Transactive Control: A Novel Technology for Smart Grids

Anuradha Annaswamy
Active-adaptive Control Laboratory
Department of Mechanical Engineering
Massachusetts Institute of Technology
Outline

• A Smart Grid – A Paradigm Shift

• Transactive Control
  – Dynamic Market Mechanisms
  – Integrated Secondary and Primary Control

• Case Studies
Paradigm Shift: From Current to Smart Grids

Main features:
- Renewable energy resources
- Demand Response
- Storage
- Advanced Metering Infrastructure

Increasing supply-demand gap
Environmental concerns
Aging infrastructures
Smart Grid Control

• To maintain power balance in the system.
• To ensure that operating limits are maintained
  – Generators limit
  – Tie-lines limit
• To ensure that the system frequency is constant (at 50 Hz or 60Hz).
• To achieve the above with renewable energy despite intermittency & uncertainty
• To ensure affordable power
GRID CONTROL: CURRENT PRACTICE
TRANSACTIVE CONTROL: The connecting entity

Anuradha Annaswamy, Transactive Control
The Overall Vision

Distributed Decision and Control

• Primary control
  – Immediate (automatic) action to sudden change of load.
  – For example, reaction to frequency change.

• Secondary control
  – Restore system frequency,
  – Restore tie-line capacities to the scheduled value, and,
  – Make the areas absorb their own load.

• Tertiary control
  – Make sure that the units are scheduled in the most economical way.
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: Dynamic Pricing

• Feedback Signal: Adjustable Demand

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

- Pacific Northwest Demonstration Project
- 112 Households participating in 2009
- 60,000 households in an ongoing project (2010-2015)
- Spans several states

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

Anuradha Annaswamy, Transactive Control
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 (Market Level)
    - (Price Responsive, and Regulation Responsive)
  - Area Control Error (Secondary Level)
  - Governor Control (Primary Level)
**Transactive Control Framework**

*Incentive Signal*

Market Transactions

**Feedback Signal**

- Demand
- Generation

~5 mins

**Area Control Error (ACE)**

**AREA-LEVEL**

SECONDARY (FREQUENCY) CONTROL

UNIT-LEVEL

PRIMARY (POWER) CONTROL

~10 secs


Anuradha Annaswamy, Transactive Control
Primary Level

\[
\begin{bmatrix}
\dot{x}_G \\
\dot{x}_L \\
\dot{e}P_G \\
\dot{e}P_L
\end{bmatrix}
= 
\begin{bmatrix}
A_G & 0 & -c_G & 0 \\
0 & A_L & 0 & c_L \\
Y_{GG} & Y_{GL} & -I & 0 \\
Y_{LG} & Y_{LL} & 0 & -I
\end{bmatrix}
\begin{bmatrix}
x_G \\
x_L \\
P_G \\
P_L
\end{bmatrix}
- 
\begin{bmatrix}
0 \\
0 \\
\phi_G \\
\phi_L
\end{bmatrix}
+ 
\begin{bmatrix}
b_G & 0 \\
0 & b_L \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\omega_{ref} \\
P_{ref}^L
\end{bmatrix}
+ 
\begin{bmatrix}
\Delta_G \\
\Delta_L
\end{bmatrix}
\]

- time scale \( t \)

\[
x_G = 
\begin{bmatrix}
\omega_G \\
\delta \\
\vdots
\end{bmatrix}
\]

\[
z_p = 
\begin{bmatrix}
P_G \\
P_L
\end{bmatrix}
\]

\[
u[k] = P_{ref}[k] : Tie Line flow
\]

\[
u[k] = P_{L}[k] : uncertainty
\]

\[
0 = Ax_pss[k] + Bz_pss[k] + Fu[k] + p_{ss}
\]

\[
0 = Cx_pss[k] + Dz_pss[k] + p_{ss}[k] + p_{ss}
\]

Steady state

Primary \( Gss \)

Secondary \( k \)

Tertiary \( K \)

\( K+1 \)
Secondary Level

\[ 0 = Ax_{p_{ss}}[k] + Bz_{p_{ss}}[k] + Fu[k] + p_{ss} \]
\[ 0 = Cx_{p_{ss}}[k] + Dz_{p_{ss}}[k] + p_{ss}[k] + p_{ss} \]

\[ x_s[k+1] = x_s[k] + B_s u_s[k] + C_s s[k] \]
\[ x_s[k] : G_{ss} \quad u_s[k] : u[k+1] - u[k] \]

\[ s[k] : \text{Uncertainty in generation, load, and tie-line flow} \]

Goal: \( x_s \rightarrow x_t \) a reference signal set by the tertiary level

\[ e_s = x_s - x_t \quad x_t : \text{Area Control Error (ACE)} \]

Anuradha Annaswamy, Transactive Control
How do we design the Tertiary Level?
**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
Wholesale Market: A Dynamic System

Operating Day-1

12:00
DA Energy Market offer and bid period closes

16:00
DA Energy Market results published

16:00
Clear Day-ahead Market using Unit commitment and Economic Dispatch

18:00
Day ahead reliability unit commitment

22:00
Revising bids

00:10
Power Delivery Time

00:00
ISO finalizes operating plan for the next day

16:00
Real Time Energy Market opens

16:00
18:00
Real Time Energy Market clears

Anuradha Annaswamy, Transactive Control
Market Mechanisms - LMP

Nodes in New England, USA

ISO

Bids (MW-h, $)

LMP_i, Schedules

Demand

Generation

Node 1

Node 2

Node n

Anuradha Annaswamy, Transactive Control
Top Layer: A Dynamic Market Mechanism

1. Equilibrium under constant flux.
2. GenCos and ConCos adjust their power level using a recursive process.
3. Price is a Public Signal that guides all entities to adjust efficiently.

*Anuradha Annaswamy, Transactive Control*
That is, if a generator observes a market price \( \rho n(i)_k \) above the marginal cost \( c_{gi} P_{gi_k} + b_{gi} \) will expand production until the marginal cost of production equals the price.
Modeling of Consumers Company

- \[ P_{n(i)k} = c_{dj} P_{dj_k} + b_{dj} \]:
  - marginal benefit of \( P_{dj} \)
- Consumer utility function:
  \[
  U(P_{dj}) = b_{dj} P_{dj} + \frac{c_{dj}}{2} P_{dj}^2
  \]

A dynamic model, for consumer \( j = 1, \ldots, N \) can be shown as

\[
P_{dj_{k+1}} = P_{dj_k} + k_{P_{dj}} (c_{dj} P_{dj_k} + b_{dj} - \rho_{n(j)k})
\]

i.e. Demand \( P_{dj} \) with a marginal benefit above the marginal price will lead to an expansion in consumption until equilibrium is attained.
Pricing Strategy

• Energy imbalance $E_k$ at time $k$

$$E_k = \left( -\sum_{i \in \theta} P_{gi_k} + \sum_{j \in \theta} P_{dj_k} + \sum_{m \in \Omega_n} B_{nm} [\delta_n - \delta_m] \right)$$

• The pricing policy should depend on the degree of energy imbalance

$$\rho_{n_{k+1}} = \rho_{n_k} + k_{\rho} E_k$$
A Dynamic Market Model

- The market participants need not have global market information.
- Convergence of the dynamic system to the equilibrium condition implies that the market reaches the condition of Nash equilibrium.

\[
\begin{align*}
\min f(x) \\
\text{s.t.} \\
g(x) = 0 \\
h(x) < P
\end{align*}
\]

\[
\begin{align*}
x_i(K+1) &= \bar{x}_i(K) - h k_x \nabla_x L(\bar{x}_i(K), \bar{\rho}_i(K), \bar{\mu}_i(K)) \\
\rho_i(K+1) &= \bar{\rho}_i(K) - h k_\rho \nabla_\rho L(\bar{x}_i(K), \bar{\rho}_i(K), \bar{\mu}_i(K)) \\
\mu_i(K+1) &= \bar{\mu}_i(K) - h k_\mu [\nabla_x L(\bar{x}_i(K), \bar{\rho}_i(K), \bar{\mu}_i(K))]_\mu^+
\end{align*}
\]

Anuradha Annaswamy, Transactive Control
The overall dynamic model:

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

\[ x_t = \begin{bmatrix} \{P_G\}_i \{P_D\}_j \{\delta\}_n \{\rho\}_n \end{bmatrix}^T \]

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

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

\( k_g, k_d, k_\delta, k_\rho : \) Parameters of the RTM dynamic model

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

\[ \sum_{PRI} \dot{x}_p = (A + E_p)x_p(t) + Bz_p(t) + Fu[k] \]
\[ e \dot{z}_p = Cx_p(t) + Dz_p(t) + \phi_p(t) \]

\[ \sum_{SEC} x_s[k + 1] = (\tilde{A}_s + C_s E_s)x_s[k] + B_s L_t x_t[K] \]

\[ \sum_{TER} x_t[K + 1] = \tilde{A}_t x_t[K] + h k_p E_t e_s[K] + b \]
\[ e_s[k + 1] = x_s[k + 1] - R_t x_t[K] \]

\[ \tilde{S}_{PRI} : u[k + 1] = u[k] - L_s x_s[k] + L_t x_t[K] \]
\[ \tilde{S}_{SEC} : e_s[k + 1] = (\tilde{A}_s + C_s E_s)e_s[k] + C_s E_s R_s x_t[K] \]
The overall model, including the primary, secondary, and tertiary level dynamics at multiple time-scales:

\[
\begin{align*}
\Sigma_{Pri} : & \begin{cases} 
\dot{x}_p = (A + E_p)x_p(t) + Bz_p(t) + Fu(k) \\
\epsilon \dot{z}_p = Cx_p(t) + Dz_p(t) + \phi_p(t)
\end{cases} \\
J_{Pri} : & u[k + 1] = u[k] - L_s x_s[k] + L_t x_t[K] \\
\Sigma_{Sec} : & x_s[k + 1] = (\tilde{A}_s + C_s E_s)x_s[k] + B_s L_t x_t[K] \\
J_{Sec} : & e_s[k + 1] = (\tilde{A}_s + C_s E_s)e_s[k] + C_s E_s R_t x_t[K] \\
\Sigma_{Ter} : & x_t[K + 1] = \tilde{A}_t x_t[K] + hk_R E_t e_s[K] + b
\end{align*}
\]
If the transactive control is such that

\[
\Re \left[ \lambda_{\max} \{ A - BC \} \right] < 0 \quad (1a)
\]

\[
|\lambda_i(\tilde{A}_s)| < 1 \text{ for all } i = 1, \ldots n_s \quad (1b)
\]

\[
|\lambda_i(\tilde{A}_t)| < 1 \text{ for all } i = 1, \ldots n_t, \quad (1c)
\]

where \( \lambda_i \) is the \( i \)-th eigenvalue of matrix \( A \) and \( \lambda_{\max}(A) \) denoted the largest eigenvalue of the matrix \( A \), then there exists \( h^* \), and \( \epsilon^* \) such that for all \( h \in (0, h^*) \) and \( \epsilon \in (0, \epsilon^*) \), the equilibrium \( O = (x_{pss}, x^*_s, e^*_s, x^*_t) \) of the overall hierarchical Transactive control is asymptotically stable.

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 (Market Level)
    - (Price Responsive, and Regulation Responsive)
  - Area Control Error (Secondary Level)
  - Governor Control (Primary Level)
Simulation Results

- 4-bus network with two generator units at node 1 and wind at bus 2 \( (P_{g1}: \text{Base-load}; P_{g2}: \text{Reserve}) \)
- \( L_1, L_2: \text{DR-Compatibles demand} \)

Parameters with following values:

- \( c_{g1} = 0.25; c_{g2} = 0.55 \); generator cost coefficients
- \( b_{g1} = 40.2; b_{g2} = 60 \); generator cost coefficients
- \( k_{g1} = 0.3; k_{g2} = 0.8 \); generator time constants
- \( c_{d1} = c_{d2} = 0.4 \); consumer utility coefficients
- \( b_{d1} = b_{d2} = 70 \); consumer cost coefficients
- \( k_{d1} = k_{d2} = 0.3 \); demand time constants
- \( k = 0.7 \); LMP time constant (market time constant)
Market Stability & Volatility

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

Stability: With increased latency ($k_{\rho}$)
Simulation Results: Market Stability & Volatility

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

Stability: With increased latency ($k_{\rho}$)
Simulation Results

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

Figure 5.3: 4-bus system example for Transactive control

It follows that the equilibrium of (5.59) - (5.60) is asymptotically stable if and only if the origin of (5.67) - (5.68) is asymptotically stable, see Theorem 5.1.

Defining \( \tau = t / \epsilon \), we can represent (5.68) in the stretched \( \tau \)-scale as

\[
\dot{y}_p(\tau) = \frac{D}{\tau} (\tau y_p(\tau)) + \epsilon (D^{-1} C (A - BD^{-1} C \Delta_p) x_p(\tau) + \epsilon \dot{\phi}_p(\tau) + \epsilon (D^{-1} CB y_p(\tau) + \dot{\phi}_p(\tau)) + \epsilon (D^{-1} C \Delta_p).
\]

In order to evaluate the stability of the dynamics in the stretched time-scale of \( \tau \), we let \( \epsilon \) tend to zero in (5.69), which leads to the boundary-layer system, see Theorem 5.1 [102].

\[
\dot{y}_p(\tau) = \frac{D}{\tau} (\tau y_p(\tau)).
\]

Since \( D = -I \), (5.70) is asymptotically stable, with \( y_p(\tau) \) tending to zero as \( \tau \to \infty \). Therefore, it suffices to focus on the reduced system

\[
\dot{x}_p(t) = (A - BD^{-1} C \Delta_p) x_p(t).
\]

by setting \( y_p(t) \) to zero. From Assumption 5.5 and (5.66a), it follows that the origin of (5.71) is asymptotically stable, see Section A.1.2 [102]. This establishes the stability of \( x_p = 0 \) in (5.59) and (5.60).

It therefore follows that for any bounded \( u(k) = 0 \), the solutions of (5.59) - (5.60) are globally bounded.

Step 2: Stability of the secondary level

Let \( x_t[K] \equiv 0 \) and consider the two lower levels defined by Eqs. (5.59) - (5.63). From (5.26), Eq. (5.62) can be rewritten as

\[
x_s[k + 1] = (\tilde{A}_s + C_s E_s) x_s[k].
\]

(5.72)
Simulation Results: Effect of Wind Uncertainty

Less reserve is required.

Hierarchical coordination

Anuradha Annaswamy, Transactive Control
Simulation Results: IEEE 30 bus Case

Anuradha Annaswamy, Transactive Control

<table>
<thead>
<tr>
<th>Name</th>
<th>$P_{G_{min}}$</th>
<th>$P_{G_{max}}$</th>
<th>$k_{p_{G}}$</th>
<th>$c_{G}$</th>
<th>$b_{G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{G1}$</td>
<td>0</td>
<td>100</td>
<td>0.012</td>
<td>0.28</td>
<td>47.2</td>
</tr>
<tr>
<td>$P_{G2}$</td>
<td>0</td>
<td>100</td>
<td>0.02</td>
<td>0.55</td>
<td>53.8</td>
</tr>
<tr>
<td>$P_{G5}$</td>
<td>0</td>
<td>150</td>
<td>0.06</td>
<td>0.25</td>
<td>40</td>
</tr>
<tr>
<td>$P_{G_{11}}$</td>
<td>0</td>
<td>150</td>
<td>0.06</td>
<td>0.25</td>
<td>40</td>
</tr>
<tr>
<td>$P_{G_{13}}$</td>
<td>0</td>
<td>100</td>
<td>0.02</td>
<td>0.015</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Generation Cost</th>
<th>Reserve Cost</th>
<th>Social Welfare</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Transactive Control</td>
<td>$/h 3040.1$</td>
<td>$/h 827.2$</td>
<td>$/h 134.2$</td>
</tr>
<tr>
<td>Without Transactive Control</td>
<td>$/h 3980.8$</td>
<td>$/h 1342.8$</td>
<td>$/h 97.8$</td>
</tr>
</tbody>
</table>

Reserve
Summary

• Transactive Control
  – Dynamic Market Mechanisms
  – Integrated Secondary and Primary Control

• Case Studies
A 2013 Publication!

IEEE Vision for Smart Grid Controls: 2030 and Beyond

Authors

Jacob Aho
Massoud Amin
Anuradha M. Annaswamy
George Arnold
Andrew Buckspan
Angela Cadena
Duncan Callaway
Eduardo Camacho
Michael Caramanis
Aranya Chakrabortty
Amit Chakraborty
Joe Chow
Munther Dahleh
Christopher L. DeMarco
Alejandro Dominguez-Garcia
Daniel Dotta
Amro Farid
Paul Flikkema
Dennis Gayme
Sahika Gene

Mercè Griera i Fisa
Ian Hiskens
Paul Houpt
Gabriela Hug
Pramod Khargonekar
Himanshu Khurana
Arman Kiani
Steven Low
John McDonald
Eduardo Mojica-Nava
Alexis Legbedji Motto
Lucy Pao
Alessandra Parisio
Adrian Pinder
Michael Polis
Mardavij Roozbehani
Zhihua Qu
Nicanor Quijano
Tariq Samad
Jakob Stoustrup

Anuradha Annaswamy, Transactive Control
Thank You!