Coordinated Scheduling of Interdependent Electricity and Natural Gas Infrastructures

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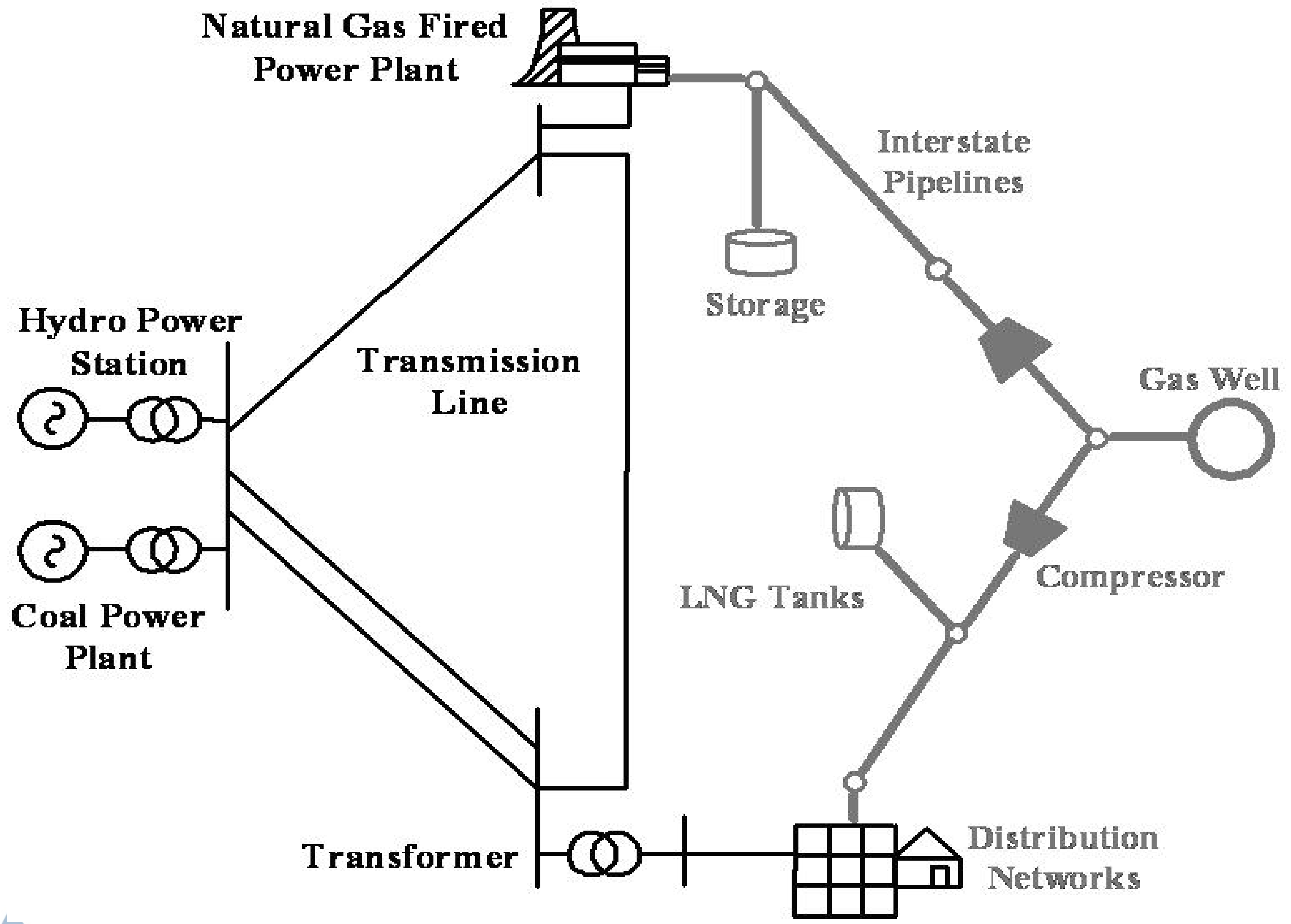
Outline

- Background and proposed problems
- Modeling of components in natural gas system and electric power system
- Least social cost of scheduling coordination of power system and natural gas system
- Security-constrained scheduling of electric power system with natural gas transmission constraints
- Summary

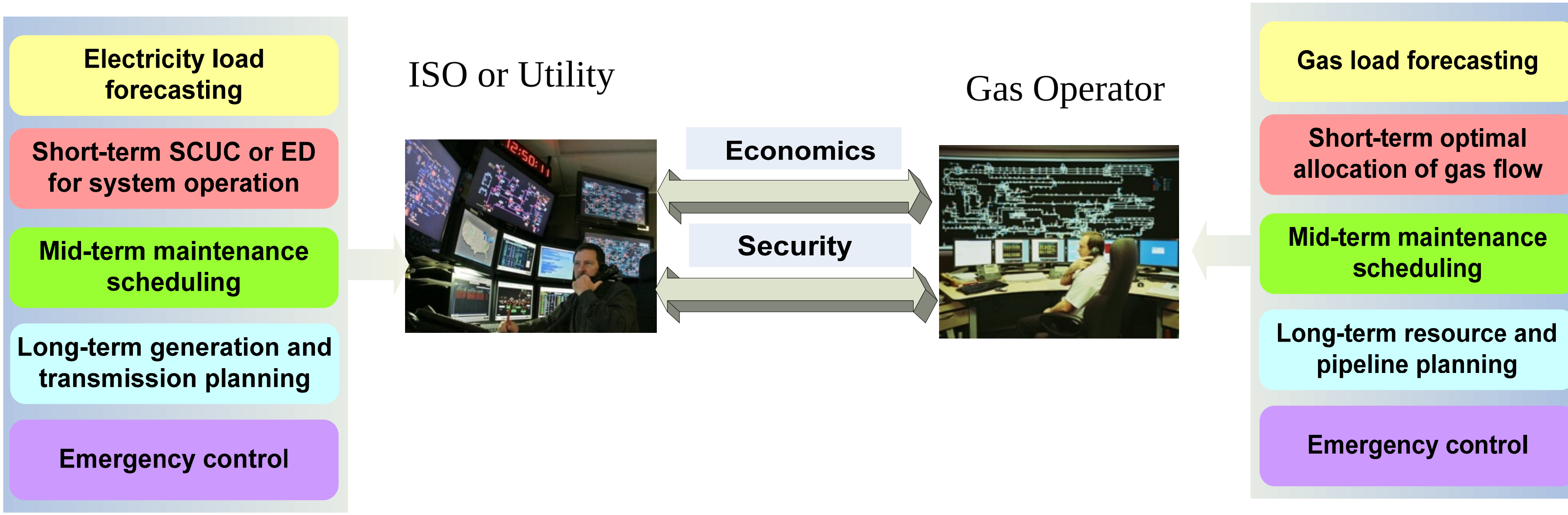
Background

- Intermittent and volatile renewable energy in the future's grid require more quick-start units to cover its uncertainty
- Gas-fired combined-cycle power plants have mushroomed in the last decade due to their characteristics of lower investment cost and high-efficiency.
- Power system depends on natural gas supply increasingly
- The natural gas supply of power plants can be interrupted with little notice and can be bumped by higher priority services if they sign a interruptible contract
- Line pack resource in pipeline is crucial to the ramping capacities and reserve capabilities of gas-fired generators

Coupled Infrastructures



Interdependency of NG and Power Infrastructures



- Similarity and difference between power and natural gas infrastructures
- Coordination schemes: two different ways with different optimization problems
- Decomposition strategies

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Difference between natural gas flow and power flow

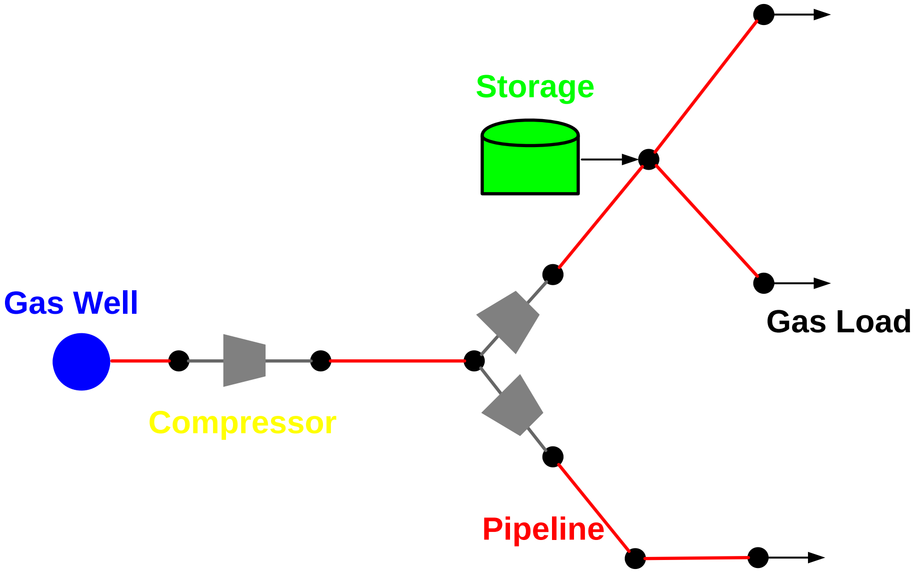
- Power flow and natural gas flow travel through infrastructures with different speeds
- Natural gas pipelines have storage capability especially for high pressure interstate pipelines
- For different purpose, natural gas flow can be modeled as steady-state formulations and transient-state formulations
- In operation planning, power systems can be modeled using steady-state formulations. However, steady-state models of natural gas transmission systems may lead to inaccurate results

Modeling of electric power system in steady state

- DC or AC power flow: algebraic equations
- Reserve constraints
- Power balance constraints
- Unit commitment and economic dispatch constraints such as ramping constraints, minimum on/off time and so on
- Cascaded-hydro reservoirs constraints

Natural gas transmission system in steady state

- Pipeline
- Compressor
- Gas load
- Gas well and storage



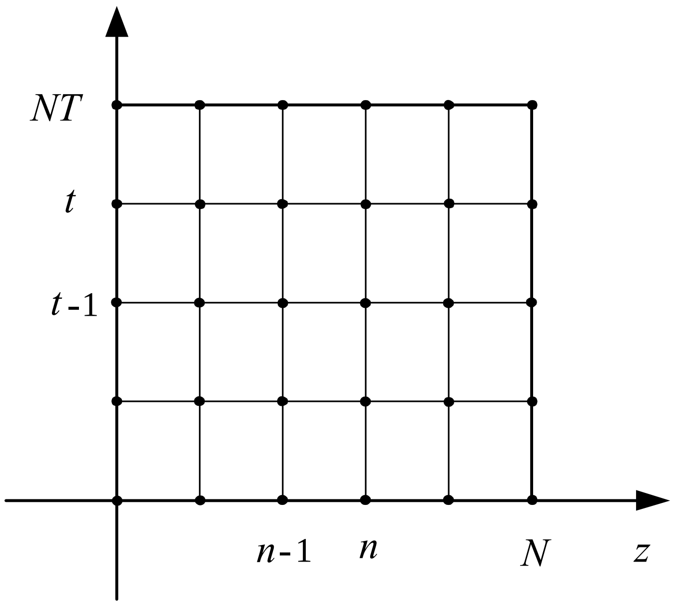
- All components are modeled as algebraic equations

Transient state model of pipelines

- We focus on the slow transient process in terms of hours caused by gas load swings, those formulations can be simplified without sacrificing calculation accuracy
- Natural gas flow equations are represented as a group of partial differential equations and algebraic equations
- In order to solve partial differential equations (PDEs), it is required to know its boundary conditions. At t = 0, the initial values can be given by various measurements in the natural gas transmission system. At the beginning point and terminal end of a pipeline (Space boundary), gas flows satisfy nodal gas flow balance constraints

Implicit finite difference

- The philosophy of finite difference methodology is to evaluate the dependent variables at discrete points in a spanning region of time and space as shown in the figure.
- Implicit finite difference method are used to replace derivative expressions in space and time with equivalent difference equations.



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Coordinated scheduling outline

- This model treats natural gas and power system evenly, and minimized sum of operating costs of power system and natural gas system.

$$Min \left\{ \begin{array}{l} \text{Power generation costs} \\ + \text{Electricity load not serve costs} \end{array} \right\} EC(\boldsymbol{x})$$

$$+ \left\{ \begin{array}{l} \text{Natural gas allocation costs} \\ + \text{Gas load not serve costs} \end{array} \right\} GC(\boldsymbol{y})$$

$s.t.$

(a)Power balance and reserve requirements

(b)Individual generator constraints (Including min on/off time, min/max generation, startup/ shutdown characteristics, ramp rate limits, etc)

(c)Cascaded-hydro reservoirs constraints

(d)Electricity network constraints

(e)Gas source limits and gas storage constraints

(f)Natural gas network constraints

(g)Electricity-gas coupling constraints $\boldsymbol{e}(\boldsymbol{x}_c) - \boldsymbol{g}(\boldsymbol{y}_c) = 0$

Lagrangian Relaxation

- Lagrangian Function:

$$\mathcal{L}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\lambda}) = EC(\boldsymbol{x}) + GC(\boldsymbol{y}) + \boldsymbol{\lambda}^T \boldsymbol{e}(\boldsymbol{x}_c) - \boldsymbol{\lambda}^T \boldsymbol{g}(\boldsymbol{y}_c)$$

- Lagrangian Dual:

$$\phi(\boldsymbol{\lambda}) = \underset{\boldsymbol{x},\boldsymbol{y}}{Min}\left\{\mathcal{L}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\lambda}) \mid (a)-(f)\right\}$$

- Dual Problem:

$$\underset{\boldsymbol{\lambda}}{Max}\ \underset{\boldsymbol{x},\boldsymbol{y}}{Min}\left\{\mathcal{L}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\lambda}) \mid (a)-(f)\right\}$$

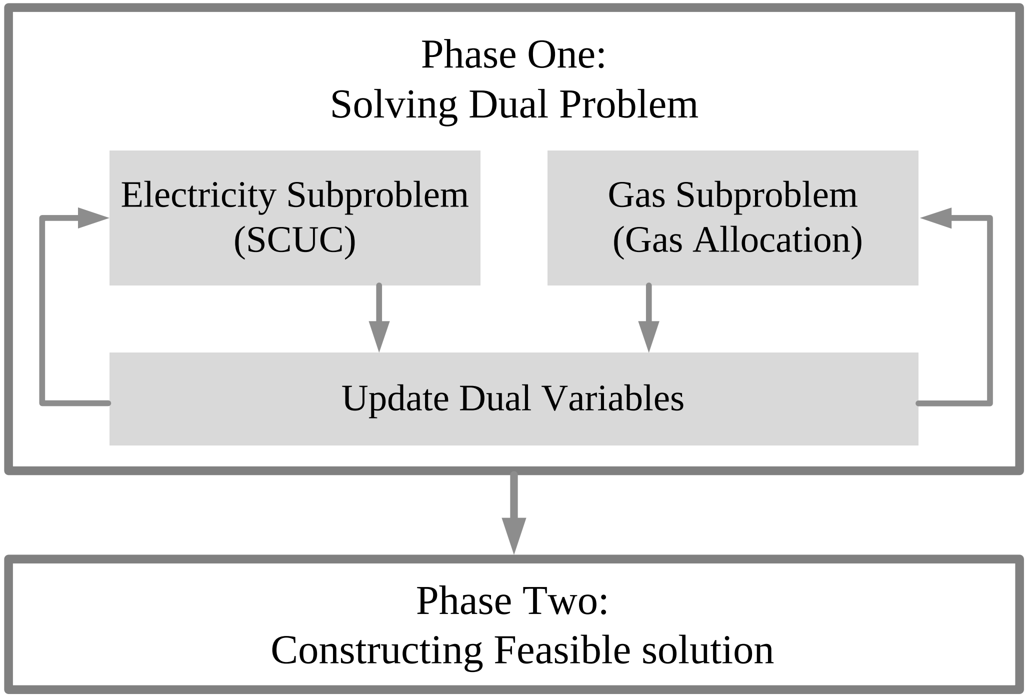
- For given $\boldsymbol{\lambda}^{(k)}$:

SCUC $$\underset{\boldsymbol{x}}{Min}\left\{ EC(\boldsymbol{x}) + \boldsymbol{\lambda}^{(k)} \cdot \boldsymbol{e}(\boldsymbol{x}_c) \mid (a)-(d)\right\}$$

Gas Allocation $$\underset{\boldsymbol{y}}{Min}\left\{GC(\boldsymbol{y}) - \boldsymbol{\lambda}^{(k)} \cdot \boldsymbol{g}(\boldsymbol{y}_c) \mid (e)-(f)\right\}$$

Decomposition Strategies

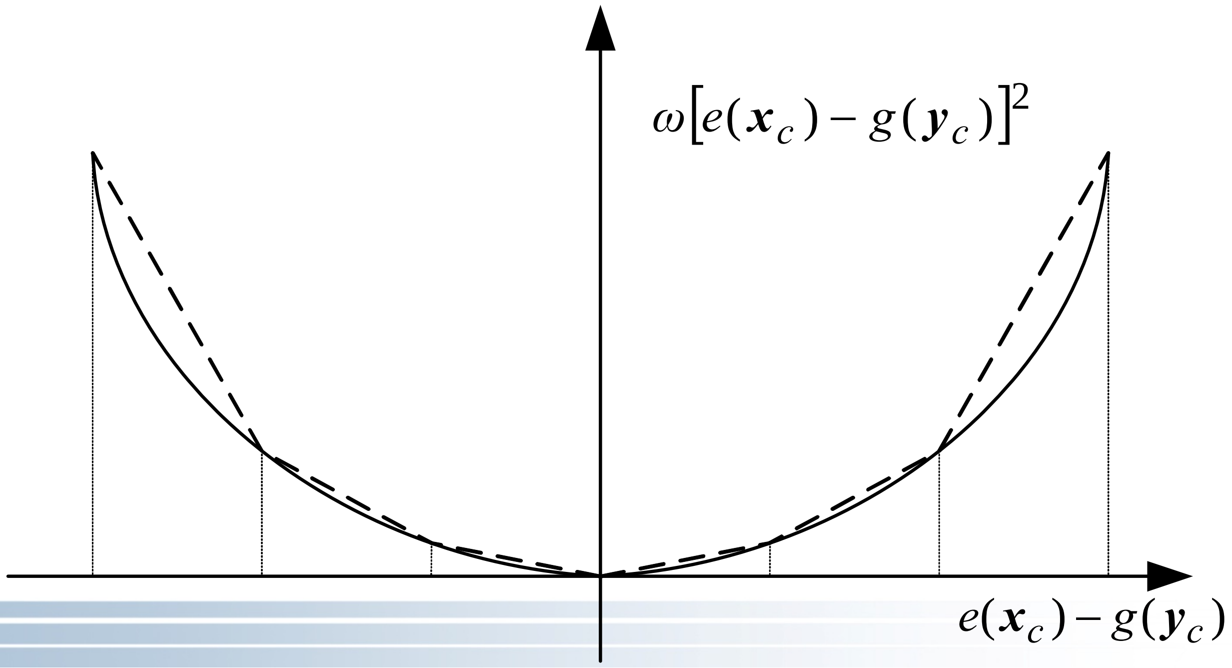
- Dual decomposition by Lagrangian relaxation



Augmented Lagrangian Relaxation

- For avoiding numerical oscillations and improve quality of solution, we introduce quadratic penalty terms to Lagrangian function

- Piecewise linear approximation of quadratic penalty terms $\mathcal{A}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\omega},\boldsymbol{\lambda}) = EC(\boldsymbol{x}) + GC(\boldsymbol{y}) + \boldsymbol{\lambda}^T\left[\boldsymbol{e}(\boldsymbol{x}_c) - \boldsymbol{g}(\boldsymbol{y}_c)\right] + \boldsymbol{\omega}^T\left\|\boldsymbol{e}(\boldsymbol{x}_c) - \boldsymbol{g}(\boldsymbol{y}_c)\right\|^2$



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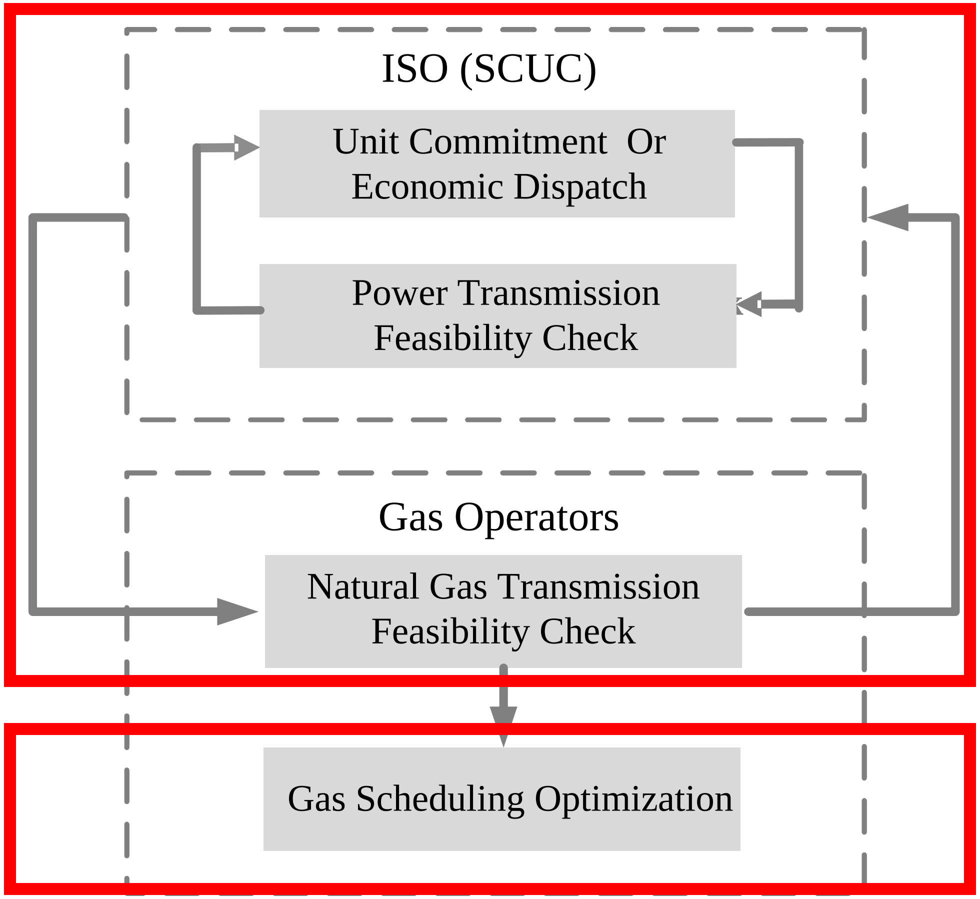
Security-constrained unit commitment with natural gas transmission constraints

- The bilevel model is to optimize operating cost of power system while satisfying unit commitment constraints and power transmission constraints. Gas scheduling problem is nested into upper level problem as a constraints

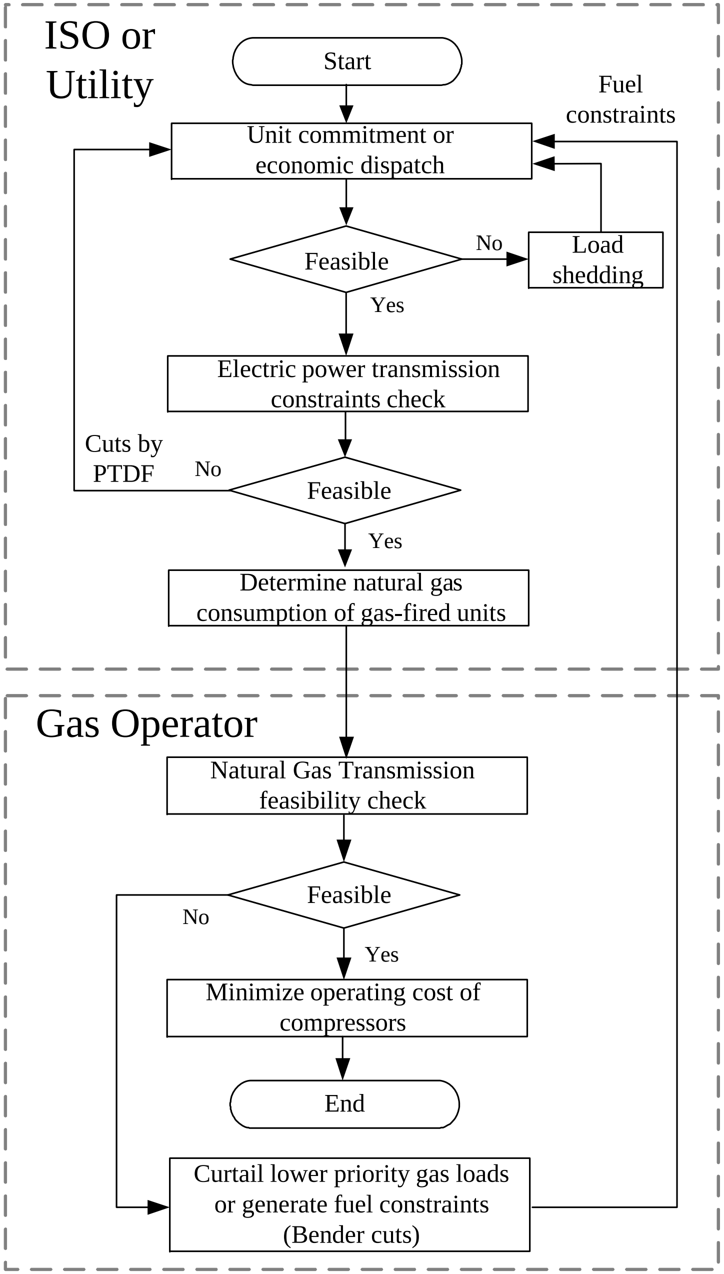
$\underset{\boldsymbol{x}}{Min} \quad EC(\boldsymbol{x})$	UC and generation cost
$s.t. \qquad \boldsymbol{EU}(\boldsymbol{x}) \leq \boldsymbol{0}$	UC constraints
$\boldsymbol{EN}(\boldsymbol{x}) \leq \boldsymbol{0}$	Power transmission constraints
$\boldsymbol{e}(\boldsymbol{x}_c) - \boldsymbol{g}(\boldsymbol{y}_c) = 0$	Power gas coupling constraints
$\underset{\boldsymbol{y}}{Min} \quad GC(\boldsymbol{y})$	Compressor operating cost
$s.t. \quad \boldsymbol{GN}(\boldsymbol{y}) \leq \boldsymbol{0}$	Transient state gas transmission constraints

Coordination scheme



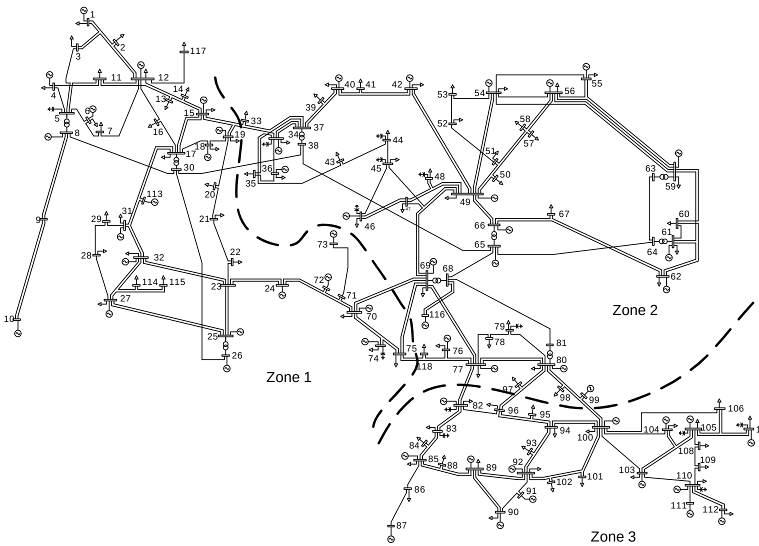
Solutions

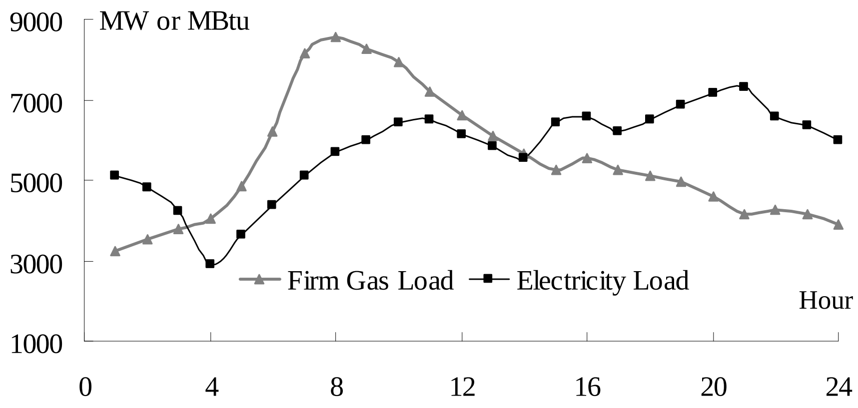
- Master UC: Solve MIP formulations by branch and cuts (CPLEX)
- Power and gas transmission feasibility check: Successive linear programming
- Gas scheduling problem: Successive linear programming

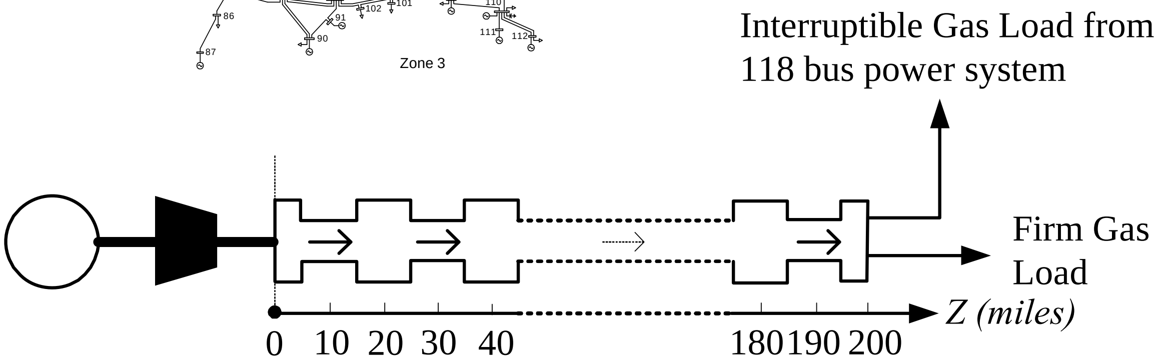


Case study

118 bus system supplied by a interstate pipeline



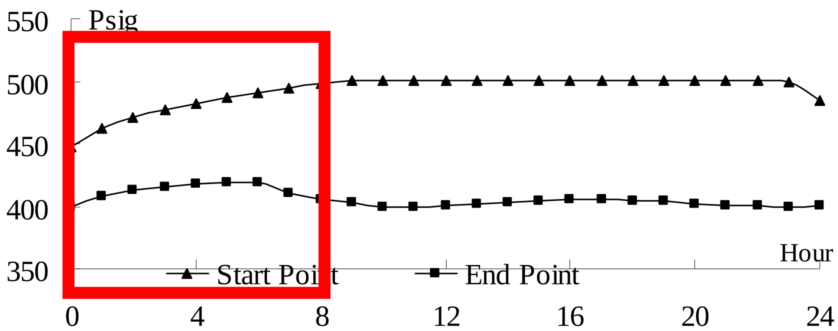




Case study

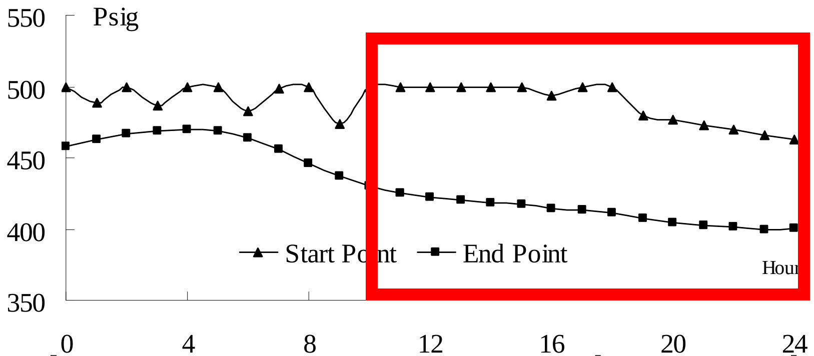
- Case 1: Scheduling coordination with steady-state gas transmission constraints
- Case 2: Scheduling coordination with transient gas flow model based on lower initial line pack
- Case 3: Scheduling coordination with transient gas flow model based on higher initial line pack

Case study



Charging pipeline

Hourly Pressure at Starting and Ending Points of the Pipeline in Case 2 (lower initial pressure)



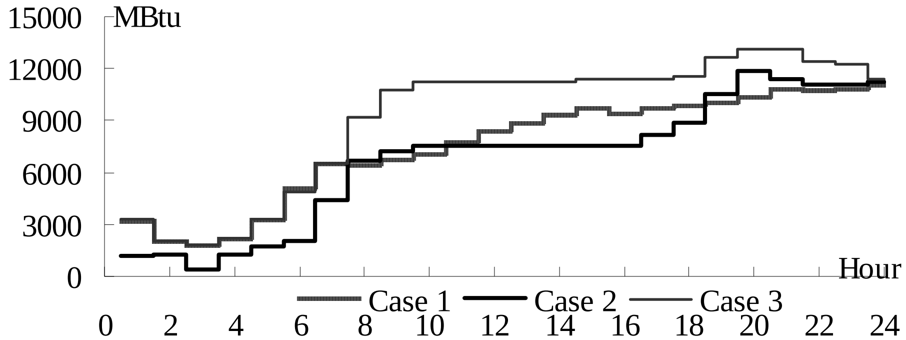
Releasing line pack resources

Hourly Pressure at Starting and Ending Points of the Pipeline in Case 3 (higher initial pressure)

Case study

Unit commitment and dispatches are different in Case 1-3

Daily Results	Case 1	Case 2	Case 3
Daily operating cost ($) of electric power system	2,046,006	2,044,479	2,037,255
Daily natural gas amount consumed by compressor (MBtu)	8,965	12,273	5,056
Daily gas well output (MBtu)	322,031	408,621	201,383
Daily natural gas amount delivered to power plants (MBtu)	181,766	163,200	220,649
Daily electric power generated by natural gas plants (MW)	13,962	12,995	17,316



Hourly Gas Amount Delivered to Power Plants in Case 1-3

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- Different scheduling coordination schemes between the power system operator and the natural gas operator are proposed
- L-shaped decomposition and dual decomposition based on sensitivity and augmented Lagrangian relaxation are developed to solve the coordinated scheduling problem
- Electricity and natural gas energy are transported through infrastructures by different ways and speeds. Both steady state and transient state formulations of natural gas transmission system are applied in our proposed integrated scheduling model.
- Proposed model provides a foundation for mid-term or long-term study analysis for integrated planning.

References

[1]C. Liu, M. Shahidehpour, Y. Fu, Z. Li, "Security-constrained unit commitment with natural gas transmission constraints," IEEE Transactions on power systems, Vol 24, 2009

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Questions?
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