Optimal Transmission Switching: When Economic Efficiency and FTR Markets Collide

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Overview

- **Motivation for transmission switching**
  - Economic efficiency through topology improvements with no reliability degradation
  - Smart grid application by exploiting short term network reconfiguration flexibility

- **Analyze market implications of optimal transmission switching**
  - May undermine prevailing market mechanisms – cause revenue inadequacy in the FTR market
  - Unpredictable distributional impacts on LMPs, generation rent, congestion rent, etc.
Overview of Optimal Transmission Switching Concept

- Control of transmission not fully utilized today
  - Transmission assets are seen as static in the short term
  - Currently operators change transmission assets’ states on ad-hoc basis (per private communication with Andy Ott, VP, PJM)

- Network redundancies
  - Required for reliability, not required for every market realization
  - Redundancies may cause dispatch inefficiency

- Optimal transmission switching: co-optimize network topology with generation dispatch
Transmission Switching Example

- 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)
Literature Review

Corrective switching
- [Mazi, Wollenberg, Hesse 1986]: Corrective control of power systems flows
- [Schnyder, Glavitsch 1990]: Security enhancement using an optimal switching power flow
- [Glavitsch 1993]: Power system security enhanced by post-contingency switching and rescheduling
- [Shao, Vittal 2006]: Corrective switching algorithm for relieving overloads and voltage violations

Switching to reduce losses
- [Bacher, Glavitsch 1988]: Loss reduction by network switching
- [Fliscounakis, Zaoui, et al. 2007]: Topology influence on loss reduction as a mixed integer linear program

Switching to relieve congestion
- [Granelli, Montagna, et al. 2006]: Optimal network reconfiguration for congestion management by deterministic and genetic algorithms
Traditional DCOPF

Minimize: Total generation cost
Subject to:
- Generator min & max operating constraints
- Node balance constraints
- Line flow constraints

\[ B_k (\theta_n - \theta_m) - P_k = 0 \]
- Line capacity constraint

Variables:
- \( P_k \): real power flow from bus \( m \) to bus \( n \) for line \( k \)
- \( P_g \): Gen \( g \) supply at bus \( n \)
- \( \theta_n \): Bus \( n \) voltage angle
- \( z_k \): Transmission line status (1 closed/in service, 0 open/out of service)

Parameters:
- \( B_k \): Susceptance of line \( k \)
- \( d_n \): Real power load at bus \( n \)
Incorporating Transmission Switching into DCOPF

- $z_k$: State of transmission line (Binary: 0 open/offline, 1 closed/operational)

- Update line thermal (capacity) constraints:
  - Original: $P_k^{\text{min}} \leq P_k \leq P_k^{\text{max}}$
  - New: $P_k^{\text{min}}z_k \leq P_k \leq P_k^{\text{max}}z_k$

- Update line flow constraints:
  - Original: $B_k(\theta_n - \theta_m) - P_k = 0$
  - New: $B_k(\theta_n - \theta_m) - P_k + (1 - z_k)M_k \geq 0$
    $B_k(\theta_n - \theta_m) - P_k - (1 - z_k)M_k \leq 0$
Optimal Transmission Switching

DCOPF

Minimize: \[ \sum_g \left( c_g P_g \right) \]

s.t.
Node Balance Constraints:
\[ \sum_{k\in N} P_k - \sum_{k\in N} P_k + \sum_{g\in G} P_g = d_n, \forall n \]

Generator Constraints:
\[ 0 \leq P_g \leq P_{g,\text{max}}, \forall g \]

Transmission Constraints:
\[ P_{k,\text{min}} z_k \leq P_k \leq P_{k,\text{max}} z_k, \forall k \]
\[ B_k (\theta_n - \theta_m) - P_k + (1 - z_k) M_k \geq 0, \forall k \]
\[ B_k (\theta_n - \theta_m) - P_k - (1 - z_k) M_k \leq 0, \forall k \]
\[ z_k \in \{0,1\}. \]
Economic Savings for DCOPF and N-1 DCOPF Models

- DCOPF Transmission Switching Model (one hour):
  - IEEE 118 Bus Model: saves 25% saving (10 lines off)
  - ISONE 5000 Bus Model: 5%-13% savings ($70,000 savings)
  - With advanced smart grid technology, switch lines back into service for a contingency to meet N-1 (just-in-time transmission)

- N-1 DCOPF Transmission Switching Model (one hour):
  - IEEE 73-Bus Model: up to 8% savings
  - IEEE 118-Bus Model: up to 16% savings
  - Ensures N-1 within transmission switching model
  - Improves efficiency of grid while ensuring N-1 Reliability
Results – DCOPF – IEEE 118

- Transmission switching solution saves 25% of total generation cost

![Graph showing system dispatch cost vs. number of open lines. The best solution found is $1,543/h with 31 open lines.](image-url)
Results – DCOPF – IEEE 118

- IEEE 118 opened lines for J=10

- Note: this diagram has additional gens than our model
Economic Savings for UC with Transmission Switching

- Generation Unit Commitment N-1 DCOPF Transmission Switching Model:
  - IEEE 73-Bus Model: 3.7% savings ($120,000 savings for 24-hour model)
  - Unit commitment solution changes when topology changes
  - Peaker units committed with original topology - not committed under co-optimization of network topology and unit commitment
  - Optimal topology varies hour to hour
Impact on Market Participants

- Results are % of static network’s DCOPF solution
- Unpredictable distributional effects for market participants
Impact on LMPs

- Max and min percent change in LMP
- IEEE 118 bus test case – DCOPF optimal transmission switching problem
Overview of Financial Transmission Rights

- FTRs are used to hedge price risk
- FTR settlements are financed by congestion rents
- Revenue inadequacy occurs when ISO does not collect enough congestion rent to fulfill its obligation to FTR holders
  - ISO may then allocate shortfall to participants or carry it forward and try to recover it from surplus at other times
- Revenue adequacy of FTRs is guaranteed for the static DC topology (since the simultaneous FTR feasible solution corresponds to a suboptimal feasible power flow)
- Revenue adequacy is not guaranteed if the network topology changes
  - Optimal transmission switching undermines the assumption of a static topology
3-Bus FTR Revenue Adequacy Example
Revenue Inadequacy due to Transmission Switching

### 3-bus example C optimal dispatch results (no switching)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Gen Pg:</th>
<th>LMP:</th>
<th>Gen Cost:</th>
<th>Transaction</th>
<th>MW:</th>
<th>Cong. Rent:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>90MW</td>
<td>$50/MWh</td>
<td>$4,500</td>
<td>A – B</td>
<td>60MW</td>
<td>$3,000</td>
</tr>
<tr>
<td>B</td>
<td>40MW</td>
<td>$100/MWh</td>
<td>$4,000</td>
<td>A – C</td>
<td>30MW</td>
<td>$750</td>
</tr>
<tr>
<td>C</td>
<td>0MW</td>
<td>$75/MWh</td>
<td>$0</td>
<td>Total</td>
<td></td>
<td>$3,750</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Congestion Rent:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Generation Cost:** $8,500

### 3-bus example C optimal dispatch results (lines A-B1 and A-B2 open)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Gen Pg:</th>
<th>LMP:</th>
<th>Gen Cost:</th>
<th>Transaction</th>
<th>MW:</th>
<th>Cong. Rent:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100MW</td>
<td>$50/MWh</td>
<td>$5,000</td>
<td>A – B</td>
<td>70MW</td>
<td>$3,500</td>
</tr>
<tr>
<td>B</td>
<td>30MW</td>
<td>$100/MWh</td>
<td>$3,000</td>
<td>A – C</td>
<td>30MW</td>
<td>$1,500</td>
</tr>
<tr>
<td>C</td>
<td>0MW</td>
<td>$100/MWh</td>
<td>$0</td>
<td>Total</td>
<td></td>
<td>$5,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Congestion Rent:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Generation Cost:** $8,000

### 3-bus example C results – FTR settlements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A to B</td>
<td>45MW</td>
<td>$2,250 (LMP gap: $50/MWh)</td>
<td>$2,250 (LMP gap: $50/MWh)</td>
</tr>
<tr>
<td>A to C</td>
<td>60MW</td>
<td>$1,500 (LMP gap: $25/MWh)</td>
<td>$3,000 (LMP gap: $50/MWh)</td>
</tr>
<tr>
<td><strong>Total FTR Settlements:</strong></td>
<td><strong>$3,750</strong></td>
<td></td>
<td><strong>$5,250</strong></td>
</tr>
</tbody>
</table>
Revenue Inadequacy due to Transmission Switching

- FTR allocation is revenue adequate for initial topology but revenue inadequate for optimal network topology with both A-B lines open.

### FTR Allocation

1. **Original Optimal Dispatch**
2. **Optimal Dispatch with Both A-B Lines Open**
3. **FTR Allocation**

Mathematical Constraints:

\[
\begin{align*}
2AB + AC &\leq 150 \\
AB + AC &\leq 100 \\
AB &\geq 0 \\
AC &\geq 0
\end{align*}
\]
Transmission Switching Can Help Regain Revenue Adequacy

### 3-bus example C results (line A-B1 failed)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Gen Pg:</th>
<th>LMP:</th>
<th>Gen Cost:</th>
<th>Transaction:</th>
<th>MW:</th>
<th>Cong. Rent:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65MW</td>
<td>$50/MWh</td>
<td>$3,250</td>
<td>A – B</td>
<td>35MW</td>
<td>$1,750</td>
</tr>
<tr>
<td>B</td>
<td>65MW</td>
<td>$100/MWh</td>
<td>$6,500</td>
<td>A – C</td>
<td>30MW</td>
<td>$750</td>
</tr>
<tr>
<td>C</td>
<td>0MW</td>
<td>$75/MWh</td>
<td>$0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total Generation Cost:</strong></td>
<td>$9,750</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3-bus example C optimal dispatch results (lines A-B1 failed A-B2 open)

<table>
<thead>
<tr>
<th>Bus</th>
<th>Gen Pg:</th>
<th>LMP:</th>
<th>Gen Cost:</th>
<th>Transaction:</th>
<th>MW:</th>
<th>Cong. Rent:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100MW</td>
<td>$50/MWh</td>
<td>$5,000</td>
<td>A – B</td>
<td>70MW</td>
<td>$3,500</td>
</tr>
<tr>
<td>B</td>
<td>30MW</td>
<td>$100/MWh</td>
<td>$3,000</td>
<td>A – C</td>
<td>30MW</td>
<td>$1,500</td>
</tr>
<tr>
<td>C</td>
<td>0MW</td>
<td>$100/MWh</td>
<td>$0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total Generation Cost:</strong></td>
<td>$8,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3-bus example C results – FTR settlements (line A-B1 failed)

<table>
<thead>
<tr>
<th>Source to Sink</th>
<th>FTR Quantity</th>
<th>FTR Settlement (No Switching):</th>
<th>FTR Settlement (Line A-B2 Opened):</th>
</tr>
</thead>
<tbody>
<tr>
<td>A to B</td>
<td>60MW</td>
<td>$3,000 (LMP gap: $50/MWh)</td>
<td>$3,000 (LMP gap: $50/MWh)</td>
</tr>
<tr>
<td>A to C</td>
<td>30MW</td>
<td>$750 (LMP gap: $25/MWh)</td>
<td>$750 (LMP gap: $25/MWh)</td>
</tr>
<tr>
<td><strong>Total FTR Settlements:</strong></td>
<td>$3,750</td>
<td></td>
<td>$3,750</td>
</tr>
</tbody>
</table>
Transmission Switching Can Help Regain Revenue Adequacy

- Line outage causes revenue inadequacy (loss of A-B 1)
- Further grid modifications may regain revenue adequacy and improve market surplus (open line A-B 2)

Optimal Dispatch

Original Optimal Dispatch

Optimal Dispatch with Both A-B Lines Open

FTR Allocation

AB ≥ 0

AC ≥ 0

A-B

A-C

50

50

2AB + AC ≤ 150

2AB + AC ≤ 100

AB + AC ≤ 100
Policy Implications

- Optimal transmission switching improves social welfare
  - Yet market participants may object since it can cause revenue inadequacy, affects LMPs, generation rents, congestion rents, etc.
- How to deal with revenue inadequacy?
  - Implement side payments and who pays?
  - De-rate FTR payments?
- Emerging “smart grid” technologies may make certain market mechanisms obsolete
  - Rethink market design principles?
- How would optimal transmission switching affect FTR auctions?
Summary

- FTRs are important as they are used to hedge price risk
- Revenue adequacy of FTRs is vulnerable to grid topology changes
- Co-optimizing generation and network topology improves market surplus even while maintaining reliability criteria
  - Unfortunately, it undermines prevailing market mechanisms
  - Can cause revenue inadequacy in FTR markets
  - It has unpredictable distributional effects on market participants
QUESTIONS?
Thank you!

http://www.ieor.berkeley.edu/~oren/index.htm
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