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

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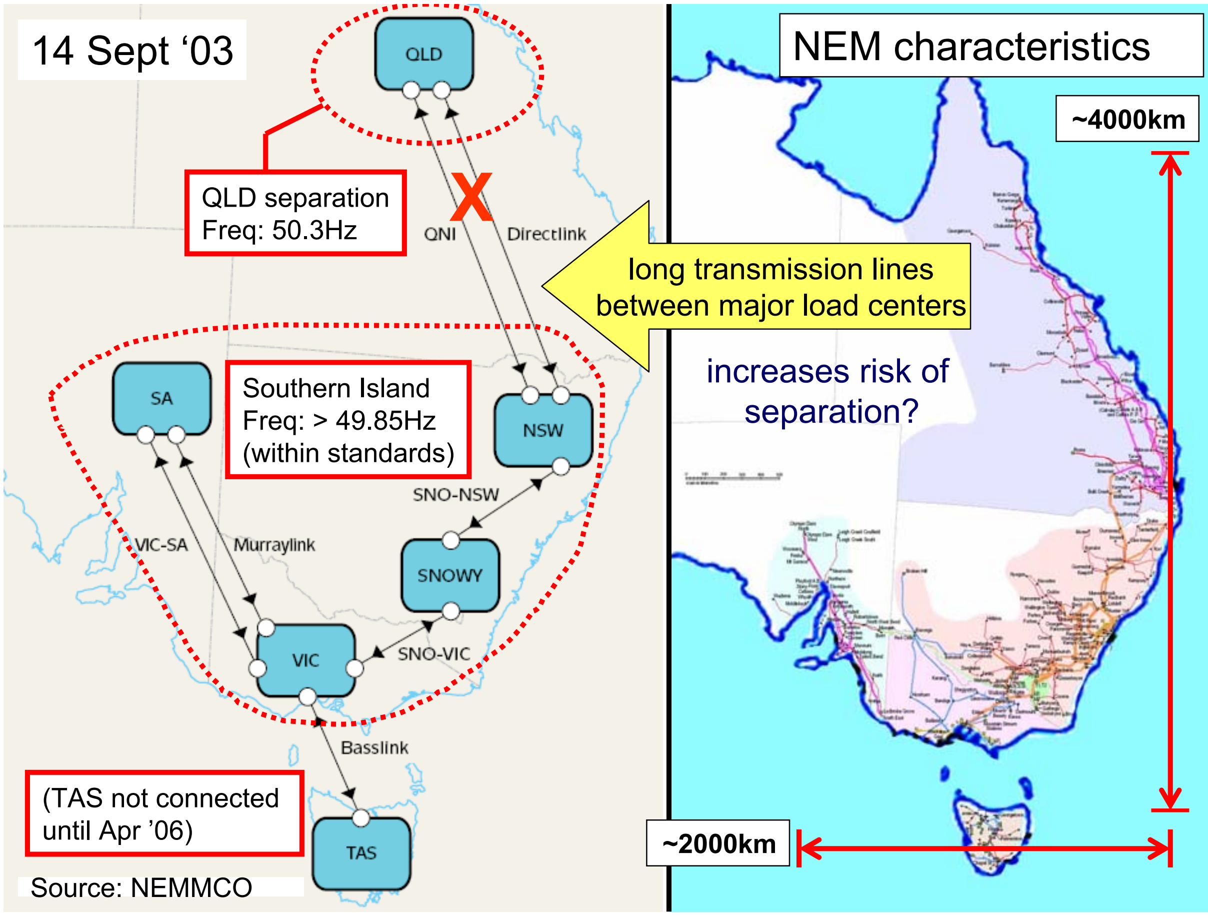
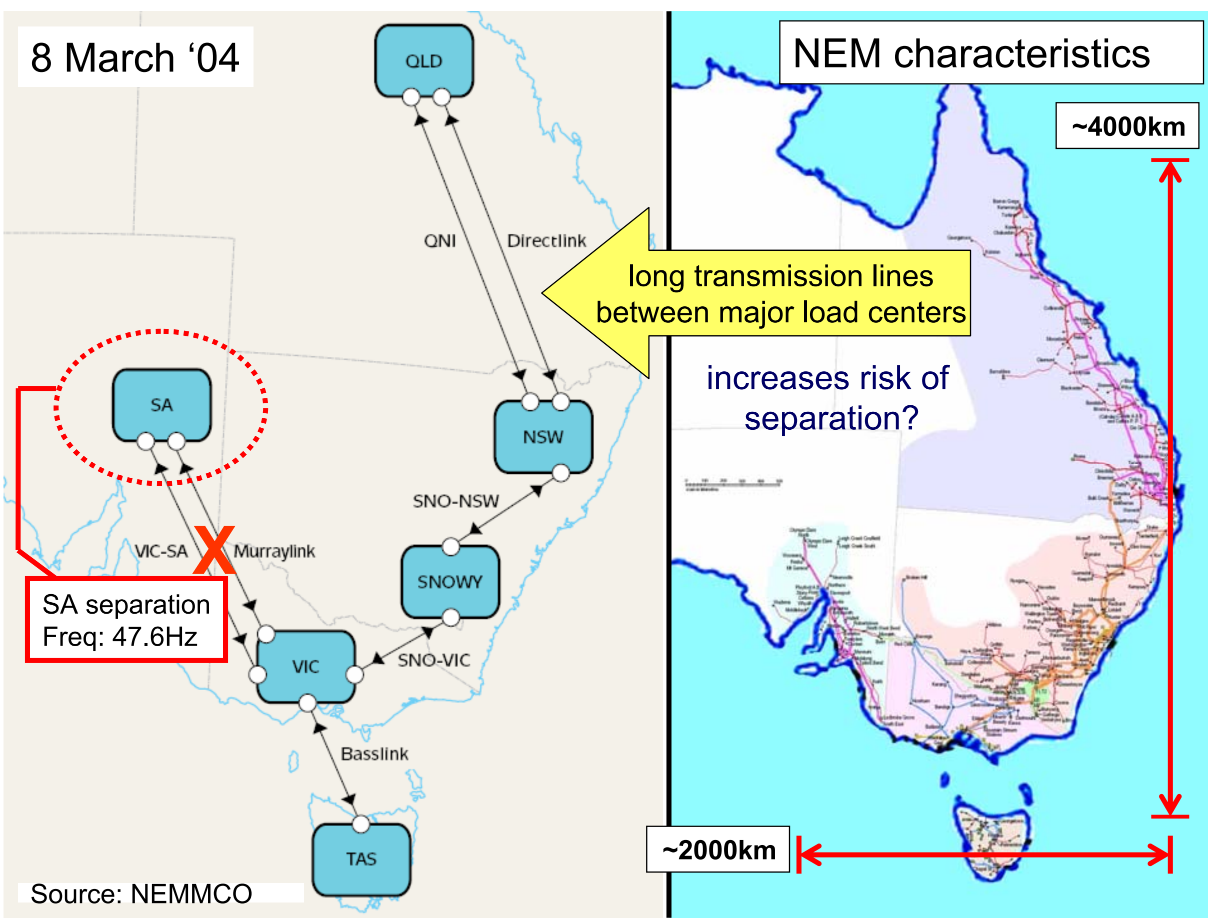
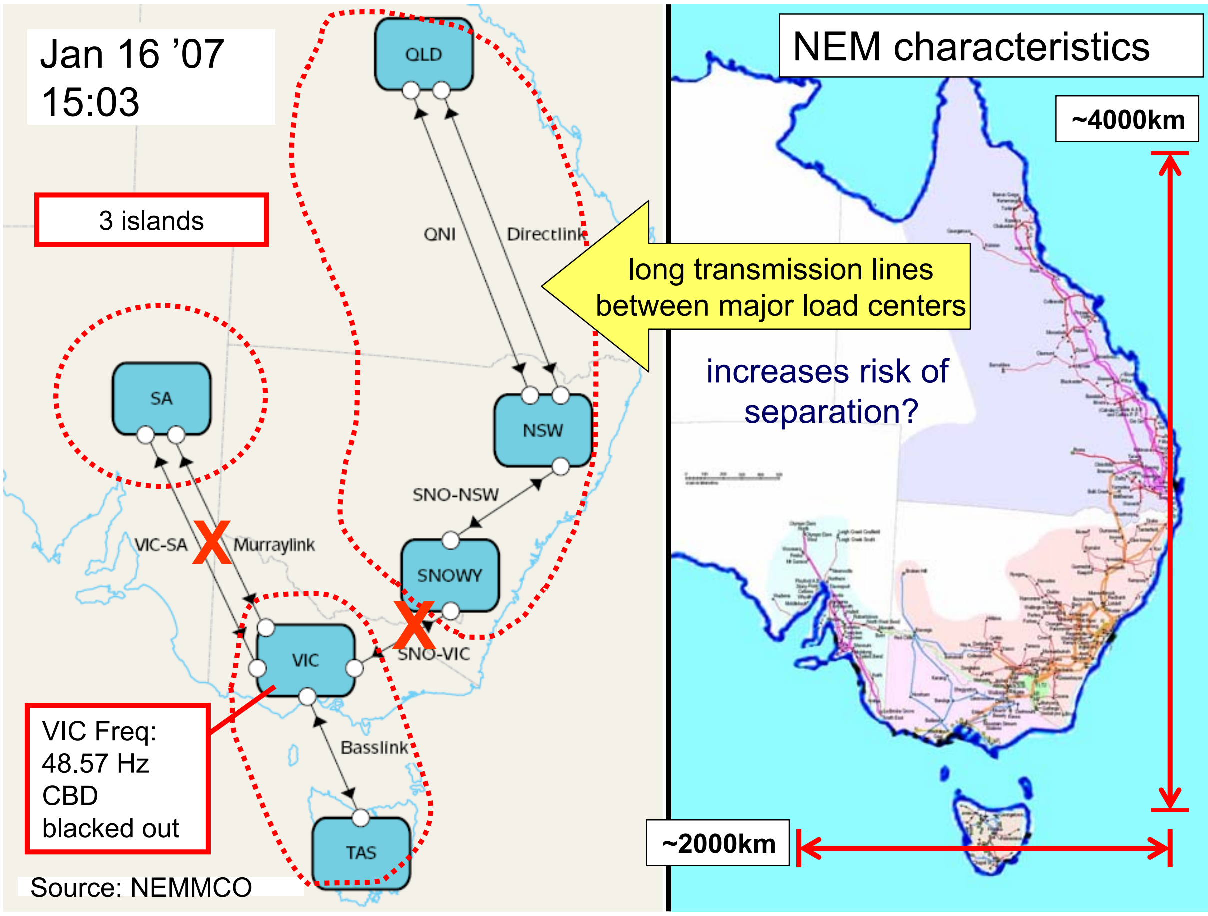
Outline

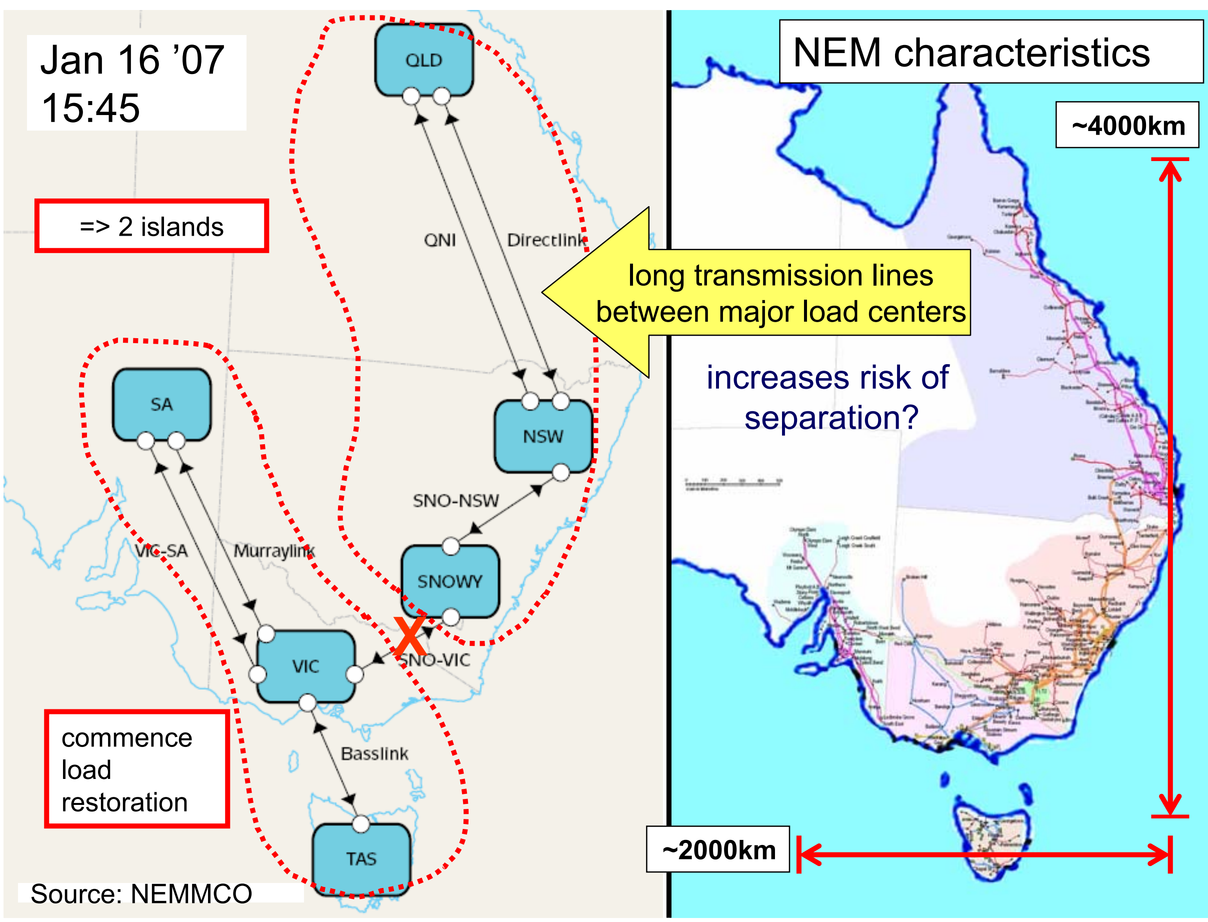
- brief motivation for work
  - separation events
  - conceptual view of security management in a restructured electricity industry
- post-separation power system model
- derivation of linear constraint sets from model
- security management & electricity market interface
- illustrative example
- conclusions and further work


14 Sept '03
QLD
QLD separation
Freq: 50.3Hz
X
QNI
Directlink
Southern Island
Freq: > 49.85Hz
(within standards)
SA
NSW
SNO-NSW
VIC-SA
Murraylink
SNOWY
VIC
SNO-VIC
Basslink
(TAS not connected
until Apr '06)
TAS
Source: NEMMCO
NEM characteristics
~4000km
long transmission lines
between major load centers
increases risk of
separation?
~2000km


8 March '04
QLD
QNI
Directlink
SA
NSW
SNO-NSW
VIC-SA
X
Murraylink
SA separation
Freq: 47.6Hz
SNOWY
VIC
SNO-VIC
Basslink
TAS
Source: NEMMCO
NEM characteristics
~4000km
long transmission lines
between major load centers
increases risk of
separation?
~2000km

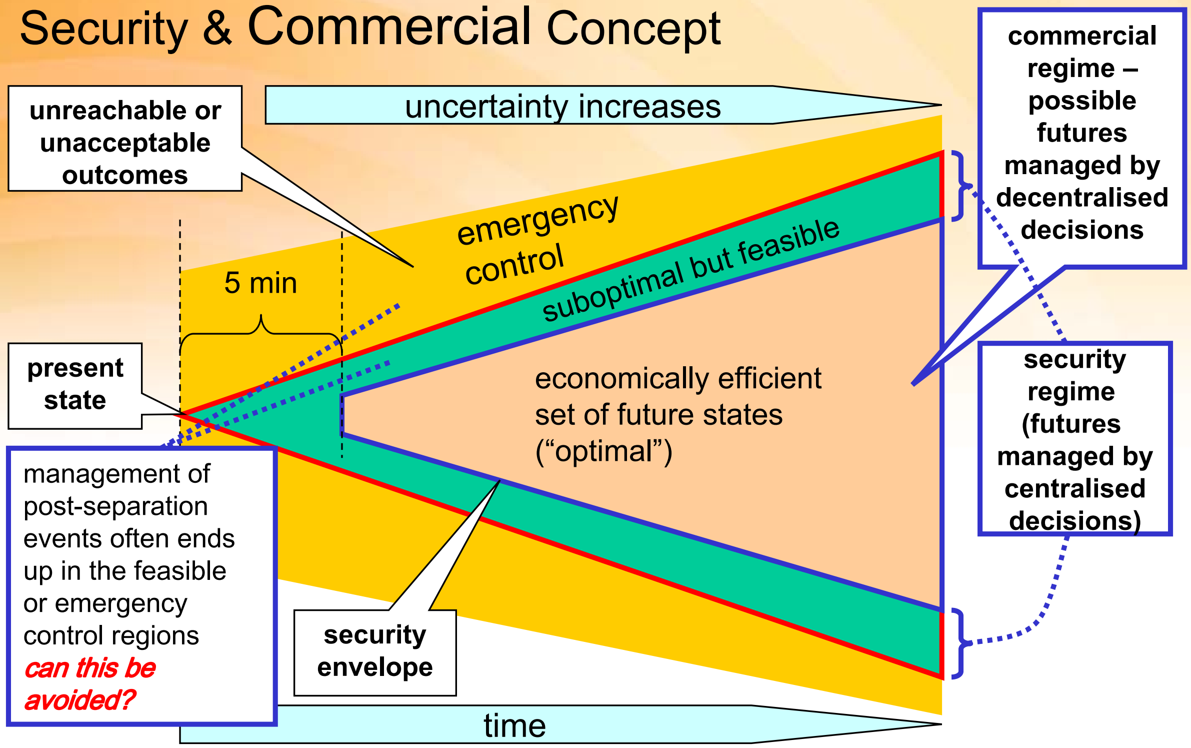


Jan 16 '07
15:03
3 islands
QLD
QNI
Directlink
SA
NSW
SNO-NSW
VIC-SA
Murraylink
SNOWY
VIC
SNO-VIC
VIC Freq:
48.57 Hz
CBD
blacked out
Basslink
TAS
Source: NEMMCO
NEM characteristics
~4000km
long transmission lines
between major load centers
increases risk of
separation?
~2000km



Jan 16 '07
15:45
=> 2 islands
QLD
QNI
Directlink
SA
NSW
SNO-NSW
VIC-SA
Murraylink
SNOWY
VIC
SNO-VIC
commence
load
restoration
Basslink
TAS
Source: NEMMCO
NEM characteristics
~4000km
long transmission lines
between major load centers
increases risk of
separation?
~2000km

Security & Commercial Concept

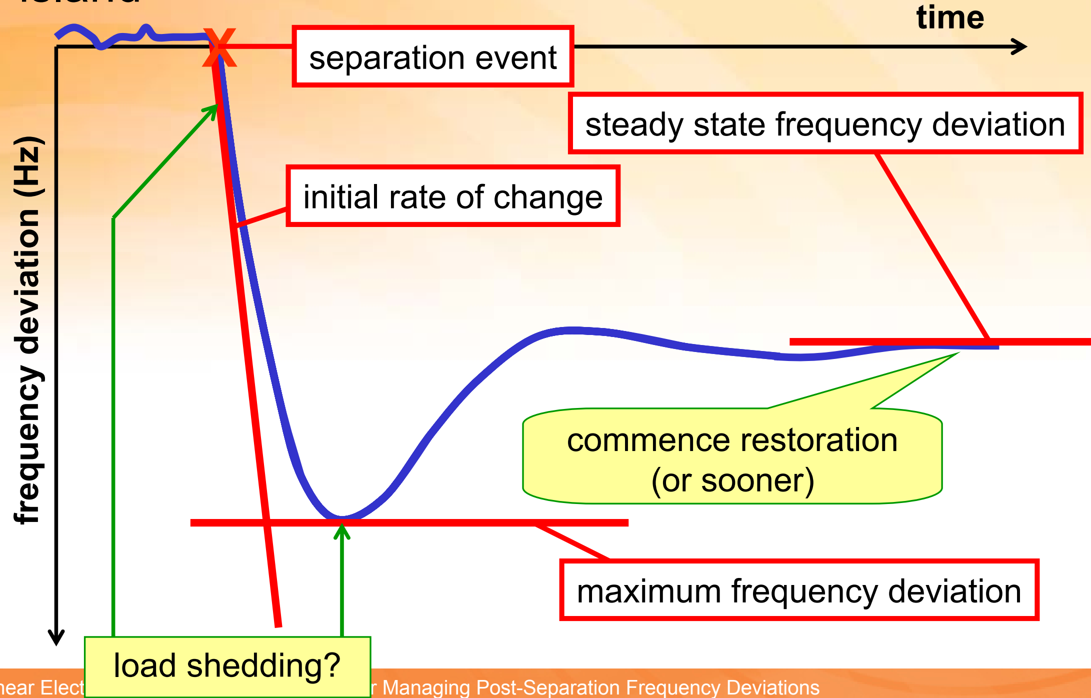


Source: H. Outhred, CEEM

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



Post-Separation Dynamic Power System Model

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

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

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

$$\begin{aligned} \dot{\mathbf{x}}_i(t) &= A_i \mathbf{x}_i(t) + \mathbf{b}_i p(t) \\ y_{ik}(t) &= \mathbf{e}_{ik}^T \mathbf{x}_i(t) \end{aligned}$$

standard LTI system
for each possible island

Steady-State Frequency Deviations

- set derivatives to zero & solve

$$
\begin{aligned}
f_i(\infty) &= y_{i1}(\infty) \\
&= -\mathbf{e}_1^T (A_i)^{-1} \mathbf{b}_i \Delta p \\
&\triangleq K_i \Delta p
\end{aligned}
$$

$$
\begin{aligned}
p_{ij}(\infty) &= y_{i,j+1}(\infty) \\
&= -\mathbf{e}_{j+1}^T (A_i)^{-1} \mathbf{b}_i \Delta p \\
&\triangleq K_{ij} \Delta p
\end{aligned}
$$

power lost or gained in island

power output of generator j, island i

Initial Rate of Change of Frequency

- put $t = 0$ & consider initial conditions

$$
\dot{\mathbf{x}}_i(0) = A_i \mathbf{x}_i(0) + \mathbf{b}_i \Delta p
$$

initial state (freq & power outputs)

$$
\begin{aligned}
\dot{f}_i(0) &= -\sigma_i \Delta p \\
&\triangleq L_i \Delta p
\end{aligned}
$$

(not necessary) put initial conditions = 0

Maximum Frequency Deviation (1)

- use standard analytical expression

$$\begin{aligned}\mathbf{x}_i(t) &= \exp(A_i t)\mathbf{x}_i(0) + \int_0^t \exp\big(A_i(t-\tau)\big)\mathbf{b}_i d\tau.\Delta p \\ &= A_i^{-1}\big(\exp(A_i t) - I\big)\mathbf{b}_i \Delta p\end{aligned}$$

solve for t to find extreme values of states

$$\begin{aligned}\dot{f}_i(t) &= \mathbf{e}_1^T \dot{\mathbf{x}}_i(t) \\ &= \mathbf{e}_1^T \exp(A_i t)(A_i \mathbf{x}_i(0) + \mathbf{b}_i \Delta p) \\ &= \mathbf{e}_1^T \exp(A_i t)\mathbf{b}_i \Delta p\end{aligned}$$

find $t = t_{max} \geq 0$ to make zero

$$\begin{aligned}\dot{p}_{ij}(t) &= \mathbf{e}_{j+1}^T \dot{\mathbf{x}}_i(t) \\ &= \mathbf{e}_{j+1}^T \exp(A_i t)\mathbf{b}_i \Delta p\end{aligned}$$

find $t = t_j \geq 0$ to make zero

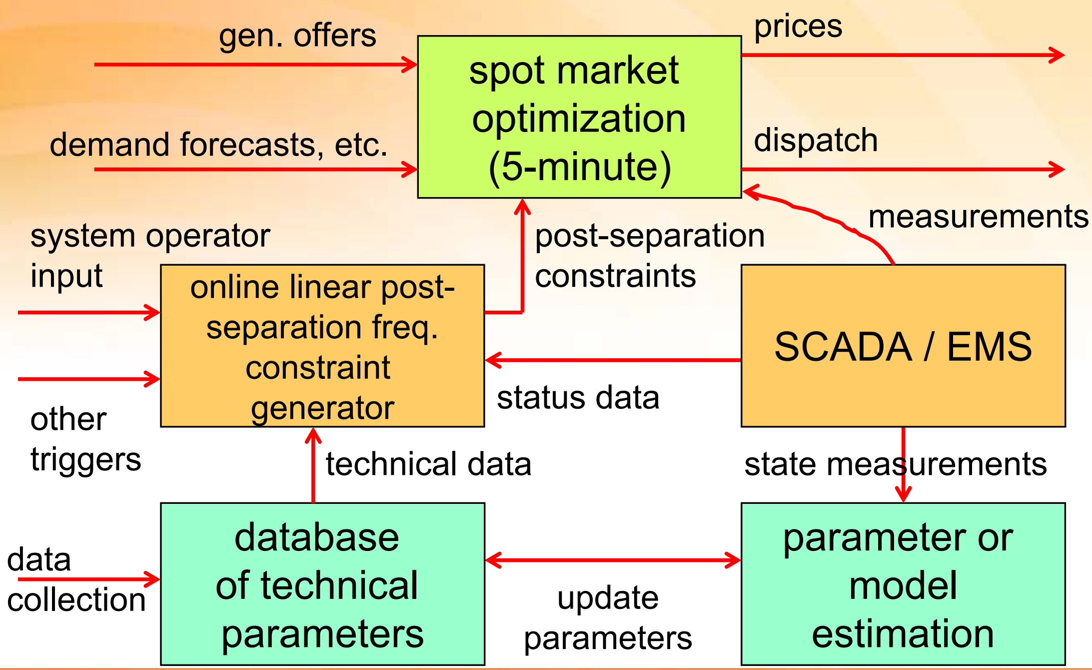
Maximum Frequency Deviation (2)

- Find t_{max} & t_j to get maximum deviations

$$\begin{aligned}f_i(t_{\max}) &= \mathbf{e}_1^T A_i^{-1}\big(\exp(A_i t_{\max}) - I\big)\mathbf{b}_i \Delta p \\ &= M_i \Delta p \\ p_{ij}(t_j) &= \mathbf{e}_{j+1}^T A_i^{-1}\big(\exp(A_i t_j) - I\big)\mathbf{b}_i \Delta p \\ &\triangleq M_{ij}\Delta p\end{aligned}$$

can also compute maximum output deviations

Automatic Constraint Generation



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

Minimize:

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

Subject to:

$$0 \leq g_j \leq G_j^{\max}, \qquad j \in \mathcal{G}$$

$$|p_k| \leq P_k^{\max}, \qquad k \in \mathcal{L}$$

$$\sum_{j \in \mathcal{G}_i} g_j - N_i = \sum_{k \in \mathcal{F}_i} p_k - \sum_{k \in \mathcal{T}_i} p_k, \qquad i \in \mathcal{I}$$

basic LP market formulation (lossless model)

$$|f_i(\infty)| \leq F_{\text{ss}}^{\max}, \qquad i \in \mathcal{I}$$

$$f_i(\infty) = -K_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{T}_i$$

$$f_i(\infty) = K_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{F}_i$$

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

$$0 \leq g_j + K_{ij} p_k \leq G_j^{\max}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{F}_i$$

post-separation steady-state linear frequency constraints

Spot Market + Post-Separation Security Constraints LP Optimization (2)

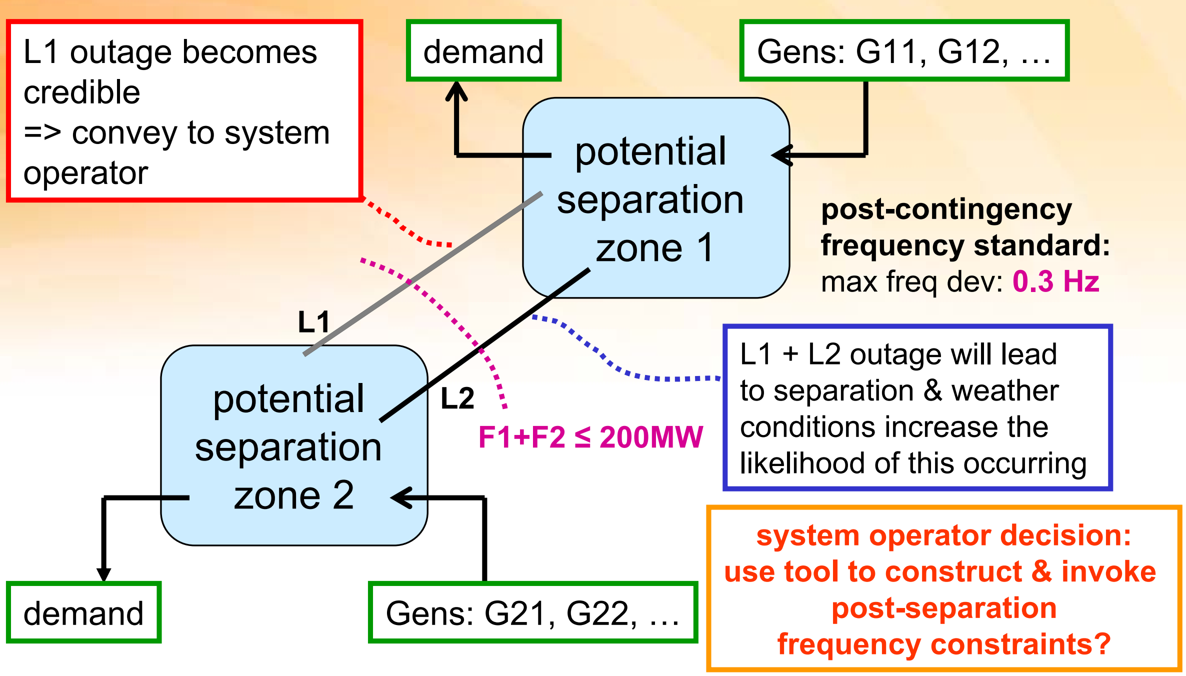
$$|\dot{f}_i(0)| \leq \dot{F}^{\max}, \quad i \in \mathcal{I}$$
$$f_i(0) = -L_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{T}_i$$
$$f_i(0) = L_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{F}_i$$

post-separation rate-of-change of frequency linear constraints

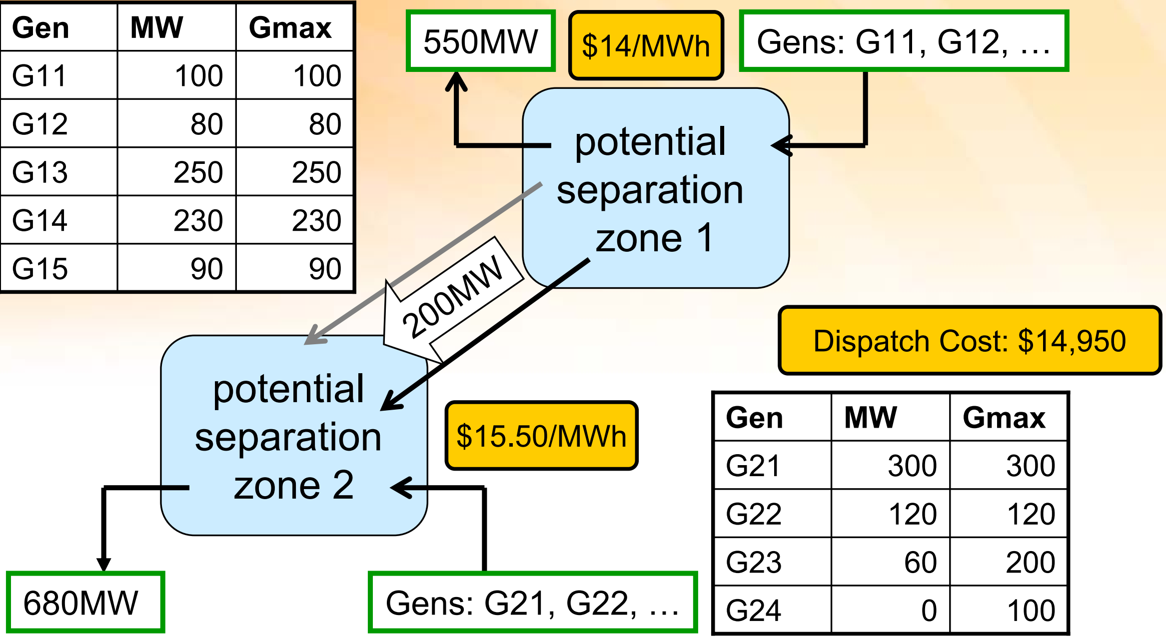
$$|f_i(t^{\max})| \leq F^{\max}, \qquad i \in \mathcal{I}$$
$$f_i(t^{\max}) = -M_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{T}_i$$
$$f_i(t^{\max}) = M_i p_k, \quad i \in \mathcal{I}, \quad k \in \mathcal{F}_i$$
$$0 \leq g_j - M_{ij} p_k \leq G_j^{\max}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{T}_i$$
$$0 \leq g_j + M_{ij} p_k \leq G_j^{\max}, \quad i \in \mathcal{I}, \quad j \in \mathcal{S}_i, \quad k \in \mathcal{F}_i$$

post-separation frequency deviation linear constraints

Simple example: hypothetical scenario



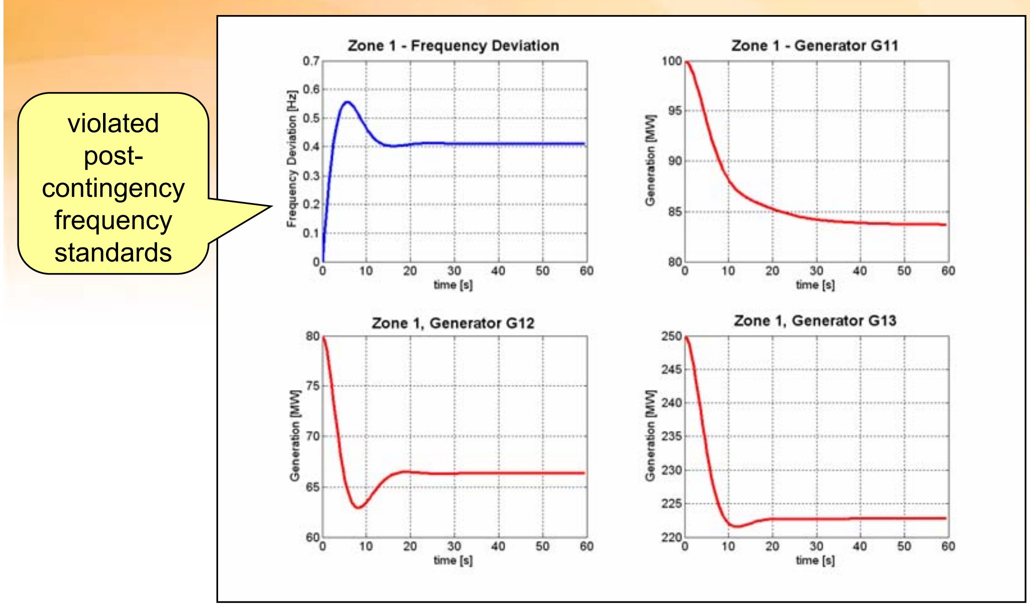
Simple example: **without** PSF constraints



Gen	MW	Gmax
G11	100	100
G12	80	80
G13	250	250
G14	230	230
G15	90	90

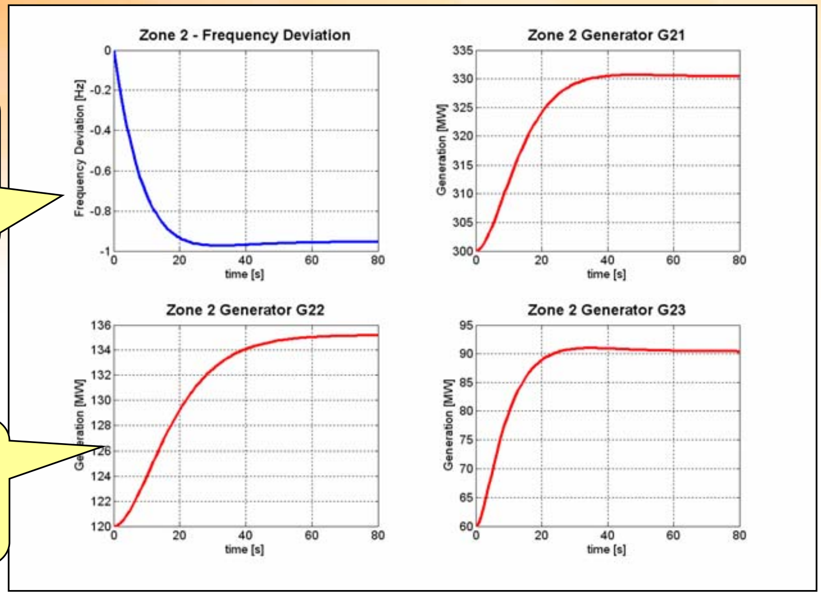
Gen	MW	Gmax
G21	300	300
G22	120	120
G23	60	200
G24	0	100

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



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

Gen	MW	Gmax
G11	100.00	100
G12	80.00	80
G13	151.82	250
G14	29.40	230
G15	0	90

550MW

$13/MWh

Gens: G11, G12, …

potential separation zone 1

flow backed-off & increased dispatch costs

61.22MW

Dispatch Cost: $15,310.16

potential separation zone 2

$16.50/MWh

Gen	MW	Gmax
G21	290.62	300
G22	115.35	120
G23	190.52	200
G24	22.28	100

680MW

Gens: G21, G22, …

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

reduced generation: head-room for responding to separation event

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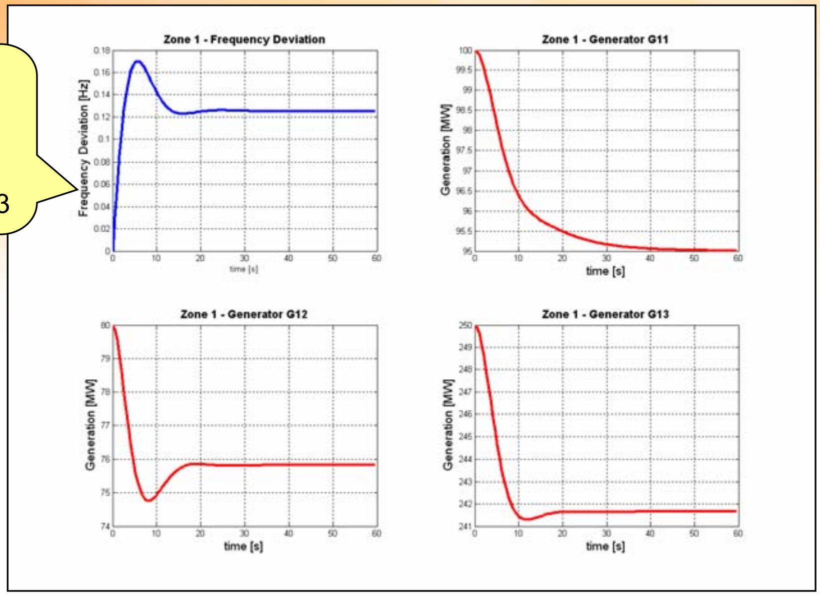
Simple example: post-separation outcome in zone 1 **with** PSF constraints

post-contingency frequency is OK:
freq dev < 0.3



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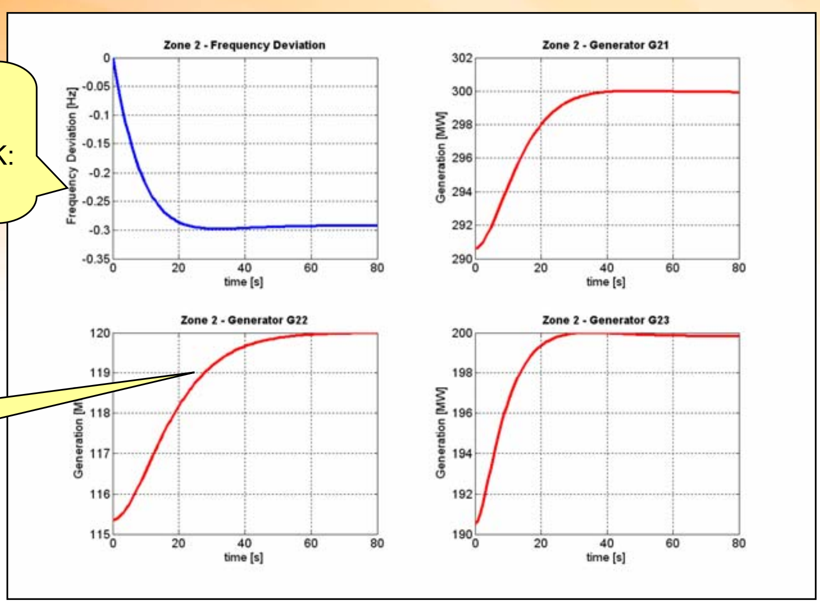
Simple example: post-separation outcome in zone 2 **with** PSF constraints

post-contingency frequency is OK:
freq dev ≤ 0.3

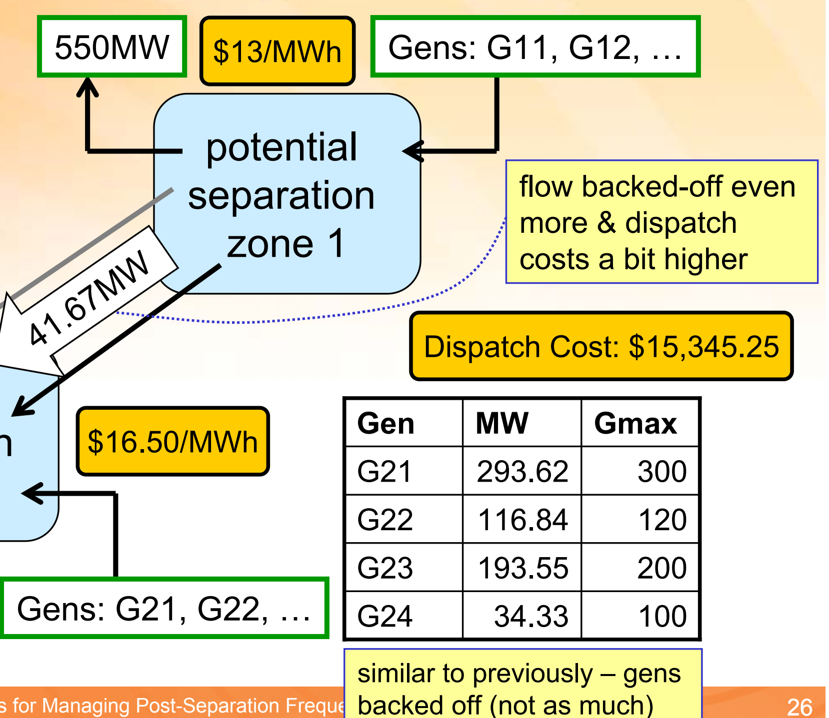
generators within limits



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

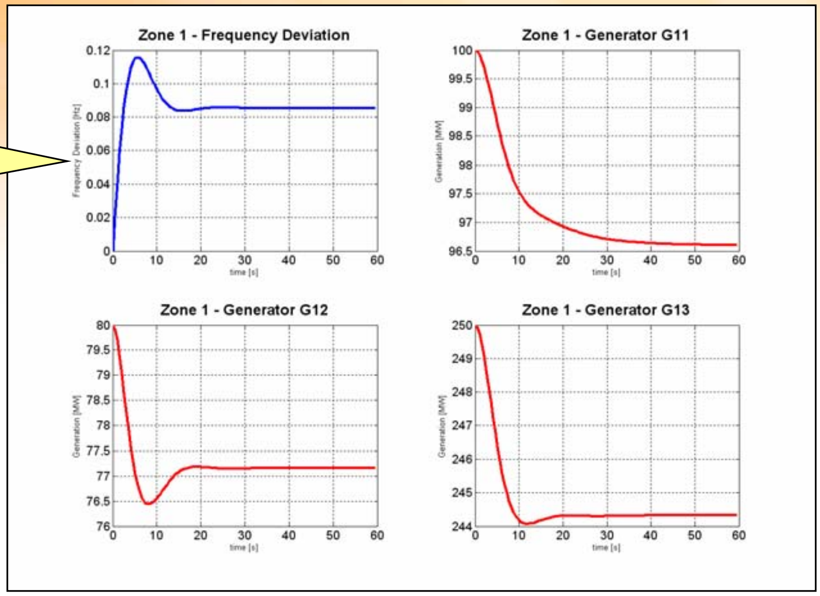


Gen	MW	Gmax
G11	100.00	100
G12	80.00	80
G13	141.66	250
G14	20.01	230
G15	0	90

Gen	MW	Gmax
G21	293.62	300
G22	116.84	120
G23	193.55	200
G24	34.33	100

Simple example: post-separation outcome in zone 1 **with** alternative PSF constraints

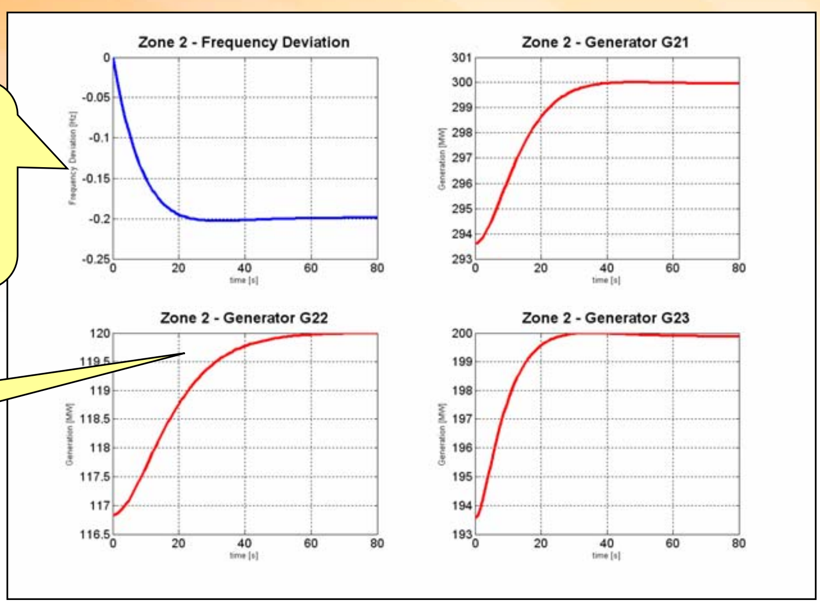
post-contingency freuency OK



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

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

generators within limits



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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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S. R. Thorncraft, H. R. Outhred, D. J. Clements, "Linear Electricity Spot Market Constraints for Managing Post-Separation Frequency Deviations", to be published in the Proceedings of the IEEE PES General Meeting Tampa Florida, USA, June 24-28 2007, available: www.ceem.unsw.edu.au.

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