Control and Electricity Markets

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Outline

• Current Market Practice
  – Goals
  – Tools and timeline

• Smart Grid Implications

• Control & Electricity Markets
  – Current Mechanisms – LMP, TOU, CPP
  – Emerging Framework: Transactive Control
  – Simulation studies
Power Grids: Goals

Maintain balance between generation and load

• Generation = Demand + Losses
• Voltage & Frequency regulation

Main Tools:

• Economic Dispatch - determines set-points
  ➢ Generation resources dispatched from least to most expensive, based on demand projections
  ➢ Use reserves to meet actual demand

• Regulation
  ➢ Automatic Generation Control (AGC)
    o Secondary and Primary Control
Electricity Market

Goals of Market Operation

• Ensure a reliable and secure grid
• Facilitate economical operation

Reliability

Affordability
Electricity Market

- Centralized mechanism that facilitates trading of energy between buyers and sellers.
- The market operator conducts an auction market and schedules generators based on bids received.
- Determines a market clearing price (Locational Marginal Price (LMP)) and provides commitments and schedules based on security-constrained unit commitments.
- Day-ahead (DA) Markets
- Real-time Markets (RTM)
Wholesale Market: A Dynamic System

- **DA Energy Market** offer and bid period closes at 12:00.
- **DA Energy Market results published** at 16:00.
- Clear **Day-ahead Market** using Unit commitment and Economic Dispatch at 16:00.
- Day ahead reliability unit commitment at 18:00.
- **Revising bids** at 22:00.
- **ISO finalizes operating plan for the next day** at 00:10.
- **Real Time Energy Market Market opens** at 00:00, clears at 00:10.
- **Real Time Energy Market** clears at 00:10.
- **Power Delivery Time**

The operations are summarized as follows:

- **Operating Day-1**
- **Operating Day**

**Power Delivery Time**
Market Mechanisms - LMP

Node 1
- Demand
- Generation

Node 2
- Demand
- Generation

Node n
- Demand
- Generation

... Nodes in New England, USA

Bids (MW-h, $)

LMP_i, Schedules

ISO
Wholesale Market: Constrained Optimization

\[
\text{Min. } \sum_{i=1}^{N} C_i(P_{gi})
\]

Subject to:

\[B = \sum_{i=1}^{N} P_{gi} - \sum_{j=1}^{L} C_i(P_{lj}) - Loss = 0 \quad \text{System balance}\]

\[T = \sum_{i=1}^{N} S_{ki} P_{gi} \leq T_k^{\text{max}}, k = 1,2, \ldots, K \quad \text{Transmission constraints}\]

\[P_{gi}^{\text{min}} \leq P_{gi} \leq P_{gi}^{\text{max}}, i = 1,2, \ldots, N \quad \text{Capacity constraints}\]

Equivalent to

\[
\text{Min } L = \sum_{i=1}^{N} C_i(P_{gi}) + \rho B + \mu(T - T_k^{\text{max}}) \quad \text{if no capacity constraints}\]

\(P_{Gi}: \text{Generation Schedule at Node } i, \rho: LMP, \mu: \text{Congestion rent}\)
# Smart Grid Implications

## Goals
- Reliable and affordable power
- Voltage and frequency control
- Security

## Drivers
- High penetration of Renewables
  - Decarbonization
  - Climate changes
- Increasing demand for energy

## Challenges
- System of Distributed Systems
  - Heterogeneous
  - Intermittencies and uncertainties
  - Time-scales: Seconds to seasons
  - Synergy between power & communication

## Emerging Tools
- Demand Response
  - Adjustable demand in response to grid/market conditions
- Smart meters/ PMUs
- Transactive Control
  - the use of distributed communications to send an incentive signal and receive a feedback signal within the power system’s node structure.
Renewable Energy – Intermittency & Uncertainty

Five-turbine WindBlade Simulation

Power Output (MW)

Time (sec)

1st Turbine  2nd  3rd  4th  5th

0  50  100  150  200  250

0  1  2  3  4  5  6

Courtesy of the Los Alamos National Laboratory
Renewable Energy – Intermittency & Uncertainty

Courtesy of the California ISO PV output in 3 typical days Dec. 2-5, 2011
Demand Response – “Actuators”

- Customers reduce consumption in response to
  - Reliability events, wholesale prices
- Ways of reduction
  - Load reduction for a specific time
  - Load shifting
- Incentives based on time and amount
Transactive control: An Emerging Paradigm

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

- Incentive Signal: Dynamic Pricing
- Feedback Signal: Adjustable Demand

- Grid-wise Implications

• Transactive Control → Control architecture that coordinates
  - Market Transactions
  - Active Control at the AGC level
Transactive control: Dynamic Pricing

Some Examples:

• **Critical Peak Pricing (CPP)**
  - During scarcity in production
  - Power retailer can assign a high price
  - Sometimes linked with TOU

• **Peak-time Rebate**
  - Each customer entity has its own baseline calculated based on similar days surrounding event
  - Customer gets a bill credit for all reduction below their baseline

• **Real-time pricing (RTP)**
  - Assign the actual price of that hour for consumption
Transactive control: Introduces Feedback!

Goals

- Reduced congestion
- Integration of renewables
- Reduced utility cost

Transactive Control

(ISO)

Bids

$$

Demand

Must accommodate
- grid-constraints
- costs

RTP

Needs to be properly modeled
Proposed Transactive Control Framework

Market Transactions

Demand Generation
Demand Generation
Demand Generation

~5 mins

TRANSACTION CONTROL

Area Control Error (ACE)
AREA-LEVEL
SECONDARY (FREQUENCY) CONTROL
UNIT-LEVEL
PRIMARY (POWER) CONTROL

Set-points
Set-points

~secs
~msec
Transactive control framework: Market Level

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

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

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

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

\[ \Delta \gamma(k) = k_\gamma \max(0, T - T_{max}) \quad \text{(Congestion)} \]
Transactive Control: Market Mechanism

The overall dynamic model:

\[ x[K + 1] = (l_n + hA)x[K] + hk_p\Delta + b \]

\[ x(K) = \{\{P_G\}_i\ \{P_D\}_j\ \{d\}_n\ \{\rho\}_n\}^T_{(n)\times1} \]

\[ A = \begin{bmatrix}
-k_gc_g & 0 & 0 & k_gA_g^T \\
0 & k_dc_d & 0 & -k_dA_d^T \\
0 & 0 & 0 & k_\delta Y^T \\
-k_pA_g & k_pA_d & k_pY & 0
\end{bmatrix} \]

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

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

- Quantifies effect of volatility and stability
- Can help reduce reserve costs with wind uncertainty
Simulation Results

• 4-bus network with two generator units at node 1 and wind at bus 2 (\(P_{g1}\): Base-load; \(P_{g2}\): Reserve)

• \(L_1, L_2\): DR-Compatible demand

Parameters with following values:

cg1 = 0.25; cg2 = 0.55; generator cost

bg1 = 40.2; bg2 = 60; generator cost

kg1 = 0.3; kg2 = 0.8; generator time

constants

cd1 = cd2 = 0.4; consumer utility

coefficientes

bd1 = bd2 = 70; consumer cost coefficientes

kd1 = kd2 = 0.3; demand time constants

k = 0.7; LMP time constant (market time constant)
Simulation Results: Market Stability & Volatility

Volatility: With increased demand-elasticity ($k_d$)

Stability: With increased latency ($k_\rho$)
Simulation Results: Effect of Wind Uncertainty

Wind Properties:
- : Actual Wind Power
- : Mean value of the projected wind. → Current Market Practice
- : ARMA model of the actual wind power. → With Transactive Control
Transactive Control: Reserve costs

• Less reserve is required.
Transactive Control: Hierarchical coordination

Demand Response:
- Tertiary level (PR-DR)
- Secondary level (RR-DR)

- Primary (Power) Control
- Secondary (Frequency) Control
- Transactive Control
- Area-Level
Summary

• Current Market Practice
  – Goals
  – Tools and timeline

• Smart Grid Implications

• Control & Electricity Markets
  – Emerging Framework: Transactive Control
  – Provides guidelines for volatility and stability
  – Helps reduce reserve costs
  – Hierarchical coordination