# Static Security and Multiple Solutions in Multi-period Transmission Switching

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# Outline

- I. Introduction and proposed problems
- II. Static security in multi-period transmission switching
- III. Multiple solutions in multi-period transmission switching
- III. Summary and future work

# Introduction and proposed problems

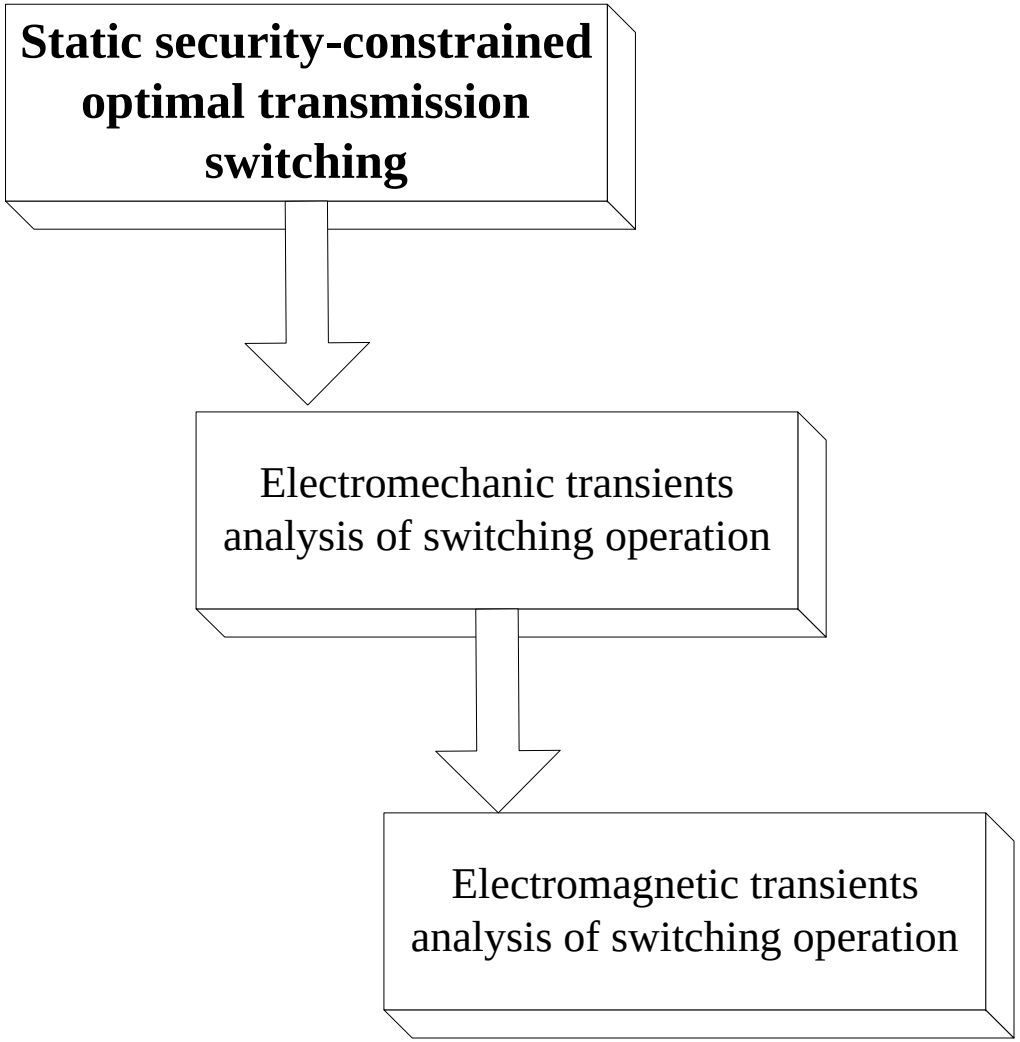
- **Economic benefits**
  - **Production cost savings through changing the network topology during operations**
  - **Transmission switching is a discrete control to alleviate congestions**

- **Security of transmission switching**
  - **The switching operation itself represents a step change in power systems that is, to some extent, similar to a contingency**
  - **The adverse impacts on power system operations by transmission switching should be prevented**

# Introduction and proposed problems

- **Power engineers use different models in different time scales for security evaluation**

- **Hierarchical structure**
- Static security
  - Algebraic equations
- Dynamic model
  - Ordinary differential equations or partial differential equations



# Introduction and proposed problems

- At a minimum, decision making for transmission switching should satisfy static security constraints

- Mathematical formulation
  - Optimal transmission switching is a mixed integer linear (DC power flow) or nonlinear (AC power flow) problem
  - Branch and cuts
  - Mixed integer programming (MIP) may have multiple solutions. How could we reduce unnecessary switching operations when solving the optimization problem?

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# Static Security in multi-period transmission switching

- **Previous optimal transmission switching models**
- **The variables in different hours are only coupled by ramp limits**

$$Min \ \sum_i \sum_t F_i(P_{it})$$

Minimize the generation cost

$$s.t.$$

$$P_{i,min} \le P_{it} \le P_{i,max}$$

Generation capacity

$$P_{it} - P_{it-1} \le UR_i$$

Ramp up limits

$$P_{it-1} - P_{it} \le DR_i$$

Ramp down limits

$$\sum_{b \in Br(m)} f_{bt} + \sum_{i \in G(m)} P_{it} - L_{mt} = 0$$

Nodal power flow balance

$$\begin{bmatrix} U_t^o \\ f_{bt} = 0 \end{bmatrix} \vee \begin{bmatrix} U_t^1 \\ f_{bt} = B_{mn}(\theta_{mt} - \theta_{nt}) \\ -f_{b,max} \le f_{bt} \le f_{b,max} \end{bmatrix}$$

$$U_t^j \in \{TRUE, FALSE\}$$

Two disjunctions to represent the cases that the transmission line is on or off respectively

# Static Security in multi-period transmission switching

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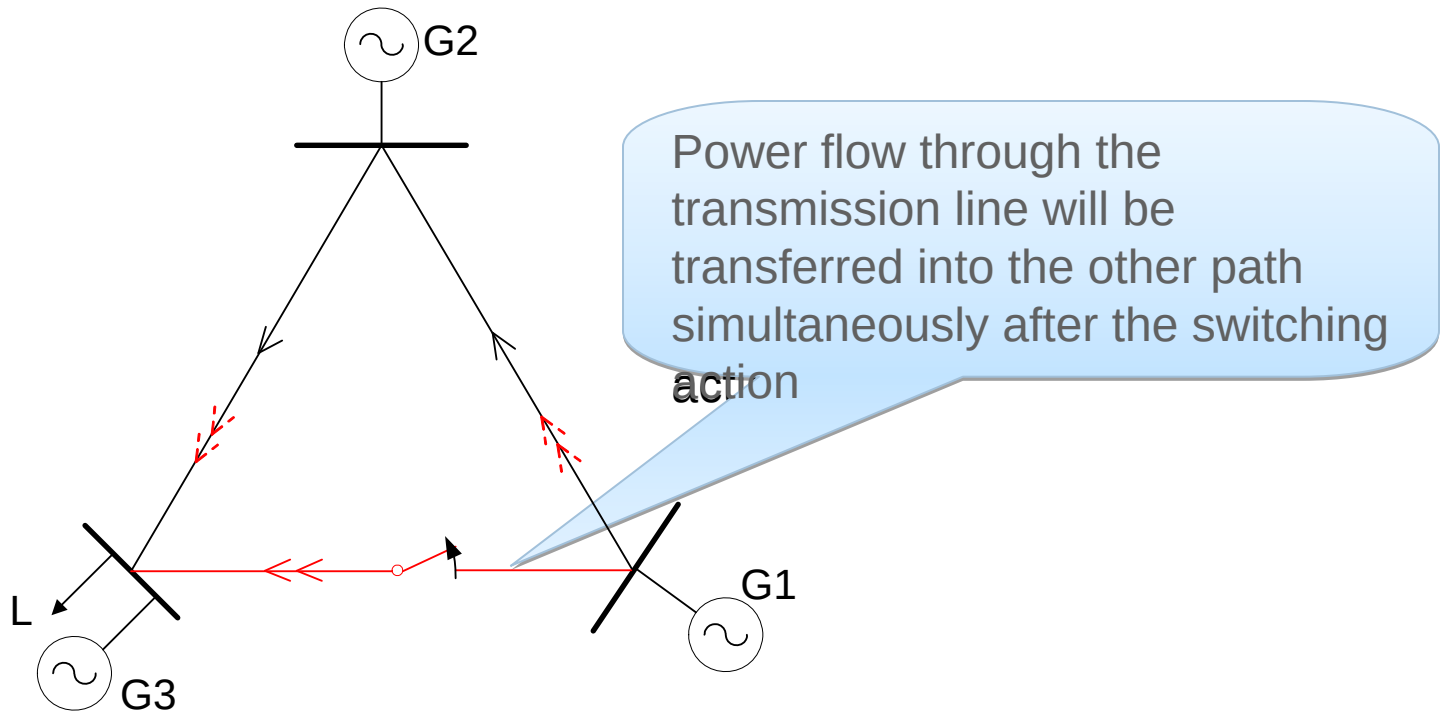
Two disjunctions to represent the cases that the transmission line is on or off respectively

# Static Security in multi-period transmission switching

- According to the formulations, the outputs of generating units at the current time only satisfy the power flow equations and line flow bounds under the current network topology.
- However, the switching action is very fast. All generators are considered to maintain approximately the same outputs due to their relatively slow dynamics.
- In comparison, the power flow that passes through the switched branches will be redistributed instantaneously after switching.

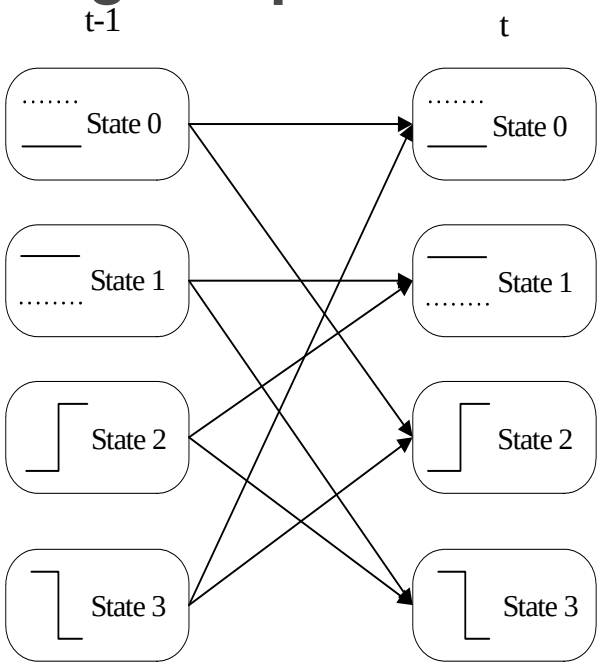
# Static Security in multi-period transmission switching

- **The instant redistribution of power flow during switching operations may violate normal or emergent rates of transmission lines**



# Static security in multi-period transmission switching

- Define four different actions in each time interval
- Action transition diagram
- Feasible transition diagram will be represented by logic expressions in the optimization model.




| Action Index | Switching actions | Feasible transition paths |
|---|---|---|
| 0 | Stay offline | To action 0 or action 2 |
| 1 | Stay online | To action 1 or action 3 |
| 2 | Change from offline to online | To action 1 or action 3 |
| 3 | Change from online to offline | To action 0 or action 2 |

# Static Security of multi-period transmission switching

- **Proposed new static security constrained optimal transmission switching model**

$$\sum_{b\in Br(m)} f_{bt_+} + \sum_{i\in G(m)} P_{it} - L_{mt} = 0$$
$$\sum_{b\in Br(m)} f_{bt_-} + \sum_{i\in G(m)} P_{it} - L_{mt} = 0$$

Two sets of nodal power flow balance before and after the switching action

$$\begin{bmatrix} U_{bt}^{o} \\ f_{bt_+} = f_{bt_-} = 0 \end{bmatrix} \vee \begin{bmatrix} U_{bt}^{1} \\ f_{bt_+} = B_{mn}(\theta_{mt_+} - \theta_{nt_+}) \\ f_{bt_-} = B_{mn}(\theta_{mt_-} - \theta_{nt_-}) \\ -f_{b,max} \le f_{bt_+} \le f_{b,max} \\ -f_{b,max} \le f_{bt_-} \le f_{b,max} \end{bmatrix}$$

$$\vee \begin{bmatrix} U_{bt}^{2} \\ f_{bt_+} = B_{mn}(\theta_{mt_+} - \theta_{nt_+}) \\ f_{bt_-} = 0 \\ -f_{b,max} \le f_{bt_+} \le f_{b,max} \end{bmatrix} \vee \begin{bmatrix} U_{bt}^{3} \\ f_{bt_+} = 0 \\ f_{bt_-} = B_{mn}(\theta_{mt_-} - \theta_{nt_-}) \\ -f_{b,max} \le f_{bt_-} \le f_{b,max} \end{bmatrix}$$

Four disjunctions to represent distinct switching actions in each time interval

$$\Omega(\boldsymbol{U}) = TRUE$$

Logic expressions to restrict feasible transition between adjacent periods

# Proposed transmission switching model with N-1 reliability criterion

$$x^* \begin{cases} x^0 \begin{cases} Min & f(x) \\ S.t. & A \cdot x \le b \end{cases} \\ g(x, y) \le 0 \\ g(x^c, y^c) \le 0 \\ \left| x - x^c \right| \le \Delta \end{cases}$$

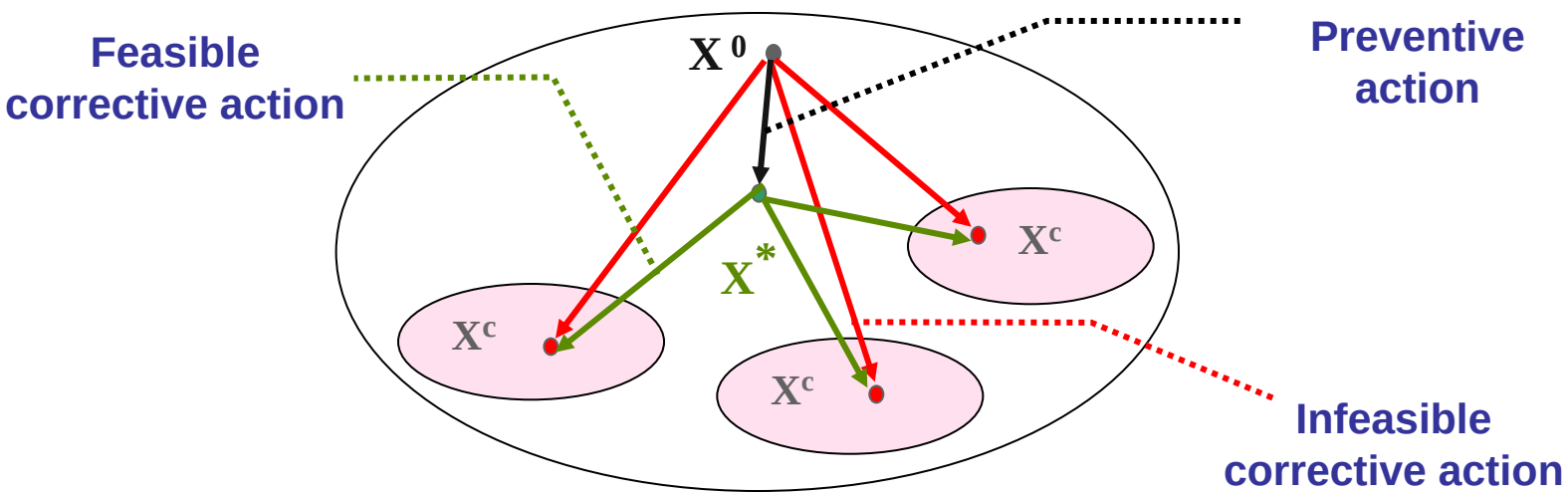
Objective

Generator constraints

Network constraints in normal state

Network constraints in each contingency

Transfer distance constraints (e.g. ramp rate limit)



# Solution of proposed model

- The disjunctive programming model can be solved in two different ways.
- The first is to use the branch-and-bound method, in which branching is implemented in term of logic conditions and propositions
- The second is to transform linear disjunctive programming equations to MIP-based equations.
- The logic expressions will be transformed into some constraints with pure integer variables.

# Case studies

- **6-bus System**

**Case 1: DCOPF without transmission switching**
**Case 2: Previous transmission switching model**
**Case 3: Proposed transmission switching model**

| Case | Line | Line Status and Action (0–24 hours) |
|---|---|---|
| 1 | 2-4 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| | 4-5 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 2 | 2-4 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 1 1 1 1 1 |
| | 4-5 | 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 |
| 3 | 2-4 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 **3** 0 0 **2** 1 1 1 1 1 |
| | 4-5 | 1 **3** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 **2** 1 1 **3** 0 0 0 0 0 |

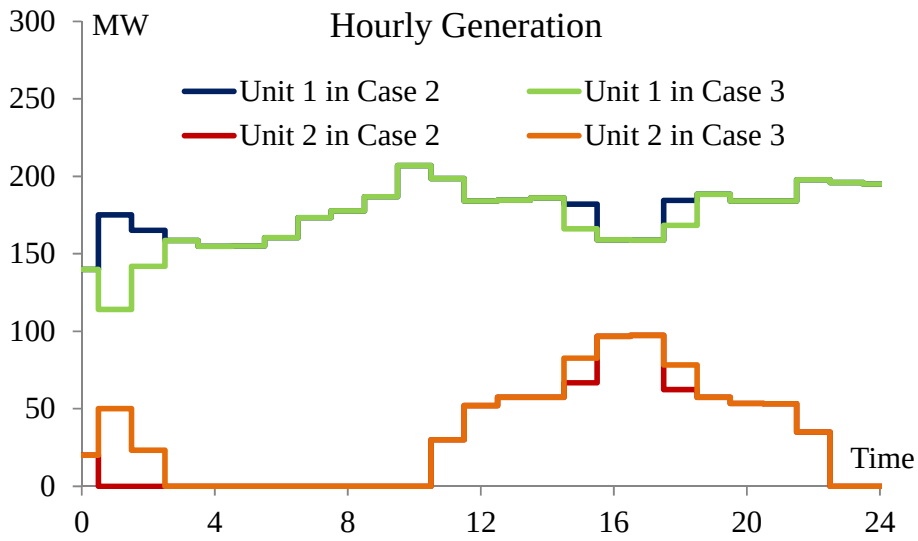
Switch from offline to online

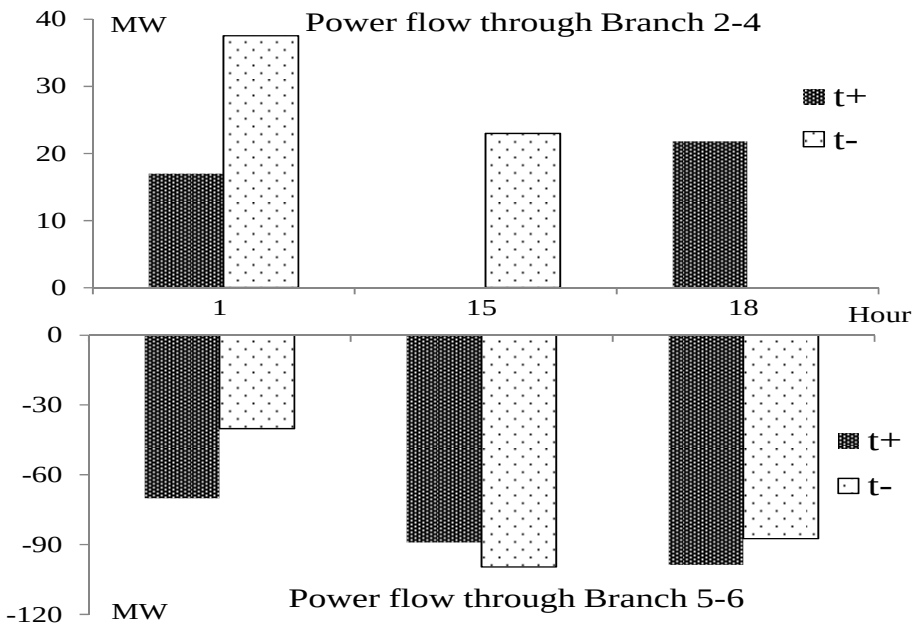
Switch from offline to online

# Case studies

- **6-bus System**

**The right figure shows the differences of generation dispatches based on different models**




**The left figure shows that power flows through branches before and after switching actions are different.**

# Case studies

- **RTS 96 System (2 hours problem)**

**Case 1: DCOPF without transmission switching**

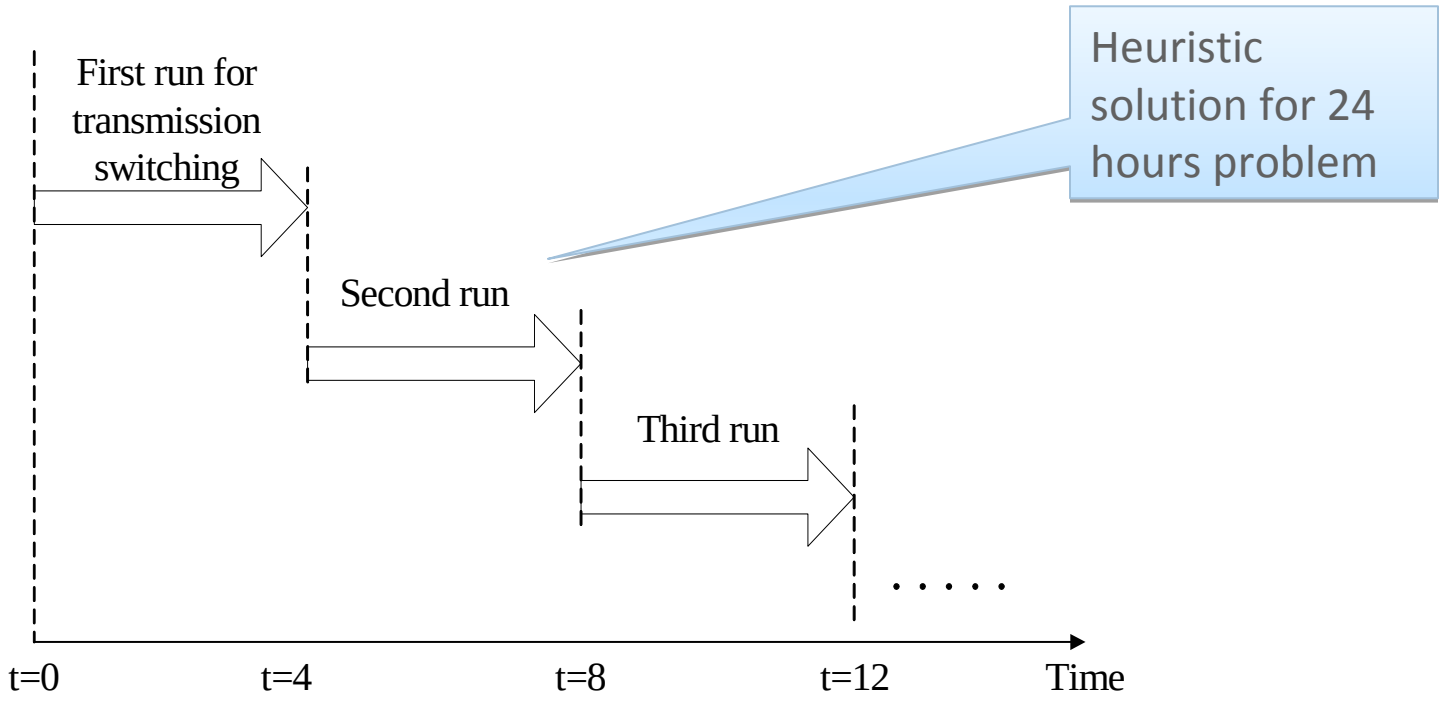
**Case 2: Previous transmission switching model**

**Case 3: Proposed transmission switching model**

| Without considering N-1 reliability<br>Switchable lines: 117 | | | | |
|---|---|---|---|---|
| **Case** | **Cost saving (%)** | **Simplex iterations in CPLEX** | **Branch-and-bound nodes in CPLEX** | **MIP gap (%)** |
| **1** | 0 | 222 | N/A | N/A |
| **2** | 9.66 | 4,282 k | 358 k | 0.88 |
| **3** | 4.65 | 1,893 k | 38 k | 0.04 |
| **Considering N-1 reliability<br>Switchable lines: 30** | | | | |
| **Case** | Cost saving (%) | Simplex iterations in CPLEX | Branch-and-bound nodes in CPLEX | MIP gap (%) |
| **1** | 0 | 40438 | N/A | N/A |
| **2** | 3.80 | 28,728 k | 10 k | 0.1 |
| **3** | 2.57 | 6,723 k | 890 | 0 |

# Case studies

- **RTS 96 System (24 hours)**




The solution based on the proposed transmission switching model is still 5.44% lower than the operating cost of DCOPF without transmission switching

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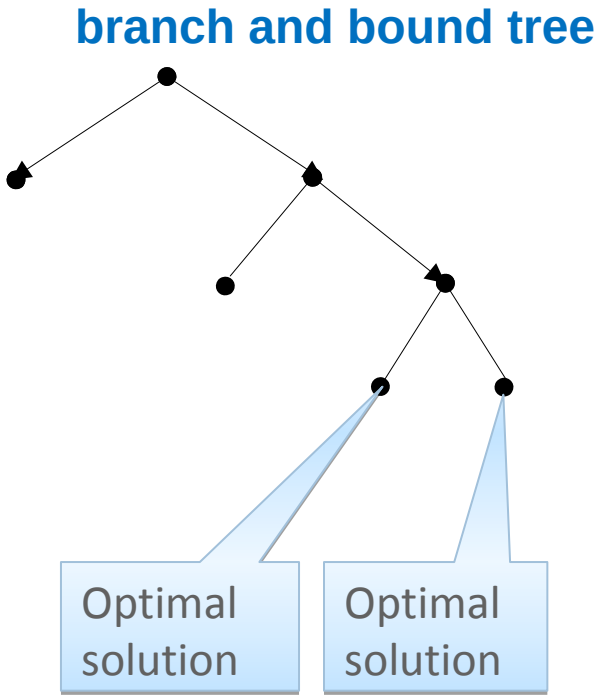
# Multiple solutions in multi-period transmission switching (on-going)

- MIP may lead to multiple integer solutions. Switching on or off some transmission branches may not impact generation dispatch.

- How could we prevent unnecessary switching decisions during optimization process?

- Introduce switching cost or use a bi-level model



# Multiple solution in multi-period transmission switching

- **Introduce switching cost**

$$Min \ \sum_i \sum_t \{F_i(P_{it}) + \begin{bmatrix} U_{bt}^2 \\ SC2 \end{bmatrix} + \begin{bmatrix} U_{bt}^3 \\ SC3 \end{bmatrix} + \begin{bmatrix} U_{bt}^0 \\ 0 \end{bmatrix} + \begin{bmatrix} U_{bt}^1 \\ 0 \end{bmatrix}\}$$

Minimize generation cost plus switching operation cost

$s.t.$

Typical constraints including ramping, power balance, etc.

$$\begin{bmatrix} U_{bt}^o \\ f_{bt_+} = f_{bt_-} = 0 \end{bmatrix} \vee \begin{bmatrix} U_{bt}^1 \\ f_{bt_+} = B_{mn}(\theta_{mt_+} - \theta_{nt_+}) \\ f_{bt_-} = B_{mn}(\theta_{mt_-} - \theta_{nt_-}) \\ -f_{b,max} \le f_{bt_+} \le f_{b,max} \\ -f_{b,max} \le f_{bt_-} \le f_{b,max} \end{bmatrix}$$

$$\vee \begin{bmatrix} U_{bt}^2 \\ f_{bt_+} = B_{mn}(\theta_{mt_+} - \theta_{nt_+}) \\ f_{bt_-} = 0 \\ -f_{b,max} \le f_{bt_+} \le f_{b,max} \end{bmatrix} \vee \begin{bmatrix} U_{bt}^3 \\ f_{bt_+} = 0 \\ f_{bt_-} = B_{mn}(\theta_{mt_-} - \theta_{nt_-}) \\ -f_{b,max} \le f_{bt_-} \le f_{b,max} \end{bmatrix}$$

# Multiple solution in multi-period transmission switching

- **Bi-level model**

$$Min \sum_i \sum_t F_i(P_{it})$$

Minimize generation cost

$s.t.$ Typical constraints including ramping, power balance, etc.

$$Min \sum_i \sum_t \left\{ \begin{bmatrix} U_{bt}^2 \\ 1 \end{bmatrix} + \begin{bmatrix} U_{bt}^3 \\ 1 \end{bmatrix} + \begin{bmatrix} U_{bt}^0 \\ 0 \end{bmatrix} + \begin{bmatrix} U_{bt}^1 \\ 0 \end{bmatrix} \right\}$$

Minimize the number of switching actions

$$\begin{bmatrix} U_{bt}^o \\ f_{bt_+} = f_{bt_-} = 0 \end{bmatrix} \vee \begin{bmatrix} U_{bt}^1 \\ f_{bt_+} = B_{mn}(\theta_{mt_+} - \theta_{nt_+}) \\ f_{bt_-} = B_{mn}(\theta_{mt_-} - \theta_{nt_-}) \\ -f_{b,max} \le f_{bt_+} \le f_{b,max} \\ -f_{b,max} \le f_{bt_-} \le f_{b,max} \end{bmatrix}$$

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# Summary and future work

- **We propose a new static, security-constrained, optimal transmission switching model that is based on disjunctive programming. The proposed model considers the power flow equations under different topologies before and after switching actions in each time interval.**

- **The numerical results show that the new model can still lead to considerable economic benefits by applying transmission switching.**

# Summary and future work

- **There is a need to develop appropriate contingency screening techniques to select critical contingencies while solving optimal transmission switching with the N-1 reliability criterion.**

- **Multiple solutions of transmission switching may lead to unnecessary switching decisions.**

- **On-going work includes the development of a pre-screening method to select a limited number of switchable line candidates, such that the number of integer variables in transmission switching problems will be reduced.**

# Thank You for Attention! Questions?

## Contacts:

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