Available Transfer Capability Computation

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## Current Status: ATC Methods

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<td>AC Power Flow Model, Thermal Limit + Voltage Limit</td>
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Example 1: 2-Area NEPA 330kV Grid
2-Area Base-Case Tie Flow

Notation
- Single transmission line contingency
- Green circle: No thermal limit (assumed 120% base flow) met
- Red circle: First thermal limit met

Tie Line Flow
- 4.64 MW
- Area 1 to Area 2

Diagram:
- Area 1 (21) to Area 2 (23)
Area 1 to Area 2 ATC Calculation

Increasing Generation

\[ \Delta P \text{ MW} \]

Area 1

\[ 21 \]

\[ 7-25 \]

\[ 0.32 \text{ MW} \]

FCITC

Area 2

\[ 23 \]

\[ 2-8 \]

Increasing Demand

\[ \Delta P \text{ MW} \]

\[ > 4.64 \text{ MW} \]

Area 1

Area 2

\[ 4.96 \text{ MW} \]

\[ FCTTC \]
Area 2 to Area 1 ATC Calculation

Increasing Demand

**ΔP MW**

Area 1

< 4.64 MW

Increasing Generation

**ΔP MW**

Area 2

Increased Demand

**0.1 MW**

Area 1

4.54 MW

Increased Generation

**0.1 MW**

Area 2
## Summary of 2-Area ATC Calculation

<table>
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<tr>
<th>Direction</th>
<th>Area 1 to Area 2</th>
<th>Area 2 to Area 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Critical Contingency</strong></td>
<td>Line 7-25 (Delta-Aladja)</td>
<td>Line 7-25 (Delta-Aladja)</td>
</tr>
<tr>
<td><strong>Thermal Limit Met</strong></td>
<td>Line 2-8 (Jebba G.S.-Jebba T.S.)</td>
<td>Line 5-24 (Alam-Aba)</td>
</tr>
<tr>
<td><strong>FCTTC</strong></td>
<td>4.96 MW</td>
<td>–4.54 MW</td>
</tr>
<tr>
<td><strong>FCITC</strong></td>
<td>0.32 MW</td>
<td>0.1 MW</td>
</tr>
</tbody>
</table>
Example 2: 4-Area NEPA 300kV Grid
4-Area Base-Case Tie Flows

Area 1

Area 4: 8.5 MW

Area 3: 8.24 MW

Area 2: 4.64 MW

16.6 MW

8.5 MW

8.24 MW

4.64 MW
Area 3 to Area 1 ATC calculation
(Example of Parallel Path Flows)

FCTTC = 9.1 + 8.65 = 17.75 MW

FCITC = 17.75 – (8.5 + 8.24) = 1.01 MW

Increased Demand 1.01 MW

Increased Generation 1.01 MW
Area 4 to Area 2 Simultaneous ATC with a Pre-existing Area 3 to Area 1 17.75 MW Transfer

\[
FCTTC = -16.99 - (-17.2) = 0.21 \text{ MW}
\]

\[
FCITC = 4.85 - 4.64 = 0.21 \text{ MW}
\]
## Optimization Technique to Calculate ATC

**Objective:**

\[
\max \sum_{i \in \text{area } A} \Delta P_i
\]

**sum of generation in sending area A**

**Subject to**

\[
\dot{x} = f(x, y)
\]

- system dynamic behavior

\[
0 = g(x, y)
\]

- power flow equations

\[
0 \leq P_i + \Delta P_i \leq P_i^{\max}
\]

- active power output

\[
-F^{\max} \leq F(x, y) \leq F^{\max}
\]

- thermal limit

\[
V^{\min} \leq V \leq V^{\max}
\]

- voltage profile

\[
EM(x, y) > 0
\]

- energy margin
Stability-Constrained ATC Calculation Method

1. Time Domain Simulation (ETMSP)
2. System trajectory
4. (EM = 0) ?
   - Yes: ATC
   - No: Energy Margin Sensitivity Analysis with BFGS Method
5. Generation Adjustment
Second-kick-based energy margin computation

- Simulation
  Perform time-domain simulation

- Trajectory
  Obtain system trajectory following a pre-specified disturbance sequence

- Potential energy
  Compute potential energy of first- and second-kick trajectories

- Energy margin
  Potential energy difference at the respective peaks of the first- and second-kick disturbances
Energy margin sensitivity computation

- Determine the search direction with the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method

\[
S^{(k)} = \begin{bmatrix}
S_1^{(k)} \\
\vdots \\
S_n^{(k)}
\end{bmatrix} = -D^{(k)} \begin{bmatrix}
\frac{\partial EM}{\partial P_{m,1}^{(k)}} \\
\vdots \\
\frac{\partial EM}{\partial P_{m,n}^{(k)}}
\end{bmatrix}
\]

*\(D\) is an approximation to the inverse of Hessian matrix.*
Generation adjustment

- Adjustment

\[
\begin{align*}
\begin{bmatrix}
\Delta P_{m,1} \\
\vdots \\
\Delta P_{m,n}
\end{bmatrix}
&= 
\begin{bmatrix}
\alpha_1^{(k)} \times \left( S_1^{(k)} \right)^{-1} \\
\vdots \\
\alpha_n^{(k)} \times \left( S_n^{(k)} \right)^{-1}
\end{bmatrix} 
\times EM = k_p \cdot 
\begin{bmatrix}
P_{m,1} \\
\vdots \\
P_{m,n}
\end{bmatrix}
\end{align*}
\]

- Update

\[
\begin{align*}
\begin{bmatrix}
P_{m,1}^{\text{new}} \\
\vdots \\
P_{m,n}^{\text{new}}
\end{bmatrix}
&= 
\begin{bmatrix}
P_{m,1}^{\text{old}} \\
\vdots \\
P_{m,n}^{\text{old}}
\end{bmatrix}
+ 
\begin{bmatrix}
\Delta P_{m,1} \\
\vdots \\
\Delta P_{m,n}
\end{bmatrix}
\end{align*}
\]
Example: 2-Area Test System

- Net power transferred from area A to area B in the base case = 453 MW
## Results of Stability-Constrained ATC Calculation Method

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Power Transfer (Area A→Area B) &amp; Energy Margin</th>
<th>Gen.</th>
<th>$P_{m,k}$ (MW)</th>
<th>$\frac{\partial EM}{\partial P_{m,k}}$</th>
<th>$S_k$</th>
<th>$\alpha_k$</th>
<th>$\Delta P_{m,k}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>453 MW</td>
<td>G1</td>
<td>666</td>
<td>1.9008</td>
<td>1.9008</td>
<td>0.5333</td>
<td>3.745</td>
</tr>
<tr>
<td></td>
<td>EM = 13.35</td>
<td>G2</td>
<td>754</td>
<td>1.4688</td>
<td>1.4688</td>
<td>0.4667</td>
<td>4.242</td>
</tr>
<tr>
<td>2</td>
<td>461 MW</td>
<td>G1</td>
<td>669.745</td>
<td>1.1483</td>
<td>1.1483</td>
<td>0.5161</td>
<td>4.935</td>
</tr>
<tr>
<td></td>
<td>EM = 10.98</td>
<td>G2</td>
<td>758.242</td>
<td>0.9503</td>
<td>0.9503</td>
<td>0.4838</td>
<td>5.59</td>
</tr>
<tr>
<td>3</td>
<td>471.6 MW</td>
<td>G1</td>
<td>674.68</td>
<td>0.4748</td>
<td>1.4562</td>
<td>0.3757</td>
<td>2.833</td>
</tr>
<tr>
<td></td>
<td>EM = 5.50</td>
<td>G2</td>
<td>763.832</td>
<td>0.0864</td>
<td>2.136</td>
<td>0.6242</td>
<td>3.208</td>
</tr>
<tr>
<td>4</td>
<td>477.6 MW</td>
<td>G1</td>
<td>677.51</td>
<td>$\text{System goes unstable with the 1}^{\text{st}} \text{ kick disturbance.}$</td>
<td></td>
<td></td>
<td>-1.417</td>
</tr>
<tr>
<td></td>
<td>EM = N/A</td>
<td>G2</td>
<td>767.04</td>
<td></td>
<td></td>
<td></td>
<td>-1.604</td>
</tr>
<tr>
<td>5</td>
<td>474.6 MW</td>
<td>G1</td>
<td>676.094</td>
<td>1.8204</td>
<td>1.8204</td>
<td>0.4809</td>
<td>0.587</td>
</tr>
<tr>
<td></td>
<td>EM = 2.22</td>
<td>G2</td>
<td>765.436</td>
<td>1.7345</td>
<td>1.7345</td>
<td>0.5191</td>
<td>0.665</td>
</tr>
<tr>
<td>6</td>
<td>475.8 MW</td>
<td>G1</td>
<td>676.681</td>
<td>2.4251</td>
<td>2.4251</td>
<td>0.5125</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>EM = 0.22</td>
<td>G2</td>
<td>766.101</td>
<td>2.0364</td>
<td>2.0364</td>
<td>0.4875</td>
<td>0.054</td>
</tr>
</tbody>
</table>
Conclusions

- ATC provides a reasonable and dependable indication of available transfer capabilities in electric power markets.
- ATC considers reasonable uncertainties in system conditions and provides operating flexibility for the secure operation of the interconnected network.
- The effects of simultaneous transfers and parallel path flows are addressed from a reliability viewpoint.
- Need for ATC calculation method to incorporate voltage, angle stability limits as well as thermal limits.
References

