Co-optimization of Network Topology in Future Unit Commitment Models

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Section 1: Introduction

- Overview of Optimal Transmission Switching
- Literature Review

Overview of Optimal Transmission Switching Concept

- Control of transmission not fully utilized today
  - Transmission assets are seen as static in the short term
  - However, operators change transmission assets' states on ad-hoc basis
    - Special Protection Schemes (SPSs)
- Network redundancies
  - Required for reliability, not required for every market realization
  - Redundancies may cause dispatch inefficiency
- Incorporate state of transmission assets into generation dispatch formulation

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*
- ***[Shao, Vittal 2006]****: BIP-Based OPF for Line and Bus-bar Switching to Relieve Overloads and Voltage Violation*

Switching to reduce losses

- ***[Fliscounakis, Zaoui, et al. 2007]:*** *Topology influence on loss reduction as a mixed integer linear program*

Switching to relieve congestion

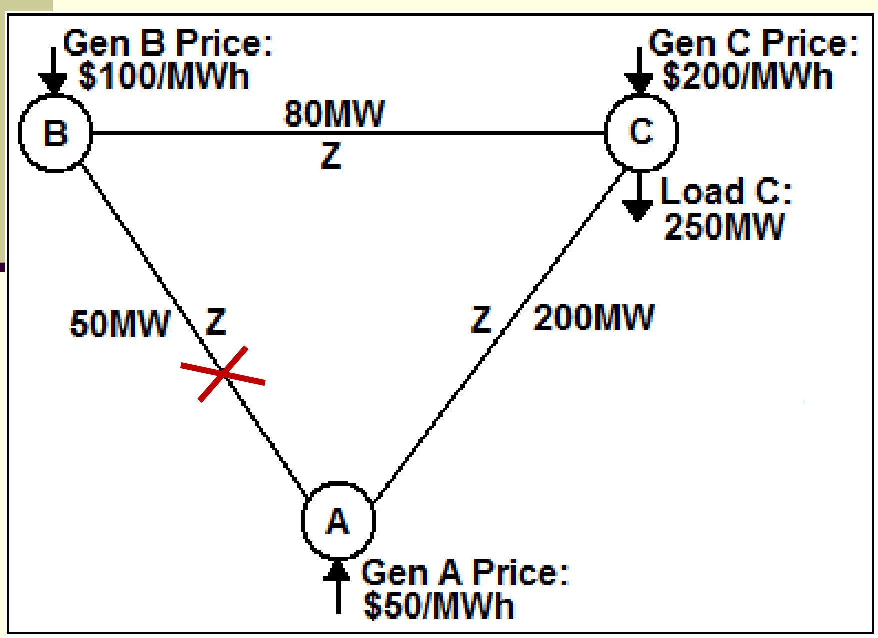
- ***[Granelli, Montagna, et al. 2006]:*** *Optimal network reconfiguration for congestion management by deterministic and genetic algorithms*

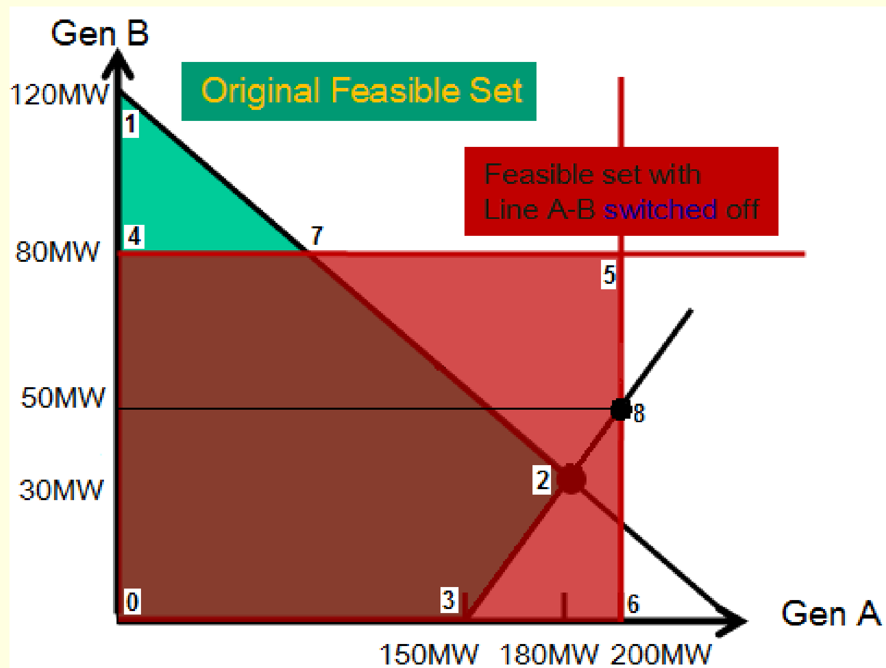
Section 2: Why Optimal Transmission Switching?

- Transmission Switching and the Feasible Set of Dispatch Solutions
- Transmission Switching and Reliability

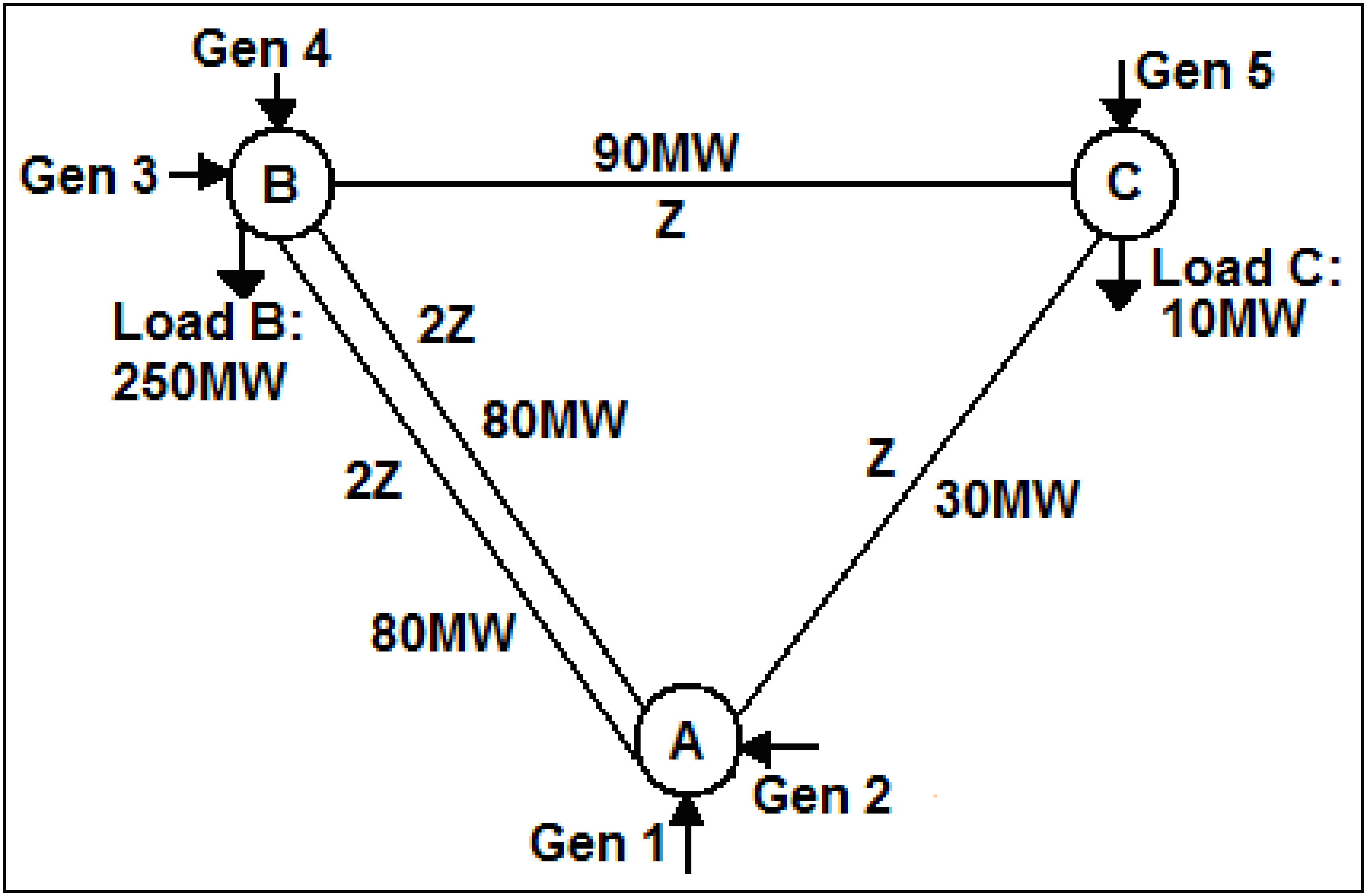
Transmission Switching and the Feasible Set of Dispatch Solutions

- 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)





Transmission Switching and Reliability



Generator Info

- Operational costs, startup costs, shutdown costs, min & max operating levels, ramp rates
- N-1 is enforced
  - System must have adequate 10 minute spinning reserve online to respond to any contingency (line or generator)

Table 1 Generator Information

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
Cost $/MWh	25	20	80	80	100
Startup Cost $	100	100	300	500	400
Gen Min MW	50	50	10	50	10
Gen Max MW	400	100	250	100	150
Ramp Rate MW/10 min	200	100	50	50	150

Optimal Solutions & Impact on Reliability

- Optimal N-1 compliant solution with static topology:
  - Solution cannot handle loss of generators 3 and 4

Table 2 Case 1: Optimal Solution without Transmission Switching

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	**Total Cost:**
Optimal Dispatch	Offline	100	40	100	20	**$16,900**

- Optimal N-1 compliant solution with optimal transmission switching (line A-C open)
  - Solution can handle loss of generators 3 and 4

Table 3 Case 2: Optimal Solution with Transmission Switching (line A-C open)

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	**Total Cost:**
Optimal Dispatch	160	Offline	10	80	10	**$13,700**

Section 3: Co-optimization of network topology and unit commitment

- Direct Current Optimal Power Flow (DCOPF)
- Incorporation of Transmission Switching
- Generation Unit Commitment

Traditional Direct Current Optimal Power Flow (DCOPF) Problem

- 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

θ_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 within DCOPF

- z_k: State of transmission line (Binary: 0 open/offline, 1 closed/operational)
- Update line thermal (capacity) constraints:
  - Original: $P_k^{\min} \le P_k \le P_k^{\max}$
  - New: $P_k^{\min} z_k \le P_k \le P_k^{\max} z_k$
- Update line flow constraints:
  - Original: $B_k(\theta_n - \theta_m) - P_k = 0$
  - New: $$B_k(\theta_n - \theta_m) - P_k + (1 - z_k) M_k \ge 0$$ $$B_k(\theta_n - \theta_m) - P_k - (1 - z_k) M_k \le 0$$

Optimal Transmission Switching Unit Commitment N-1 DCOPF

- Generation unit commitment
  - Minimum up and down time constraints
    - Facet defining valid inequalities
  - Relaxation of startup and shutdown binary variables
  - Startup costs
  - Shutdown costs
  - Ramp rate constraints
- Optimal transmission switching N-1 DCOPF
  - Explicitly model all N-1 contingency constraints
    - No reserve constraints

Generation Unit Commitment Nomenclature

- **Variables:**
- u_{gt}: Unit commitment binary variable (1 generator online, 0 generator offline)
- v_{gt}: Startup binary variable (1 generator turned on in period t, 0 otherwise)
- w_{gt}: Shutdown binary variable (1 generator turned off in period t, 0 otherwise)
- **Parameters:**
- c^{SU}_{g}: Startup cost, generator g
- c^{SD}_{g}: Shutdown cost, generator g
- UT_{g}: Minimum up time, generator g
- DT_{g}: Minimum down time, generator g

Relaxation of Startup (*V*) and Shutdown (*W*) Binary Variables

- With appropriate valid inequalities, (1)-(6), integrality constraints on v_{gt} & w_{gt} can be relaxed
- Constraints (1), (4)-(6) are a part of our formulation; (2) and (3) are dominated by the facets we use to represent min up & down time constraints, i.e. (1)-(6) are enforced in the model

$$v_t - w_t = u_t - u_{t-1}, \forall t \quad (1)$$

$$v_t \le 1 - u_{t-1}, \forall t \quad (2)$$

$$w_t \le u_{t-1}, \forall t \quad (3)$$

$$0 \le v_t \le 1, \forall t \quad (4)$$

$$0 \le w_t \le 1, \forall t \quad (5)$$

$$u_t \in \{0,1\}, \forall t \quad (6)$$

U_t	U_{t-1}	**Outcome:**
0	0	(3) forces $W_t = 0$ then (1) forces $V_t = 0$
0	1	(1) forces $V_t = 0$, $W_t = 1$
1	0	(1) forces $V_t = 1$, $W_t = 0$
1	1	(2) forces $V_t = 0$ then (1) forces $W_t = 0$

Min Up/Down Time Constraints

- Facet defining valid inequalities

$$\sum_{q=t-UT_g+1}^{t} v_{g,q} \le u_{g,t},\ \forall g,t \in \{UT_g,..,T\}$$

$$\sum_{q=t-DT_g+1}^{t} w_{g,q} \le 1-u_{g,t},\ \forall g,t \in \{DT_g,..,T\}$$

- D. Rajan and S. Takriti, "Minimum up/down polytopes of the unit commitment problem with start-up costs," *IBM Research Report*, June 2005.
  - Produces the convex hull of the *U*, *V* projection (with additional trivial valid inequalities)

Intertemporal Ramp Rate Constraints

- With unit commitment variables only:

$$P_{g0t} - P_{g0,t-1} \le R_g^{+} u_{g,t-1} + R_g^{SU}(1 - u_{g,t-1}),\ \forall g,t$$
$$P_{g0,t-1} - P_{g0t} \le R_g^{-} u_{g,t} + R_g^{SD}(1 - u_{g,t}), \forall g,t$$

- With unit commitment, startup, and shutdown binary variables:

$$P_{g0t} - P_{g0,t-1} \le R_g^{+} u_{g,t-1} + R_g^{SU} v_{g,t},\ \forall g,t$$
$$P_{g0,t-1} - P_{g0,t} \le R_g^{-} u_{g,t} + R_g^{SD} w_{g,t}, \forall g,t$$

Unit Commitment Formulation

Minimize: $\sum_{t}\sum_{g}\left(c_g P_{g0t} + c_g^{SU} v_{gt} + c_g^{SD} w_{gt}\right)$

s.t. ***N-1 DCOPF Transmission Switching Constraints***

Generator upper and lower bounds:

$$P_g^{\min} N1_{gc} u_{gt} \le P_{gct} \le P_g^{\max} N1_{gc} u_{gt},\ \forall g,c,t$$

Unit commitment, startup, and shutdown variable equality:

$$v_{g,t} - w_{g,t} = u_{g,t} - u_{g,t-1},\ \forall g,t$$

Minimum up and down time constraints:

$$\sum_{q=t-UT_g+1}^{t} v_{g,q} \le u_{g,t},\ \forall g, t \in \{UT_g,..,T\};\ \sum_{q=t-DT_g+1}^{t} w_{g,q} \le 1 - u_{g,t},\ \forall g, t \in \{DT_g,..,T\}$$

Ramp rate constraints:

$$P_{g0t} - P_{g0,t-1} \le R_g^{+} u_{g,t-1} + R_g^{SU} v_{g,t};\ P_{g0,t-1} - P_{g0,t} \le R_g^{-} u_{g,t} + R_g^{SD} w_{g,t}, \forall g,t$$

$$P_{gct} - P_{g0,t} \le R_g^{+c};\ P_{g0,t} N1_{gc} - P_{gct} \le R_g^{-c}, \forall g,c,t$$

$$0 \le v_{g,t} \le 1;\ 0 \le w_{g,t} \le 1;\ u_{g,t} \in \{0,1\},\ \forall g,t$$

Reserve Constraints in Unit Commitment (UC)

- Spinning and non-spinning reserve constraints are typically included in UC
- Reserve constraints are surrogate constraints to enforce N-1 reliability requirements
  - Typically too computationally challenging to explicitly list every single contingency in UC problems
- This UC formulation explicitly enforces N-1
  - Reserve constraints are not included
- Question as to whether reserve constraints would suffice as surrogates to N-1 when the network topology is optimized

Overview of Past Results: DCOPF & N-1 DCOPF

- IEEE 118 Bus Model:
  - Up to **16% savings with N-1 DCOPF** transmission switching (for feasible solutions)
- IEEE 73 (RTS 96) Bus Model
  - Up to **8% savings with N-1 DCOPF** transmission switching (for feasible solutions)
- ISONE 5000 Bus Model (includes NEPOOL, NYISO, NB, NS – costs for NEPOOL only)
  - **5% to 13% savings of $600k total cost for 1hr (feasible solutions) - DCOPF**

Results: Co-optimization of Network Topology and UC

- **3.7% overall savings or over $120,000 (24hr)** (3.2% optimality gap) for the medium sized IEEE test case (RTS96 - IEEE 73 bus test case)
- Optimal network topology varies
- Changing the network topology can change the optimal generation unit commitment solution
- UC solution with static topology:
  - 3 peaker units turned on for 1 hour
- UC solution when co-optimizing network topology:
  - These 3 peaker units always off

Future Research

- Transient stability
- ACOPF
- Faster solution times
- Relay settings
- Cost of switching (breakers)
- FTR market
- Wind energy
- Just-in-time transmission

Summary

- Substantial savings possible without reliability degradation
- Optimal network topology varies hour to hour
- Changes optimal unit commitment solution
- 3.7% savings for the RTS96 unit commitment test case
- Unfortunately, emerging smart grid technologies may undermine prevailing market mechanisms
  - Optimal transmission switching can cause revenue inadequacy in FTR markets and it has unpredictable distributional effects on market participants

QUESTIONS?
Thank you!

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Publications

Journal Papers:

[1] **K. W. Hedman**, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching – sensitivity analysis and extensions," *IEEE Trans. Power Syst.,* vol. 23, no. 3, pp. 1469-1479, Aug. 2008.

[2] **K. W. Hedman**, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching with contingency analysis," *IEEE Trans. Power Syst.,* vol. 24, no. 3, Aug. 2009.

[3] **K. W. Hedman**, M. C. Ferris, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," *IEEE Trans. Power Syst.*, accepted for publication.

[4] **K. W. Hedman**, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Smart flexible just-in-time transmission and flowgate bidding," *IEEE Trans. Power Syst.*, accepted for publication.

[5] R. P. O'Neill, **K. W. Hedman**, E. A. Krall, A. Papavasiliou, M. C. Ferris, E. B. Fisher, and S. S. Oren, "Economic analysis of the N-1 reliable unit commitment and transmission switching problem using duality concepts," *Energy Systems*, accepted for publication.

Publications cont'd

Submitted Papers:

[6] **K. W. Hedman**, R. P. O'Neill, and S. S. Oren, "Optimal transmission switching: economic efficiency and market implications," *Journal of Regulatory Economics,* submitted for publication.

Peer-Reviewed Conference Publications:

[7] **K. W. Hedman**, R. P. O'Neill, and S. S. Oren, "Analyzing valid inequalities of the generation unit commitment problem," in *Proc. Power Syst. Conf. and Expo.,* March 2009.

[8] E. B. Fisher, **K. W. Hedman**, R. P. O'Neill, M. C. Ferris, and S. S. Oren, "Optimal transmission switching in electric networks for improved economic operations," in *INFRADAY Conference* 2008.