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Modeling, Simulation, And Optimization for the 21st Century Electric Power Grid

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Transmission Switching in Power System Operations

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Outline

I. Introduction

II. A disjunctive programming model for static security in transmission switching

III. A prescreening method to accelerate the solution of transmission switching

IV. Anti-islanding in transmission switching

V. Summary and future work

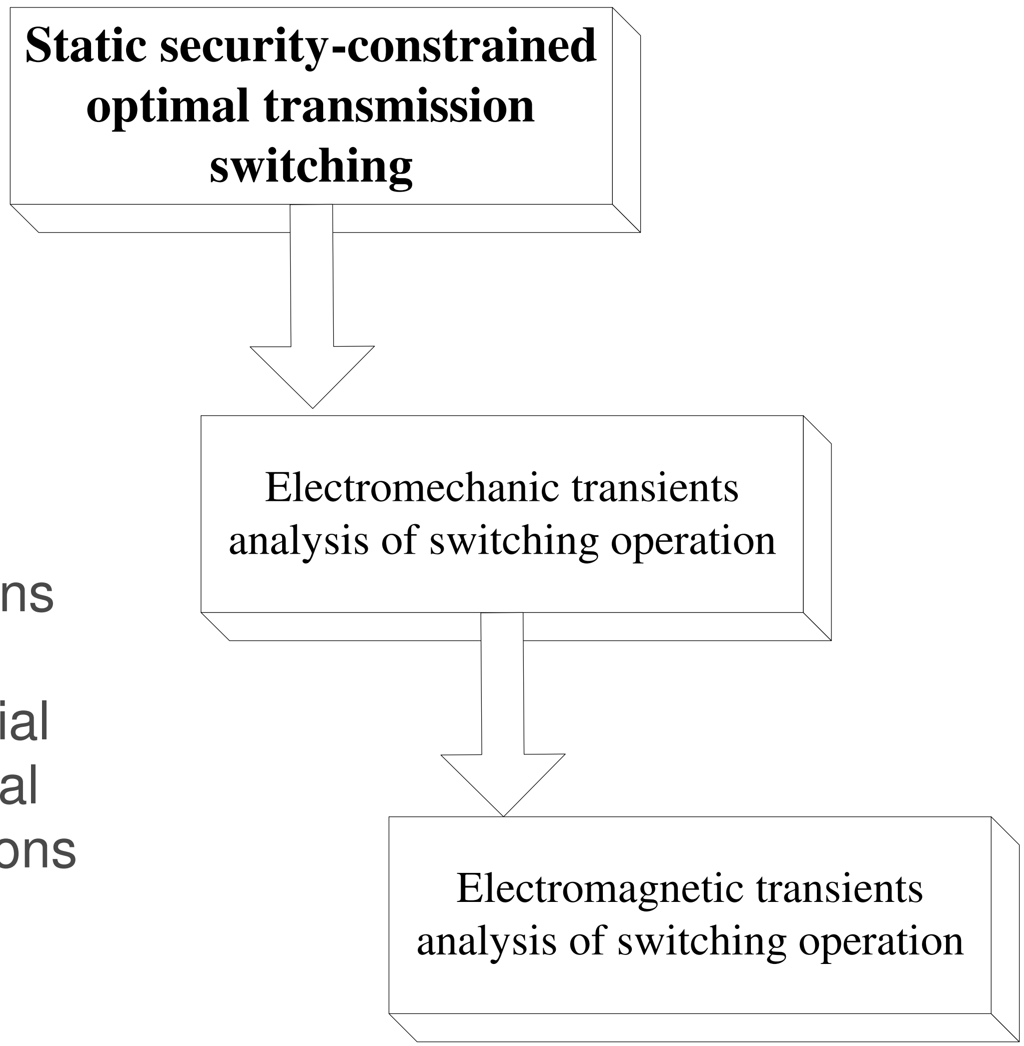
Introduction – Transmission switching

- **Economic benefits**
  - Production cost savings through changing the network topology during operations
  - Congestion alleviation
- **System security issues**
  - Step change in power systems that is, to some extent, similar to a contingency
  - Adverse impact of transmission switching to power system security
- **Increased computational burden**
  - Computationally intractable to find the optimal day-ahead production schedule with transmission switching

Introduction

- A variety of models in different time scales are used for security evaluation

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



Previous Model for Static Security Constrained Transmission Switching

- Previous optimal transmission switching models
- Variables in different hours 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

A Disjunctive Programming Model for Static Security Constrained Transmission Switching

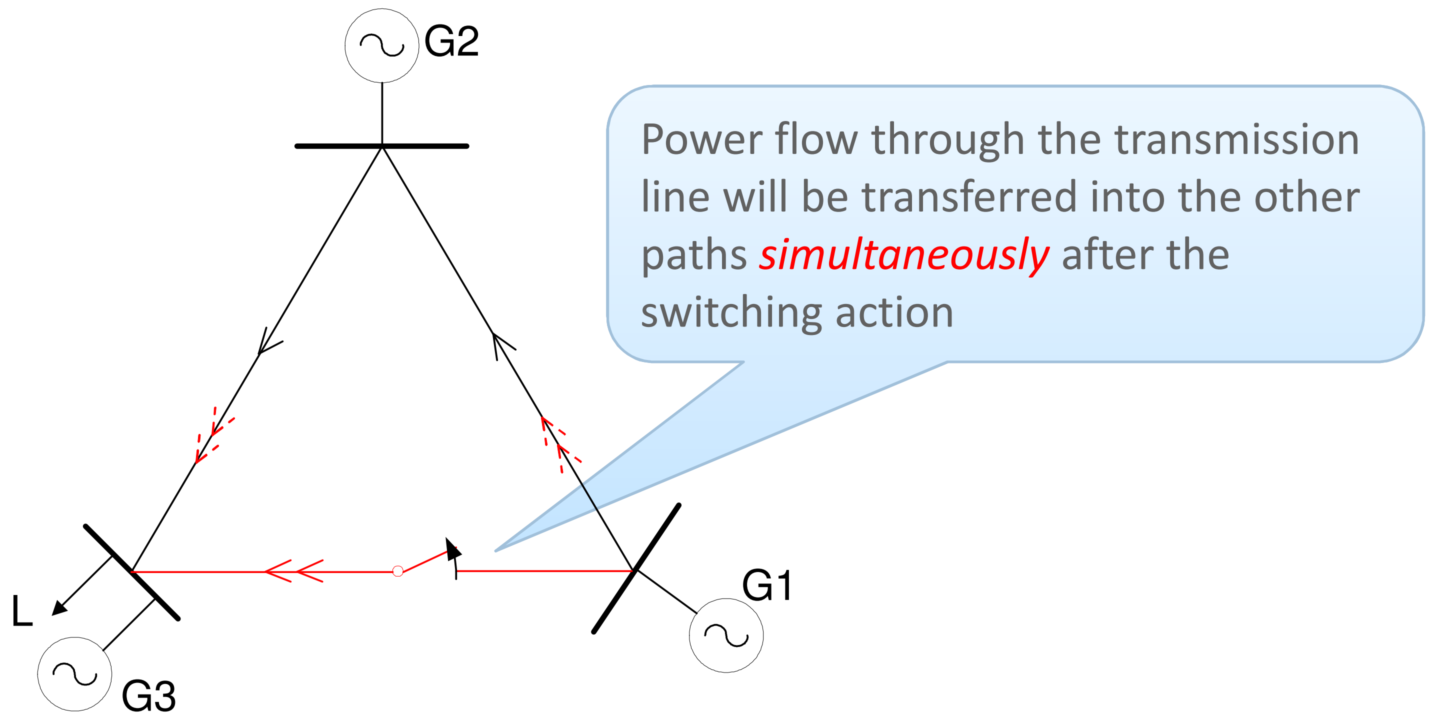
- According to the formulations, the current output of generating units only satisfies the power flow equations and line flow bounds under the current network topology.

- However, the switching action is instant. All generators are considered to maintain approximately the same output due to their relatively slow dynamics.

- In comparison, the power flow that passes through the switched branches will be redistributed instantaneously after switching.

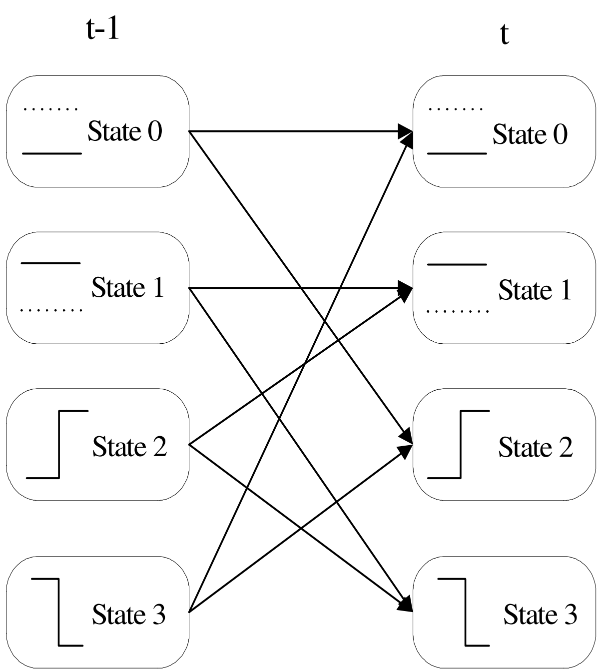
Static Security in Multi-period Transmission Switching

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



A Disjunctive Programming Model for Transmission Switching

- Define four different actions in each time interval
- Develop action transition diagram
- Represent feasible transition diagram 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

A Disjunctive Programming Model for 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

Solution of Proposed Model

- Two methods can be used to solve the disjunctive programming model.
  - The first is to use the branch-and-bound method, in which branching is implemented in terms of logic conditions and propositions.
  - The second is to transform linear disjunctive programming equations to mixed integer programming (MIP)-based equations. The logic expressions will be transformed into constraints with 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 0 0 1 1 1 1 1 1 1
	4-5	1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0
3	2-4	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 **3** 0 0 **2** 1 1 1 1 1 1
	4-5	1 **3** 0 0 0 0 0 0 0 0 0 0 0 0 0 **2** 1 1 **3** 0 0 0 0 0 0

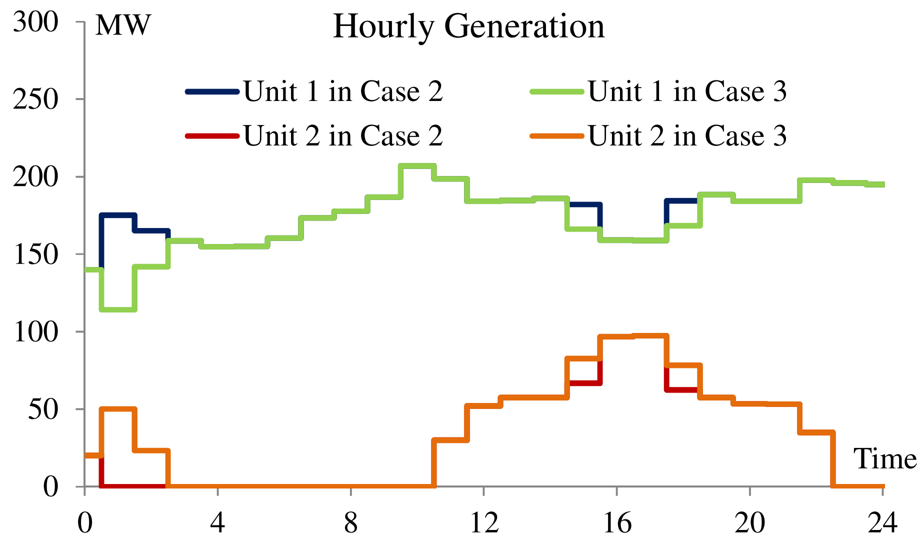
Switch from online to offline

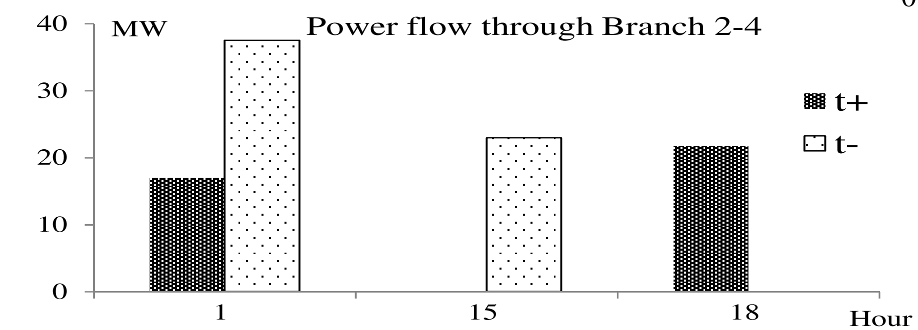
Switch from offline to online

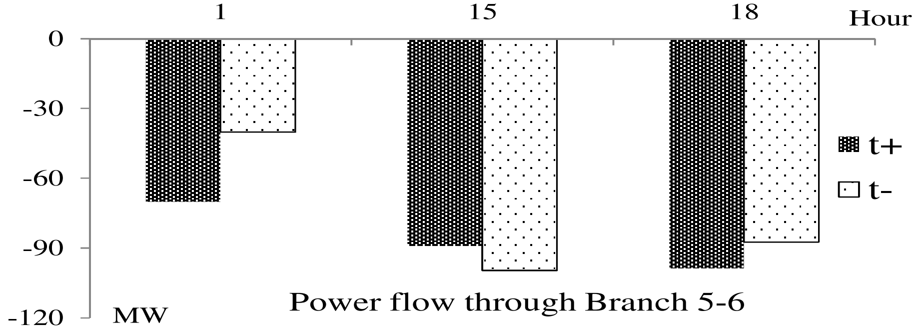
Testing Results

- **6-bus System**

The figure to the right shows the differences of generation dispatch based on the different models.







The figure to the left shows that the power flow through branches are different before and after switching actions.

The previous model is insufficient!

Testing results

- **RTS-96 System**

Case 1: DCOPF without transmission switching

Case 2: Previous transmission switching model

Case 3: Proposed transmission switching model

Without considering N-1 reliability 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 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

A Prescreening Method to Accelerate the Solution of Transmission Switching

- Computational complexity due to binary variables and big-M constraints.
- Huge branch-and-node tree and the memory issues.
- The motivation here is to use a prescreening method to select a few switchable line candidates, such that the number of integer variables in transmission switching problems will be reduced.

Prescreening Branches in Transmission Switching

- **Prescreening strategy A: Degree of alleviating congestion**
  We design an index to select switching candidates based on the degree of alleviated congestion by those lines

- **Prescreening strategy B: Estimation of switching benefit**
  We estimate the benefits of switching lines by a function of dual variables and power transfer distribution factors.

Dual price

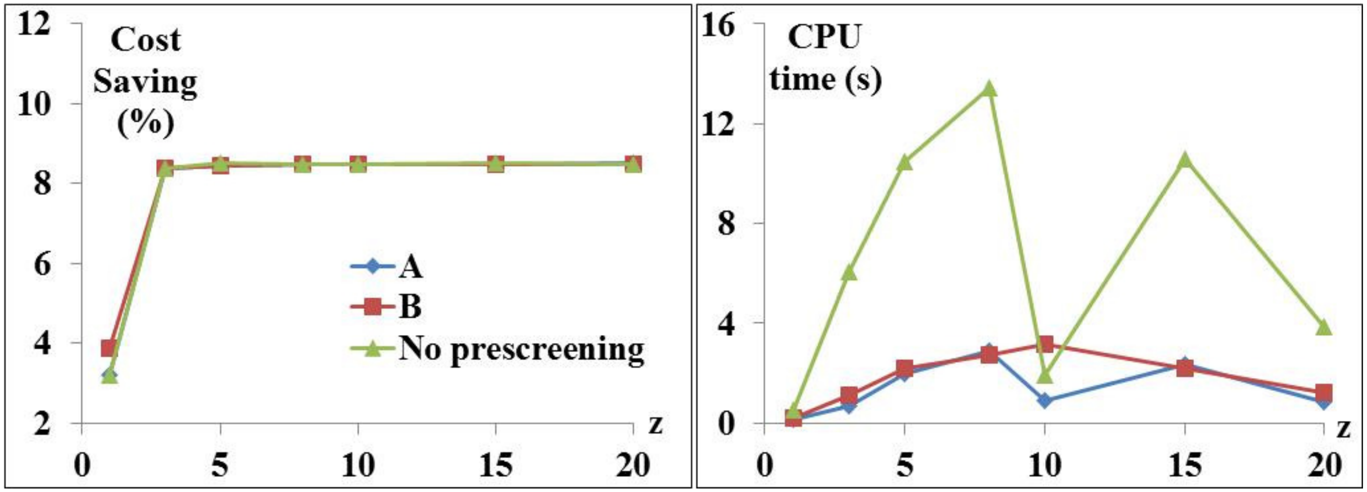
$$\Delta Pf_k = \frac{(\lambda_m - \lambda_n) \cdot f_k^0}{1 - PTDF_{k,mn}}$$

Power transfer distribution factor

We rank all elements from the highest to the lowest and select the switchable candidates with lower value. The lower value represents higher potential benefit when switching off the branch.

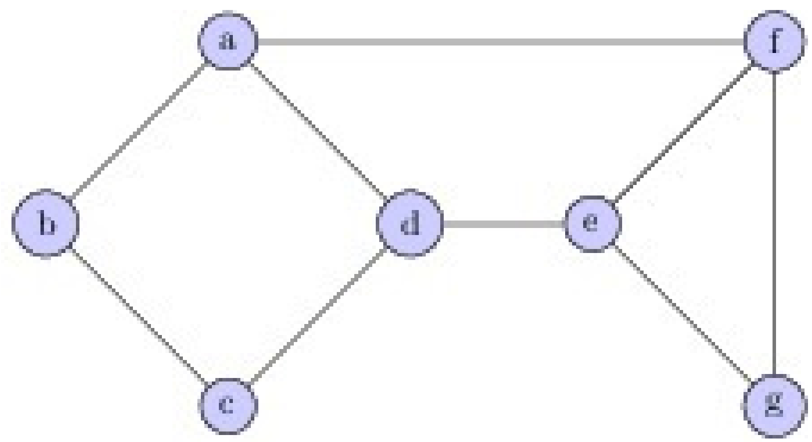
Prescreening Branches in Transmission Switching

- Less integer variables in MIP and less time to find a feasible solution in a given reasonable gap.
- Also, we can solve linear programming problems and prescreening problems successively rather than solving MIP problems to find a heuristic solution very quickly.



Maximum number of switching branches

Islanding and Transmission Switching



- Consider the above transmission network.
  - It may be profitable to switch the line connecting buses ***a*** and ***f*** as well as the line connecting ***d*** and ***e***.
  - But doing so would disconnect the transmission network, causing islands.

Islanding

- Islands typically occur after a line failure.
- Once islands are created, it is difficult to reconnect the system.
  - Synchronizing the system may result in equipment failure. .
- Any solution to the transmission switching problem that contains islands would be deemed unacceptable.
- However, formulations of the transmission switching problem found in the literature do not prohibit the existence of islands.
  - An exponential number of constraints is required to exclude all solutions that contain islands.

Formulating Anti-Islanding Constraints

- Let $z_k(t)$ be the binary variable representing if transmission line k is switched or not.
- Let F be a set of transmission lines such that if all lines in F be a set of transmission lines such that if all lines in F were turned off, the transmission network would be disconnected.
- The constraints

$$\sum_{f \in F} z_f(t) \geq 1 \quad \forall t \in T$$

ensures all lines in F are not removed.

- Let L be the set containing all such sets F
- The constraints

$$\sum_{f \in F} z_f(t) \geq 1 \quad \forall F \in L, \forall t \in T$$

ensures there are no islands in the network.

How Many Anti-Islanding Constraints?

- We generated a subset of anti-islanding constraints for the RTS-96 test case. There are almost ***500,000*** sets of transmission lines containing at most four lines that, when switched, create islands.
- Adding constraints for every set will make the problem impossible to solve. We need to find another way to enforce network connectivity.
- We enforced network connectivity by modifying the branching algorithm, using callback functions in the software.

Eliminating Islanding through Branching

- Transmission switching problems are typically modeled as mixed-integer linear programming problems and are solved by branch and bound.

- Rather than adding anti-islanding constraints to the problem formulation, we remove islands through the branching decision.

- If a transmission line is switched as a result of branching, the new network (without the switched line) is examined.

  * Additional variables are fixed if there are lines that would create islands if they are switched.

  # Additional constraints are added to tighten the problem formulation.

- Our algorithm runs in linear time (with respect to the size of the network).

Computational Results: Anti-islanding

- We test the impact of our anti-islanding procedure on a four-hour transmission switching (economic dispatch) problem.
- The procedure can also be extended to ensure that no islands will exist if at most one line fails.
- Incorporating the anti-islanding procedure can have a large impact on the overall solution times.

System	Time: Default Formulation (s)	Time: No Islands (s)	Time: No Islands After Failure (s)
RTS 96	524	204	32

This is a reduction of 94% in computation time!

Conclusion

- Static security of transmission switching needs to be considered. A prescreening method is necessary to reduce the computational requirement.

- Commercial solvers are very effective at solving integer programming problems. However, some reliability constraints can be efficiently modeled, and enforcing them can improve solution times.

- There are opportunities to improve solution times by adapting general integer programming techniques to exploit the structure of the transmission switching problem.

Questions?