An Analytical Framework for Combined Natural Gas and Electricity Markets

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Outline

• The two markets
  – Underlying networks
  – Physics
  – Coupling between the two

• Proposed Market Framework for Transactive Control
  – Wholesale Electricity Market
  – Advantages

• Extension to coupled gas and elec. markets
From NY Times, Feb 16, 2013

In New England, a Natural Gas Trap...

- Electricity prices were 4 to 8 times higher than normal earlier this month in New England
- Dominance of single fuel source - Natural gas: Supplies at least 50% of NE’s electricity
- Lower costs of gas have led to accelerated shut down of aging power plants
- Gas pipeline capacity is inadequate; LNG mostly exported to outside US
- Poor meshing of the two markets – Elec around the clock, Gas closing down at night
The two networks*

The two networks: Comparisons

• Physics
  – Speed of transmission (8 vs. $3 \times 10^8$ m/s)
  – Storage of gas: {inexpensive, large-scale} vs. {expensive, highly limited, emerging}
  – Transmission network: introduction of LNG can cause a huge change

• Constraints
  – Unit Constraints: ramping on gas-fired reserves
  – Capacity constraints: Limit on pipe-line
  – Contractual – supply can be interrupted by higher priority services
The two networks: Dependency

- Gas-fired power plants provide a linkage between natural gas transmission and power transmission systems.
- Natural gas transmission could affect the economics and the security of power transmission.
  - **Economics:** Natural gas contracts could affect the commitment, dispatch, and the operation of power systems.
  - **Security:** Pressure losses, pipeline contingencies, lack of storage or natural gas supply disruptions may lead to forced outages, dramatically increase the operating costs and congestion, and jeopardize security of power systems.

- Has implications on the unit commitment (UC) problem

- In this talk: A Transactive Control Framework to analyze and accommodate this dependency
Transactive control: An Emerging Paradigm*

The use of dynamic market mechanism to send an incentive signal and receive a feedback signal within the power system’s node structure

• Incentive Signal: Ex. Dynamic Pricing
• Feedback Signal:
  • Adjustable Demand (Tertiary Level)
    • (Price Responsive, and Regulation Responsive)

* Hammerstorm et al., “Standardization of a Hierarchical Transactive Control System”
Transactive Control: Example

• Pacific Northwest Demonstration Project
• Approximately 40 TC test cases in project
• Examples include:
  – Voltage optimization
  – Load control
  – Storage system control

Courtesy of Olympic Peninsula Project, IBM
TIS: Transactive Incentive Signal
TFS: Transactive Feedback Signal
Transactive control: Introduces Feedback!

Advantages
- Reduced congestion
- Integration of renewables
- Reduced utility cost

Disadvantages
- May introduce volatility
- Time-scale and parameter dependent

(ISO)

Demand

Feedback Signal

Transactive Control

Must accommodate
- grid-constraints
- costs
Incentive signal
Transactive control: Our Definition

The use of dynamic market mechanism to send an incentive signal and receive a feedback signal within the power system’s node structure

- Incentive Signal: Ex. Dynamic Pricing
- Feedback Signal:
  - Adjustable Demand (Tertiary Level)
    - (Price Responsive, and Regulation Responsive)
  - Area Control Error (Secondary Level)
  - Governor Control (Primary Level)
Proposed Transactive Control Framework*

Analytical Framework
Top Level: Market Mechanism

Minimize $f(x)$ (Cost)

Subject to
\[ g(x) = 0 \] (Power balance, losses)
\[ h(x) \leq c \] (Constraints)

Equivalent to Optimization of
\[ L(x, \lambda, \mu) = f(x) + \lambda^T g(x) + \mu^T (h(x) - c) \]

$\lambda$: Locational Marginal Price
$\mu$: Congestion Price

\[ \lambda(k) = \lambda(k-1) + \gamma \partial L / \partial \lambda \]
\[ \mu(k) = \mu(k-1) + \gamma \partial L / \partial \mu \]
Transactive control framework: Market Level

\[ L = \sum_{i \in G_f} C_{G_i}(P_{Gi}) - \sum_{j \in D_q} U_{D_j}(P_{Dj}) + \sum_{n=1}^{N} \rho_n B + \sum_{k=1}^{N_t} \gamma_k [T - T_{k}^{max}] \]

\[ \Delta P_G(k) = -k_G \frac{\partial L}{\partial P_G} \]  
(Generation)

\[ \Delta P_D(k) = -k_D \frac{\partial L}{\partial P_D} \]  
(Demand)

\[ \Delta \rho(k) = k_{\rho} B \]  
(Real-time Price)

\[ \Delta \gamma(k) = k_{\gamma} \max(0, T - T_{max}) \]  
(Congestion)
Transactive Control: Top Level

Market Mechanism:

\[ x[K + 1] = (I_n + hA)x[K] + hk_\rho \Delta + b \]

\[ x(K) = \begin{bmatrix} \{P_G\}_i \{P_D\}_j \{\delta\}_n \{\rho\}_n \end{bmatrix}^T \]

\[ A = \begin{bmatrix} -k_g c_g & 0 & 0 & k_g A_g^T \\ 0 & k_d c_d & 0 & -k_d A_d^T \\ 0 & 0 & 0 & k_\delta Y^T \\ -k_\rho A_g & k_\rho A_d & k_\rho Y & 0 \end{bmatrix} \]

\[ n : N_g + N_d + 2N - 1 \quad N_g : \#GenCo \quad N_d : \#ConCo \quad N : \#buses \]

\[ k_g, k_d, k_\delta, k_\rho : \text{Parameters of the RTM dynamic model} \]

- Quantifies effect of volatility and stability
- Can help reduce reserve costs with wind uncertainty
Transactive Control: Lower Levels

\[ x_t[K + 1] = \tilde{A}_t x_t[K] + b \]

Tertiary Level

\[ \dot{x}_p = (A + E_p)x_p(t) + Bz_p(t) + Fu(k) \]
\[ \epsilon \dot{z}_p = C x_p(t) + Dz(t) + \phi_p(t) \]
\[ u[k + 1] = u[k] - L_s x_s[k] + L_t x_t[K] \]
\[ x_s[k + 1] = (\tilde{A}_s + C_s E_s)x_s[k] + B_s L_t x_t[K] \]
\[ e_s[k + 1] = (\tilde{A}_s + C_s E_s)e_s[k] + C_s E_s R_t x_t[K] \]
\[ x_t[K + 1] = \tilde{A}_t x_t[K] + h k_\rho E_t e_s[K] + b \]

The overall model, including the primary, secondary, and tertiary level dynamics at multiple time-scales.
Simulation Results

- 4-bus network with two generator units at node 1 and wind at bus 2 ($P_{g1}$: Base-load; $P_{g2}$: Reserve)
- $L_1$: Price-responsive (PR)-DR; $L_2$: Regulation-responsive (RR)-DR

Figure 5

Tabular 5

<table>
<thead>
<tr>
<th>Power [p.u.]</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
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<tbody>
<tr>
<td>$P_{g2}$ without Transactive control</td>
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Comparison of Dynamic Market Mechanism (DMM) and Current Market Mechanism (CMM) for 400 seconds interval

Algorithm Total Generation

Reserve requirement after applying Dynamic Market Mechanism (DMM) at tertiary level

Power [p.u.]: Base-load; $P_{D1}$, $P_{D2}$

Area 1

Area 2

$P_{D1}$, $P_{D2}$

$L_1$, $L_2$

Diagram: 4-bus network with two generator units at node 1 and wind at bus 2.
Transactive Control: Hierarchical coordination

5.3 Stability Analysis of Transactive Controller

Step fi: Stability of the tertiary level

We now consider the complete system defined by

Let us assumed that strong duality holds and there exists a regular equilibrium point

The singular perturbed tertiary level in

can be represented as

Using the method of the singular perturbation approach and time scale separations the tertiary dynamics in

and ACE dynamics in

can be transformed into slow and fast subsystems as

where

Denote the slow and fast decomposition of the original system in

From assumptions it follows that and are asymptotically stable. This in turn implies that and ensure the boundedness of the solutions of the secondary level and primary level dynamics in

Demand Response:

Tertiary level (PR-DR)

Demand Response:

Secondary level (RR-DR)

PR-DR

RR-DR

Demand
Generation
Demand
Generation
Demand
Generation

~5 mins

TRANSACTIVE CONTROL

AREA-LEVEL

SECONDARY (FREQUENCY) CONTROL

UNIT- LEVEL

PRIMARY (POWER) CONTROL
Fluctuations in the gas market are at a slower time-scale.

"Coordinated Scheduling of Interdependent Electricity and Natural Gas Infrastructures, Cong Liu, Mohammad Shahidehpour, Jianhui Wang, Argonne National Lab Report"
Coupled Markets: Underlying Model

- $x_i$: Amount of Electricity produced by Producer $i$ at node $n$
- $y_i$: Amount of Gas produced by Producer $i$ at node $n$
- $f_{1}(x)$: Cost of interest in the power network (ex. Social welfare)
- $f_{2}(y)$: Cost of interest in the gas network
- $S_{x}$: Storage at node $n$
- $S_{y}$: Storage at node $n$
- $g(x)+S_{x}=0$: Power Balance at node $n$
- $g(y)+S_{y}=0$: Mass Balance at node $n$
Coupled Electricity and Gas Markets

\[ \text{Min } f'_1(x) \]
Subject to
\[ g(x) + s_1 = 0 : \lambda x \]
\[ h(x) \leq c : \mu \]
\[ F_1(x) + F_2(y) = m \]

\[ \lambda x \]

Elec Market

Demand

\[ s_1 : \text{Storage} \]

NGFPP

Gas Market

Demand

\[ s_2 : \text{Storage} \]

\[ \text{Min } f'_2(y) \]
Subject to
\[ g(y) + s_2 = 0 : \lambda y \]
\[ h(x) \leq c \]
\[ F_1(x) + F_2(y) = m \]
Coupled, Multi-time Scale, Markets

Feedback Signal

Gas Market

Demand

Electricity Market

Incentive Signal

TRANACTIVE CONTROL

AREA-LEVEL

SECONDARY (FREQUENCY) CONTROL

UNIT-LEVEL

PRIMARY (POWER) CONTROL

~5 mins

~msec

Transactive Control

Coupled Markets

(From NY Times, Feb 16, 2013)
Summary

• The two markets
  – Underlying networks
  – Physics
  – Coupling between the two

• Our Market Framework: Enables Transactive Control
  – Wholesale Electricity Market
  – Advantages

• Extension to coupled gas and elec. markets
Vision for Smart Grid Controls: 2030 and Beyond

Project Lead: Anuradha Annaswamy
Project Editors: Amin, Annaswamy, DeMarco, and Samad

Document Outline

• Introduction
• Current Practice
• Drivers
• Scenarios
• Loci of Control: Research Challenges
• Conclusions

Will be available early 2014!