Computationally Efficient Operation of Power Flow Controllers

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Congestion Cost in US ISO/RTOs

ISO Congestion Costs – 2015

$B

CAISO  ERCOT  ISO-NE  MISO  NYISO  PJM  SPP
Transmission Bottlenecks

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

Building New Transmission Lines
- Power Lines are Ugly!
- Slow Process
- Expensive

More Efficient Utilization of the Existing Grid – Power Flow Control
- Significant Impacts
- Smarter
- Faster
- Cheaper

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

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

**DC Power Flow Equation**

This is a linear approximation of AC power flow equation:
- Relatively accurate
- Facilitates efficient computation

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

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

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

Variable Impedance FACTS

Nonlinear ➔ Computational Burden
Power Flow Physics

Computational Burden

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

No FACTS set point adjustment within EMS or MMS software

Variable Impedance FACTS

Infrequent ad hoc adjustments

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

\[ B_{\text{min}} < B < B_{\text{max}} \]
Technology – TCSC

• Thyristor-Controlled Series Compensator
Technology – Smart Wires

Power Router brochure
Objective:

Design a Computationally-efficient Algorithm to Control the Power Flow Controller Set Points
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 $B\theta$

The injection pair involves NONLINEAR terms.
Computational Complexity – NLP/MILP

\[ F_k = B_k (\Delta \theta_k) \]

\[ B_k^{\text{min}} \leq B_k \leq B_k^{\text{max}} \]

Non Convex (MIP)

Convex (LP)

Convex (LP)

\[ F_k^{\text{max}} \]

\[ F_k^{\text{min}} \]
What if we knew which B&B tree node is the optimal node?
Reformulation to an MILP

\[ \psi_k = \frac{f_k \Delta b_k}{b_k} \]

\[ f_k \geq 0: \quad \frac{f_k \Delta b_k^{\text{max}}}{b_k} \leq \psi_k \leq \frac{f_k \Delta b_k^{\text{min}}}{b_k} \]

\[ f_k \geq 0: \quad \frac{f_k \Delta b_k^{\text{max}}}{b_k} \leq \psi_k \leq \frac{f_k \Delta b_k^{\text{min}}}{b_k} \]
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.
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.

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
Results – Polish System

$B\theta$ versus PTDF

Fixed versus Adaptive Thresholds
Computational Time

LP Average

MIP Average

Max: 4630 s

Computational Time (ms)
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

![Graph showing corrective results for IEEE 118-Bus System. The graph plots Violation Reduction (%) against Reactance Change (%). Lines represent different numbers of lines (5, 10, 15, 20) and show that MILP results are more optimal compared to LP.](image-url)
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
Questions?

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