MOBILIZING GRID FLEXIBILITY FOR RENEWABLES INTEGRATION THROUGH ENHANCED COMPUTATION

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New Zealand, July 27, 2017
33% RPS - Cumulative expected VERs build-out through 2020

Source: CAISO
Could you predict the energy production for this wind park either day-ahead or 5 hours in advance?

Each Day is a different color.
Negative Correlation with Load

Graph showing the correlation between wind power output (MW) and load (MW) over time (hour). The graph indicates a negative correlation, with wind power output and load values being inversely proportional.
The “Duck Curve”

![Graph showing typical spring day with Duck Curve]

- Actual 3-hour ramp: 10,892 MW on February 1, 2016
- Ramp need: ~13,000 MW in three hours
- Over generation risk
- Net Load 11,663 MW on May 15, 2016

New Challenges

The ISO needs a **flexible resource mix** that can react quickly to adjust electricity production to meet the sharp changes in electricity net demand.

- Ramping requirements
- Flexible resources
- Over generation mitigation
Integration of Renewable Generation

Flexibility

- Flexible Generation
- Flexible Transmission (Topology Control)
- Demand Response
- Storage
Flexible Transmission Network Control

- Topology Control
  - Switch on/off lines

- Flexible Line Rating
  - Include choosing proper line ratings as decisions

- FACTS
Topology Control

- Topology control has been studied to:
  - Relieve abnormal conditions\(^1\)
  - Reduce system loss\(^2\)
  - Reduce operating cost (Optimal Transmission Switching)\(^3\)

- Utilize existing assets required by normal operating conditions. No additional cost other than the wear of breakers is incurred.

Operating Cost Reduction

Original Optimal Cost: $20,000 (A=180MW, B=30MW, C=40MW)
Open Line A-B, Optimal Cost: $15,000 (A=200MW, B=50MW)
Topology Control in Practice

Topology Control in Practical Power System Operations

PJM Manual 03: Transmission Operations

PJM uses the following techniques to control contingency or system violations:

- ...
- switching transmission facilities in/out of service
- ...

ISO New England Operating Procedure No. 19 - Transmission Operations

In the operating procedure, transmission circuit switching is listed as one of EMERGENCY system actions.

Where it is clear that opening a transmission facility will alleviate a problem existing for a specific emergency situation, consideration will be given to opening such facility.

...
- Texas A&M Engineering Experiment Station (University of California Berkeley, Arizona State University, Lawrence Livermore National Laboratory, Tennessee Valley Authority, Telcordia, Oak Ridge National Laboratory)
- $4,910,031
- College Station, TX

Robust Adaptive Topology Control (RATC)

Historically, the electric grid was designed to be passive, causing electric power to flow along the path of least resistance. The Texas Engineering Experiment Station team will develop a new system that allows real-time, automated control over the transmission lines that make up the electric power grid. This new system would create a more robust, reliable electric grid, and reduce the risk of future blackouts, potentially saving billions of dollars a year.
In deterministic unit commitment, topology control can reduce the generation cost\cite{4} and mitigate post contingency violations.

In stochastic unit commitment, topology control as a recourse action may leverage the grid controllability and mitigate the variability of renewable generation.

Two-stage Stochastic Unit Commitment

- Objective: minimize the expected operating cost
- Decision variables:

1st Stage
- Commitment of Slow Generators

2nd Stage
- Commitment of Fast Generators, Dispatch of Generation & Flexible Transmission

Uncertainty
- Renewable Generation
Formulation: Constraints

- **System-wide constraints**
  - Market clearing
  - DC power flow
  - Line capacity
  - Number of lines that can be switched off

- **Generator constraints**
  - Generation capacity
  - Ramping up/down
  - Min up/down time
  - On/off transition
Topology Control Formulation

\[ \mathbf{B} \Theta \text{ Formulation} \]

\[ -M_{ij}(1 - r_{ij,s}) \leq F_{ij,s} - B_{ij} (\theta_{ij,s} - \theta_{ij,s}) \leq M_{ij}(1 - r_{ij,s}), \quad \forall i, j \in N_z, t \in T, s \in S \]

\[ -r_{ij,s} F_{ij}^{\text{max}} \leq F_{ij,s} \leq r_{ij,s} F_{ij}^{\text{max}}, \quad \forall i, j \in N_z, t \in T, s \in S \]

\[ \min_{p, v, z} c' p \]

subject to

\[ 1'(p - 1) = 0 \]

\[ p \leq p \leq \bar{p} \]

\[ f_{\tau}^M \leq \Psi_{\tau}^M(p - 1) + \Phi_{\tau}^M v_{\tau} \leq f_{\tau}^M \quad \forall \tau \]

\[ \tilde{f}_{\tau}^S z \leq \Psi_{\tau}^S(p - 1) + (\Phi_{\tau}^{SS} - I) v_{\tau} \leq \tilde{f}_{\tau}^S z \quad \forall \tau \]

\[ -M(1 - z) \leq v_{\tau} \leq M(1 - z), \quad \forall \tau \]

\[ z_\ell \in \{0, 1\}, \quad \forall \ell \]
Test Case

- IEEE 118 system

118 buses
186 lines
19 conventional generators
Wind Modeling

- Wind Generation Simulation

  - In our test, wind speed and wind power data of three locations in Wyoming are obtained from NREL Western Wind Resources Dataset.
  - 1000 wind generation scenarios are generated using the method described in [5].
  - To reduce the computational complexity, we adopt the scenario reduction technique introduced in [6].

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Wind Speed Scenario Generation

Data → Wind model → Outcome 1

Outcome 1

Outcome 2

... 

Outcome N
Power Curve
Test Results

- Solving the problem—Branch and Bound
  - 48,336 binary variables, 80,352 continuous variables.
  - The problem is solved on a laptop: 2.6GHz CPU, 12G RAM.
  - When the MIP gap tolerance is 5%, using the default setting of CPLEX the program does not terminate after 8 hours.
  - The automatic tuning tool of CPLEX does not work for this problem. Appropriate parameters are not found after over 8 hours.
Warm Starts

- Solving the problem—Branch and Bound
  - Using CPLEX MIP warm-start

- Stochastic Unit Commitment without Topology Control
- Optimal Transmission Switching for 1 Hour with the Heaviest Net Load

Solver
Warm Start Heuristic

- Solving the problem—Branch and Bound Using CPLEX MIP
  - Unit Commitment Decisions
    - The warm-start values for unit commitment decisions are obtained from solving a stochastic unit commitment problem with no topology control recourse.
    - In practice, system operators can use the commitment decisions of previous days with similar loading conditions to construct warm-up values for commitment decisions.
Warm Start Heuristic

- Solving the problem—Branch and Bound Using CPLEX MIP

- Topology Control Decisions
  - Topology control warm-up values are obtained from solving an optimal transmission switching problem for the highest load hour (no wind).
  - The warm-start values for switching decisions are the same for different hours and scenarios.
Test Results

- Start Switching Solutions
  - We conducted 9 numerical tests
  - “x” in “TCSUC-x” stands for the maximum number of lines that can be switched off. \( J = x \)

<table>
<thead>
<tr>
<th>Case</th>
<th>Start switching solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCSUC-1</td>
<td>132</td>
</tr>
<tr>
<td>TCSUC-2</td>
<td>132, 136</td>
</tr>
<tr>
<td>TCSUC-3</td>
<td>132, 136, 153</td>
</tr>
<tr>
<td>TCSUC-4</td>
<td>132, 136, 153, 162</td>
</tr>
<tr>
<td>TCSUC-5</td>
<td>132, 136, 151, 153, 163</td>
</tr>
<tr>
<td>TCSUC-6</td>
<td>132, 136, 148, 153, 161, 162</td>
</tr>
<tr>
<td>TCSUC-7</td>
<td>63, 132, 136, 148, 153, 161, 162</td>
</tr>
<tr>
<td>TCSUC-10</td>
<td>126, 132, 136, 146, 151, 153, 157, 165</td>
</tr>
</tbody>
</table>
Test Results

Improvement over SUC with no switching

Cost Reduction: percentage of saving
Time limit: 30min
Maximum value of optimality gap: 7.88%
Results Analysis

- Sources of cost savings
  - Reduction of production cost
  - Reduction of start-up cost
  - Reduction of no-load cost
  - Reduction of load shedding
Test Results

- Reduction of production cost
Test Results

- Reduction of start-up cost (STC6<STC8)
Test Results

- Reduction of no-load cost

![Bar chart showing reduction in no-load cost for different scenarios. The chart compares SUC and TCSUC-10 scenarios, with a decrease in no-load cost observed across all scenarios.]
Test Results

- Reduction of load shedding
Solving the Problem

- The optimality gap for each sub-problem is set to be 4% and the time limit for each sub-problem is set to be 6 minutes.
- The algorithm converges after 7 iterations. The estimated time for solving the problem in parallel is 42 minutes.
- The cost is reduced by 10.1% with topology control recourse.
Switching Results

Switching solution for different scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Switching solution of Hour 18 (Lines are off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40, 94, 109, 132, 136, 146, 151, 153, 157, 165</td>
</tr>
<tr>
<td>2</td>
<td>48, 88, 126, 132, 136, 146, 151, 153, 157, 165</td>
</tr>
<tr>
<td>3</td>
<td>116, 126, 132, 136, 153, 165</td>
</tr>
<tr>
<td>4</td>
<td>94, 96, 124, 132, 136, 146, 151, 153, 157, 165</td>
</tr>
<tr>
<td>5</td>
<td>39, 40, 63, 84, 122, 132, 136, 151, 153, 165</td>
</tr>
<tr>
<td>6</td>
<td>1, 83, 126, 132, 16, 146, 151, 153, 157, 165</td>
</tr>
<tr>
<td>7</td>
<td>45, 118, 126, 132, 136, 146, 151, 153, 157, 165</td>
</tr>
<tr>
<td>8</td>
<td>63, 96, 109, 124, 127, 132, 153, 163, 168</td>
</tr>
<tr>
<td>9</td>
<td>21, 42, 79, 132, 136, 146, 151, 153, 157, 162</td>
</tr>
<tr>
<td>10</td>
<td>37, 42, 59, 103, 132, 136, 146, 151, 153, 157</td>
</tr>
</tbody>
</table>
Evaluation

- Evaluate the robustness of the solution that was based on a reduced scenario set, under a richer uncertainty representation.
- The commitment of slow generators are fixed as the slow generators commitment solution of TCSUC-10.
- The line switching decisions are optimized for each of the simulation scenarios but constrained to the union of lines switched in TCSUC-10 for the 10 optimization scenarios.
- 1000 wind generation scenarios produced using Monte Carlo simulation are used in the evaluation.
- Both unit commitment and unit commitment with transmission switching are implemented to compare the cost.
In all 1000 tests, when there is transmission switching in the recourse, the total cost is less than when there is no transmission switching.

The average total cost is reduced by 12.9% with transmission switching in the recourse.

The simulation provides a lower bound of the cost reduction for the case where there is no restriction on the lines that can be switched.
Central European System Test Case

- Central European System
  - 7 Countries
  - 679 Buses
  - 1036 Lines
  - 667 Conventional Units:
    - 183 fast units and 484 slow units
  - 10 selected scenarios for renewable generation
- Renewable Generation: 1439 units
  - Wind
  - Solar
  - Hydro
Central European Test System
## Central European Test System

<table>
<thead>
<tr>
<th></th>
<th>AT</th>
<th>BE</th>
<th>CH</th>
<th>DE</th>
<th>FR</th>
<th>LX</th>
<th>NL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>36</td>
<td>24</td>
<td>47</td>
<td>228</td>
<td>317</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>Lines</td>
<td>42</td>
<td>23</td>
<td>76</td>
<td>312</td>
<td>518</td>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>Fast Units</td>
<td>11</td>
<td>25</td>
<td>4</td>
<td>94</td>
<td>22</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>Slow Units</td>
<td>25</td>
<td>45</td>
<td>5</td>
<td>254</td>
<td>108</td>
<td>1</td>
<td>46</td>
</tr>
<tr>
<td>Peak Load (MW)</td>
<td>8044.9</td>
<td>1.3e4</td>
<td>7328</td>
<td>65018</td>
<td>69043</td>
<td>839</td>
<td>13959</td>
</tr>
<tr>
<td>Max. Gen. Cap. (MW)</td>
<td>7656.8</td>
<td>1.7e4</td>
<td>4335.1</td>
<td>1.1e5</td>
<td>9.0e4</td>
<td>375</td>
<td>24690</td>
</tr>
</tbody>
</table>
Central European Test System

Central European System

Renewable Generation Scenarios

AT

BE

DE+LX

FR+CH

NL
Test Results

- Stochastic unit commitment with topology control recourse
  - With 10 scenarios, there are over 1 million continuous decision variables and over 300,000 binary decision variables.
  - The problem cannot be solved within reasonable run time just using branching and cut even without topology control.
  - For single scenario deterministic unit commitment problem when the switching decision is relaxed as a continuous variable, the cost saving for the entire system is within 5%.
  - A good warm start solution is required for tuning Progressive Hedging.
Proposed Method

- Decompose the system into 5 control areas.
- Power exchanges between areas are obtained through solving an optimal dispatching problem for the whole system.
- Each control area solves its own SUC/TCSUC.
Test Results

Proposed Method

5 Control Areas

Norway
Great Britain

DE+LX

FR+CH

BE

AT

Spain
Italy
Great Britain

DE+LX

FR+CH

NL

DE+LX

BE

AT

Norway
Denmark
Poland
Sweden
Czech Republic

Italy
Hungary
Slovenia
Czech Republic
Proposed Method

Commitment of Generators

Power exchange between zones

Warm Start
Heuristic for Zonal Decomposition

Proposed Method

- Solve stochastic unit commitment for each control area.
- Each control area submit commitment decisions to the second step.
- The solution to the first step can serve as warm starts for the third step.
- Total amount of power exchange with other control areas are penalized.
Heuristic for Zonal Decomposition

- Proposed Method

- Solve stochastic economic dispatch for the entire system to get the power exchange between control areas.

- Commitment of generators are fixed.

- Power exchange between control areas are sent to each area in step 3.
Heuristic for Zonal Decomposition

- Proposed Method

- Solve SUC/TCSUC for each control area.
- The power exchange between control areas is given by the previous step.
- If we combine the solution of each control area, we get a feasible solution to SUC/TCSUC of the entire system.
## TCSUC vs. SUC: Cost Savings

<table>
<thead>
<tr>
<th></th>
<th>SUC (MEUR)</th>
<th>TCSUC (MEUR)</th>
<th>Cost Saving (MEUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>7.0057</td>
<td>6.8244</td>
<td>0.1813</td>
</tr>
<tr>
<td>BE+LX</td>
<td>6.2083</td>
<td>6.2083</td>
<td>0.00</td>
</tr>
<tr>
<td>DE</td>
<td>14.2089</td>
<td>14.0540</td>
<td>0.1549</td>
</tr>
<tr>
<td>FR+CH</td>
<td>17.3961</td>
<td>16.0753</td>
<td>1.3478</td>
</tr>
<tr>
<td>NL</td>
<td>10.5475</td>
<td>10.3793</td>
<td>0.1682</td>
</tr>
<tr>
<td>Total</td>
<td>55.3665</td>
<td>53.5141</td>
<td>1.8521</td>
</tr>
</tbody>
</table>

**To solve TCSUC within reasonable time, switching decision for DE+LX and FR+CH are restricted on a preselected set.**
Test Results

- TCSUC vs. SUC: Result Analysis
  - Zone FR+CH

Cost Comparison of Slow Units

<table>
<thead>
<tr>
<th>Category</th>
<th>SUC</th>
<th>TCSUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-Up Cost of Slow Units</td>
<td>0.963</td>
<td></td>
</tr>
<tr>
<td>No-Load Cost of Slow Units</td>
<td>0.995</td>
<td></td>
</tr>
<tr>
<td>Expected Fuel Cost of Slow Units</td>
<td>0.926</td>
<td></td>
</tr>
<tr>
<td>Expected Generation of Slow Units</td>
<td>1.001</td>
<td></td>
</tr>
<tr>
<td>Expected Cost of Slow Units</td>
<td>0.935</td>
<td></td>
</tr>
<tr>
<td>Average Fuel Cost of Slow Units</td>
<td>0.926</td>
<td></td>
</tr>
</tbody>
</table>
Test Results

- TCSUC vs. SUC: Result Analysis
  - Zone FR+CH
Flexible Line Rating

- Thermal Limits

Sag:

Mechanical Structure:
Line Rating Standards

- IEEE Std 738 -2012
- CIGRE Technical Brochure 601, 2014

- Current flowing in the conductor
- Solar radiation

- Convection heat loss
- Radiation heat loss

- Heat Balance Equation (HBE)

\[ q_c + q_r + mC_p \frac{dT}{dt} = q_s + I^2R(T) \]

- Ambient conditions:
  - Temperature
  - Wind speed and direction
  - Solar radiation
Static Line Rating Adjustment

- Line Ratings in Practical Power System Operations
  - PJM Manual 03: Transmission Operations
    - Three sets of thermal limits:
      - normal limit
      - emergency limit
      - load dump limit
    - Eight ambient temperatures are used with a set for the night period and a set for the day period; thus, 16 sets of three ratings are provided for each monitored facility.

All Transmission Owners’ and the PJM RTO’s security analysis programs must be able to handle all 16 sets and allow operating personnel to select the appropriate rating set to be used for system operation.
Four thermal capacity ratings:
- normal (24 hr)
- long time emergency (12 hr summer; 4 hr winter)
- short time emergency (15 min)
- drastic action limit (5 min)

For any facility that has two or more sets of thermal limits applicable (due to multiple Transmission Owners, for example), the most conservative thermal limits will be used.

Weather sensitive transmission facility ratings
Flexible Line Rating

- Static Line Ratings
  - Steady State HBE

\[ q_c + q_r + 0 = q_s + I^2 R(T) \]

- CIGRE Technical Brochure 299: Select Parameters
- Sensitivity of the ampacity w.r.t. different meteorological conditions*

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Flexible Line Rating

- Dynamic Line Ratings

Dynamic line ratings adapts the \textit{prevailing weather conditions}, \textit{real-time conductor temperatures} and \textit{actual loading} of transmission lines.

- Dynamic Line Rating in Practical Power System Operations
  - United States: Oncor, ERCOT’s security constrained economic dispatch model.
  - Europe: Currently only used for information, alarms to dispatchers and others.
Dynamic Line Ratings

- Dynamic Line Rating in Research
  - Davis, 1977: First proposed dynamic line ratings (DLR)
  - Foss, 1990: Impacts of DLR on system security
  - Michiorri, 2015; Fan, 2016: Probabilistic forecast of DLR
  - Nick, 2016: HBE in unit commitment; select representative scenarios of weather conditions
  - Tschampion, 2016: DLR in N-1 secure dispatch optimization
  - Cheung, 2016: DLR in security constrained economic dispatch
Flexible Line Rating

- **Motivation**
  - Lack of measurement/forecast of meteorological conditions in day-ahead operations.
  - HBE: thermal inertia of

\[
q_c + q_r + mC_p \frac{dT}{dt} = q_s + I^2 R(T)
\]
Flexible Line Rating

Formulation

Line Status Variables:

\[ s_{ij,t,sc}^0 : \text{1 if line } ij \text{ is switched off in scenario } sc \text{ at time } t \]

\[ s_{ij,t,sc}^1 : \text{1 if line } ij \text{ adopts normal rating in scenario } sc \text{ at time } t \]

\[ s_{ij,t,sc}^2 : \text{1 if line } ij \text{ adopts high rating in scenario } sc \text{ at time } t \]

\[ s_{ij,t,sc}^0 + s_{ij,t,sc}^1 + s_{ij,t,sc}^2 = 1, \forall ij, t, sc \]
Flexible Line Rating Formulation

1) line flow constraints:

\[-M(s_{ij,t,sc}^1 + s_{ij,t,sc}^2) \leq e_{ij,t,sc} - B_{ij}(\theta_{i,t,sc} - \theta_{j,t,sc}) \leq M(s_{ij,t,sc}^1 + s_{ij,t,sc}^2)\]

2) line flow limit constraints:

\[-r_{ij,normal} s_{ij,t,sc}^1 - r_{ij,high} s_{ij,t,sc}^2 \leq e_{ij,t,sc} \leq r_{ij,normal} s_{ij,t,sc}^1 + r_{ij,high} s_{ij,t,sc}^2\]

3) maximum time allowed to adopt high rating

\[
\sum_{t=t_0}^{t_0+u_{ij}+1} s_{ij,t,sc}^2 \leq u_{ij}
\]

4) minimum time allowed to cool down:

\[
\sum_{t=t_0}^{t_0+d_{ij}+1} (s_{ij,t,sc}^1 + s_{ij,t,sc}^0) \geq d_{ij}(s_{ij,t_0,sc}^2 - s_{ij,t_0-1,sc}^2)
\]
With flexible line rating (including switching), the cost of stochastic unit commitment can be reduced by 19%.
IEEE 118 System Test Results

- Results Analysis

Cost Comparison of Slow Units

<table>
<thead>
<tr>
<th>Category</th>
<th>SUC</th>
<th>FLRSUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-Up Cost of Slow Units</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>No-Load Cost of Slow Units</td>
<td>0.915</td>
<td></td>
</tr>
<tr>
<td>Expected Fuel Cost of Slow Units</td>
<td>0.939</td>
<td></td>
</tr>
<tr>
<td>Expected Generation of Slow Units</td>
<td>0.962</td>
<td></td>
</tr>
<tr>
<td>Expected Cost of Slow Units</td>
<td>0.938</td>
<td></td>
</tr>
<tr>
<td>Average Fuel Cost of Slow Units</td>
<td>0.976</td>
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</table>
IEEE 118 System Test Results

Results Analysis

Cost Comparison of Fast Units

<table>
<thead>
<tr>
<th>Category</th>
<th>SUC</th>
<th>FLRSUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Start-Up Cost of Fast Units</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>Expected No-Load Cost of Fast Units</td>
<td>0.81</td>
<td></td>
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<tr>
<td>Expected Fuel Cost of Fast Units</td>
<td>0.75</td>
<td>1.03</td>
</tr>
<tr>
<td>Expected Generation of Fast Units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected Cost of Fast Units</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>Average Fuel Cost of Fast Units</td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>
Model Complexity

- **TCSUC**
  - With 10 scenarios, there are around 1 million continuous decision variables and over 400,000 binary decision variables.
  - For a single scenario sub-problem, there are over 70,000 binary decision variables.
  - In the zone of FR+CH, with 10 scenarios, there are around 170,000 binary decision variables and over 500,000 continuous variables. The solution time for this zone is within 8hr.
Model Complexity

- **FLR**
  - With 10 scenarios, there are around 1 million continuous decision variables and over 900,000 binary decision variables.
  - For a single scenario sub-problem, there are over 120,000 binary decision variables.
  - In the zone of FR+CH, with 10 scenarios, there are around 450,000 binary decision variables and over 500,000 continuous variables. The solution time for this zone is around 18 hr.
Platform description

- Laptop: Intel i7 CPU (2.8GHz)+ 12 GB Memory
- Solver: CPLEX 12.5

Choosing Steepest-edge pricing as the algorithm for the pricing applied in the dual simplex algorithm for the linear relaxation problem at each node can significantly reduce the solution time caused by dual degeneracy.
Test Results

TCSUC vs. SUC: Result Analysis

We will examine the loading conditions, ramping capabilities, congestions of the two zones. We also define two other metrics to analyze the results.

- **NLR**
  
  \[ NLR_{\text{Up}}(t) = \max_{s \in S} \left( D_{s,t+1}^{\text{net}} \right) - \min_{s \in S} \left( D_{s,t}^{\text{net}} \right) \]
  
  \[ NLR_{\text{Down}}(t) = \max_{s \in S} \left( D_{s,t}^{\text{net}} \right) - \min_{s \in S} \left( D_{s,t+1}^{\text{net}} \right) \]
  
  \[ NLR(t) = \max \{ NLR_{\text{Down}}(t), NLR_{\text{Up}}(t) \}, \forall t \in T \]
  
  \[ NLR = \max_{t \in T} NLR(t) \]

- **CR**
  
  \[ CR_z = \frac{\sum_{s \in S} \sum_{t \in T} \sum_{i,j \in N_z} 1(|F_{ij,t,s} = F_{ij}^{\text{max}}|)}{(#T)(#M_z)} \]
## TCSUC vs. SUC: Result Analysis

<table>
<thead>
<tr>
<th></th>
<th>BE+LX</th>
<th>FR+CH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Max Cap. of Slow Generators</td>
<td>13899.6</td>
<td>84952</td>
</tr>
<tr>
<td>Total Max Cap. of Fast Generators</td>
<td>3086.5</td>
<td>9730</td>
</tr>
<tr>
<td>Total Slow Ramping Cap.</td>
<td>1424.4</td>
<td>10034.7</td>
</tr>
<tr>
<td>NLR</td>
<td>2381.4</td>
<td>12809.4</td>
</tr>
<tr>
<td>Max. Net Load</td>
<td>12451.3</td>
<td>77447.2</td>
</tr>
<tr>
<td>Min. Net Load</td>
<td>9682.8</td>
<td>50682.3</td>
</tr>
<tr>
<td>CR</td>
<td>0.1916</td>
<td>0.0254</td>
</tr>
</tbody>
</table>
### FLRSUC vs. SUC: Cost Savings

<table>
<thead>
<tr>
<th></th>
<th>SUC (MEUR)</th>
<th>FLRSUC (MEUR)</th>
<th>Cost Saving (MEUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>7.0057</td>
<td>6.7980</td>
<td>0.2077</td>
</tr>
<tr>
<td>BE+LX</td>
<td>6.2083</td>
<td>6.1850</td>
<td>0.0233</td>
</tr>
<tr>
<td>DE</td>
<td>14.2089</td>
<td>13.9496</td>
<td>0.2593</td>
</tr>
<tr>
<td>FR+CH</td>
<td>17.3961</td>
<td>15.5977</td>
<td>1.7984</td>
</tr>
<tr>
<td>NL</td>
<td>10.5475</td>
<td>10.3642</td>
<td>0.1833</td>
</tr>
<tr>
<td>Total</td>
<td>55.3665</td>
<td>52.8945</td>
<td>2.472</td>
</tr>
</tbody>
</table>
Test Results

- FLRSUC vs. SUC: Result Analysis
- Zone FR+CH
Test Results

- FLRSUC vs. SUC: Result Analysis
- Zone FR+CH
Test Results

- FLRSUC vs. SUC: Result Analysis
  - Zone FR+CH

![Cost Comparison of Slow Units](image-url)

- Start-Up Cost of Slow Units: SUC = 0.850, FLRSUC = 0.897
- No-Load Cost of Slow Units: SUC = 0.966, FLRSUC = 0.999
- Expected Fuel Cost of Slow Units: SUC = 0.894, FLRSUC = 0.898
- Expected Generation of Slow Units: SUC = 0.894, FLRSUC = 0.898
- Expected Cost of Slow Units: SUC = 0.894, FLRSUC = 0.898
- Average Fuel Cost of Slow Units: SUC = 0.894, FLRSUC = 0.898
Test Results

- FLRSUC vs. SUC: Result Analysis
- Zone FR+CH

Cost Comparison of Fast Units

<table>
<thead>
<tr>
<th></th>
<th>SUC</th>
<th>FLRSUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Start-Up Cost of Fast Units</td>
<td>1.08</td>
<td>0.79</td>
</tr>
<tr>
<td>Expected No-Load Cost of Fast Units</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Expected Fuel Cost of Fast Units</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Expected Generation of Fast Units</td>
<td>1.01</td>
<td>0.96</td>
</tr>
<tr>
<td>Expected Cost of Fast Units</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Average Fuel Cost of Fast Units</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Conclusion

- Topology control and flexible line rating can both reduce the operating cost
- Flexible transmission network control can mitigate the variability of renewable generations so that cheaper slow generators can commit in the first stage.
- Heuristics: PTDF formulation?
Questions?