# Challenges in Power System Optimization: Flexible Transmission Assets

**Kory W. Hedman**

Assistant Professor, Electrical Engineering, ASU

**IPAM**

**Optimization and Equilibrium in Energy Economics**

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# Purpose of this talk

- It is ***fun*** to try to solve very challenging optimization problems
- It is ***difficult*** to overcome practical barriers and initiate change
- *Opportunity is missed by most people because it is dressed in overalls and looks like work*
  - Thomas Edison
- Topic: The challenge to change industry practices of neglecting existing transmission assets and their true flexibility via ***"advanced"*** OR techniques

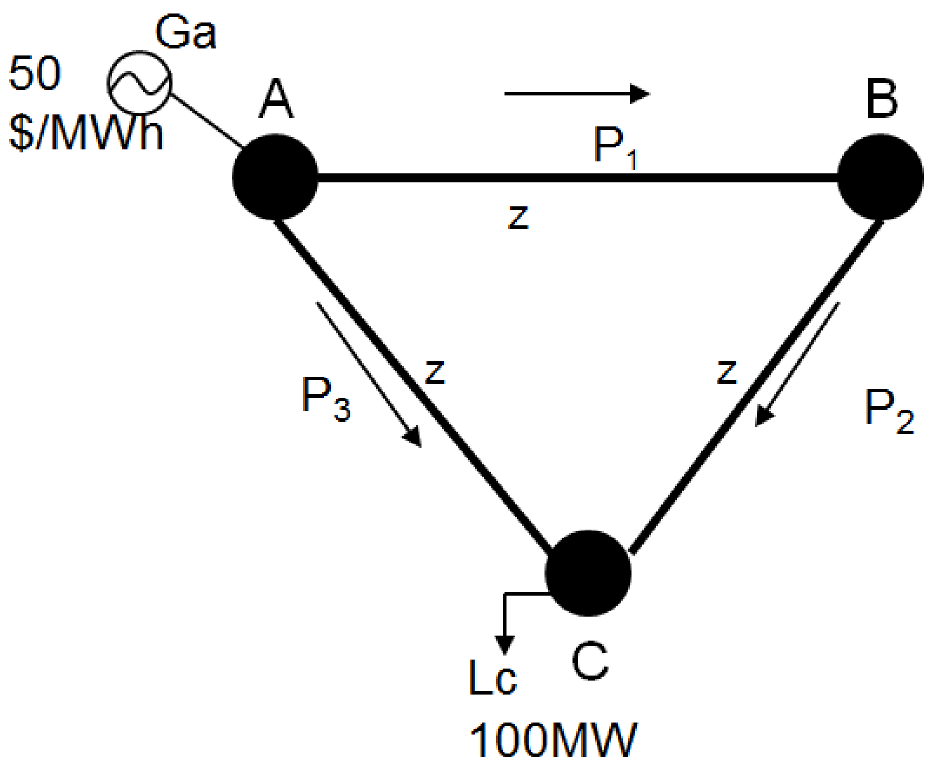
# Outline

- Flexible Transmission Assets
- Braess' Paradox for the Power System
- Transmission Switching as an MILP
- Background on Real-Time Operations
- Flexible Transmission Decision Support (FTDS): Tool Development
- Flexible Transmission Decision Support (FTDS): Flexible AC Transmission System (FACTS) Devices
- Existing Challenges: Industry Formulations for OPF
- Summary

# Flexible Transmission Assets

# Flexible Transmission Assets

- Flow of electricity must follow Kirchhoff's laws
  - Current takes path of least resistance




- Flexible transmission assets enable power flow control

# Transmission Switching (Topology Control)

- Circuit breakers enable us to de-energize a high-voltage transmission line
- Transmission switching places a binary decision variable on the status of the transmission line (or transformer)
- **Transmission Switching: Cheap hardware based power flow control technology**
  - Concerns with reliability, stability, computational complexity

# Flexible AC Transmission System (FACTS) Devices

- FACTS devices enable power flow control
  - Many different types of FACTS exist
  - Modeling of FACTS within OPF is very limited
- With infinite capability from FACTS devices, this would transform the OPF problem into a transportation problem where we control all flows
- FACTS: Expensive hardware technology for power flow control
  - Many enable continuous control (though limited in capability)

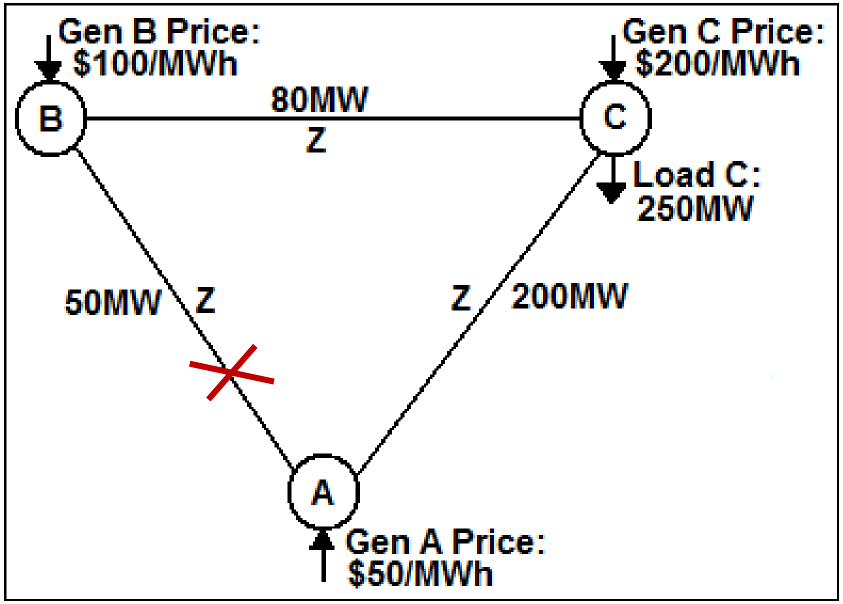
# Recent FACTS Advancement: Smart Wires

- Smart Wires: A series based variable impedance device that changes impedance of transmission lines

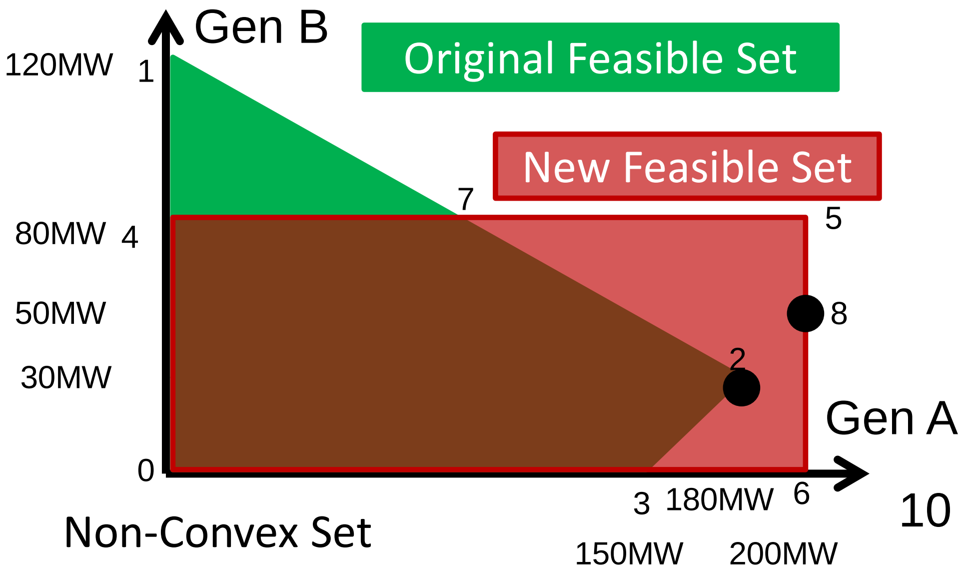
# Braess' Paradox for the Power System

# Transmission Switching and the Feasible Set of Dispatch Solutions

- Original optimal cost: \$20,000 (A=180MW,B=30MW,C=40MW) at {2}
  - Original feasible set: {0,1,2,3}
- Open Line A-B, optimal cost: \$15,000 (A=200MW, B=50MW) at {8}
  - Feasible set with Line A-B open {0, 4, 5, 6}
- Feasible set with optimal transmission switching: {0, 1, 7, 5, 6} (non-convex)




Feasible Set of Injections for Gen A & Gen B




Non-Convex Set

# Transmission Switching as a Mixed Integer Linear Program (MILP)

# DC Power Flow Assumptions

- Original AC (real power) line flow equation:

$$P_{ik} = |V_i|^2 g_{ik} - |V_i||V_k|(g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k))$$

- Assume all voltages are 1 pu:

$$P_{ik} = g_{ik} - (g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k))$$

- Assume $\theta_i - \theta_k$ is small

$$= g_{ik}(1) \qquad = b_{ik}(\theta_i - \theta_k)$$

$$P_{ik} = g_{ik} - (g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k))$$

- The real power line flow equation is now:

$$P_{ik} = -b_{ik}(\theta_i - \theta_k) = b_{ik}(\theta_k - \theta_i), \quad P_{ik} = \frac{1}{x_{ik}}(\theta_i - \theta_k)$$

- We also assume:

$$r_{ik} \ll x_{ik}, \; b_{ik} = \frac{-1}{x_{ik}}, \quad Q_{ik} = 0$$

# Linear (DC) Optimal Power Flow

$$\underset{P_g, P_k, \theta_i}{Min}: \sum_{\forall g} c_g P_g$$

*Subject to:*

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

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

$$P_k - b_k(\theta_j - \theta_i) = 0$$

$$\sum_{\forall k \epsilon \delta(i)^+} P_k - \sum_{\forall k \epsilon \delta(i)^-} P_k + \sum_{\forall g \epsilon g(i)} P_g = d_i$$

| | |
|---|---|
| $P_g$ | Generator *g*'s real power production |
| $P_k$ | Flow on line $k$, defined to be *from node i to node j* |
| $\theta_i$ | Bus voltage phase angle at node (bus) *i* |
| $\delta(i)^+$ | Set of lines defined to be *to node i* |
| $\delta(i)^-$ | Set of lines defined to be *from node i* |
| $b_k$ | Susceptance *of line k* |
| $g(i)$ | Set of generators *at node i* |
| $d_i$ | The demand *at node i* |
| $c_g$ | The cost of gen *g* |

# With Transmission Switching

$$\underset{P_g, P_k, \theta_i, z_\ell}{Min:} \sum_{\forall g} c_g P_g$$

*Subject to:*

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

$$z_k P_k^{min} \leq P_k \leq P_k^{max} z_k$$

$$P_k - b_k(\theta_j - \theta_i) + (1 - z_k)M_k \geq 0$$

$$P_k - b_k(\theta_j - \theta_i) - (1 - z_k)M_k \leq 0$$

$$\sum_{\forall k \epsilon \delta(i)^+} P_k - \sum_{\forall k \epsilon \delta(i)^-} P_k + \sum_{\forall g \epsilon g(i)} P_g = d_i$$

$$z_k \in \{0,1\}$$

| | |
|---|---|
| $P_g$ | Generator *g*'s real power production |
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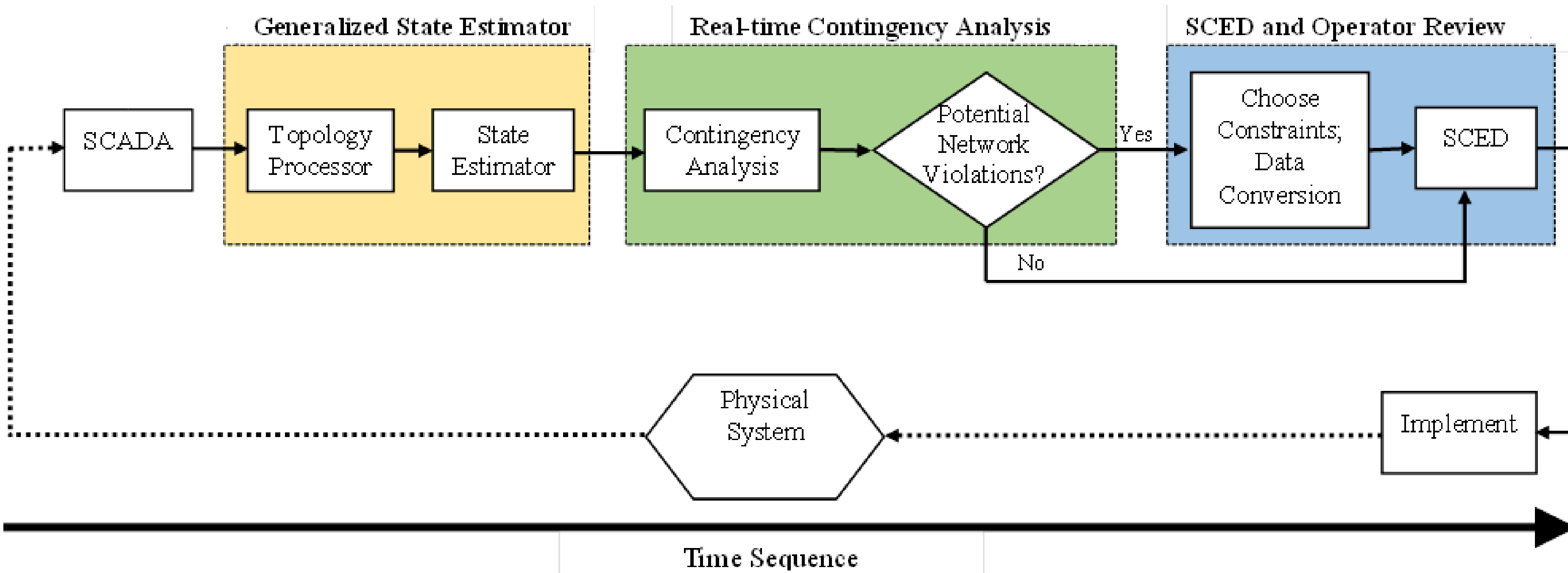
| $g(i)$ | Set of generators *at node i* |
| $d_i$ | The demand *at node i* |
| $c_g$ | The cost of gen *g* |
| $z_k$ | Status (0: out of service, 1: in service) *of line* $k$ |

# Key Observations

- Solving the full MILP for the optimal topology is very challenging
  - Ineffective to solve directly for optimal topology
  - Reliability limits number of switchable lines
  - Removal of just a few branches (and iteratively solving for a single branch at a time) produces very good solutions
  - Strong diminishing marginal returns
- Well-designed heuristics work very well and are fast enough for near-term implementation

# Background on Real-Time Operations

# Real-Time Energy Management Systems (EMS)



# RTCA Assumptions

Brief overview (further discussion, if desired):

- N-1: Transmission (Line, Transformer, >69kV), Generator
- Few seconds post-contingency (***$t_{+0}$***)
  - Single snapshot of time
  - MW compensation based on *participation factors* (various options are available)
  - Adjust PV set point (voltage control is fixed based on pre-contingency state **except when $Q_G$ violates $Q_{MIN}$ or $Q_{MAX}$**)
  - Consistent rules between vanilla RTCA & FTDS based RTCA

# Flexible Transmission Decision Support (FTDS): Tool Development

ARPA-E Funded Project

# FTDS based RTCA Tool Development

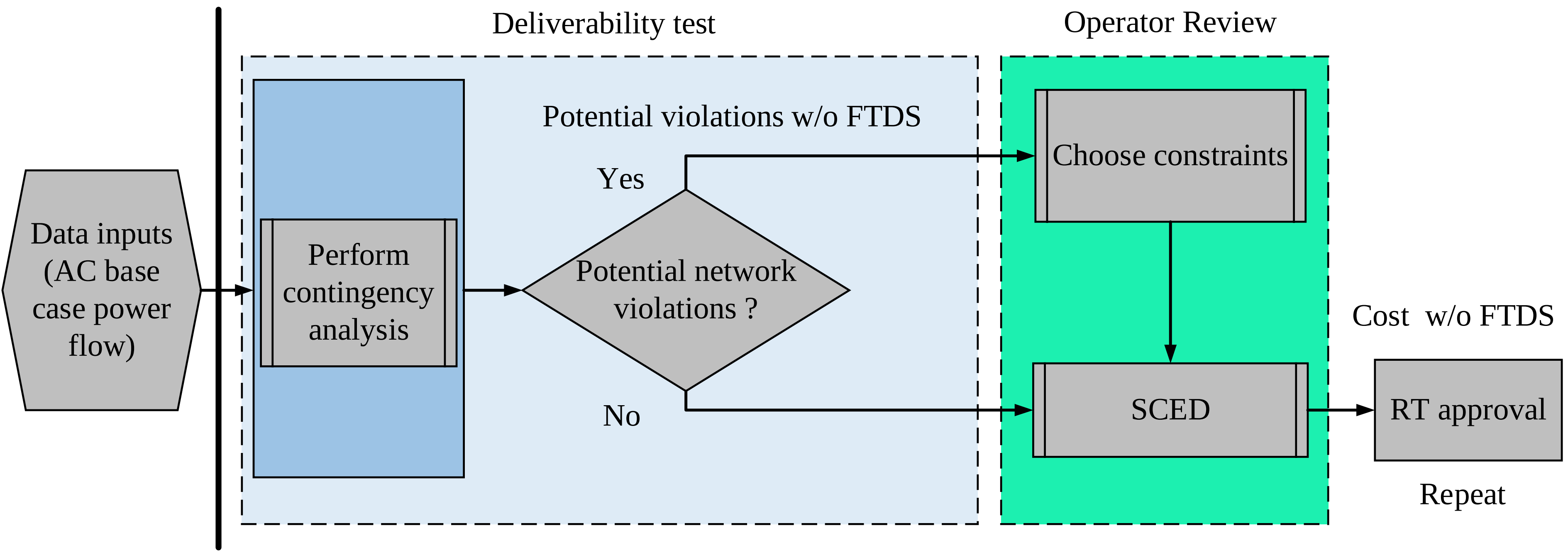
- Multi-threaded HPC base AC Power Flow Real-Time Contingency Analysis Package (RTCA) with Corrective Switching
- Open Source
- Expanded IncSys' Open Source AC Power Flow tool to create multi-threaded RTCA package with corrective control

# FTDS based RTCA

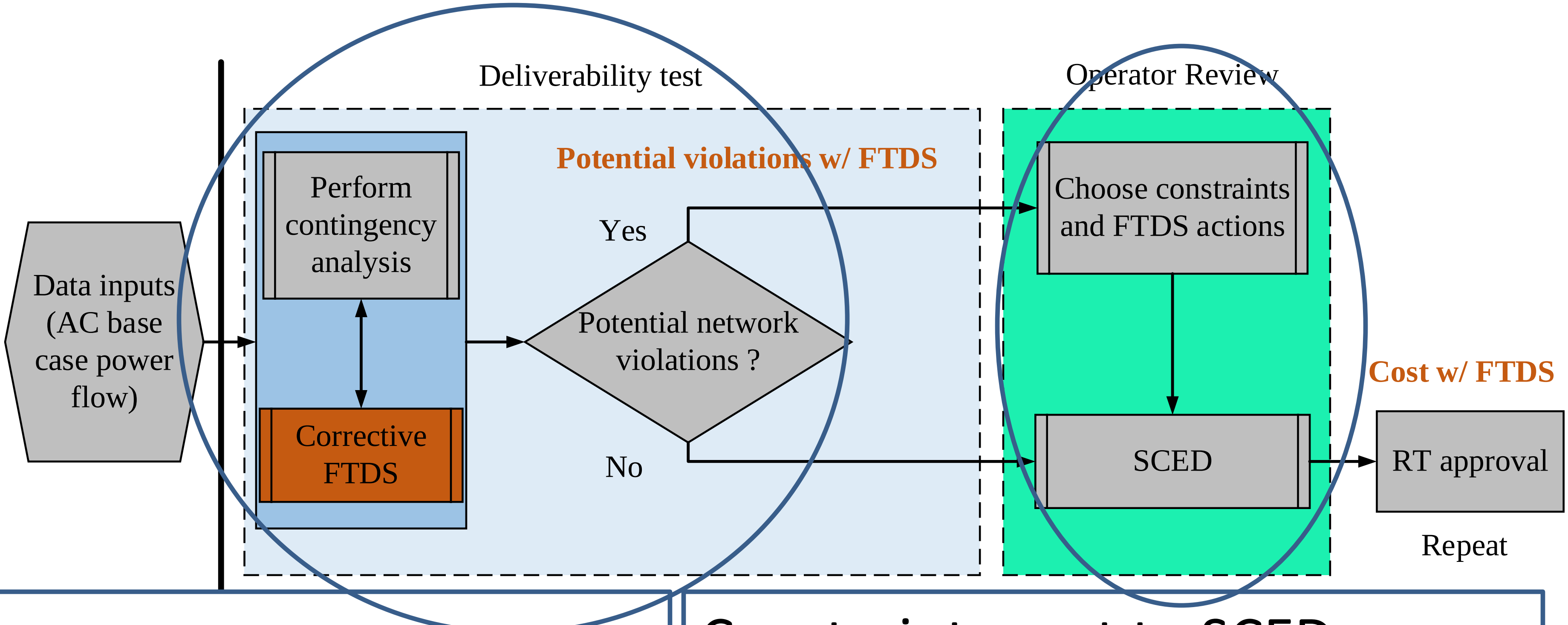
Post-contingency corrective transmission switching

- Shortly after a contingency, ***as a corrective action: take a line (or transformer) out of service***
- Implement at most 1 corrective switching action
- But: identify multiple potential switching actions, in advance, per contingency to provide operators: **choice**
- Perform stability studies to confirm switching actions
- Main benefit of corrective switching: don’t need to ever implement the action unless the event occurs

# Real-Time Contingency Analysis and Security Constrained Economic Dispatch



# Implementation of FTDS based RTCA and Impact on SCED




FTDS determines corrective transmission switching actions

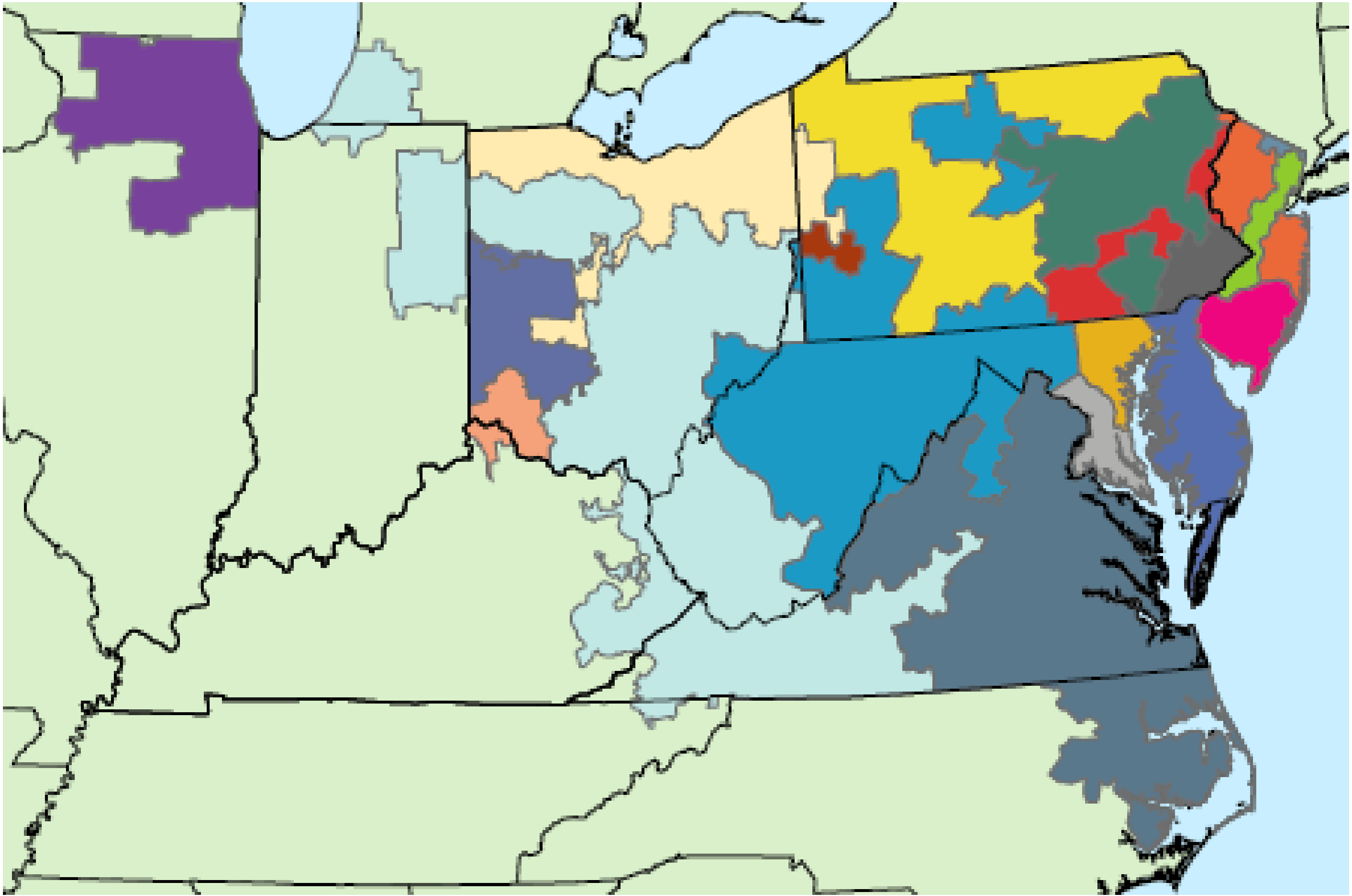
Constraints sent to SCED are reduced; operational costs decrease; reliability maintained

# Operator Review Example

| Approve FTDS, Send to SCED: | Post-Contingency Status | Approve FTDS, Send to SCED: | Post-Contingency Status |
|---|---|---|---|
| X | Contingency Line 5<br>Potential Violation: Line 8 – 120%<br>Potential Line Flow: Line 10 – 96%<br>FTDS: No Violations: Switch Line 9<br>Potential Line Flow: Line 8 – 97%<br>Potential Line Flow: Line 10 – 82%<br>Potential Line Flow: Line 11 – 95% | X | Contingency Line 52<br>Potential Violation: Line 62 – 116%<br>FTDS: No Violations: Switch Transformer 54<br>Potential Line Flow: Line 62 – 91% |
| | Contingency Line 25<br>Potential Violation: Line 8 – 118%<br>Potential Violation: Line 10 – 102%<br>FTDS: Violations Reduced: Switch Line 9<br>Potential Violation: Line 8 – 102%<br>Potential Line Flow: Line 10 – 90% | X | Contingency Line 89<br>Potential Violation: Line 90 – 102%<br>Potential Line Flow: Line 92 – 98%<br>FTDS Option 1: No Violations: Switch Line 93<br>Potential Line Flow: Line 90 – 94%<br>Potential Line Flow: Line 92 – 97% |
| | | | FTDS Option 1: No Violations: Switch Line 95<br>Potential Line Flow: Line 90 – 97%<br>Potential Line Flow: Line 92 – 96% |

# ARPA-E Project
# Tool: Flexible Transmission Decision Support (FTDS)

# PJM System



# Existing Industry Practice: PJM

about pjm | training | committees & groups | planning | markets & operations | documents

Operational Data
Data Dictionary
Interregional Data Map
PJM Tools
Tools Information
System Requirements
PJM Security
Bulletin Board
Data Miner
eCredit
eDART
eData
eDataFeed
eFTR
eGADS
eLRS
Emergency Procedures
eMKT

Home ▸ Markets & Operations ▸ PJM Tools ▸ OASIS ▸ System Information ▸ Switching Solutions

## Switching Solutions

The following is a list of potential transmission switching procedures identified by PJM that may assist to reduce or eliminate transmission system congestion. These identified potential transmission switching procedures may or may not be implemented by PJM based upon system conditions, either projected or actual, and ultimately are implemented solely at the discretion of PJM and its Transmission Owners. This posting is for informational purposes only. Consequently, PJM does not guarantee that any of these identified switching procedures will be included in any market-based auctions or in the real time analysis. Accordingly, PJM expressly disclaims any liability for financial consequences that a Member may incur in taking action in reliance on these informational postings.

| Procedure Title | Company 1 | Company 2 | Action |
|---|---|---|---|
| Darrah-Tristate switching option | AEP | | To control overloads on the Darrah-Tristate 138kV line, study opening the Darrah 'A' 138kV CB. If this cannot be done precontingency, issue a PCLLRW with the post contingency switching plan. |
| Ruth-Turner overload control | AEP | | To control loading on the Ruth-Turner 138kV line, study opening the Turner "D" 138kV CB precontingency. Studies show this provides approximately 40MVA of relief.<br>If additional relief is required, the following post contingency switching option may be available and provides ~60MVA additional relief:<br>- @ Bradley, open the "B" CB. OR<br>- @ Cabin Creek open "A" & "B" CB's AND @ Kanawha River open "G" CB<br>- A PCLLRW will be required if the switching option is only available post contingency. |
| Ohio Central-Powelson 138kV l/o Ohio Central-Coshocton 138kV | AEP | | Study opening the Philo 'D' 138kV CB. This will open end the Philo-LR Bladen 138kV line. |

PJM Switching Solutions, https://www.pjm.com/markets-and-operations/etools/oasis/system-information/switching-solutions.aspx

# PJM Switching Solutions

- PJM has publicly released ~100 Switching Solutions (corrective switching actions)
- Analyzed 167 PJM EMS data snapshots (1 snapshot per hour, over a week, July 2013):
  - Network: ~15k buses; ~21k branches; ~3k gen; ~1.6k switchable shunts; ~8.5k contingencies simulated per hour (1.4M in total)
  - 4k post-contingencies with violations over entire week
  - **104 of these incidences correspond to cases previously identified by PJM**
  - **Compare FTDS to prior PJM Switching Solutions**

# Switching Solution Example

## PJM: Galion-Leside 138kV control (FE-ATS)

- To control for actual or contingency overloads on the Galion-Leside 138kV line, study the following options:
- 1.) Transfer load from Longview to Galion on the 69kV for ~9MVA of relief.
  2.) Open the Leside-Longview 69kV line for an additional ~5MVA of relief
- **3.) Open the Galion #3 345/138kV Transformer provided the transformer will not go into an actual or contingency overload.**
- 4.) Close the N.O. Alta 'A2' 69kV disconnect
- If the switching can't be performed pre-contingency, issue a PCLLRW with the post contingency switching plan.

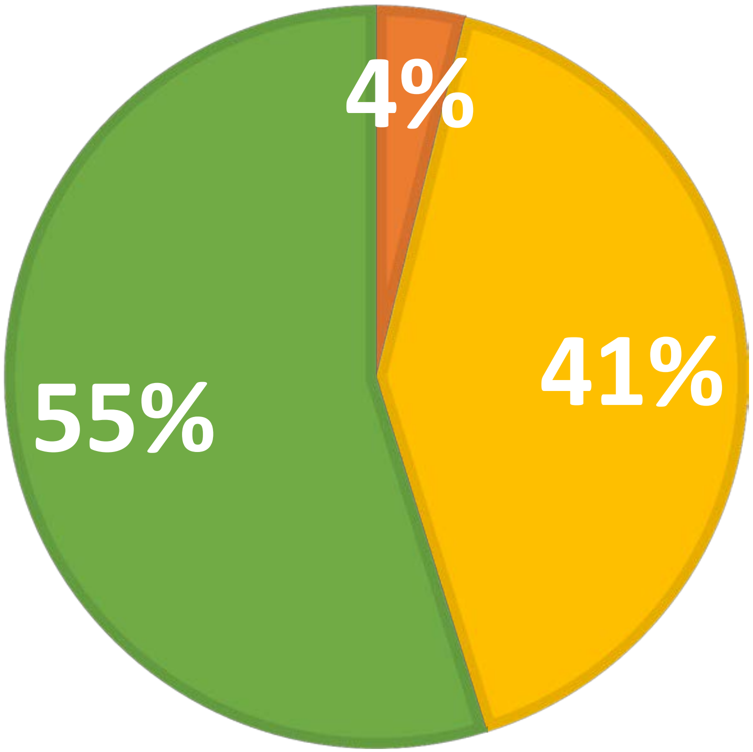
PJM Switching Solutions, https://www.pjm.com/markets-and-operations/etools/oasis/system-information/switching-solutions.aspx

# Results when studying what PJM already knows:

# PJM Switching Solutions

**FTDS VS. PJM PERFORMANCE**
**ALL CASES**

- PJM outperforms FTDS
- FTDS outperforms PJM
- Similar



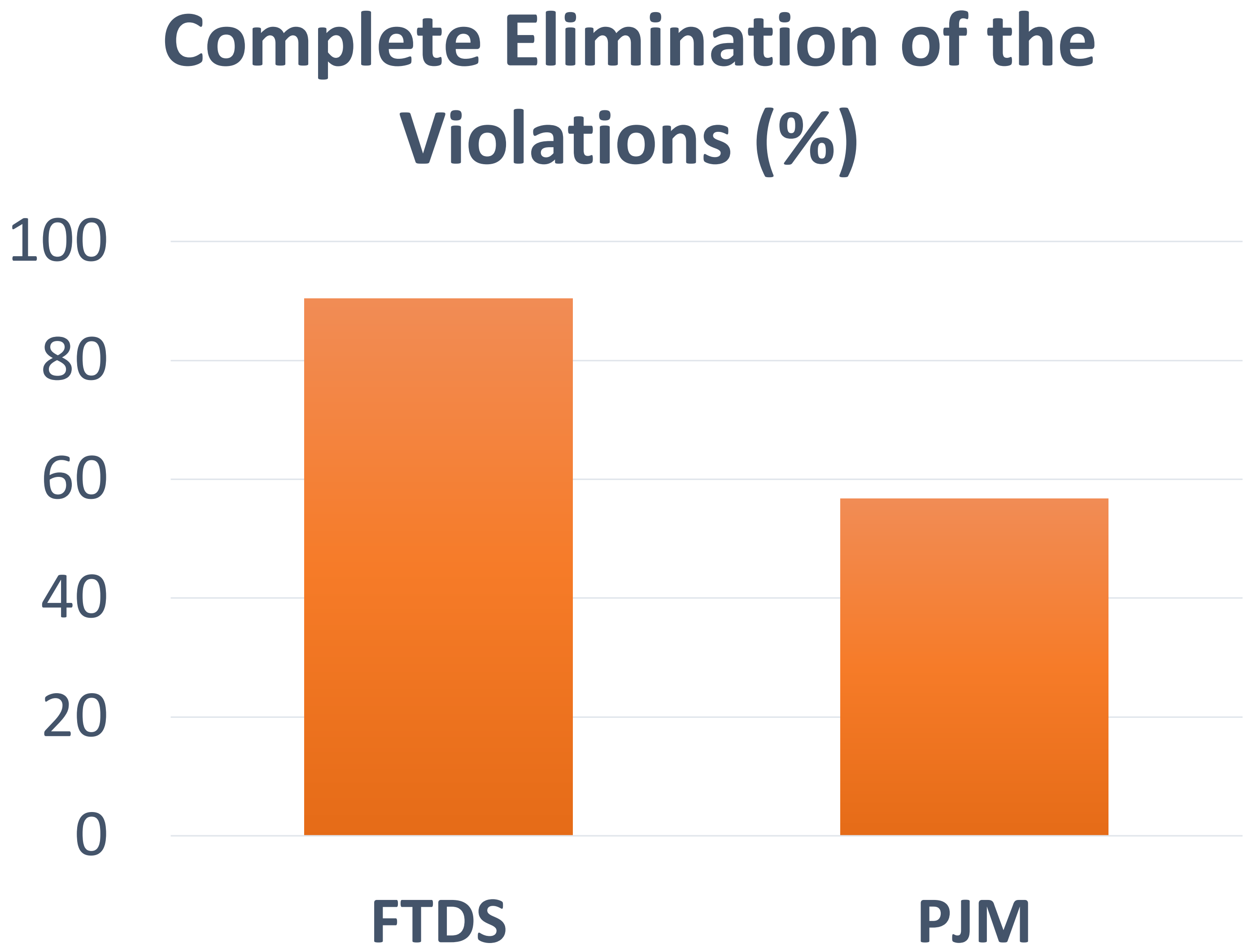

For the cases that are similar: FTDS either proposes the same solution as PJM's switching solution or FTDS proposes a different solution that performs equally well

FTDS VS. PJM PERFORMANCE

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

switching solution or FTDS proposes a different solution that performs equally well

# PJM Switching Solutions



Results when studying all potential post-contingency violations:

# PJM Switching Solutions

- PJM has publicly released ~100 Switching Solutions (corrective switching actions)
- Analyzed 167 PJM E S data snapshots (1

**Study the remaining cases for additional improvement**

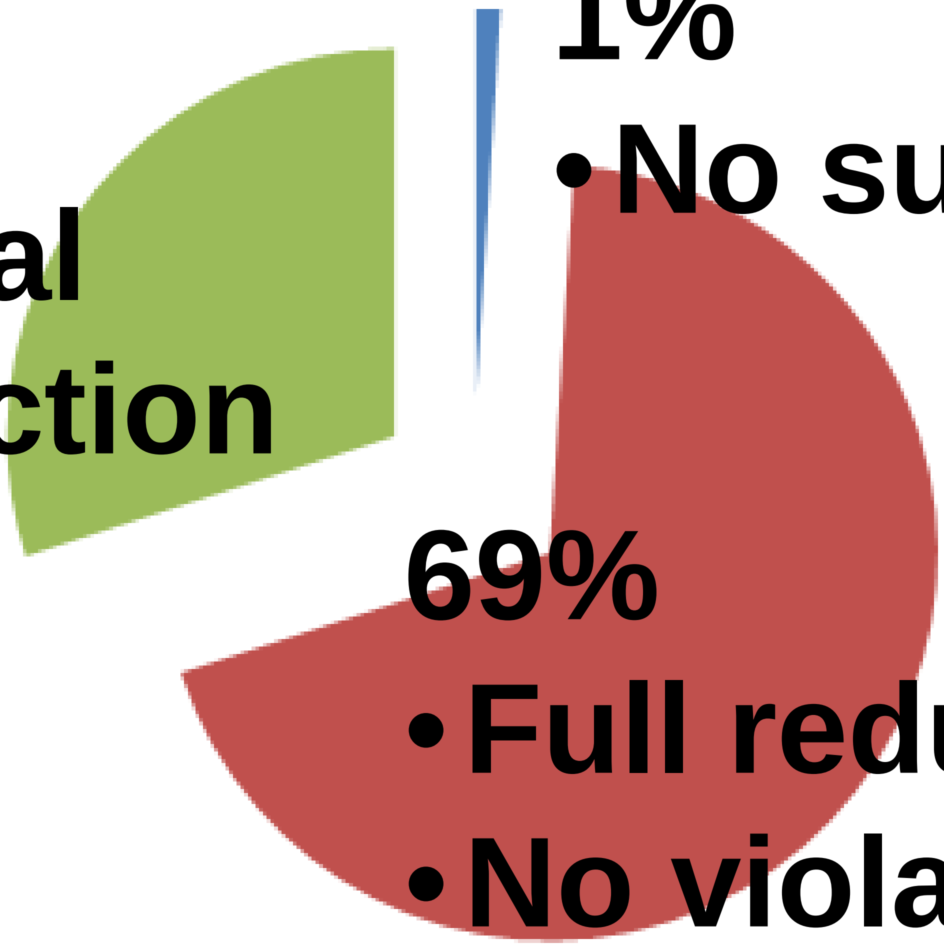
  - **4,000 post-contingency cases with violations over entire week**
  - 104 of these incidences correspond to cases previously identified by PJM
  - **Compare FTDS to prior PJM Switching Solutions**

# FTDS based RTCA Results

- Full success:
  - Post-contingency violations are fully eliminated
- Partial success:
  - Post-contingency violations are reduced but not fully eliminated
- No success:
  - No beneficial FTDS solution found

# FTDS Benefit: PJM

For 4,000 critical post-contingency violations over 7 days:

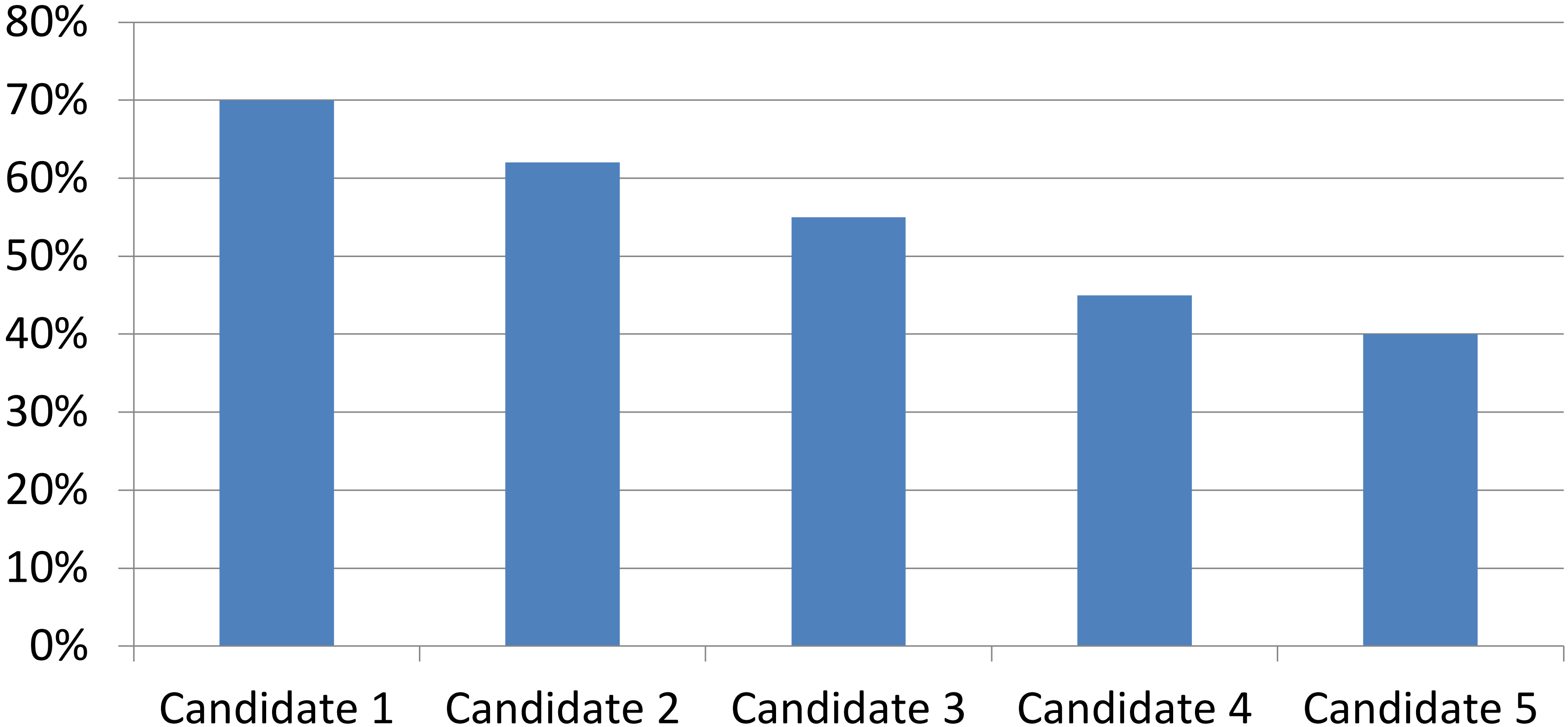


**30%**
- **Partial reduction**

**1%**
- **No success**

**69%**
- **Full reduction**
- **No violations**

# Percent Corrective Action Eliminates All Post-Contingency Violations




**FTDS algorithm suggests 5 candidate switching actions; all perform well**

# PJM's Response

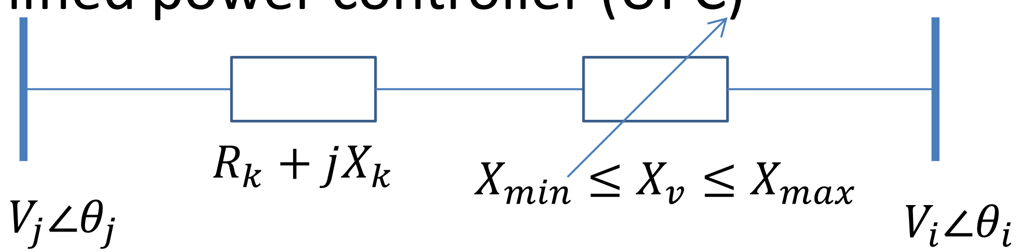
- April 2015: results presented to PJM
- July 2015: PJM issued a request for proposals for a decision support system to determine, in real-time, potential corrective switching solutions
- Estimate >$50M savings a year for this application alone (only for recourse decisions)
- Estimate >$100M in savings if we optimize not just the recourse decisions but the first-stage decisions (switching under normal operations and not just during emergencies)

How sophisticated of an optimization algorithm does it take to get the tool to find candidate corrective switching solutions?

# Flexible Transmission Decision Support: Flexible AC Transmission System (FACTS) Devices

# Variable Impedance FACTS

- Provide power flow control
- Less stability concerns compared to transmission switching
- Creates nonlinearities in DC power flow
- Variable impedance FACTS
  - Changes the impedance of the lines
    - Smart Wires (invented by Deepak Divan)
    - Thyristor controlled series compensator (TCSC)
    - Unified power controller (UPC)



# DCOPF with Variable Impedance

## FACTS

$$\underset{P_g, P_k, \theta_i, b_k}{Min:} \sum_{\forall g} c_g P_g$$

*Subject to:*

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

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

$$P_k - b_k(\theta_j - \theta_i) = 0$$

$$\sum_{\forall k \epsilon \delta(i)^+} P_k - \sum_{\forall k \epsilon \delta(i)^-} P_k + \sum_{\forall g \epsilon g(i)} P_g = d_i$$

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

| | |
|---|---|
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| $P_k$ | Flow on line $k$, defined to be *from node i to node j* |
| $\theta_i$ | Bus voltage phase angle at node (bus) *i* |
| $\delta(i)^+$ | Set of lines defined to be *to node i* |
| $\delta(i)^-$ | Set of lines defined to be *from node i* |
| $b_k$ | Susceptance *of line $k$ (now a variable)* |
| $g(i)$ | Set of generators *at node i* |
| $d_i$ | The demand *at node i* |
| $c_g$ | The cost of gen *g* |

$b_k$ becomes a variable: NLP

# Reformulation: MILP

- Substitute out the equality: $P_k - b_k(\theta_j - \theta_i) = 0$
- If: $(\theta_j - \theta_i) \geq 0$, then let: $z_k = 1$
- For $z_k = 1$: $b_k^{min}(\theta_j - \theta_i) \leq P_k \leq b_k^{max}(\theta_j - \theta_i)$

- If: $(\theta_j - \theta_i) \leq 0$, then let: $z_k = 0$
- For $z_k = 0$: $b_k^{max}(\theta_j - \theta_i) \leq P_k \leq b_k^{min}(\theta_j - \theta_i)$
- Can represent this relationship with indicator constraints or use a Big-M reformulation
- Both MILP and NLP are very difficult to solve

# MILP: very difficult to solve

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

**Empirical results:**

>98% success rate at getting optimal solution with a simple LP heuristic (the remaining 2% have very small optimality gaps)

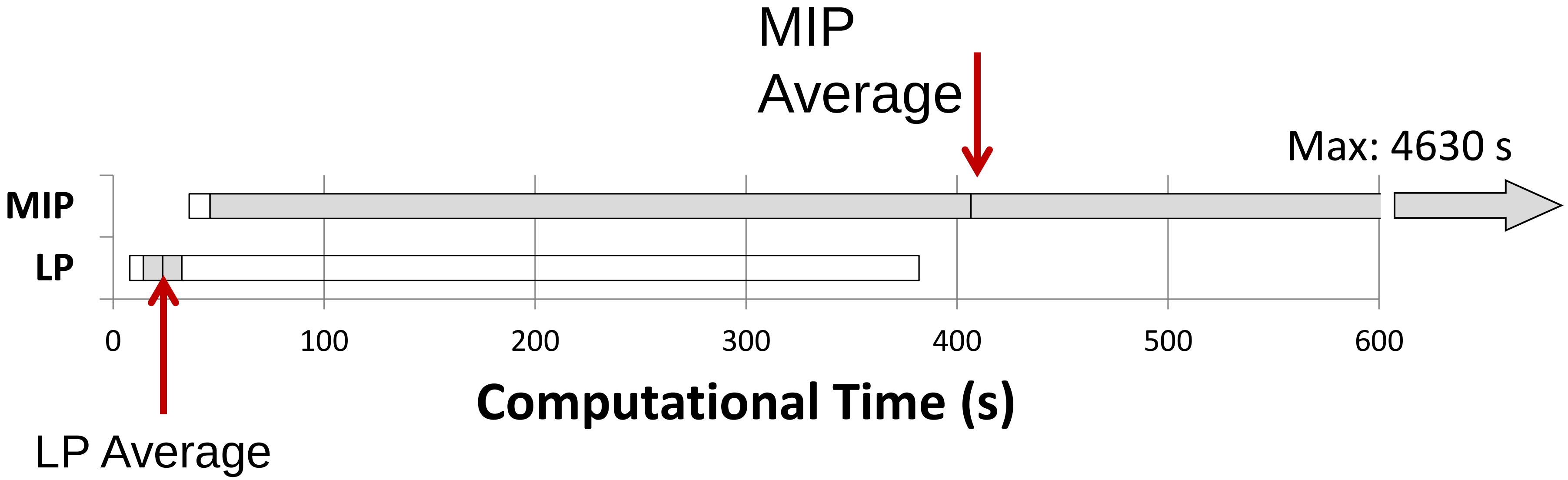
# Summary of Results

Implementation of an LP heuristic

Empirical results:

- Testing on the IEEE 118 Bus System & Polish 3000 Bus System
  - >4,000 OPFs studied
- Random placement of variable impedance FACTS: obtain global optimum 98%
- Placement on heavily loaded lines: obtain global optimum 100%

# Computational Time



# Engineering Insight

$$P_k - b_k(\theta_j - \theta_i) = 0$$

- Binary variable: sign of voltage angle difference
  - Determines the direction of the power flow
- Key corridors: easy to know the flow direction
- Even if we do not know the direction in advance, simply run a two-stage DCOPF (first solve without FACTS to get flow)
- For real-time operations, we will already know the direction of the flow!
- ***Knowing the direction reduces the complexity to an LP***

# Existing Challenges: Industry Formulation for OPF

# DCOPF: B-θ Formulation

$$\underset{P_g, P_k, \theta_i}{Min:} \sum_{\forall g} c_g P_g$$

*Subject to:*

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

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

$$P_k - b_k(\theta_j - \theta_i) = 0$$

$$\sum_{\forall k \epsilon \delta(i)^+} P_k - \sum_{\forall k \epsilon \delta(i)^-} P_k + \sum_{\forall g \epsilon g(i)} P_g = d_i$$

**Variables:** G+K+I (gen, branches, nodes) - for a DCOPF simpler than industry's model

**Constraints:**
2*G + 3*K + I

No SCUC/SCED optimization software today uses this formulation

# DCOPF with Power Transfer Distribution Factors (PTDF)

$$\underset{P_g}{Min}: \sum_{\forall g} c_g P_g$$

*Subject to:*

$$P_k^{min} \leq \sum_{\forall i} PTDF_{k,i}^{R} \left( \sum_{\forall g \epsilon g(i)} P_g - d_i \right) \leq P_k^{max}$$

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

$$\sum_{\forall g} P_g = \sum_{\forall i} d_i$$

$$PTDF_{k,i}^{R}:$$

Power transfer distribution factor for a net injection at bus *i* sent to reference bus *R*, the resulting flow on line $k$

**Variables:** G (gen alone)

**Constraints:**

2*G + 2*K + 1 (at most – almost always far far less)

# Industry DCOPF Formulations

- Commercial grade SCED software uses PTDFs
- PTDF formulations are far easier to solve
- PTDF formulations allow you to ignore transmission lines that you know (or assume) will not be congested
  - With the B-$\theta$ formulation, you must have variables for all bus voltage angles and line flows, making it harder to reduce the problem size even if you know that you do not have to model all transmission lines
- Main setback: PTDFs depend on impedance of lines and topology

# Industry Approximations

- PTDF cutoff
  - California ISO: 2%
  - PJM: 5%
    - PJM system has: >300M non-zero PTDF values
    - Remaining nonzero elements: 1%
- Only critical lines modeled
  - Beyond the reduction occurring with rounding the PTDFs, out of 20,000 branches that can be modeled and roughly 500M first stage and second stage flows, they model on the order of 3k
  - Nomograms and interface limits

# Solution

- To maintain the PTDF structure for variable impedance based FACTS, we have an approach that uses PTDFs and flow canceling transactions

# Summary

# Summary: Flexible Transmission Assets

- Existing optimization engines neglect transmission asset flexibility (lines, transformers, FACTS, Smart Wires)
  - Handled outside optimization/power flow engines
  - Actions determined on an ad-hoc basis
- **New hardware to reduce congestion: expensive**
- **New optimization software** that improves utilization of existing hardware: **very cheap!**
- ***Need: decision support software solutions for power flow control – great opportunity***

# Key Challenge in Power Systems

A quote:

Between the idea….

and reality…

Falls the shadow

T. S. Eliot, The Hollow Men

# Questions?


**Kory W. Hedman**

Kory.Hedman@asu.edu

(480) 965-1276