Unified Gas and Electric Unit Commitment with Coordinated Generator Contingency

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* Part of the Security Gaps Arising Due to Coupled Energy Delivery Sub-systems Activity

Outline

Motivation

- Natural-Gas fired generators produce a significant portion of electricity in the US.
- Electric grid operation cannot neglect the gas grid constraints, and vice versa.
- Goals:
  - Solving unified unit commitment (UC) for gas and electric grid,
  - Coordinated generator contingency analysis.

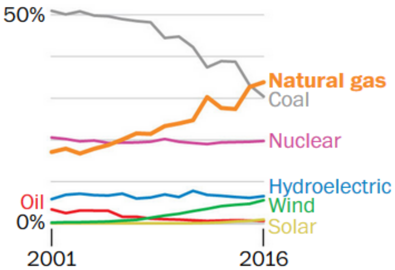
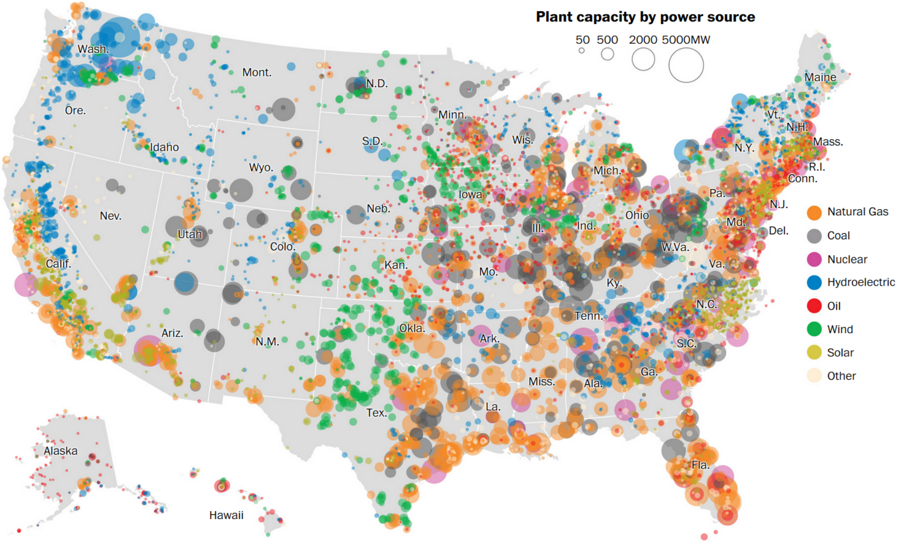


Figure: Share of U.S. Electricity Generation.
source: U.S. Energy Information Agency.

How US Generates its Electricity?



By John Muyskens, Dan Keating and Samuel Granados

Gas Grid Components

For our modeling purposes, a gas network is composed of the following components:

- Gas wells/storage,
- Pipelines,
- Compressors,
- Demand.

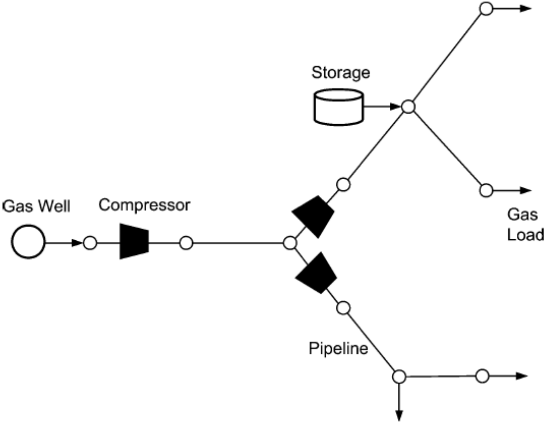


Figure: Natural Gas Grid Model.

Steady-State Gas-Flow Equation

In one-dimensional steady-state, the gas flow equation over a pipeline of length L is:

$$\pi_{in}^2 - \pi^2(x) = h \underbrace{\frac{x}{L}}_{\alpha} (f)^2 sgn(f) \tag{1}$$

f: gas flow [m^3/h],
π: gas pressure [N/m^2],
h: constant that depends on the pipeline friction factor, diameter, length, gas compressibility factor, gas constant, and gas temperature.

Optimal Gas Flow (OGF)

Minimize: $\sum_{t \in \mathcal{T}} \sum_{w \in \mathcal{W}} d_w G_{t,w} + d_w^{res} rg_{t,w}$
Subject to:

.

Optimal Gas Flow (OGF)

Minimize: $\sum_{t\in\mathcal{T}}\sum_{w\in\mathcal{W}} d_w G_{t,w} + d_w^{res} rg_{t,w}$
Subject to:

$$G_{t,w} \geq G_w^{min}, \qquad \forall t, w \qquad (2a)$$

.

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$$\sum_{w\in\mathcal{W}(i)} G_{t,w} + \sum_{k\in\mu^+(i)} f_{t,k} - \sum_{k\in\mu^-(i)} f_{t,k} = GL_{t,i}, \qquad \forall t, i \qquad (2c)$$

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$$\rho_{t,k} = \left(\frac{\pi_{t,j}^2 + (1 - \alpha_k) h_k f_{t,k}^2 . sgn(f_{t,k})}{\pi_{t,i}^2 - \alpha_k h_k f_{t,k}^2 . sgn(f_{t,k})} \right)^{sgn(f_{t,k})}, \qquad \forall t, k \qquad (2d)$$

.

Optimal Gas Flow (OGF)

Minimize: $\sum_{t\in\mathcal{T}}\sum_{w\in\mathcal{W}} d_w G_{t,w} + d_w^{res} rg_{t,w}$
Subject to:

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$$\pi_i^{min} \leq \pi_{t,i} \leq \pi_i^{max}, \qquad \forall t,i \qquad (2e)$$

.

Optimal Gas Flow (OGF)

Minimize: $\sum_{t\in\mathcal{T}}\sum_{w\in\mathcal{W}} d_w G_{t,w} + d_w^{res} rg_{t,w}$
Subject to:

$$
\begin{aligned}
& G_{t,w} \geq G_w^{min}, && \forall t, w && \text{(2a)}\\
& G_{t,w} + rg_{t,w} \leq G_w^{max}, && \forall t, w && \text{(2b)}\\
& \sum_{w\in\mathcal{W}(i)} G_{t,w} + \sum_{k\in\mu^+(i)} f_{t,k} - \sum_{k\in\mu^-(i)} f_{t,k} = GL_{t,i}, && \forall t, i && \text{(2c)}\\
& \rho_{t,k} = \left(\frac{\pi_{t,j}^2 + (1-\alpha_k)h_k f_{t,k}^2.sgn(f_{t,k})}{\pi_{t,i}^2 - \alpha_k h_k f_{t,k}^2.sgn(f_{t,k})}\right)^{sgn(f_{t,k})}, && \forall t, k && \text{(2d)}\\
& \pi_i^{min} \leq \pi_{t,i} \leq \pi_i^{max}, && \forall t, i && \text{(2e)}
\end{aligned}
$$

$\rho_{t,k} \geq 1$ is the compressor ratio, and is usually added as a parameter in the base case[1].

[1] $\rho_{t,k} = 1$ for pipelines without compressor.

Transforming (2d) and (2e) into linear constraints[2]

If $sgn(f_{t,k}) > 0$:

$$\underbrace{\sqrt{\max\left\{0, \frac{\rho_{t,k}(\pi_i^{min})^2 - (\pi_j^{max})^2}{h_k + (\rho_{t,k} - 1)h_k\alpha_k}\right\}}}_{\gamma_d^+} \leq f_{t,k} \leq \underbrace{\sqrt{\frac{\rho_{t,k}(\pi_i^{max})^2 - (\pi_j^{min})^2}{h_k + (\rho_{t,k} - 1)h_k\alpha_k}}}_{\gamma_u^+}$$

[2] pipelines with compressor only pass the flow in one direction.

Transforming (2d) and (2e) into linear constraints

If $sgn(f_{t,k}) > 0$:

$$\underbrace{\sqrt{\max\left\{0, \frac{\rho_{t,k}(\pi_i^{min})^2 - (\pi_j^{max})^2}{h_k + (\rho_{t,k} - 1)h_k\alpha_k}\right\}}}_{\gamma_d^+} \leq f_{t,k} \leq \underbrace{\sqrt{\frac{\rho_{t,k}(\pi_i^{max})^2 - (\pi_j^{min})^2}{h_k + (\rho_{t,k} - 1)h_k\alpha_k}}}_{\gamma_u^+}$$

Else if $sgn(f_{t,k}) < 0$:

$$\underbrace{-\sqrt{\frac{(\pi_j^{max})^2 - (\pi_i^{min})^2}{h_k}}}_{\gamma_u^-} \leq f_{t,k} \leq \underbrace{-\sqrt{\max\left\{0, \frac{(\pi_j^{min})^2 - (\pi_i^{max})^2}{h_k}\right\}}}_{\gamma_d^-}$$

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Else if $sgn(f_{t,k}) < 0$:

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Key Point: Non-linear constraint is mapped onto two linear constraints. Mapping is one-to-one, no simplifications/assumptions are made.

Handling the $sgn()$ function

Define:

$$f_{t,k} = f_{t,k}^{+} - f_{t,k}^{-}, \qquad f_{t,k}^{+} \geq 0, f_{t,k}^{-} \geq 0$$

$$Z_{t,k} = \begin{cases} 1 & \text{if } f_{t,k} > 0 \\ 0 & \text{else} \end{cases}$$

Handling the $sgn()$ function

Define:

$$f_{t,k} = f_{t,k}^{+} - f_{t,k}^{-}, \qquad f_{t,k}^{+} \geq 0, f_{t,k}^{-} \geq 0$$

$$Z_{t,k} = \begin{cases} 1 & \text{if } f_{t,k} > 0 \\ 0 & \text{else} \end{cases}$$

The following constraints are added:

$$f_{t,k}^{-} = 0, \qquad \forall t, k \in \mathcal{E}_g^a \tag{3a}$$

$$\gamma_d^{+}.Z_{t,k} \leq f_{t,k}^{+} \leq \gamma_u^{+}.Z_{t,k}, \qquad \forall t, k \tag{3b}$$

Handling the $sgn()$ function

Define:

$$f_{t,k} = f^{+}_{t,k} - f^{-}_{t,k}, \qquad f^{+}_{t,k} \geq 0, f^{-}_{t,k} \geq 0$$

$$Z_{t,k} = \begin{cases} 1 & \text{if } f_{t,k} > 0 \\ 0 & \text{else} \end{cases}$$

The following constraints are added:

$$f^{-}_{t,k} = 0, \qquad \forall t, k \in \mathcal{E}^{a}_{g} \qquad (3a)$$

$$\gamma^{+}_{d}.Z_{t,k} \leq f^{+}_{t,k} \leq \gamma^{+}_{u}.Z_{t,k}, \qquad \forall t, k \qquad (3b)$$

$$\gamma^{-}_{d}.(1 - Z_{t,k}) \leq f^{-}_{t,k} \leq \gamma^{-}_{u}.(1 - Z_{t,k}), \qquad \forall t, k \notin \mathcal{E}^{a}_{g} \qquad (3c)$$

Handling the *sgn*() function

Define:

$$f_{t,k} = f^+_{t,k} - f^-_{t,k}, \qquad f^+_{t,k} \geq 0, f^-_{t,k} \geq 0$$

$$Z_{t,k} = \begin{cases} 1 & \text{if } f_{t,k} > 0 \\ 0 & \text{else} \end{cases}$$

The following constraints are added:

$$f^-_{t,k} = 0, \qquad \forall t, k \in \mathcal{E}^a_g \qquad (3a)$$

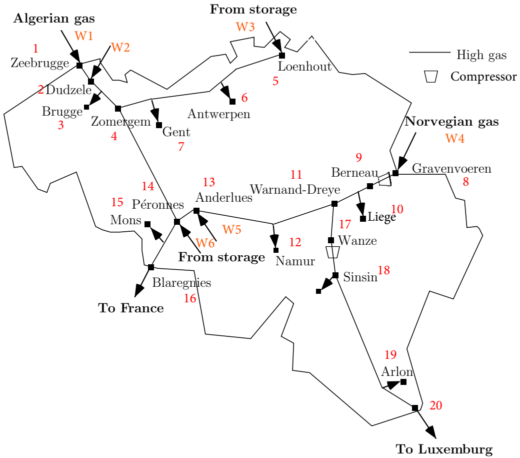
$$\gamma^+_d . Z_{t,k} \leq f^+_{t,k} \leq \gamma^+_u . Z_{t,k}, \qquad \forall t, k \qquad (3b)$$

$$\gamma^-_d .(1 - Z_{t,k}) \leq f^-_{t,k} \leq \gamma^-_u .(1 - Z_{t,k}), \qquad \forall t, k \notin \mathcal{E}^a_g \qquad (3c)$$

Pros Flow direction considered implicitly.

Cons 1) Introduction of binary variables, 2) larger number of constraints.

Modified Belgium Gas Grid



Well	cost [\$/m^3]
w1	0.089 34
w2	0.089 34
w3	0.089 34
w4	0.065 83
w5	0.065 83
w6	0.065 83

Figure: Belgium High Calorific Natural Gas Grid.

source: De Wolf and Smeers, "The gas transmission problem solved by an extension of the simplex algorithm"

OGF Numerical Results

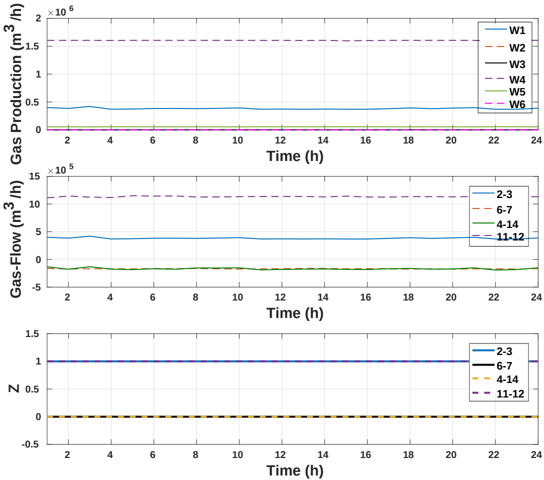


Figure: OGF for Modified Belgium High Calorific Gas Network. Cost: $3.6015M. Setting: $\rho_{t,8-9} = 1, \rho_{t,17-18} = 1.25$

Uncoordinated Gas and Electric Grid Unit Commitment: Setup

Assumptions

- 1 ft^3 of natural gas = 1109 BTU (1 MW h = 3.412 14 BTU)
- 50 MW generators in RTS are treated as gas-fired combined cycle with efficiency 50%.
- 20 MW generators in RTS are treated as gas-fired turbines with efficiency 35%.
- Conversion between gas and electric power:

$$P_g[\mathrm{MW}] \times \frac{3.412\,14\,\mathrm{BTU}}{1\,\mathrm{MW\,h}} \times \frac{1\,\mathrm{ft}^3}{1109\,\mathrm{BTU}} \times \frac{1\,\mathrm{m}^3}{35.3147\,\mathrm{ft}^3} \times \frac{1}{\mathrm{efficiency}} = GL$$

- $\rho_{t,8-9} = 1, \rho_{t,17-18} = 1.25$

Uncoordinated Gas and Electric Grid Unit Commitment: Setup

The connections between RTS and the Belgium Grid are:

Gas Node #	RTS Bus #	Generators IDs
12	101	1,2 (of 4)
18	102	1,2 (0f 4)
20	122	1,2 (of 6)
6	322	3,4,5 (of 6)

Uncoordinated Gas and Electric Grid Unit Commitment: Setup

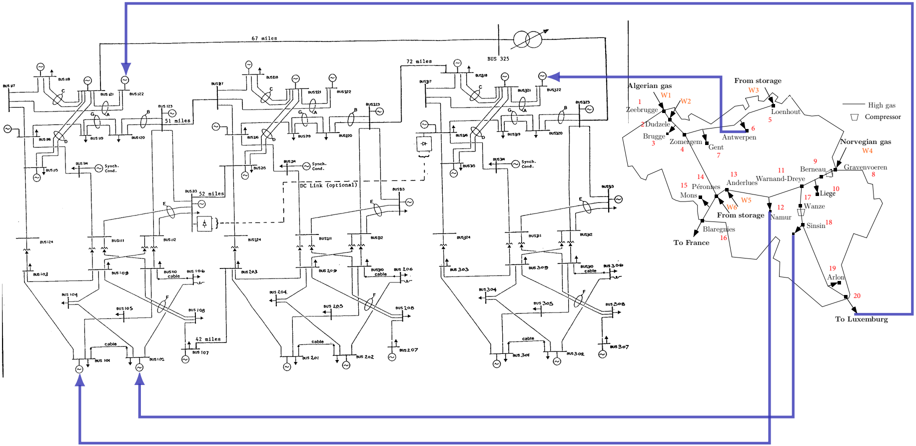


Figure: Coupling between RTS96[3] system and Modified Belgium Gas Grid.

[3] Grigg, Wong, Albrecht, Allan, Bhavaraju, Billinton, Chen, Fong, Haddad, Kuruganty, *et al.*, "The IEEE reliability test system-1996. A report prepared by the reliability test system task force of the application of probability methods subcommittee"

Uncoordinated Gas and Electric Grid Unit Commitment: Result

Solve electric grid unit commitment → get results from UC and solve GF.

violation of gas pipeline limit in the uncoordinated case.

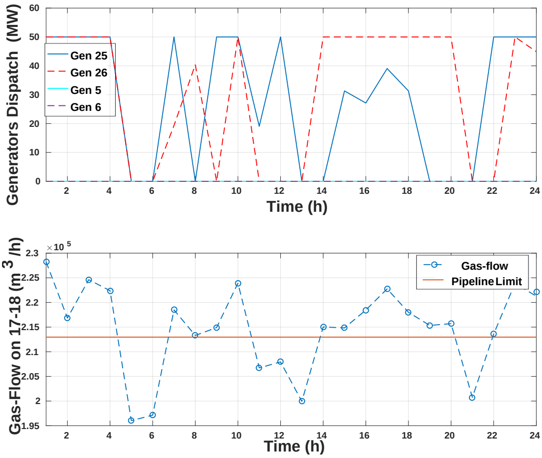


Figure: Uncoordinated Unit Commitment.

Unified Gas and Electric Grid Unit Commitment

$$\textbf{Minimize} \quad \sum_{t \in \mathcal{T}} c_g(G_w) + c_e(P_g, r_g)$$

$$\textbf{Subject to} \quad \text{Gas Grid Constraints}$$

$$\text{Electric UC Constraints}$$

$$\sum_{w \in \mathcal{W}(i)} G_{t,w} + \sum_{k \in \mu^+(i)} f_{t,k} - \sum_{k \in \mu^-(i)} f_{t,k} - \sum_{g \in \mathcal{S}(i)} P_{t,g}\eta_g = GL_{t,i}, \quad \forall t, i$$

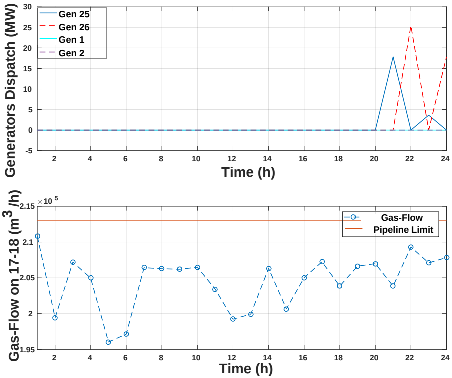


Figure: Unified UC.

Case	Electric UC optimal cost
Unified	\$2.9676M
Uncoordinated	\$2.9484M

Cost of Unified is *greater than* cost of Uncoordinated. However, the Uncoordinated case has *infeasibility*.

Coordinated Generator Contingency Analysis

Premise

- Gas-fired generators provide much non-spinning reserves and are crucial during generator contingencies.
- Generation from gas-fired generators *during* a contingency must also respect pipeline constraints.

Coordinated Generator Contingency Analysis

The following constraints are added to the typical generator contingency analysis:

$$0 \leq rg_{t,w}^{c} \leq rg_{t,w}, \qquad \forall c, t, w \tag{4a}$$

$$\sum_{w \in \mathcal{W}} rg_{t,w}^{c} = \sum_{g \in \mathcal{G}_w} r_{t,g}^{c} \eta_g, \qquad \forall c, t \tag{4b}$$

Coordinated Generator Contingency Analysis

The following constraints are added to the typical generator contingency analysis:

$$0 \leq rg^{c}_{t,w} \leq rg_{t,w}, \qquad \forall c,t,w \tag{4a}$$

$$\sum_{w \in \mathcal{W}} rg^{c}_{t,w} = \sum_{g \in \mathcal{G}_w} r^{c}_{t,g}\eta_g, \qquad \forall c,t \tag{4b}$$

$$\sum_{w \in \mathcal{W}(i)} (G_{t,w} + rg^{c}_{t,w}) + \sum_{k \in \mu^{+}(i)} f^{c}_{t,k} - \sum_{k \in \mu^{-}(i)} f^{c}_{t,k} - \sum_{g \in \mathcal{S}(i)} (P_{t,g} + r^{c}_{t,g})\eta_g = GL_{t,i}, \qquad \forall c,t,i \tag{4c}$$

Coordinated Generator Contingency Analysis

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$$0 \leq rg^c_{t,w} \leq rg_{t,w}, \qquad \forall c, t, w \qquad (4a)$$

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$$f^{c^-}_{t,k} = 0, \qquad \forall c, t, k \in \mathcal{E}^a_g \qquad (4d)$$

$$\gamma^+_d . Z^c_{t,k} \leq f^{c^+}_{t,k} \leq \gamma^+_u . Z^c_{t,k}, \qquad \forall c, t, k \qquad (4e)$$

$$\gamma^-_d .(1 - Z^c_{t,k}) \leq f^{c^-}_{t,k} \leq \gamma^-_u .(1 - Z^c_{t,k}), \qquad \forall c, t, k \notin \mathcal{E}^a_g \qquad (4f)$$

Unified Generator Contingency: Setup

The connections between RTS and the Belgium Grid are slightly modified:

Gas Node #	RTS Bus #	Generators IDs
20	101	1,2 (of 4)
18	102	1,2 (0f 4)
12	122	1,2,3 (of 6)
6	322	3,4,5 (of 6)

Unified Generator Contingency: Setup

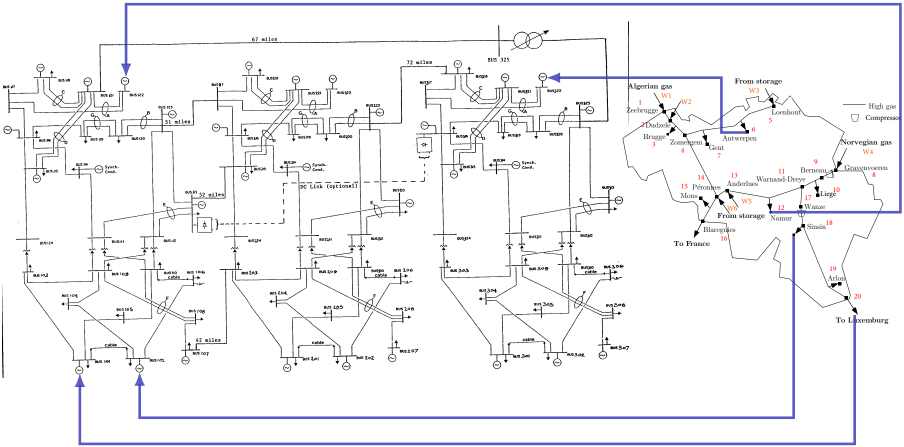


Figure: Coupling between RTS96 system and Modified Belgium Gas Grid for generator contingency test.

Unified Generator Contingency: Results

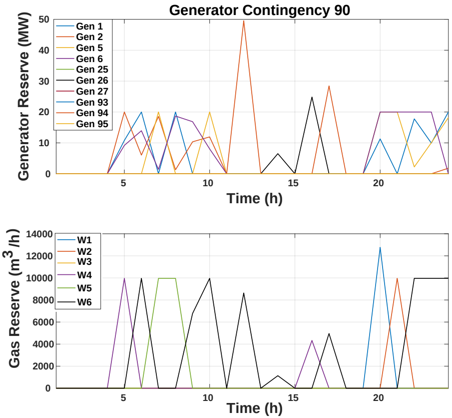


Figure: Activated Gas Generators and Gas Wells Reserve for Gen-90 Contingency.

Interpretation

Activated gas well reserves follow the activated gas generators reserves as expected.

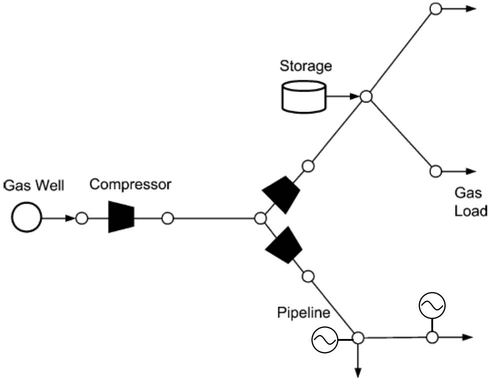
Note: Separate testing reveals that reserves are correctly allocated, such that even if *all* are activated no flow violations will occur.

Future Direction: Impact of Dynamics

- Line pack is a slow moving processes $\Rightarrow$ Gas generation cannot be consumed immediately at load points.
- We need a dynamic model to understand the impacts of these restrictions.
- E.g. quick step changes by gas-fired generators. Is there enough pressure?

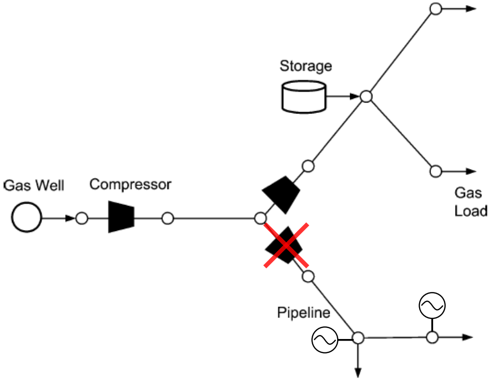
Future Direction: Contingencies in Gas Grid

- We are used to considering $N-1$ contingencies in the electric grid



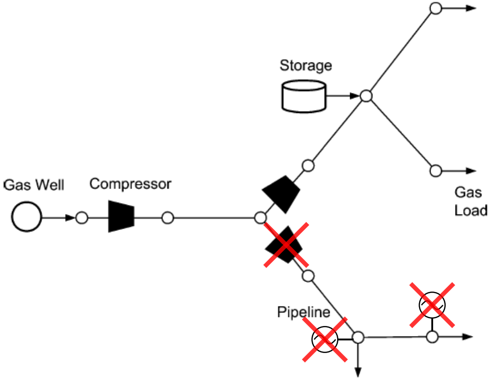
Future Direction: Contingencies in Gas Grid

- We are used to considering $N-1$ contingencies in the electric grid
- A single failure in the gas supply system



Future Direction: Contingencies in Gas Grid

- We are used to considering $N - 1$ contingencies in the electric grid
- A single failure in the gas supply system can be directly linked to a *set* of contingencies in the electric grid.
- We should consider these specific sets of $N-$many contingencies[4].



[4] Also suggested in NERC 2013 Special Reliability Assessment: "Accommodating an Increased Dependence on Natural Gas for Electric Power" (chapter 3).

Conclusion

- Violation of the gas grid limits due to uncoordinated planning of electric grid is shown,
- Unified gas and electric grid unit commitment is presented to mitigate the issue,
- Generator contingency analysis is extended to consider coupled planning and operation,

Thank You!
Questions?

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