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

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Transmission Bottlenecks

- Option 1: build more lines
- Option 2: power flow control
Congestion Cost in US ISO/RTOs

ISO Congestion Costs – 2015

$B

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

CAISO  ERCOT  ISO-NE  MISO  NYISO  PJM  SPP

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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
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

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

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

Variable Impedance FACTS

Power Electronics
Economic Example

Cost Reduction!

G1: Cheap
- Capacity: 100 MW, X
- Capacity: 150 MW, X

1. Load: 250 MW
   - 240 MW
   - 100 MW
   - 140 MW

2. G2: Expensive
   - 10 MW

Cost Reduction!
Thyristor-Controlled Series Compensator

In a TCSC, the whole capacitor bank or alternatively, a section of it, is provided with a parallel thyristor controlled inductor which circulates current pulses that add in phase with the line current so as to boost the capacitive voltage beyond the level that would be obtained by the line current alone. Each thyristor is triggered once per cycle and has a conduction interval that is shorter than half a cycle of the rated mains frequency. By controlling the additional voltage to be proportional to the line current, the TCSC will be seen by the transmission system as having a virtually increased reactance beyond the physical reactance of the capacitor.

The thyristor valve is integrated in the capacitor overvoltage protection scheme. It replaces the Fast Protective Device and allows a reduction of the rating of the protective parallel varistor.
Technology – Smart Wire Grid

- Smart Wire Grid Device

Power Router brochure
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)

\[
\begin{align*}
\text{min} & \quad \sum_g c_g P_g \\
& \quad \text{subject to} \\
& \quad P_g^{\text{min}} \leq P_g \leq P_g^{\text{max}} \quad \forall g \\
& \quad -F_k^{\text{max}} \leq F_k \leq F_k^{\text{max}} \quad \forall k \\
& \quad F_k - B_k (\theta_n - \theta_m) = 0 \quad \forall k \\
& \quad \sum_{k \in \sigma^+(n)} P_k - \sum_{k \in \sigma^-(n)} P_k + \sum_{g \in g(n)} P_g = d_n \quad \forall n
\end{align*}
\]

Linear Program
Variable Impedance FACTS

Computational Burden

- No FACTS set point adjustment within EMS or MMS software
- Infrequent ad hoc adjustments

\[
V_n \angle \theta_n \\
R_k + jX_k \leq jX_v \leq jX_{\text{max}} \\
F_k = B_k (\theta_j - \theta_i) \\
B_{\text{min}} \leq B \leq B_{\text{max}}
\]
Computational Complexity – NLP/MIP

Non Convex (MIP)

Convex (LP)

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

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

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
Computational Time

- MIP Average
- LP Average

Computational Time (ms)

Max: 4630 s
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
• 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 $B\theta$

\[
\begin{align*}
\text{from} & \quad b_k + \Delta b_k \quad \text{to} \\
\text{from} & \quad f_k \left( \frac{\Delta b_k}{b_k} \right) \quad \text{to} \quad f_k \left( \frac{\Delta b_k}{b_k} \right)
\end{align*}
\]
• 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

\[ \text{Computational Time (ms)} \]

\[ \text{Number of Lines Equipped with FACTS} \]

$>70\%$

$>80\%$

$>85\%$

$>90\%$

$>95\%$
MARKET PARTICIPATION
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!

G1: Cheap

- Load: 250 MW
- Capacity: 100 MW, X
- 200 MW

G2: Expensive

- Load: 250 MW
- Capacity: 150 MW, X
- 100 MW
- 50 MW

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Proposed Payment System

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

\[ F_k = B_k (\theta_j - \theta_i) \]  \hspace{1cm} (S_k)

\[ S_k (\theta_j - \theta_i) \times \Delta B_k \]

- Marginal Value: Price
- Quantity
Two Node System

\[ MC_1 = \$30/\text{MWh} \quad \text{-700 p.u., 400 MW} \quad MC_2 = P_2 + 50 \ (\$/\text{MWh}) \]

\[ G_1 \quad -700 \text{ p.u., 450 MW} \quad G_2 \]

FACTS control range: 2%

\[ \Delta B_1 + |\Delta B_2| (\text{p.u.}) \]

\[ \text{FACTS Price} (\$/\text{p.u.}) \]

\[ \text{Saving} (\$/\text{h}) \]

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Fig. 10. Cost savings due to the improved transfer capability offered by the FACTS devices.

Fig. 11. Congestion rent in thousands of dollars with and without FACTS devices. Payments are much smaller than congestion rents shown in Fig. 11, making the market revenue adequate.

Fig. 12. Payments to the FACTS owners. FACTS revenue is clearly smaller than the congestion rent shown in Fig. 11. According to the proof presented in Section III-A, payments to the owner of \( \Delta B \) should be less than the congestion rent collected by line 2 since the FACTS adjustment aims at increasing the flow of this line by increasing the absolute value of its susceptance. However, revenue adequacy is not guaranteed for \( \Delta B \), since the susceptance adjustment is in the opposite direction. Despite the absence of proof, FACTS payments are much smaller than congestion rents shown in Fig. 11, making the market revenue adequate.

Fig. 13 provides additional insight into how the market would work. The marginal value of FACTS capacity for the device installed on line one is depicted in the figure. This is depicted according to (8). It shows how the price is set at different levels of demand. In this example, each per unit change in the susceptance of the line would decrease the marginal value forming an negatively sloped curve. Note that the slope may very well be positive due to the non-convexities of the market. In a perfectly competitive market, FACTS owners would submit a bid of $0/p.u., which would be a horizontal line at zero until their capacity is exhausted; then, it would be a vertical line, meaning that they cannot offer more adjustment at any price. When the load is low and FACTS capacity is enough to relieve the congestion, the price would be zero. For example, the market results in a price of $0 per p.u. for demand of 805 MW. However, for large enough demand, that FACTS capacity is not enough for removal of the congestion, the marginal value of the FACTS adjustment sets the price. For example, for the load of 830 MW, the price would be $18.11 per p.u. change in the susceptance of the first line.

Under Cournot competition, the players find their optimal capacity to offer to the market based on the marginal value function. Thus, even when the FACTS capacity is enough to relieve the congestion, the device owners would strategically withhold some of their capacity to keep the marginal value positive. If the congestion is removed this value would go down to zero.
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

- Marginal Value of Susceptance ($/p.u.)
- FACTS 133
- FACTS 155
- % Change in Reactance

- FACTS Revenue ($/h)
- Post-Adjustment
- Sensitivity-Based
- FACTS 133
- FACTS 155
- % Change in Reactance

- System Cost ($/h)
- % Change in Reactance

- Congestion Rent ($/h)
- Line 133
- Line 155
- % Change in Reactance
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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