission

Motivation

Economic size of the industry: $350 billion

Transmission system is under stress

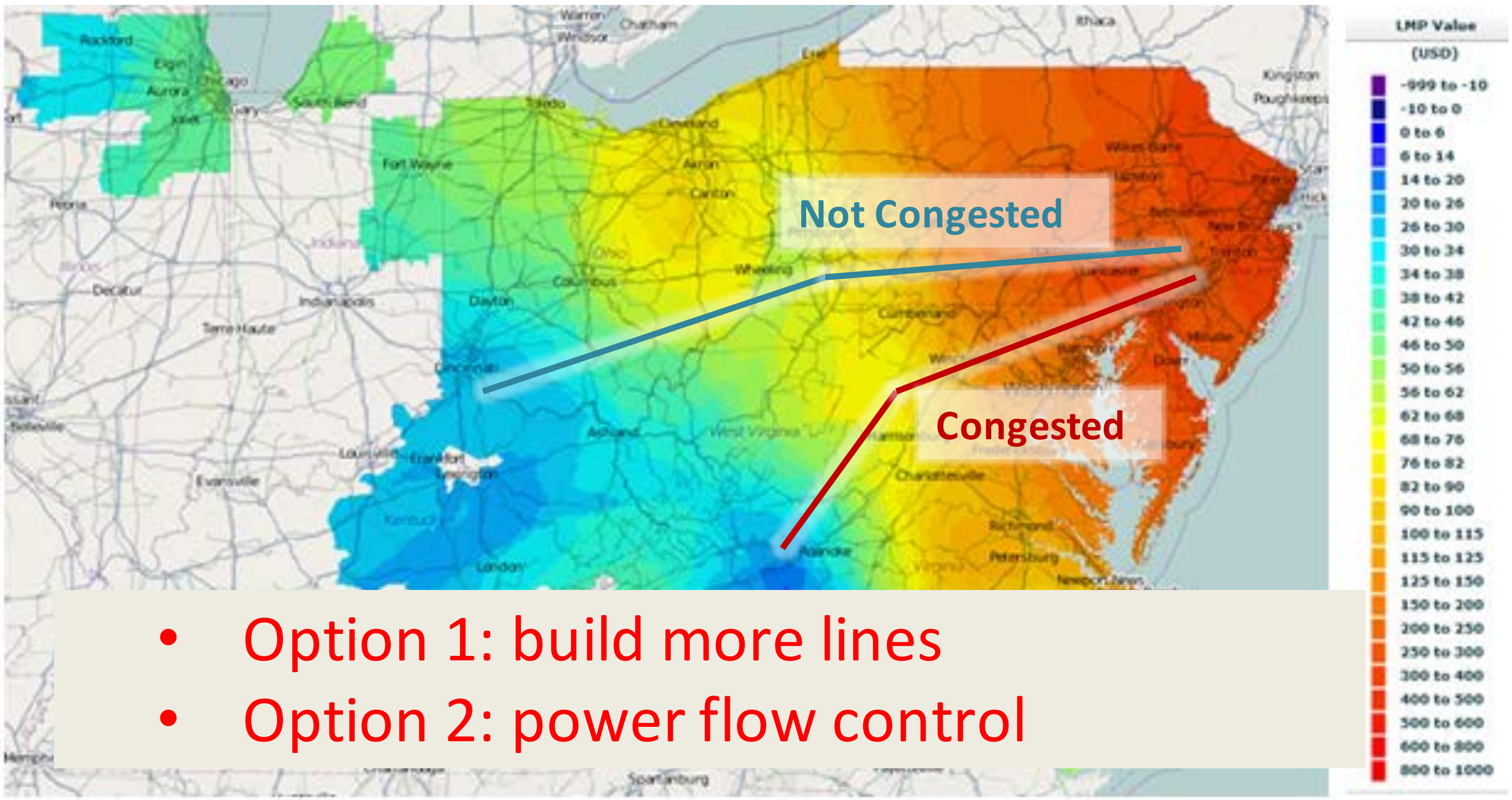


Transmission bottlenecks create economic inefficiency

Transmission system needs to be upgraded

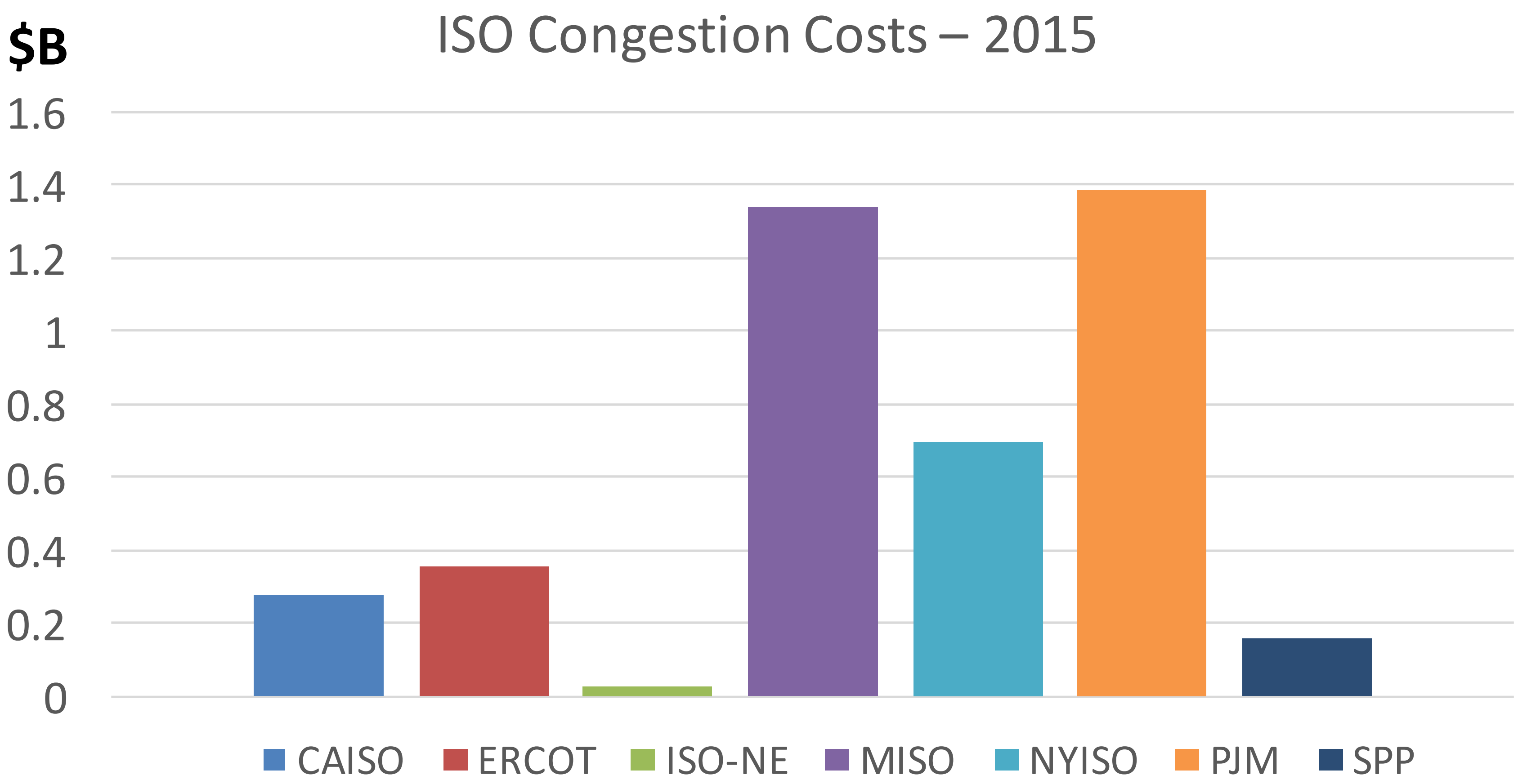
- Improved economic efficiency
- Reliability-motivated upgrades

Transmission Bottlenecks

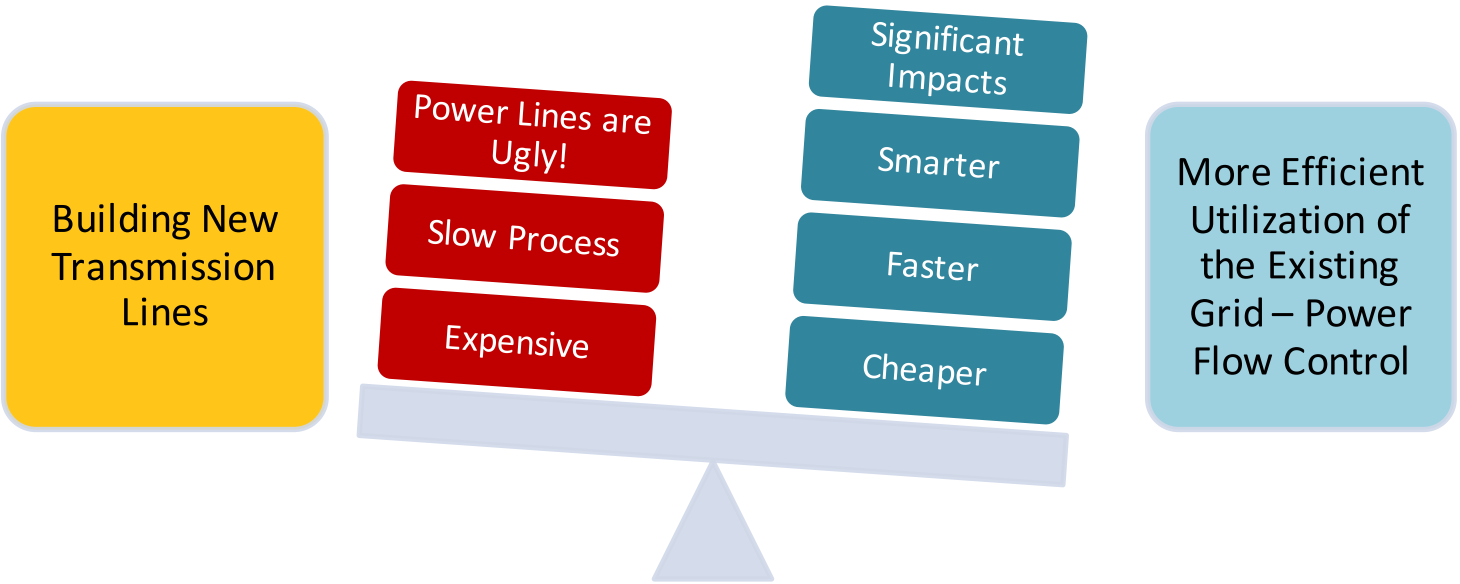


- Option 1: build more lines
- Option 2: power flow control

Congestion Cost in US ISO/RTOs



Choices



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

Research and Development Efforts

- ARPA-E GENI initiative: Over 40 million dollars for power control hardware and software

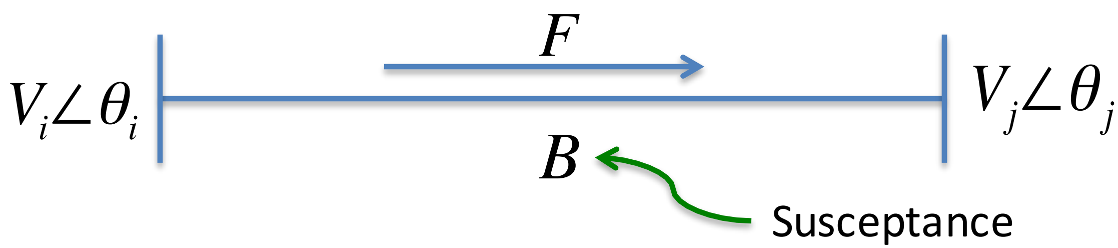
Hardware:

- Smart wire grid device
- Flexible AC Transmission System (FACTS)

Software:

- Transmission switching (TS)
  - Fast convergence
  - Quality AC solution
  - Dynamic stability analysis
- Enhanced FACTS adjustment (not supported by ARPA-E)
  - Same benefits
  - More or less the same concerns

Power Flow Physics



Electricity flows according to the laws of physics, not economics!

DC Power Flow Equation

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

This is a linear approximation of AC power flow equation:

- Relatively accurate
- Facilitates efficient computation

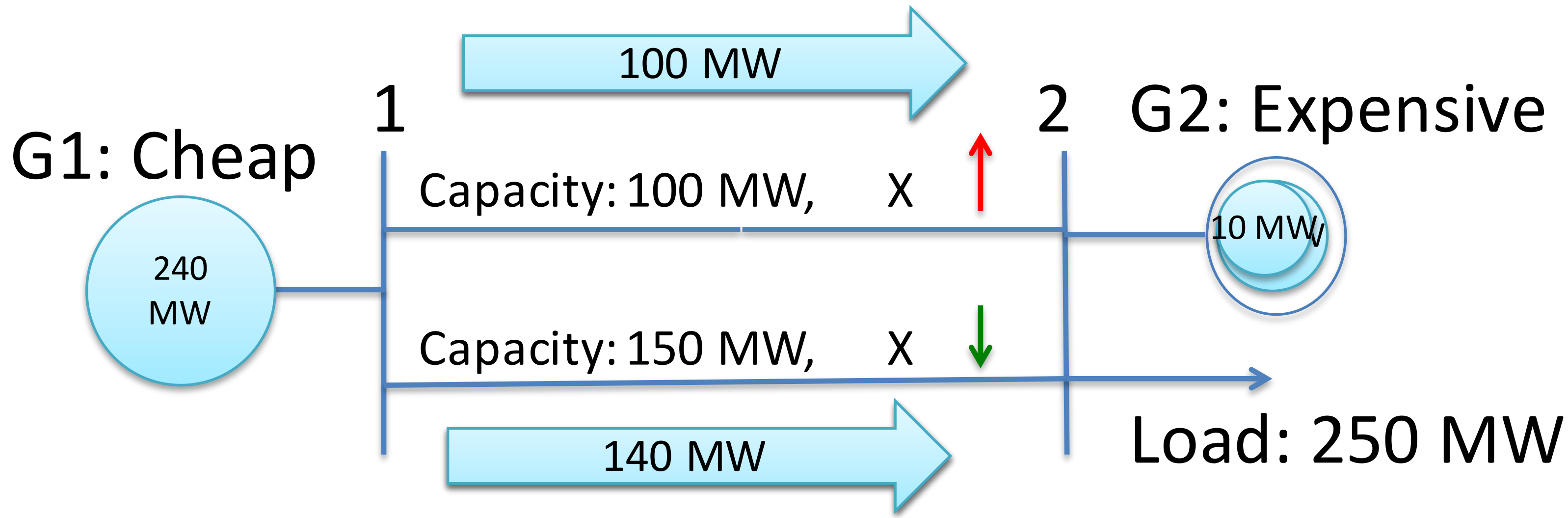
$$\begin{cases} F_k = B_k(\theta_j - \theta_i) \\ B^{\min} \le B \le B^{\max} \end{cases}$$

Variable Impedance FACTS

Power Electronics

Economic Example

Cost Reduction!



Technology – TCSC

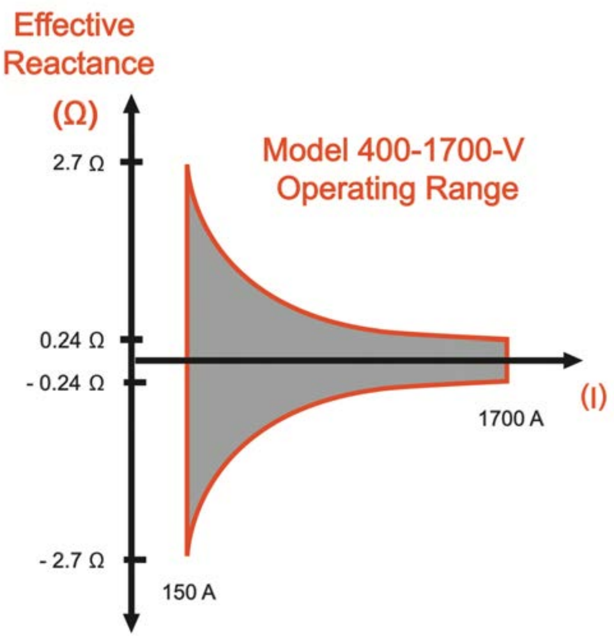
- Thyristor-Controlled Series Compensator

ABB – TCSC brochure

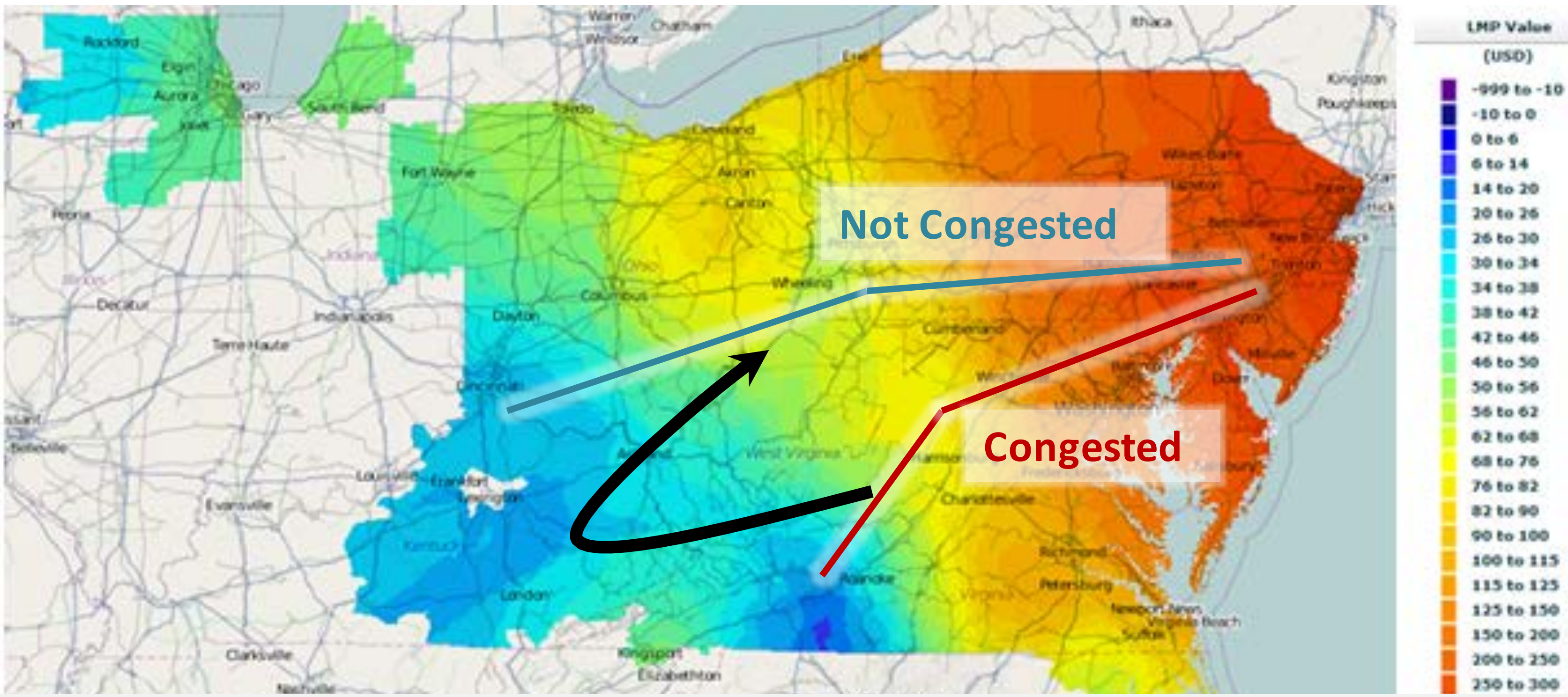
Technology – Smart Wire Grid

- Smart Wire Grid Device

Power Router brochure



Economic Impacts



With power flow control, cheaper resources can replace the local expensive resources.

Research Objective

- Challenges:
  1. **Computational complexity** (limited time)
  2. **Power flow controllers are a part of the transmission network**
     - **Regulated**
     - **No incentive to operate in a socially optimal way**
- **Goal**: Design a market mechanism that would allow power electronics to participate in the market!

COMPUTATIONAL COMPLEXITY

Computational Complexity – DCOPF

- DCOPF – Linear Program (LP)

$$\min \sum_g c_g P_g \qquad (1)$$

$$P_g^{min} \le P_g \le P_g^{max} \qquad \forall g \qquad (2)$$

$$-F_\mathrm{k}^{\max} \le F_\mathrm{k} \le F_\mathrm{k}^{\max} \qquad \forall k \qquad (3)$$

$$F_\mathrm{k} - B_k(\theta_n - \theta_m) = 0 \qquad \forall k \qquad (4)$$

$$\sum_{k\in\sigma^+(n)} P_k - \sum_{k\in\sigma^-(n)} P_k + \sum_{g\in g(n)} P_g = d_n \qquad \forall n \qquad (5)$$

Linear Program

Variable Impedance FACTS

Computational Burden

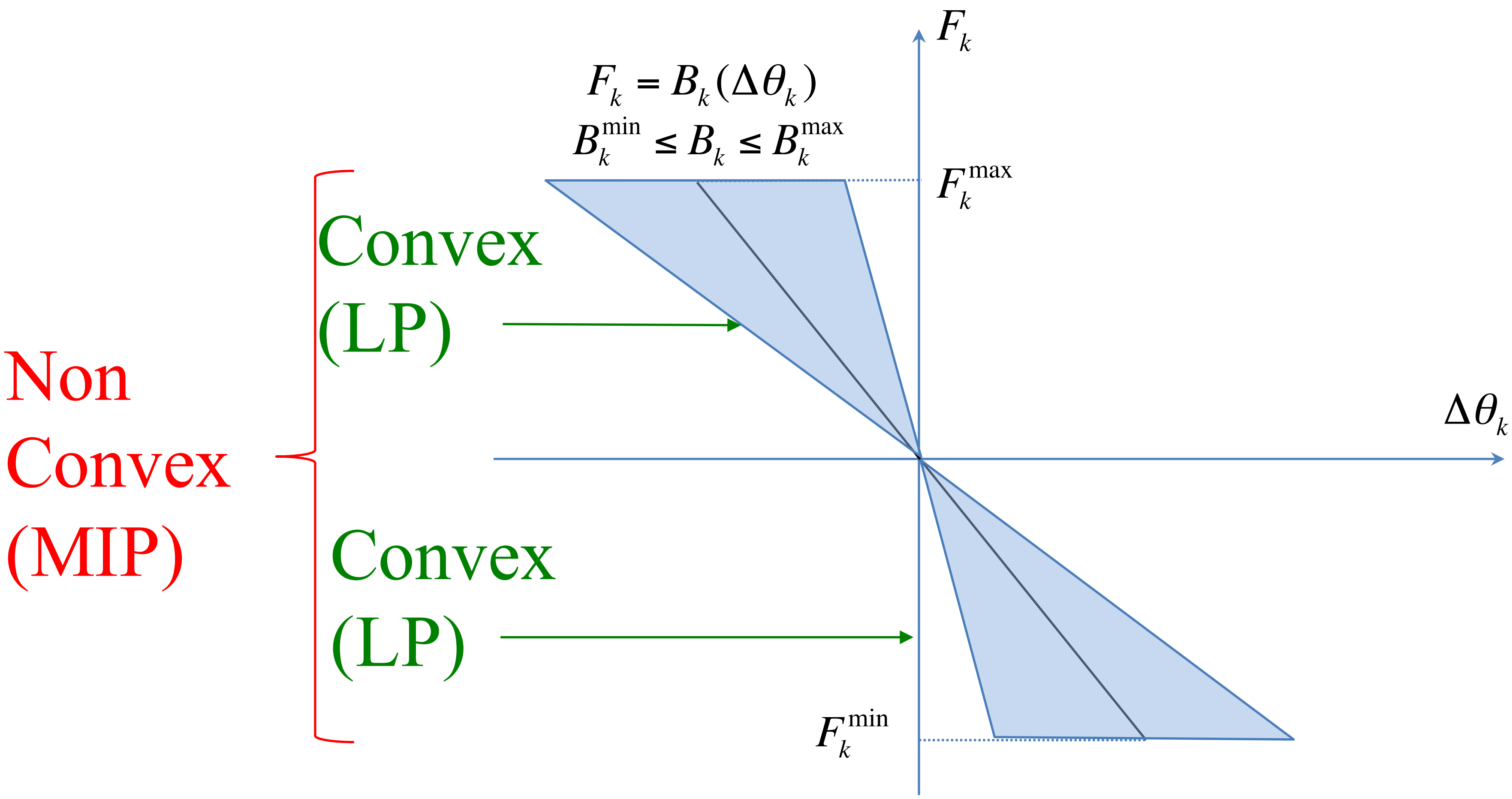
↓

No FACTS set point adjustment within EMS or MMS software

↓

Infrequent ad hoc adjustments

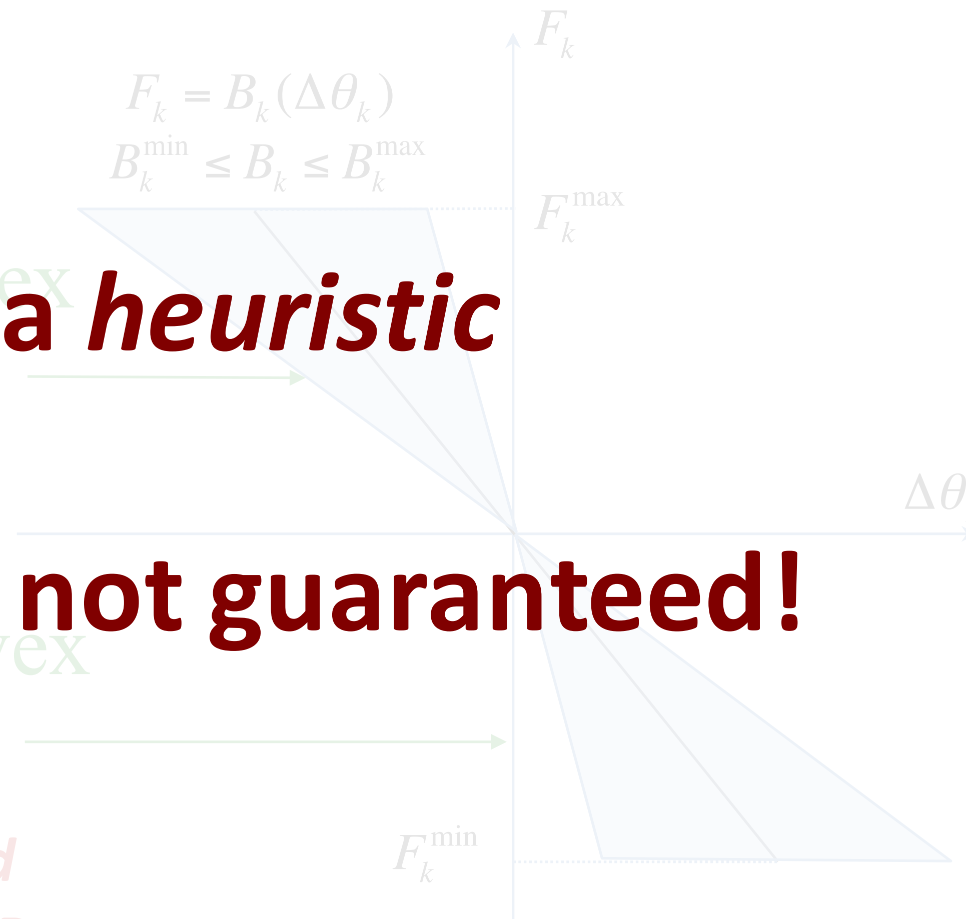
Computational Complexity – NLP/MIP



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 directi for major lines (COI)
- *Even if we do not know the direction, we can run a two-stage DCOPF and i ify it*



This is a *heuristic*

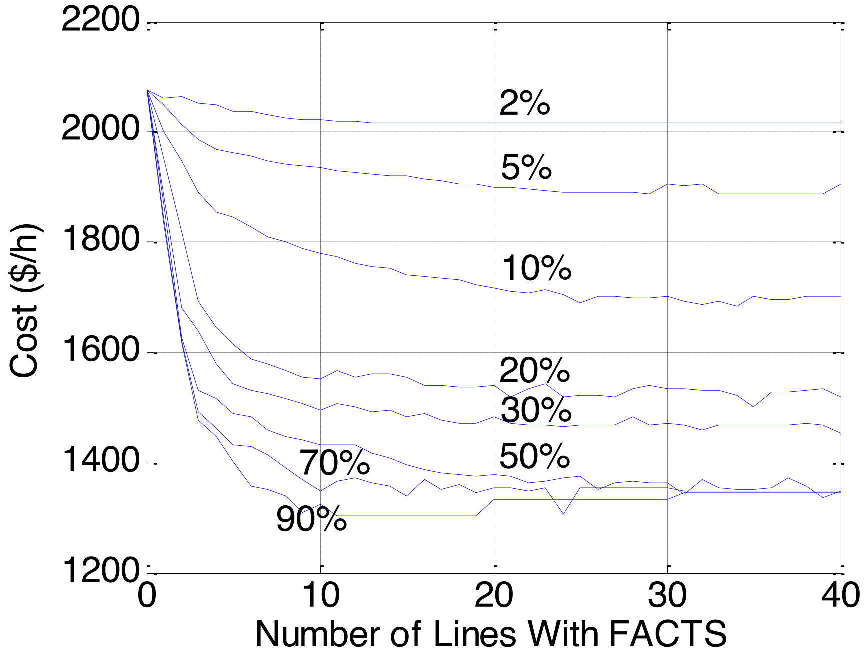
Optimality is not guaranteed!

Knowing the direction would reduce the complexity to a LP

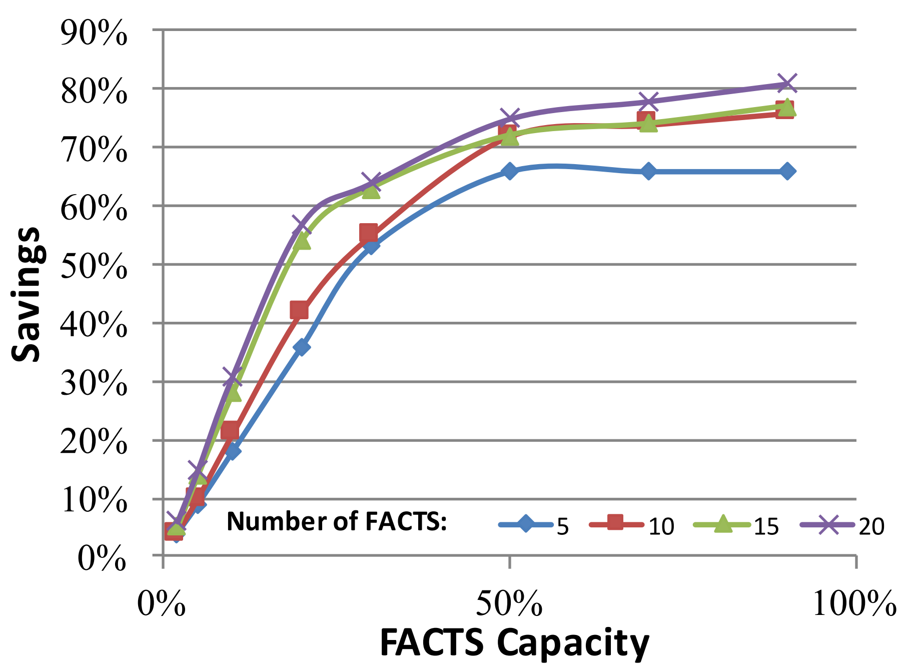
SCED Cost Savings IEEE 118-Bus System

Savings are calculated compared to a transportation model

Optimal FACTS Placement:
>98% Optimal



Located on More Heavily Utilized Lines: 100% Optimal

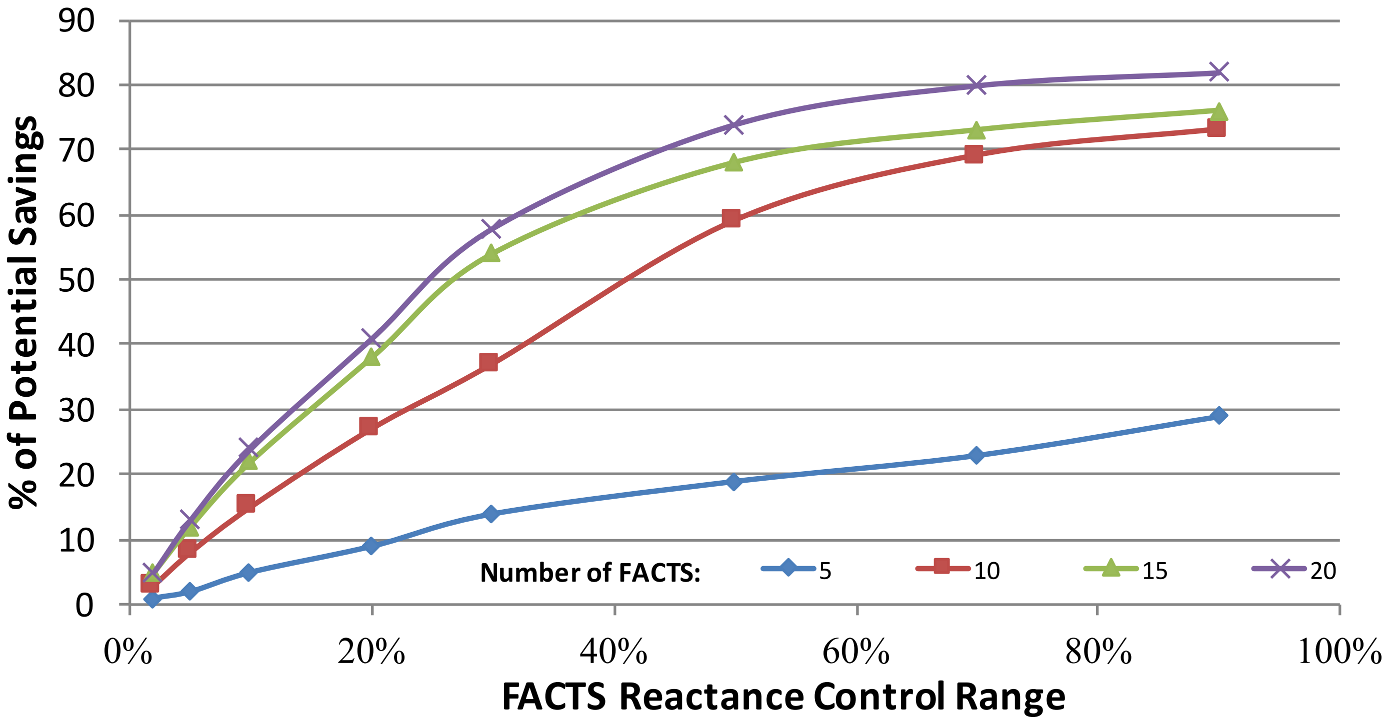


SCED Cost Savings
Polish System

Located on More Heavily Utilized Lines: 100% Optimal

~2,400 buses

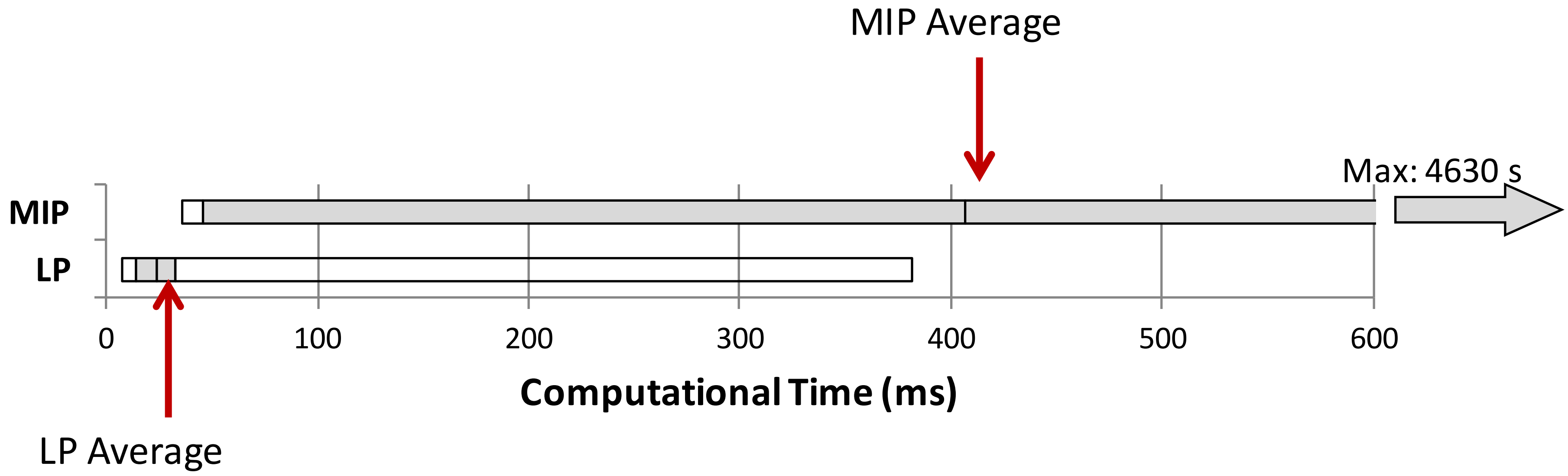
~2,900 branches



Savings are calculated compared to a transportation model

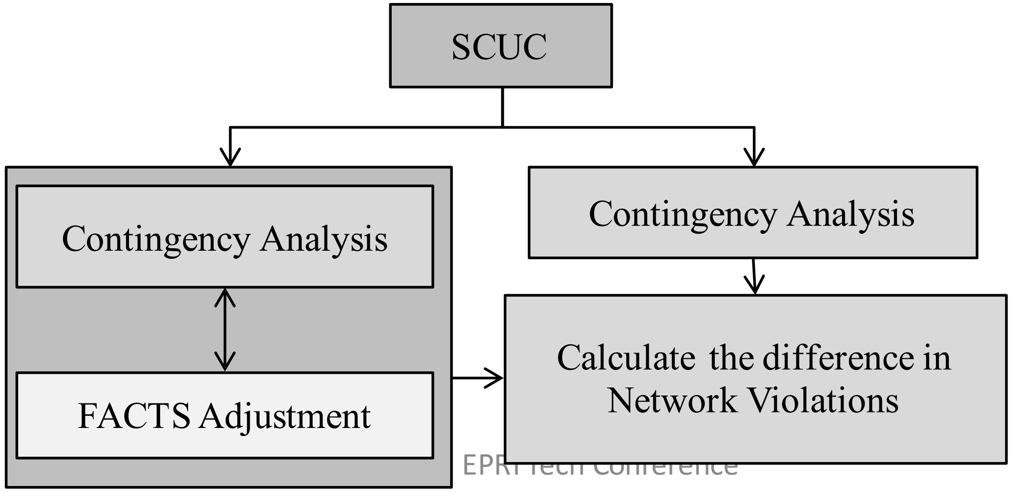
Department of Electrical & Computer Engineering
College of Engineering | The University of Utah

Computational Time

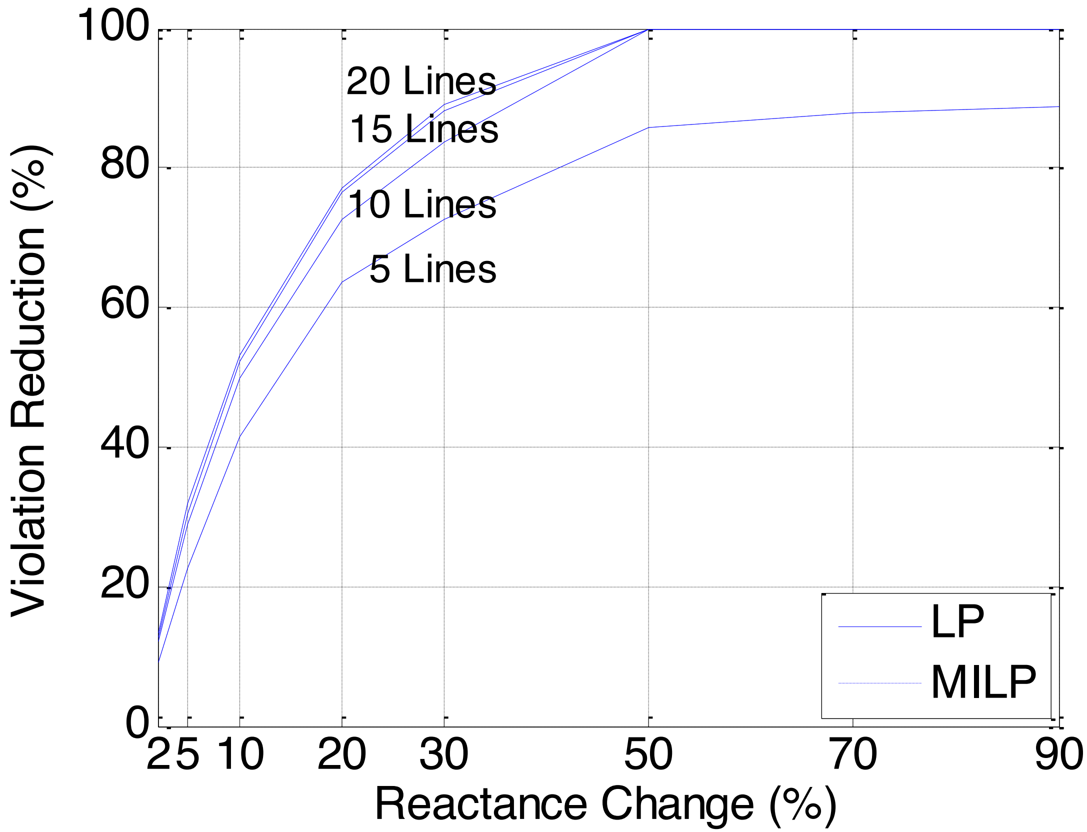


Corrective Adjustments

- In corrective adjustments we have even better insight about the direction of the power flow: pre- or post- contingency flows
- Goal: minimization of post-contingency network violations
- **Optimal utilization of FACTS in recourse state only**



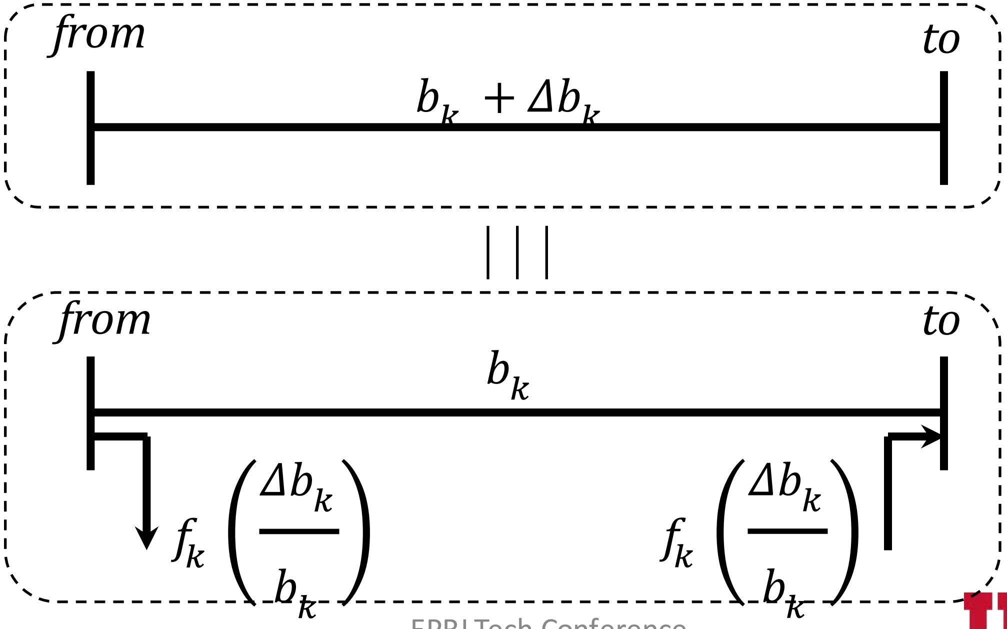
Corrective Results
IEEE 118-Bus System



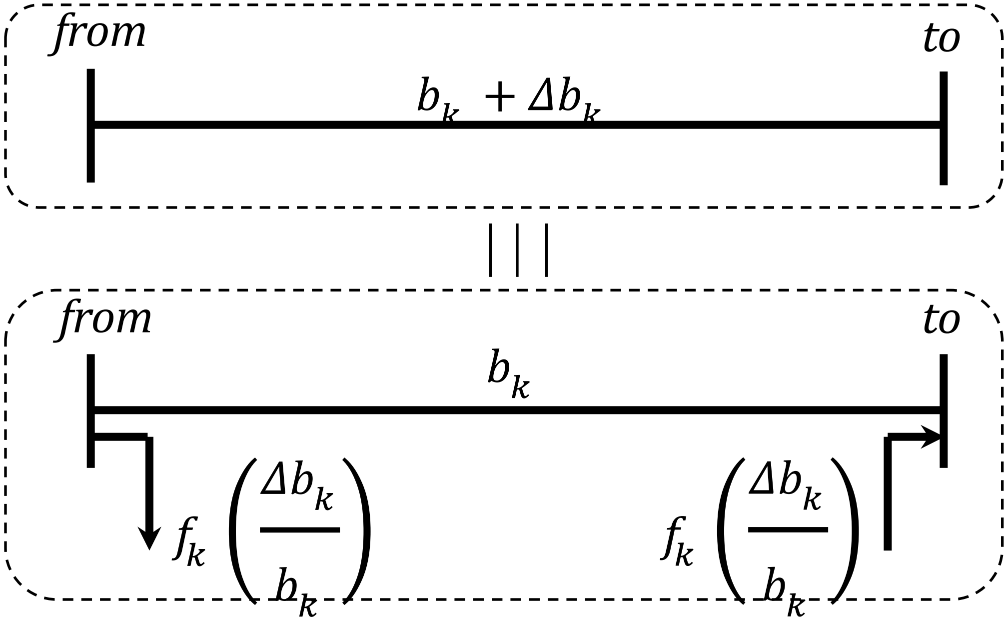
Located on More Heavily Utilized Lines:
100% Optimal

Shift Factor Structure

- Industry implementations of SCUC and SCED do not use $B\theta$ structure; they use PTDFs.
  - No need to model all the voltage angles
  - No need to calculate all the flows
  - Significantly faster compared to $B\theta$



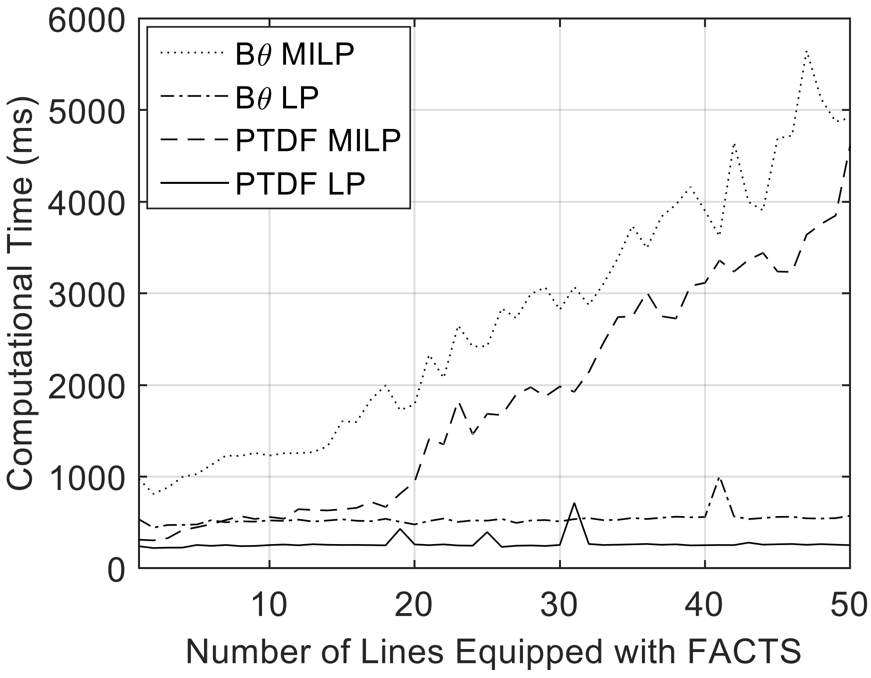
Injection Model of Reactance Control



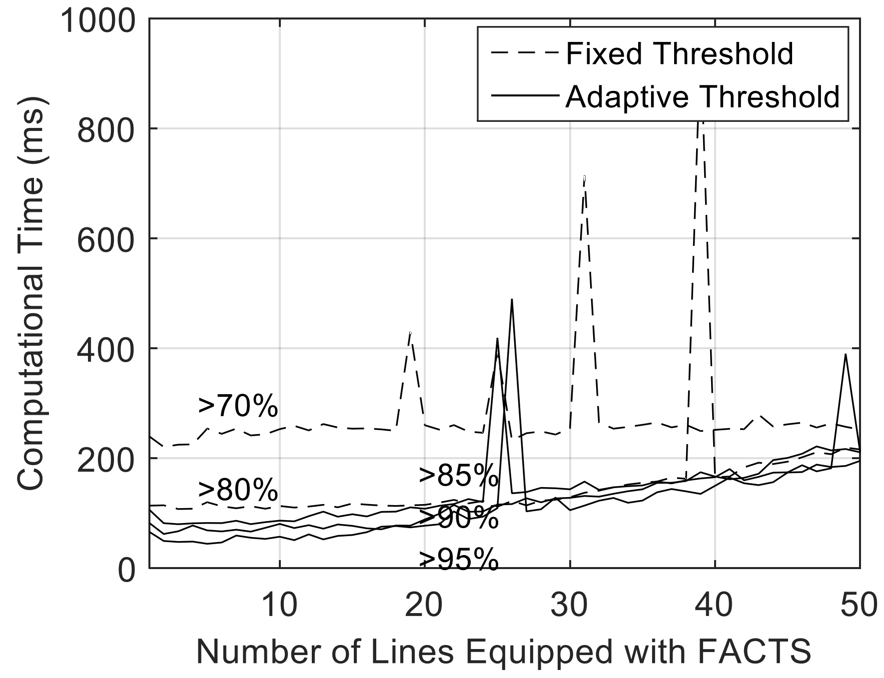
- **Again, we end up with a Mixed-Integer Linear Program!**
- **We can use the same engineering insight to convert this to a LP.**
- **Similar method can be used to generate contingency constraints.**

Results – Polish System

$B\theta$ versus PTDF



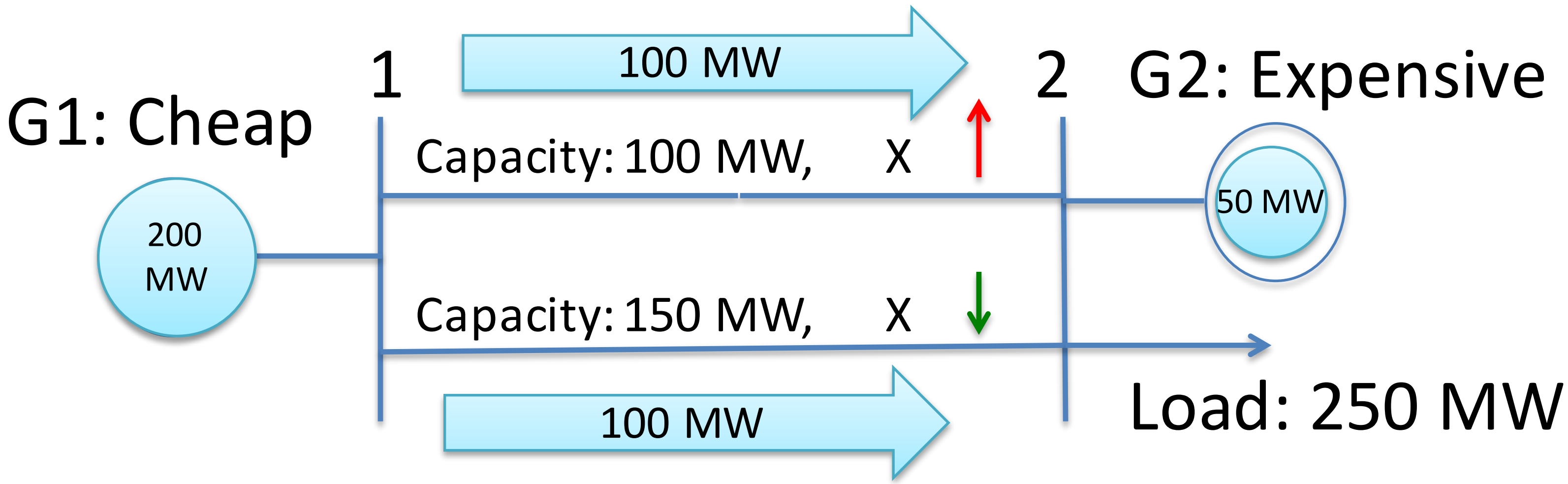
Fixed versus Adaptive Thresholds



MARKET PARTICIAPTION

O'Neill's Complete Market Proposal

- Positive externality in Dr. O'Neill's complete market proposal:
  - **Payment to line: (Flow) x (LMP Difference)**
- No matter which line changes the reactance, it is always the second line that will carry more power and get paid!



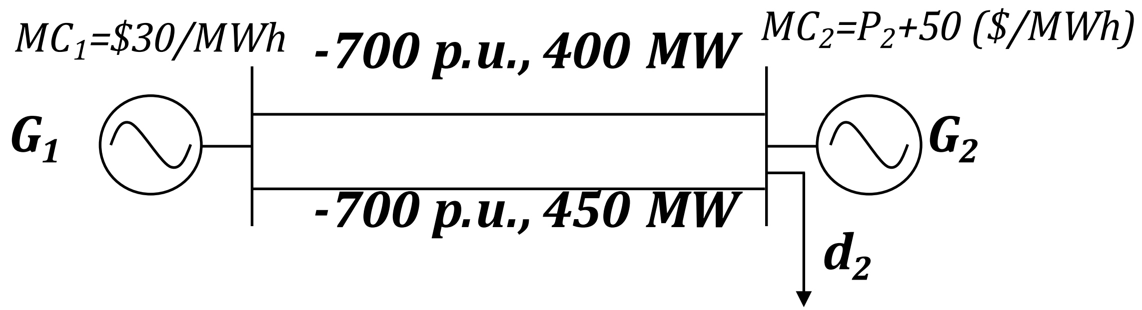
Proposed Payment System

- Use the susceptance price to calculate the marginal value of susceptance:

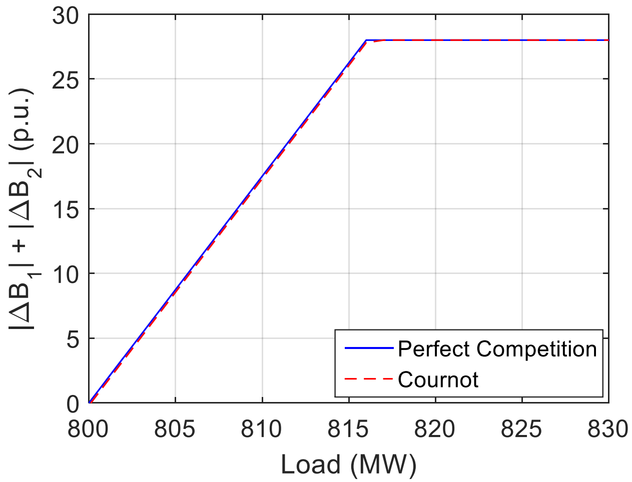
$$F_k = B_k(\theta_j - \theta_i) \qquad (S_k)$$

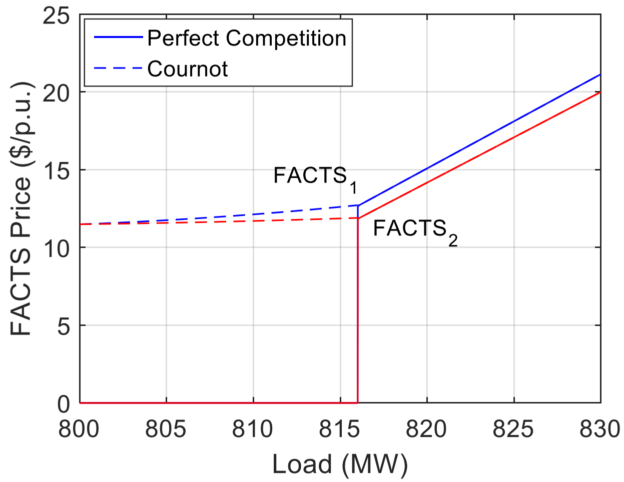
$$\underbrace{S_k(\theta_j - \theta_i)}_{\text{Marginal Value: Price}} \times \underbrace{\Delta B_k}_{\text{Quantity}}$$

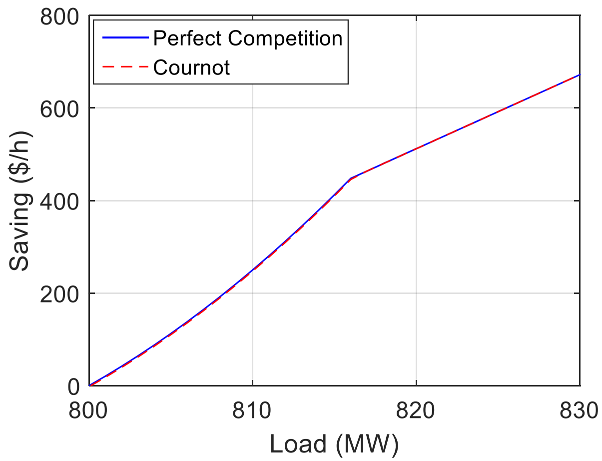
Two Node System



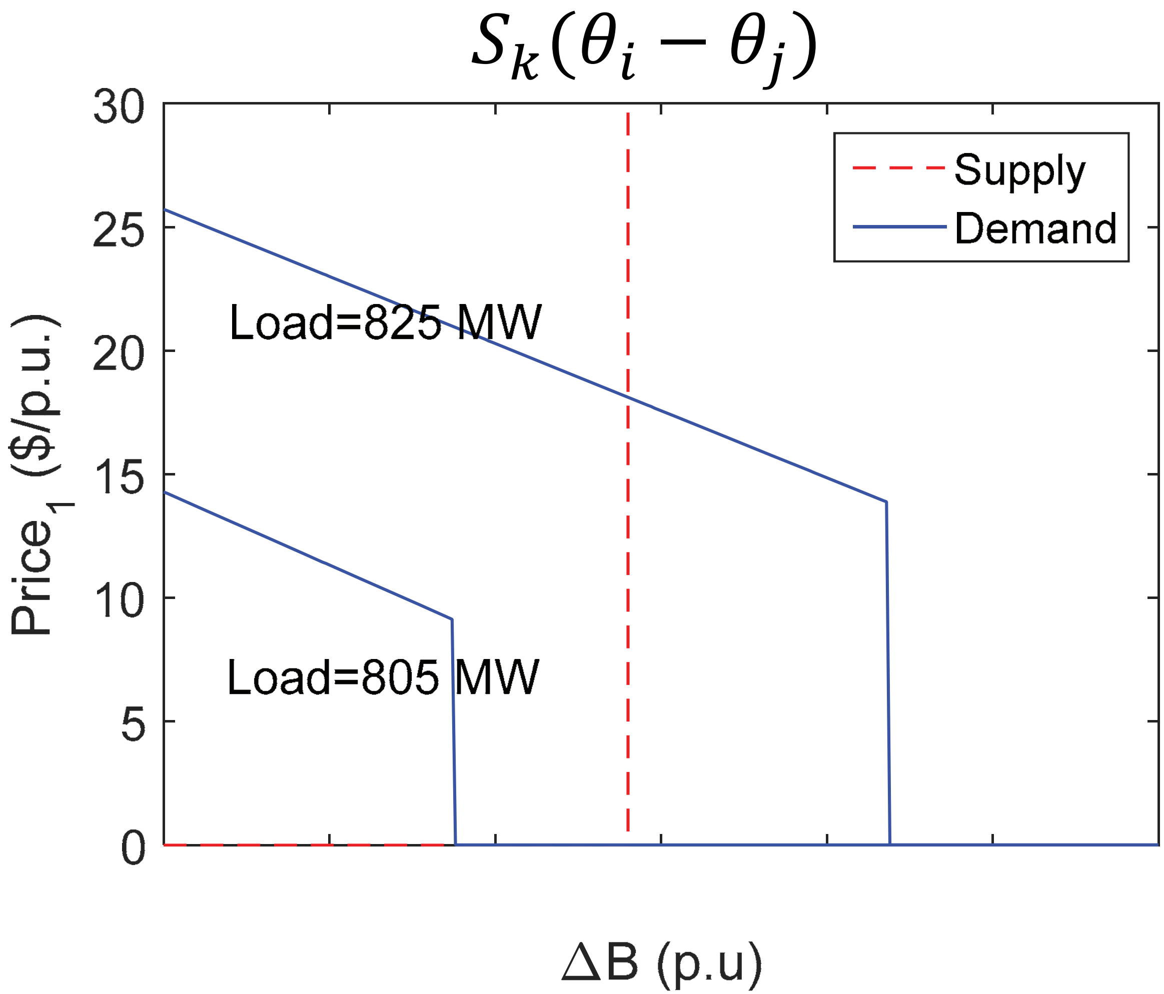
FACTS control range: 2%







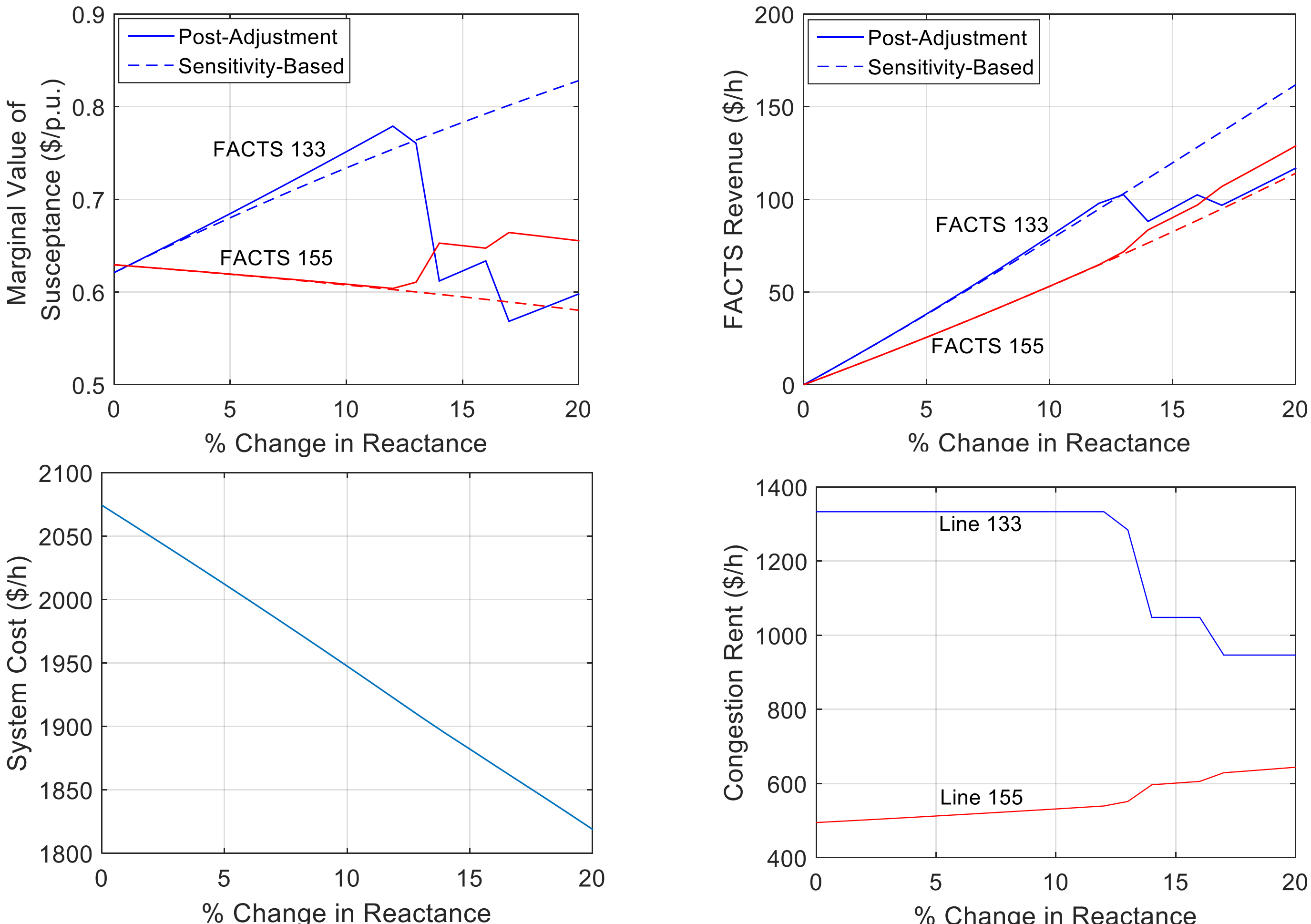
Marginal Value



Revenue Adequacy

- **Congestion rent is the payment source**
- **Revenue adequate if the adjustments lead to increased loading!**
- **Not necessarily guaranteed in all cases**
- **It is highly unlikely that the market is revenue inadequate**

IEEE 118 Bus System
2 FACTS Devices



Conclusions

- Mathematical representation of OPF with FACTS: NLP
- We reformulated the NLP to a MILP; using our knowledge of electricity flow physics, we reformulate the problem to an LP
- The LP heuristic is extremely effective: it found the optimal solution more than 98% of the time.
- The heuristic is extremely fast (LP) and would not add to the complexity of the OPF problem
- We designed a compensation mechanism to signal enhanced operation of the devices.

Thank you!

Questions?

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- M. Sahraei-Ardakani and K. Hedman, “A Fast LP Approach for Enhanced Utilization of Variable Impedance Based FACTS Devices,” *IEEE Transactions on Power Systems*
- M. Sahraei-Ardakani and K. Hedman, “Day-Ahead Corrective Adjustment of FACTS Reactance: A Linear Programming Approach,” *IEEE Transactions on Power Systems*
- M. Sahraei-Ardakani and S. Blumsack, “Transfer Capability Improvement through Market-Based Operation of Series FACTS Devices,” *IEEE Transactions on Power System*
- M. Sahraei-Ardakani and K. Hedman, “Computationally Efficient Adjustment of FACTS Set Points in DC Optimal Power Flow with Shift Factor Structure,” *IEEE Transactions on Power Systems*