Linear Electricity Spot Market Constraints for Managing Post-Separation Frequency Deviations

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Outline
- brief motivation for work
  - separation events
  - conceptual view of security management in a restructured electricity industry
- post-separation power system model
- derivation of linear constraint sets from model
- security management & electricity market interface
- illustrative example
- conclusions and further work
3. Linear Electricity Spot Market Constraints for Managing Post-Separation Frequency Deviations

4. Operation of Ancillary Service Markets for Large Amounts of Wind Energy

NEM Scope

NEM characteristics

Source: NEMMCO

~4000km

~2000km

14 Sept '03

QLD separation
Freq: 50.3Hz

Southern Island
Freq: > 49.85Hz (within standards)

(TAS not connected until Apr '06)

Source: NEMMCO

8 March '04

SA separation
Freq: 47.6Hz

Source: NEMMCO
NEM Scope

NEM characteristics

Source: NEMMCO

Jan 16 '07
15:03

3 islands

VIC Freq: 48.57 Hz
CBD blacked out

Source: NEMMCO

Jan 16 '07
15:45

=> 2 islands

commence load restoration

Source: NEMMCO
Security & Commercial Concept

- unreachable or unacceptably outcomes
- uncertainty increases
- emergency control
- suboptimal but feasible
- economically efficient set of future states ("optimal")
- management of post-separation events often ends up in the feasible or emergency control regions
- can this be avoided?
- time

Security & Market Operation

- conflicting objectives between system operations & market participants
- power system operations concerned with
  - keeping core system intact (has cost implications)
  - Identifying & preventing rare events (potentially ‘high impact’)
  - uncertain physical outcomes => uncertain control actions
- market & industry participants
  - profit maximisation => push system to boundary
  - commercial transactions can’t proceed if system fails
  - consistent & objective decision-making framework reduces uncertainty
- security concept:
  - system operators compute and apply a secure envelope
  - secure envelope is based on objective criteria: system standards
- can the security space for managing post-separation frequency deviations be defined in this way?
Basic Definitions: Consider an under-frequency island

- Separation event
- Steady state frequency deviation
- Initial rate of change
- Commence restoration (or sooner)
- Maximum frequency deviation

Post-Separation Dynamic Power System Model

- Low-order frequency response model for each island (deviations):

\[
\begin{bmatrix}
\dot{f}_i(t) \\
p_{i1}(t) \\
\vdots \\
p_{iN}(t)
\end{bmatrix}
= \begin{bmatrix}
\delta_i \\
\gamma_{i1} & \tau_{i1} & \ddots & 0 \\
\vdots & \ddots & \ddots & \vdots \\
\gamma_{iN} & 0 & \cdots & \tau_{iN}
\end{bmatrix}
\begin{bmatrix}
f_i(t) \\
p_{i1}(t) \\
\vdots \\
p_{iN}(t)
\end{bmatrix}
+ \begin{bmatrix}
-\sigma_i \\
0 \\
\vdots \\
0
\end{bmatrix}
p(t), \quad i \in \mathcal{I}
\]

\[
\delta_i = -\frac{D_i}{2H_i}; \quad \sigma_i = \frac{f_0}{2H_i S_0};
\gamma_{ij} = -\frac{S_0}{f_0 T_{ij} R_{ij}}; \quad \tau_{ij} = -\frac{1}{T_{ij}}
\]

\[
\dot{x}_i(t) = A_i x_i(t) + b_i p(t)
\]

\[
y_{ik}(t) = e_{ik}^T x_i(t)
\]

Standard LTI system for each possible island
Steady-State Frequency Deviations

- set derivatives to zero & solve

\[ f_i(\infty) = y_i(\infty) = -e_i^T(A_i)^{-1}b_i \Delta p \]
\[ \triangleq K_i \Delta p \]

\[ p_{ij}(\infty) = y_{i,j+1}(\infty) = -e_{j+1}^T(A_i)^{-1}b_i \Delta p \]
\[ \triangleq K_{ij} \Delta p \]

Initial Rate of Change of Frequency

- put \( t = 0 \) & consider initial conditions

\[ \dot{x}_i(0) = A_i x_i(0) + b_i \Delta p \]

\[ \dot{f}_i(0) = -\sigma_i \Delta p \]
\[ \triangleq L_i \Delta p \]
Maximum Frequency Deviation (1)

- Use standard analytical expression

\[ x_i(t) = \exp(A_i t)x_i(0) + \int_0^t \exp(A_i(t-\tau))b_i \Delta p \%
= A_i^{-1}(\exp(A_i t) - I)b_i \Delta p \]

\[ \dot{x}_i(t) = e_i^T \dot{x}_i(t) \%
= e_i^T \exp(A_i t)(A_i x_i(0) + b_i \Delta p) \%
= e_i^T \exp(A_i t)b_i \Delta p \]

\[ \ddot{p}_{ij}(t) = e_{j+1}^T \dot{x}_i(t) \%
= e_{j+1}^T \exp(A_i t)b_i \Delta p \%
\]

Find \( t_{max} \) and \( t_j \) to get maximum deviations.

\[ f_i(t_{max}) = e_i^T A_i^{-1}(\exp(A_i t_{max}) - I)b_i \Delta p \%
= M_i \Delta p \%
\]

\[ p_{ij}(t_j) = e_{j+1}^T A_i^{-1}(\exp(A_i t_j) - I)b_i \Delta p \%
\triangleq M_{ij} \Delta p \%
\]

Find \( t = t_{max} \geq 0 \) to make zero.

Find \( t = t_j \geq 0 \) to make zero.

Solve for \( t \) to find extreme values of states.

Can also compute maximum output deviations.
Automatic Constraint Generation

- gen. offers
- demand forecasts, etc.
- system operator input
- other triggers
- data collection
- online linear post-separation freq. constraint generator
- database of technical parameters
- SCADA / EMS
- parameter or model estimation
- state measurements
- technical data
- status data
- updates

Spot Market + Post-Separation Security Constraints LP Optimization (1)

Minimize:

\[ J = \sum_{j \in \mathcal{G}} C_j g_j \]

Subject to:

\[ 0 \leq g_j \leq C_j^{\max}, \quad j \in \mathcal{G} \]

\[ |p_k| \leq p_k^{\max}, \quad k \in \mathcal{L} \]

\[ \sum_{j \in \mathcal{G}} g_j - N_i = \sum_{k \in \mathcal{T}_i} p_k - \sum_{k \in \mathcal{T}_i} p_k, \quad i \in \mathcal{I} \]

\[ |f_i(\infty)| \leq F_{s i}^{\max}, \quad i \in \mathcal{I} \]

\[ f_i(\infty) = -K_{ik} p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{T}_i \]

\[ f_i(\infty) = K_{ik} p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{F}_i \]

\[ 0 \leq g_j - K_{ij} p_k \leq G_{ij}^{\max}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{T}_i \]

\[ 0 \leq g_j + K_{ij} p_k \leq G_{ij}^{\max}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{F}_i \]
Spot Market + Post-Separation Security Constraints LP Optimization (2)

\[ |f_i(0)| \leq F^\text{max}, \quad i \in \mathcal{I} \]
\[ f_i(0) = -L_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{T}_i \]
\[ f_i(0) = L_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{F}_i \]

\[ |f_i(t^{\text{max}})| \leq F^\text{max}, \quad i \in \mathcal{I} \]
\[ f_i(t^{\text{max}}) = -M_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{T}_i \]
\[ f_i(t^{\text{max}}) = M_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{F}_i \]

\[ 0 \leq g_j - M_{ij} p_k \leq G_j^{\text{max}}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{T}_i \]
\[ 0 \leq g_j + M_{ij} p_k \leq G_j^{\text{max}}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{F}_i \]

Simple example: hypothetical scenario

L1 outage becomes credible
=> convey to system operator

L1 + L2 outage will lead to separation & weather conditions increase the likelihood of this occurring

system operator decision: use tool to construct & invoke post-separation frequency constraints?

post-contingency frequency standard: max freq dev: 0.3 Hz

\[ F_1 + F_2 \leq 200 \text{MW} \]
Simple example: **without** PSF constraints

<table>
<thead>
<tr>
<th>Gen</th>
<th>MW</th>
<th>Gmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>G12</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>G13</td>
<td>250</td>
<td>250</td>
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<tr>
<td>G14</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>G15</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Potential separation zone 1

- 550 MW
- $14/MWh
- Gens: G11, G12, ...

Potential separation zone 2

- 200 MW
- $15.50/MWh

680 MW
- Gens: G21, G22, ...

Post-separation outcome in zone 1 **without** PSF constraints

- Dispatch Cost: $14,950

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Simple example: post-separation outcome in zone 1 **without** PSF constraints

- Zone 1 - Frequency Deviation
- Zone 1 - Generator G11
- Zone 1, Generator G12
- Zone 1, Generator G13

- violated post-contingency frequency standards
Simple example: post-separation outcome in zone 2 without PSF constraints

violated post-contingency frequency standards

Some generators exceed limits

Simple example: with PSF constraints

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<tr>
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<td>100</td>
</tr>
<tr>
<td>G12</td>
<td>80.00</td>
<td>80</td>
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<tr>
<td>G13</td>
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<td>250</td>
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<td>29.40</td>
<td>230</td>
</tr>
<tr>
<td>G15</td>
<td>0</td>
<td>90</td>
</tr>
</tbody>
</table>

potential separation zone 1

flow backed-off & increased dispatch costs

550MW $13/MWh Gens: G11, G12, ...

potential separation zone 2

$16.50/MWh

680MW Gens: G21, G22, ...

out-of merit dispatch: ensures G14 >= Gmin (0MW)

Dispatch Cost: $15,310.16

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<th>Gen</th>
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<tr>
<td>G21</td>
<td>290.62</td>
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</tr>
<tr>
<td>G22</td>
<td>115.35</td>
<td>120</td>
</tr>
<tr>
<td>G23</td>
<td>190.52</td>
<td>200</td>
</tr>
<tr>
<td>G24</td>
<td>22.28</td>
<td>100</td>
</tr>
</tbody>
</table>

reduced generation: head-room for responding to separation event
Simple example: post-separation outcome in zone 1 with PSF constraints

post-contingency frequency is OK: freq dev < 0.3

generators within limits

Simple example: post-separation outcome in zone 2 with PSF constraints

post-contingency frequency is OK: freq dev ≤ 0.3
Variation – change in freq standards

- say the post-contingency frequency standard is modified to be:
  - maximum post-contingency frequency excursion ≤ 0.3 Hz; and
  - steady-state frequency deviations within 0.2 Hz
- Invoke 2 sets of post-separation frequency constraints:
  - one set to ensure max frequency deviation is ≤ 0.3 Hz; and
  - one set to ensure steady-state frequency deviations within 0.2 Hz

Simple example: with alternative PSF constraints

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<td>G15</td>
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</thead>
<tbody>
<tr>
<td>G21</td>
<td>293.62</td>
<td>300</td>
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<tr>
<td>G22</td>
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<tr>
<td>G23</td>
<td>193.55</td>
<td>200</td>
</tr>
<tr>
<td>G24</td>
<td>34.33</td>
<td>100</td>
</tr>
</tbody>
</table>

Dispatch Cost: $15,345.25

Flow backed-off even more & dispatch costs a bit higher

Slight variation to dispatch pattern

Similar to previously – gens backed off (not as much)
Simple example: post-separation outcome in zone 1 \textbf{with} alternative PSF constraints

post-contingency frequency OK

Simple example: post-separation outcome in zone 2 \textbf{with} alternative PSF constraints

post-contingency frequency is OK – deviations hit - 0.2Hz

generators within limits
Conclusions

- separation events are rare but are high impact therefore warrants investigation into mitigation
- important to have a consistent & well-defined interface between security processes & electricity market that:
  - enables system operators to protect the core system
  - can still enable market to proceed
- shown a simple way of linking the following:
  - dynamic power system model
  - post-contingency frequency standards
  - security envelope & system operator decision-making
  - interface to electricity market
- while the process may only be used infrequently, it could prevent high-costs of a post-separation frequency collapse
- more research to be done though!


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