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

Natural Gas Fired Power Plant

Hydro Power Station

Coal Power Plant

Transmission Line

Interstate Pipelines

Storage

Gas Well

LNG Tanks

Compressor

Distribution Networks
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 purposes, 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.

\[
\begin{align*}
\text{Min} & \quad \left\{ \begin{array}{l}
\text{Power generation costs} \\
\quad + \text{Electricity load not serve costs}
\end{array} \right\} \quad EC(x) \\
\quad + \left\{ \begin{array}{l}
\text{Natural gas allocation costs} \\
\quad + \text{Gas load not serve costs}
\end{array} \right\} \quad GC(y)
\end{align*}
\]

\[s.t.\]
(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 \( e(x_c) - g(y_c) = 0 \)
Lagrangian Relaxation

- Lagrangian Function:

\[
\mathcal{L}(x, y, \lambda) = EC(x) + GC(y) + \lambda^T e(x_c) - \lambda^T g(y_c)
\]

- Lagrangian Dual:

\[
\phi(\lambda) = \min_{x, y} \left\{ \mathcal{L}(x, y, \lambda) \mid (a) - (f) \right\}
\]

- Dual Problem:

\[
\max_{\lambda} \min_{x, y} \left\{ \mathcal{L}(x, y, \lambda) \mid (a) - (f) \right\}
\]

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

  SCUC \quad \min_x \left\{ EC(x) + \lambda^{(k)} \cdot e(x_c) \mid (a) - (d) \right\}

  Gas Allocation \quad \min_y \left\{ GC(y) - \lambda^{(k)} \cdot g(y_c) \mid (e) - (f) \right\}
Decomposition Strategies

- Dual decomposition by Lagrangian relaxation

Phase One:
Solving Dual Problem

- Electricity Subproblem (SCUC)
- Gas Subproblem (Gas Allocation)

Update Dual Variables

Phase Two:
Constructing Feasible solution
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

\[
\mathcal{A}(x, y, \omega, \lambda) = EC(x) + GC(y) + \lambda^T [e(x_c) - g(y_c)] + \omega^T \|e(x_c) - g(y_c)\|^2
\]
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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 constraint.

\[
\begin{align*}
\text{Min}_{x} & \quad EC(x) \\
\text{s.t.} & \quad EU(x) \leq 0 \\
& \quad EN(x) \leq 0 \\
& \quad e(x_c) - g(y_c) = 0 \\
\text{Min}_{y} & \quad GC(y) \\
\text{s.t.} & \quad GN(y) \leq 0
\end{align*}
\]

UC and generation cost
UC constraints
Power transmission constraints
Power gas coupling constraints
Compressor operating cost
Transient state gas transmission constraints
Coordination scheme

ISO (SCUC)
- Unit Commitment Or Economic Dispatch
- Power Transmission Feasibility Check

Gas Operators
- Natural Gas Transmission Feasibility Check

Gas Scheduling Optimization
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

Interruptible Gas Load from 118 bus power system
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

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

Charging pipeline

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

Releasing line pack resources
Case study

Unit commitment and dispatches are different in Case 1-3

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

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

Questions?
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