Unit Commitment of Integrated Electric and Gas Systems with an Enhanced Second-Order Cone Gas Flow Model

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Technical Conference: Increasing Real-Time and Day-Ahead Market Efficiency and Enhancing Resilience through Improved Software
Federal Energy Regulatory Commission
Washington, D.C.
26–28 June, 2018

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The following are our own views and not necessarily those of the Electricity Advisory Committee or the U.S. Department of Energy.

Outline

1. Introduction and Background
2. Model Formulations
3. Case Study
   - Four-Node System
   - IEEE 118-Bus Test System
4. Concluding Remarks

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Future U.S. Power System

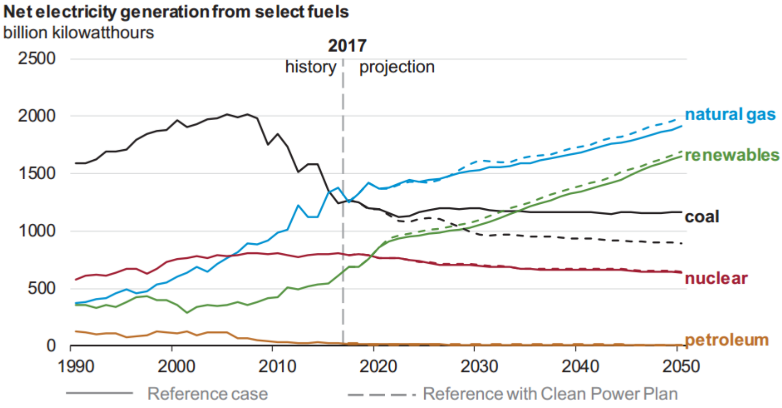

Figure : https://www.eia.gov/outlooks/aeo/

- More natural gas and renewables $\Longrightarrow$ increasingly interdependent electricity and gas systems

Operational Challenges

[Hibbard and Schatzki, 2012]

- Large-scale cascading electricity and gas service outage in southwest U.S. in February, 2011
- Gas-supply failures $\Longrightarrow$ loss of gas-fired generation $\Longrightarrow$ loss of electricity service $\Longrightarrow$ loss of electrically driven compressors $\Longrightarrow$ further loss of gas supply $\Longrightarrow \cdots$
- 1.3 million electricity and 50000 gas customers disrupted

Motivation

- It is important to coordinate the operations of increasingly interdependent electricity and gas networks
- The dependence of the energy price of one system on the other system has not been fully investigated

Contributions

- We propose a unit commitment model for the integrated electric and gas systems that incorporates an enhanced second order conic dynamic gas flow model
- We enhance this model using convex envelopes of bilinear terms, resulting in a tight UC formulation
- We investigate the impact of gas system congestion on electric LMPs (ELMPs) and the impact of power system congestion on gas LMPs (GLMPs)

Outline

Gas System-Operation Constraints

$$F_{S,m,t} - F^D_{L,m,t} - \sum_{k \in C(m)} \tau_{k,t} - \sum_{i \in G_p(m)} F_{G,i,t} = \sum_{n \in G(m)} F_{m,n,t} + \sum_{k \in C(m)} F_{C,k,t} \quad \forall m \in \Psi_G, t \in T$$

$$\frac{\bar{F}^2_{m,n,t}}{C^2_{m,n}} = \pi^2_{m,t} - \pi^2_{n,t} \quad \forall m,n \in G_B, t \in T$$

$$\bar{F}_{m,n,t} = \frac{1}{2}(F_{m,n,t} - F_{n,m,t}) \quad \forall m,n \in G_B, t \in T$$

$$F_{m,n,t} + F_{n,m,t} = L_{m,n,t} - L_{m,n,t-1} \quad \forall m,n \in G_B, t \in T$$

$$L_{m,n,t} = \frac{1}{2} K_{m,n} \cdot (\pi_{m,t} + \pi_{n,t}) \quad \forall m,n \in G_B, t \in T$$

$$\tau_{k,t} = \theta_k F_{C,k,t} \quad \forall k \in G_C, t \in T$$

- Inequalities: Nodal pressure, gas production, gas compressor, and line-pack limits

Second-Order Conic Model

- Non-convex equality:

$$\frac{\bar{F}^2_{m,n,t}}{C^2_{m,n}} = \pi^2_{m,t} - \pi^2_{n,t} \quad \forall m,n \in G_B, t \in T \tag{1}$$

- Second-order conic relaxation:

$$\frac{\bar{F}^2_{m,n,t}}{C^2_{m,n}} + \pi^2_{n,t} \leq \pi^2_{m,t} \quad \forall m,n \in G_B, t \in T \tag{2}$$

- Enhanced second-order conic non-convex relaxation:

$$\frac{\bar{F}^2_{m,n,t}}{C^2_{m,n}} \geq \pi^2_{m,t} - \pi^2_{n,t} \quad \forall m,n \in G_B, t \in T \tag{3}$$

- ***NB***: (2) + (3) = (1)

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Convexification

- To convexify (3):

$$\frac{\bar{F}_{m,n,t}^2}{C_{m,n}^2} \geq \pi_{m,t}^2 - \pi_{n,t}^2 \quad \forall m, n \in G_B, t \in T$$

  replace the bilinear terms with their convex envelopes [McCormick, 1976]
- Convex envelope of $\bar{F}_{m,n,t}^2$:

$$\left\langle \bar{F}_{m,n,t}^2 \right\rangle^M = \begin{cases} \kappa_{m,n} \geq \bar{F}_{m,n,t}^2 \\ \kappa_{m,n} \leq (F_{m,n,t}^{\max} + F_{m,n,t}^{\min})\bar{F}_{m,n,t} - F_{m,n,t}^{\max} F_{m,n,t}^{\min} \end{cases}$$

- Convexify $\pi_{m,t}^2 - \pi_{n,t}^2$ by defining $a_{m,n,t} = \pi_{m,t} + \pi_{n,t}$, $b_{m,n,t} = \pi_{m,t} - \pi_{n,t}$, and:

$$\left\langle a_{m,n,t} b_{m,n,t} \right\rangle^M = \begin{cases} \lambda_{m,n,t} \geq a_{m,n,t}^{\min} b_{m,n,t} + b_{m,n,t}^{\min} a_{m,n,t} - a_{m,n,t}^{\min} b_{m,n,t}^{\min} \\ \lambda_{m,n,t} \geq a_{m,n,t}^{\max} b_{m,n,t} + b_{m,n,t}^{\max} a_{m,n,t} - a_{m,n,t}^{\max} b_{m,n,t}^{\max} \\ \lambda_{m,n,t} \leq a_{m,n,t}^{\min} b_{m,n,t} + b_{m,n,t}^{\max} a_{m,n,t} - a_{m,n,t}^{\min} b_{m,n,t}^{\max} \\ \lambda_{m,n,t} \leq a_{m,n,t}^{\max} b_{m,n,t} + b_{m,n,t}^{\min} a_{m,n,t} - a_{m,n,t}^{\max} b_{m,n,t}^{\min} \end{cases}$$

- (3) becomes: $\kappa_{m,n} / C_{m,n}^2 \geq \lambda_{m,n,t}$

Convexification

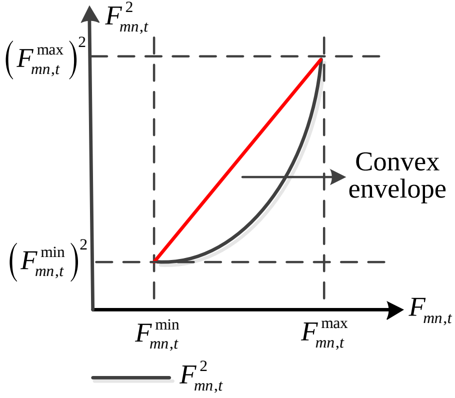

Figure : Convex envelope of $\bar{F}^2_{m,n,t}$

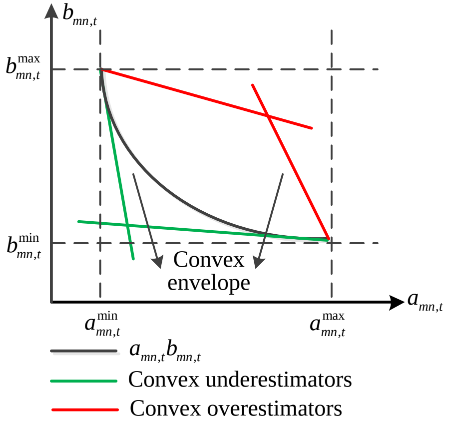

Figure : Convex envelope of $\pi^2_{m,t} - \pi^2_{n,t}$

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Unit Commitment Models

- We compare three unit commitment models:
  1. UC with exact non-convex gas-flow constraints
  2. UC with SOC gas-flow constraints
  3. UC with enhanced SOC gas-flow constraints
- Tightness of the enhanced SOC gas-flow constraints depends on the choices of $F^{\max}_{m,n,t}$, $F^{\min}_{m,n,t}$, $a^{\max}_{m,n,t}$, $a^{\min}_{m,n,t}$, $b^{\max}_{m,n,t}$, and $b^{\min}_{m,n,t}$
- We update these iteratively when solving model 3 as:

$$F^{\max}_{m,n,t} = (1+\epsilon)F^{*}_{m,n,t} \qquad F^{\min}_{m,n,t} = (1-\epsilon)F^{*}_{m,n,t}$$

$$a^{\max}_{m,n,t} = (1+\epsilon)a^{*}_{m,n,t} \qquad a^{\min}_{m,n,t} = (1-\epsilon)a^{*}_{m,n,t}$$

$$b^{\max}_{m,n,t} = (1+\epsilon)b^{*}_{m,n,t} \qquad b^{\min}_{m,n,t} = (1-\epsilon)b^{*}_{m,n,t}$$

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Test System

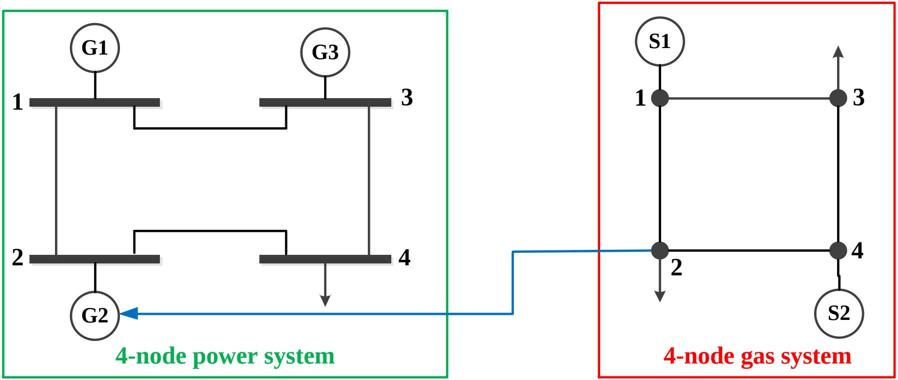


Figure : Four-Bus Power System with Four-Node Natural Gas System

Cases

1. Baseline electricity and natural gas demands
2. $+10\%$ natural gas demands
3. $+20\%$ natural gas demands

Objective-Function Values

Case 3: +20% Natural Gas Demands

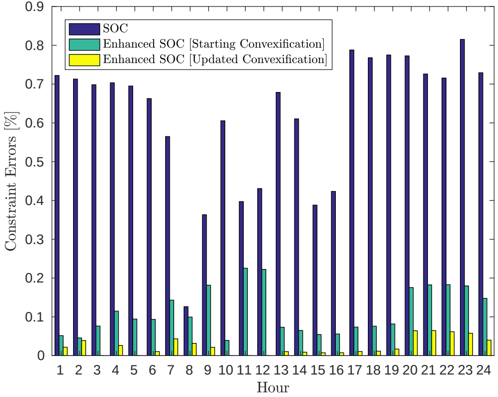
	Objective-Function Value [$ million]	Error [%]
UC + Non-Convex	3.943	
UC + SOC	3.907	0.91
UC + Enhanced SOC (Starting Convexification)	3.913	0.76
UC + Enhanced SOC (Updated Convexification)	3.928	0.38

Constraint Errors

Case 3: +20% Natural Gas Demands

- Defined as:

$$\sum_{m,n \in G_B} \frac{\pi_{m,t}^2 - \bar{F}_{m,n,t,}^2 / C_{m,n}^2 - \pi_{n,t}^2}{\pi_{m,t}^2}$$



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Gas LMPs

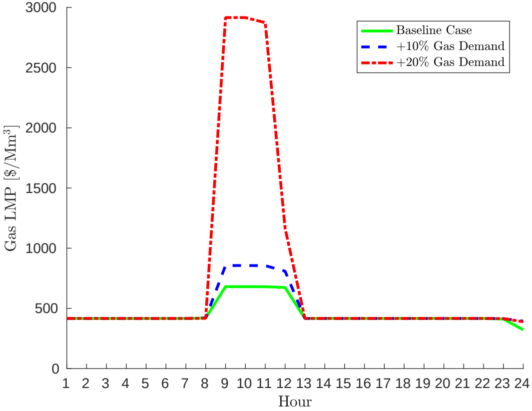

Figure : Load-Weighted Gas LMPs

- Increase in hours 9–12 due to gas system congestion and unavoidable gas-demand curtailment

Electric LMPs

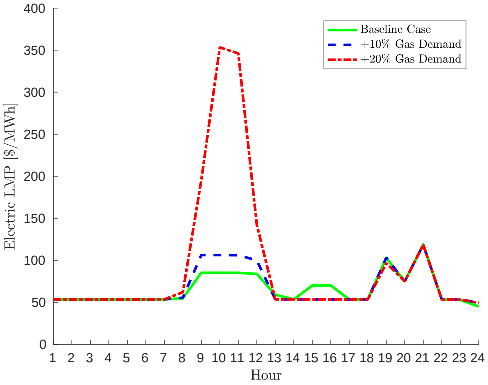

Figure : Load-Weighted Electric LMPs

- High GLMPs yield high ELMPs
- 19 GW of gas-fired generation with baseline demand, reduced to 17 GW and 13 GW in other cases due to its higher relative cost

Test System

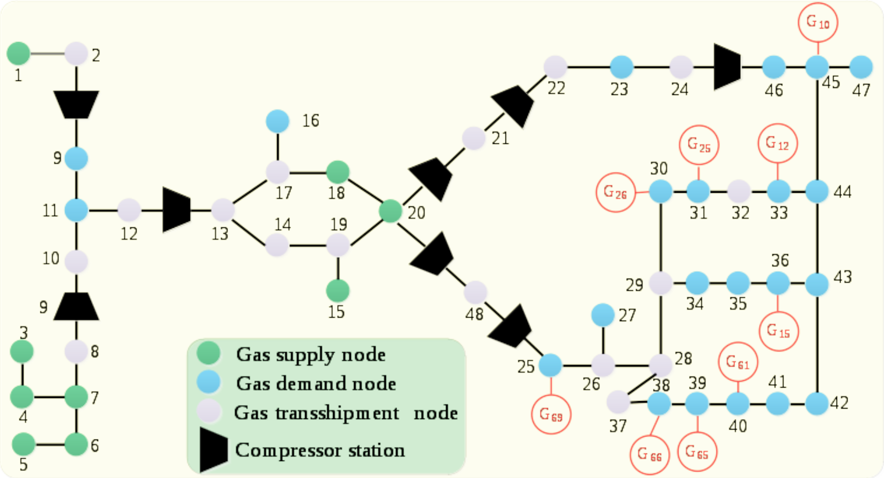

Figure : IEEE 118-Bus Test System with 48-Node Natural Gas System

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Cases

1. Baseline
2. -20% capacity on all transmission lines
3. -40% capacity on all transmission lines

Electric LMPs

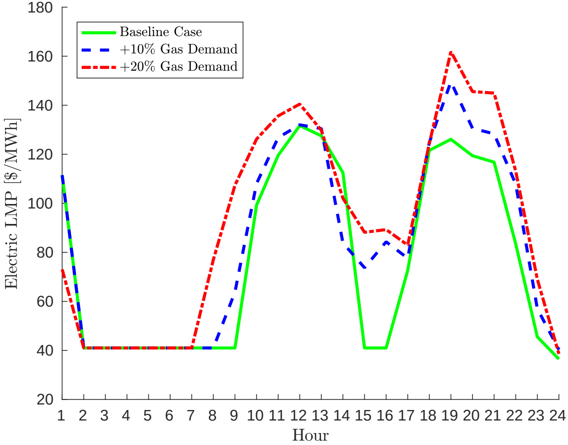

Figure : Load-Weighted Electric LMPs

- Reduced transmission capacity affects ELMPs in hours 8–24

Gas LMPs

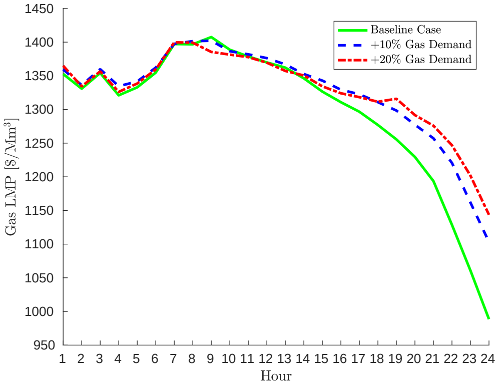

Figure : Load-Weighted Gas LMPs

- Increased GLMPs during hours 19–22 (peak-electric-demand periods)
- Power system congestion results in higher ELMPs and GLMPs simultaneously

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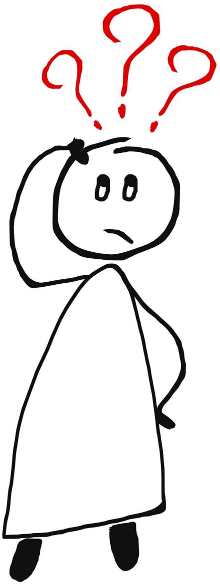
Summary

- Our proposed convex UC model with an enhanced second-order conic gas flow model results in a tighter and more efficient UC solution compared with a simple SOC or non-convex gas flow models
- Four-node case study shows the impact of gas system congestion on ELMPs
- IEEE 118 bus test system case study shows the impact of power system congestion on GLMPs
- Our proposed model could serve as an effective tool for analyzing interdependencies of electric and natural gas system

Questions?



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