Gas-Grid Resilience Planning

The Grid of the Future Workshop

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Emerging Gas-Grid Challenges

- **Natural Gas variability increasing beyond historical norms**
  - Largely driven by the electric power sector
  - Variability limits the ability to ship gas
  - Southern California Gas—Aliso Canyon capacity studies
    - Max capacity is 4.56 B CFD in winter
    - Max capacity is 3.60 B CFD in summer

- **Correlated Vulnerabilities**
  - Polar vortex, catastrophic pipeline failure
  - Failures in natural gas propagate to electric power and vice-versa
  - Risk posture of electric power increases
    - Power industry nervous about dependencies
  - Our Goal: Reduce risk through coordinated design and/or operations
Modeling Gas-Grid Coordination

- In the US, gas and power transmission have very different planning processes and very different price formation processes.

- Few large-scale gas transmission models.

- Limited US public domain computational test beds for gas-grid simulation (no equivalent to GasLib or IEEE test systems).
Gas Grid Expansion Planning

Operational options:
- EP: power generation dispatch (Optimal power flow)
- NG: load locations and quantities, compressor dispatch

Infrastructure options:
- EP: new transmission lines and generation or converted generation
- NG: new/upgraded pipelines, compressor stations

Joint gas-grid model’s main blocks:

\[
\begin{align*}
\min_{\lambda, \omega} & \left( c_{\text{exp}}(\lambda) + g_{\text{mix}}(\omega) \right) \\
\text{subject to:} & \\
\text{(Power grid constraints)} & \\
\text{Power flow equations} & \\
\text{Line limits} & \\
\text{Voltage limits (AC)} & \\
\text{Generation bounds} & \\
\text{Gas flow constraints} & \\
\text{Gas flow equations} & \\
\text{Pressure bounds} & \\
\text{Mass flow balance} & \\
\text{Compressor ratio limits} & \\
\text{Coupling constraints} & \\
\text{Expansion/design constraints} & \\
\end{align*}
\]

where the objective represents the capital expenditures (upgrades) and generation mix costs (generation dispatch):

\[
\begin{align*}
\frac{c_{\text{exp}}}{(\text{Capital expenditures})} &= \text{EP generation capital} + \\
& \quad \text{EP transmission capital} + \\
& \quad \text{NG transmission capital} + \\
& \quad \text{NG compression capital} \\
\frac{g_{\text{mix}}}{(\text{Generation mix})} &= \min \sum_{i} \sum_{t} C(g_{i}^{t}) \\
\text{where: } C(g_{i}^{t}) &= \text{cost of power generation \(g\) of fuel type \(t\) at bus \(i\)}
\end{align*}
\]

Develop principled formulations and solvers to find synergistic expansion planning solutions across electrical power and natural gas infrastructures.
Power Flow Formulation – AC Steady State Formulation

Voltage and Reactive Power often sources of problems during extreme events

\[ p_{ij}^g - p_i^l - g s_i v_i^2 = \sum_{j \in \Gamma_i} p_{ij}, \]
\[ q_{ij}^g - q_i^l + b s_i v_i^2 = \sum_{j \in N_i^e} q_{ij}, \]

Kirchhoff's Current Law

Ohm’s Law

\[ p_{ij} = \frac{g a}{r_a^2 + \Delta_a^2} v_i^2 - \frac{g a r_a + b a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_i - \theta_j) - \frac{b a r_a - g a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_i - \theta_j), \]
\[ q_{ij} = \frac{b a + c_a}{r_a^2 + \Delta_a^2} v_i^2 + \frac{b a r_a + g a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_i - \theta_j) - \frac{a r_a - b \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_i - \theta_j), \]
\[ q_{ji} = (-b a + c_a) v_j^2 + \frac{b a r_a - g a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_i - \theta_j) - \frac{a r_a - b \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_i - \theta_j), \]

Thermal Limits
Phase Angle Limits
Generator Output
Voltage Limits

https://github.com/lanl-ansi/PowerModels.jl
Gas Flow Formulation—Weymouth Formulation

**Flow Balance**

\[ \sum_{a=a_{ij} \in A^g} x_a - \sum_{a=a_{ji} \in A^g} x_a = s_i - d_i - \bar{d}_i, \]

\[ y_a^- U \leq x_a \leq y_a^+ U, \]

\[ y_a^- \pi_i \leq \pi_i - \pi_j \leq y_a^+ \bar{\pi}_i, \]

\[ y_a^- + y_a^+ = 1, \]

\[ \beta_a \geq \pi_i - \pi_j + (\pi_j - \pi_j)(y_a^+ - y_a^- - 1), \]

\[ \beta_a \leq \pi_i - \pi_j + (\pi_j - \pi_j)(y_a^+ - y_a^- - 1), \]

\[ \beta_a = \omega_a x_a^2, \]

**Weymouth Relationships**

\[ \pi_i \alpha_a - y_a^- (\pi_i \alpha_a - \pi_j) \leq \pi_j \leq \pi_i \bar{\alpha}_a + y_a^+ (\pi_j - \pi_i \bar{\alpha}_a), \]

\[ \pi_j \alpha_a - y_a^+ (\pi_j \alpha_a - \pi_i) \leq \pi_i \bar{\alpha}_a + y_a^+ (\pi_i - \pi_j \bar{\alpha}_a), \]

**Compression Limits**

\[ d_j \leq d_i \leq \bar{d}_i, \]

\[ s_i \leq s_i \leq \bar{s}_i, \]

**Injection Limits**

\[ \pi_i \leq \pi_i \leq \bar{\pi}_i, \]

**Pressure Limits**


Pressure often a source of problems during extreme events
Elasticity Formulation—Endogenous Pricing

- Locational Marginal Pricing for Electricity
- Historical price and pressure data used to calibrate a pressure-price relationship for natural gas

\[ d_i = \sum_{j \in \Gamma} (h_1^j + h_2^j p_j^g + h_3^j (p_j^g)^2), \]

Heat rate consumption curve

Cost

\[ \sum_{a \in A^e} \kappa_a^e z_a^e + \sum_{a \in A^g} \kappa_a^g z_a^g + \sum_{i \in \Gamma} (\mu_1 p_i^g + \mu_2 (p_i^g)^2) + \sum_{z \in Z} \lambda_z \left( \sum_{i \in \zeta} d_i \right), \]

- Cost of expanding power lines
- Cost of expanding pipelines
- Cost of Non-gas fired generation
- Elastic cost of gas


https://github.com/lanl-ansi/GasGridModels.jl
Extreme Event Formulation

- **Objective: Model Extreme Temperature Induced Stress**
  - Polar-vortex like events
  - Modeled as increased firm gas load
    - Causes congestion in pipes
    - Raises gas prices
    - Limits gas to non-firm gas load (gas-fired generators)

- **Formulation**
  - Split gas load into firm and non-firm load
  - Introduce zone-based, firm load scaling factors
Extreme Event Formulation

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- **Formulation**
  - Split gas load into firm and non-firm load
  - Introduce zone-based, firm load scaling factors
  - Analyze how increased demand for gas impacts electricity prices
  - Understand where gas-fired capacity decreases
  - Explore network expansion to increase throughput or lower electricity prices
Solution Methodology

• Challenging (NP-Hard) Optimization Problem
  • Power equations and gas equations are not convex
  • Example
    • $\beta_a = w_a x_a^2$
    • Relates pipeline pressure squared difference to flux squared

• Approach
  • Relax the non-convexities—Special approximation
    • Relaxed solution is a lower bound of the original problem’s best solution
    • If relaxed solution says electricity price is 15 cents per kwh, the actual solution is $\geq 15$ cents
  • Example
    • $\beta_a \geq w_a x_a^2$
Solution Methodology

• Challenging (NP-Hard) Optimization Problem
  • Power equations and gas equations are not convex
  • Example
    • $\beta_a = w_a x_a^2$
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• Approach
  • Use gradient descent to find a feasible solution from the relaxed solution
    • Feasible solution is an upper bound of the original problem’s best solution
    • If feasible solution says electricity price is 20 cents per kwh, the actual solution is $\leq 20$ cents
    • Combined, we have an actual solution that is 20 cents and we can’t do better than 15 cents
Gas-Grid Test System

• Grid model is the 36-node Allen-Lang-Ilic northeastern test system (IEEE Transactions on Power Systems. 2008)

• Gas transmission model assembled from public operator data

• Stress Cases
  • Increase gas demand by up to 200%
  • Increase electricity demand by up to 35%
  • Uniform and non-uniform demand increases
  • Expansions needed to avoid extreme price spikes

* In these examples, we treated this model as single market, single area
Example Results – 225% Gas Stress, 35% Gas Stress

- Expansions for demand growth only—5 power line upgrades
- Relieves thermal congestion in the west

- Expansions for demand growth and electricity price reductions—13 power lines upgrades
- Electric power upgrades in southern New York and New England to support “Gas-by-wire”
  - Move gas from low congestion areas (in the form of electricity)
Questions

Publications


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