Transactive Control: A Novel Technology for Smart Grids

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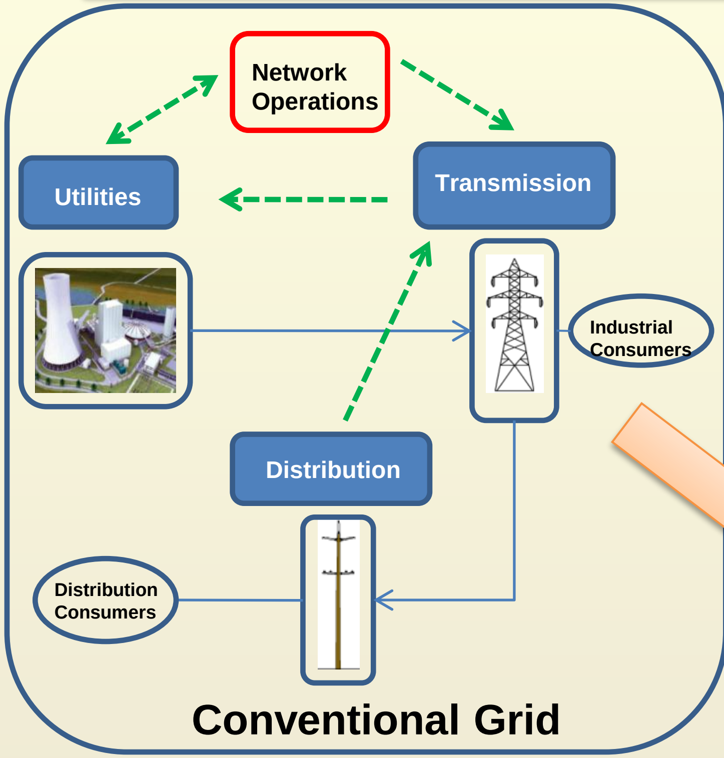
Outline

- A Smart Grid – A Paradigm Shift
- Transactive Control
  - Dynamic Market Mechanisms
  - Integrated Secondary and Primary Control
- Case Studies

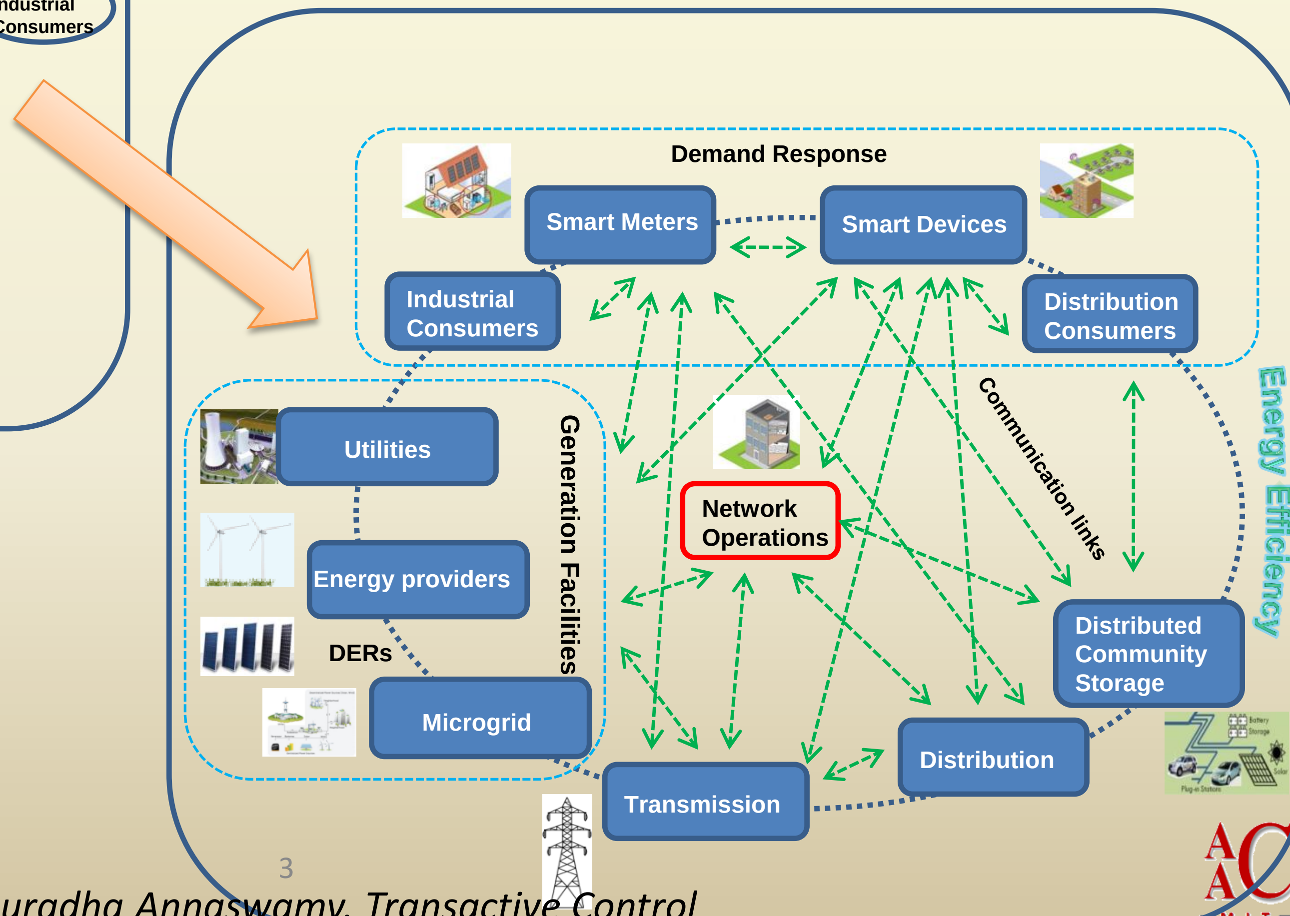
Paradigm Shift: From Current to Smart Grids



Increasing supply-demand gap

Environmental concerns

Aging infrastructures



Main features:

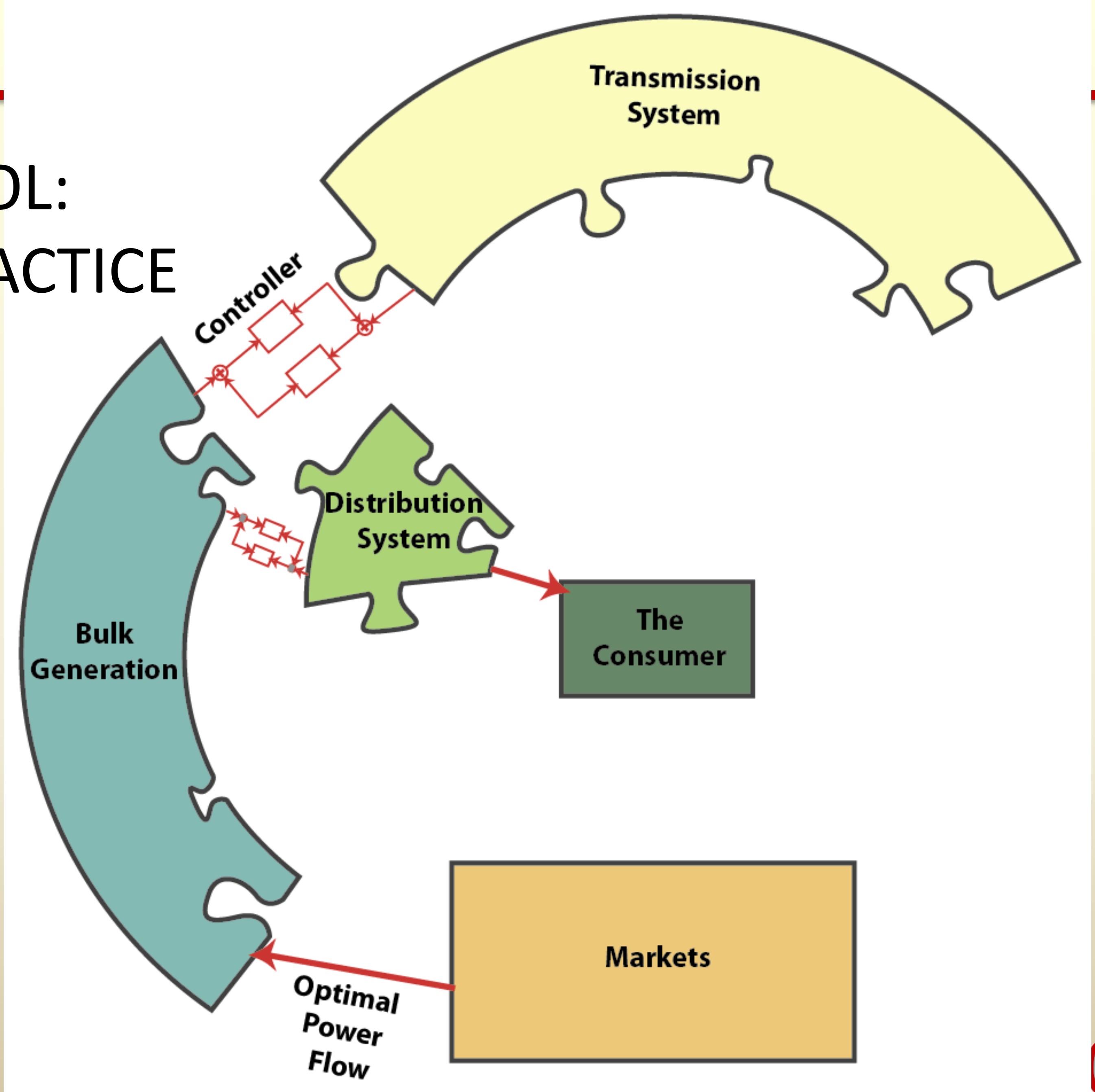
- Renewable energy resources
- Demand Response
- Storage
- Advanced Metering Infrastructure

Smart Grid Control

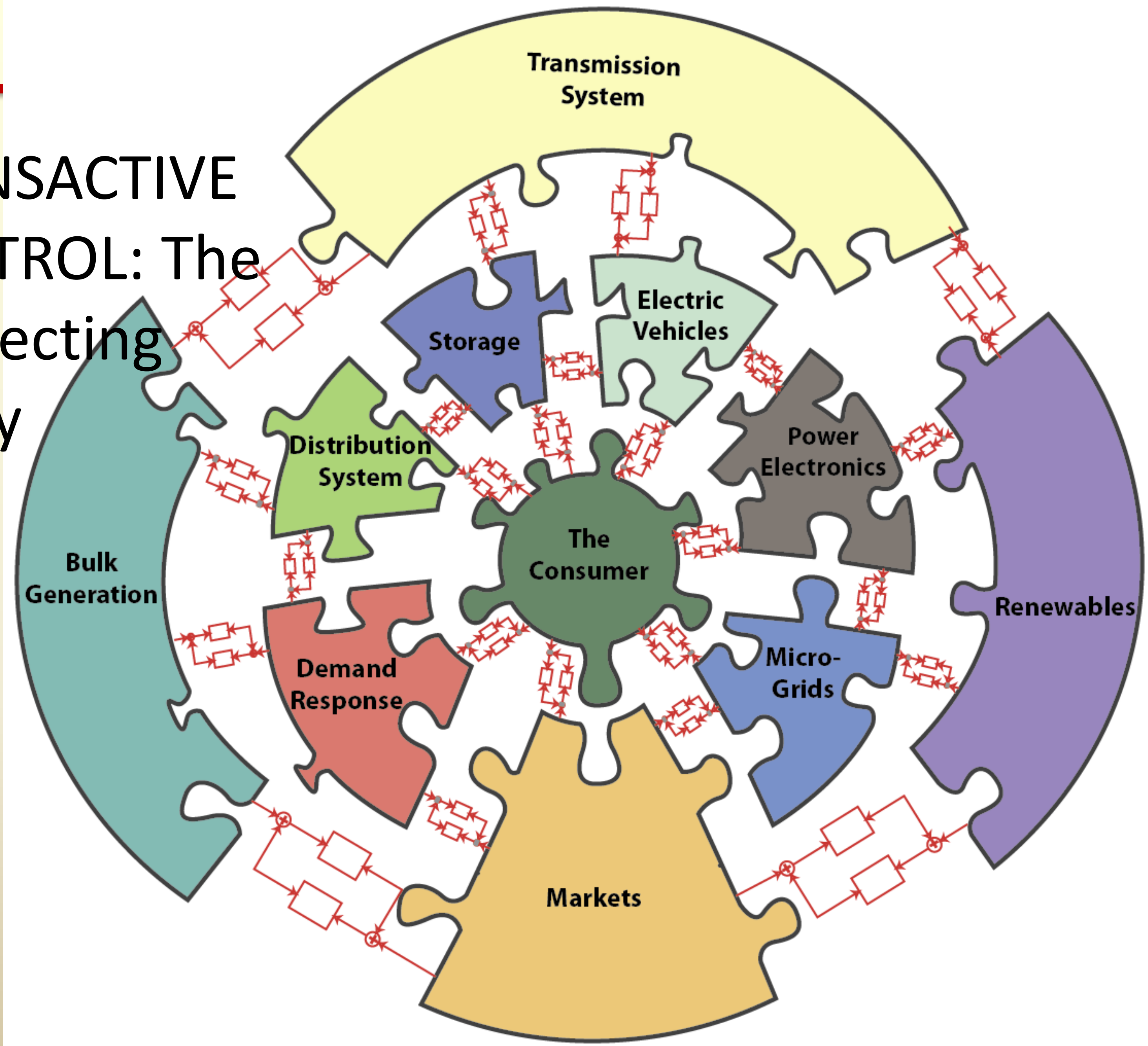
- To maintain power balance in the system.
- To ensure that operating limits are maintained
  - Generators limit
  - Tie-lines limit
- To ensure that the system frequency is constant (at 50 Hz or 60Hz).

- To achieve the above with renewable energy despite intermittency & uncertainty
- To ensure affordable power

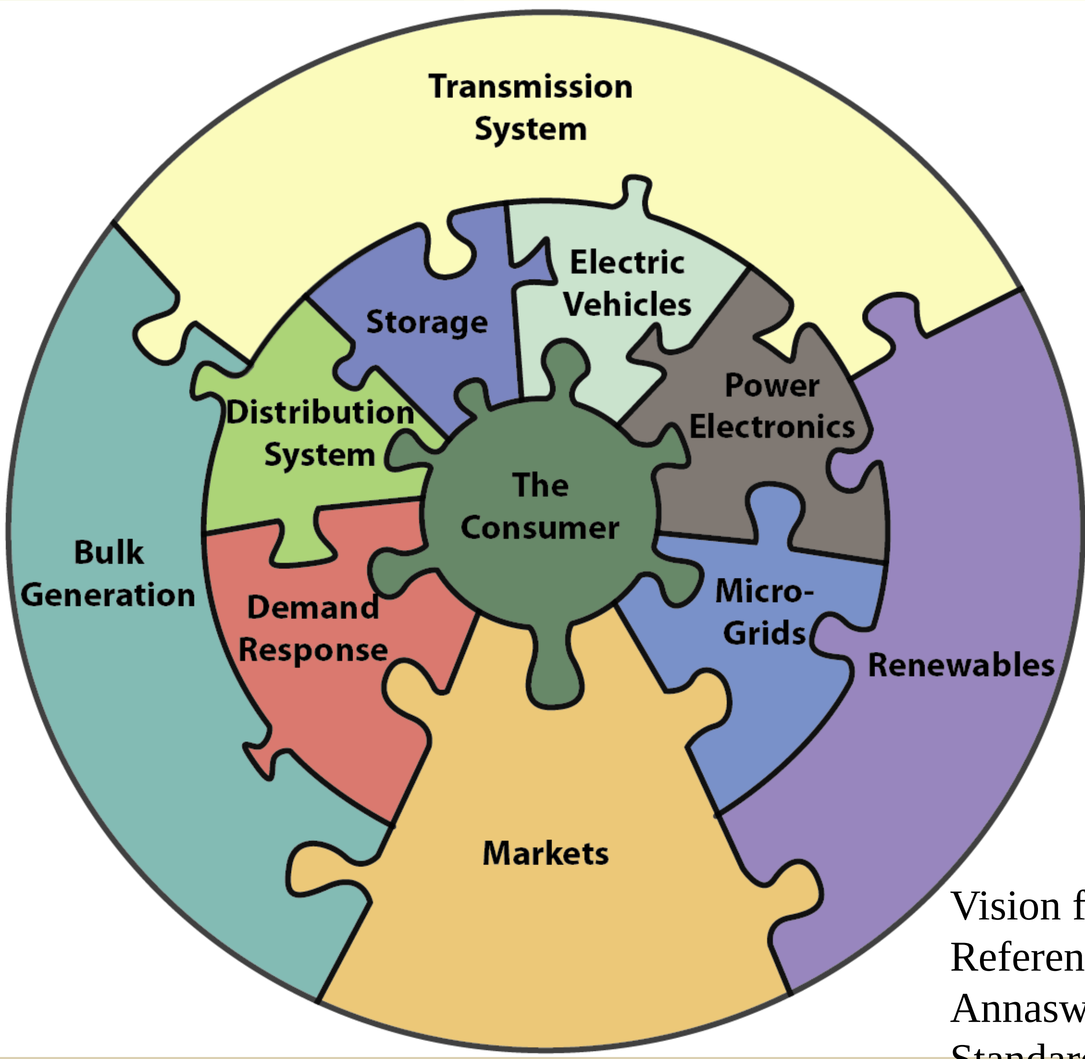
GRID CONTROL: CURRENT PRACTICE



TRANSACTIVE CONTROL: The connecting entity



THE OVERALL VISION



Vision for Smart Grid Control: 2030 and Beyond: Reference Model and Roadmap (Eds. M. Amin, A.M. Annaswamy, C. DeMarco, and T. Samad), IEEE Standards Publication, November 2013.

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*

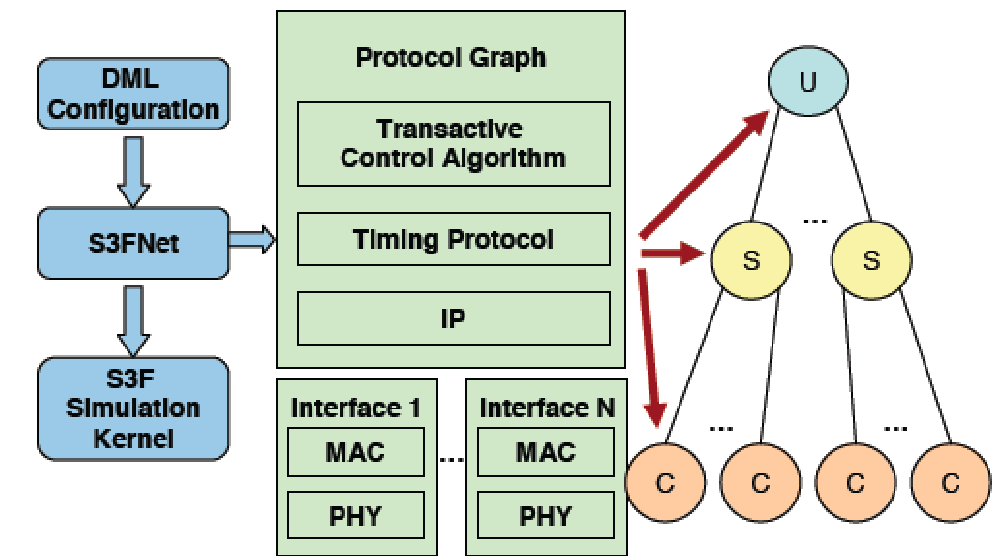
The use of dynamic market mechanism to send an incentive signal and receive a feedback signal within the power system's node structure

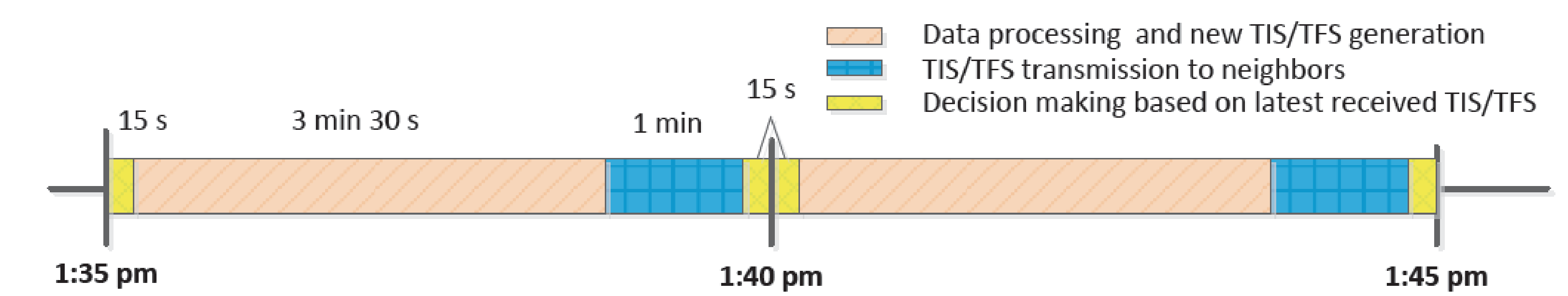
- Incentive Signal: Dynamic Pricing
- Feedback Signal: Adjustable Demand

* 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

Transactive control: Our Definition

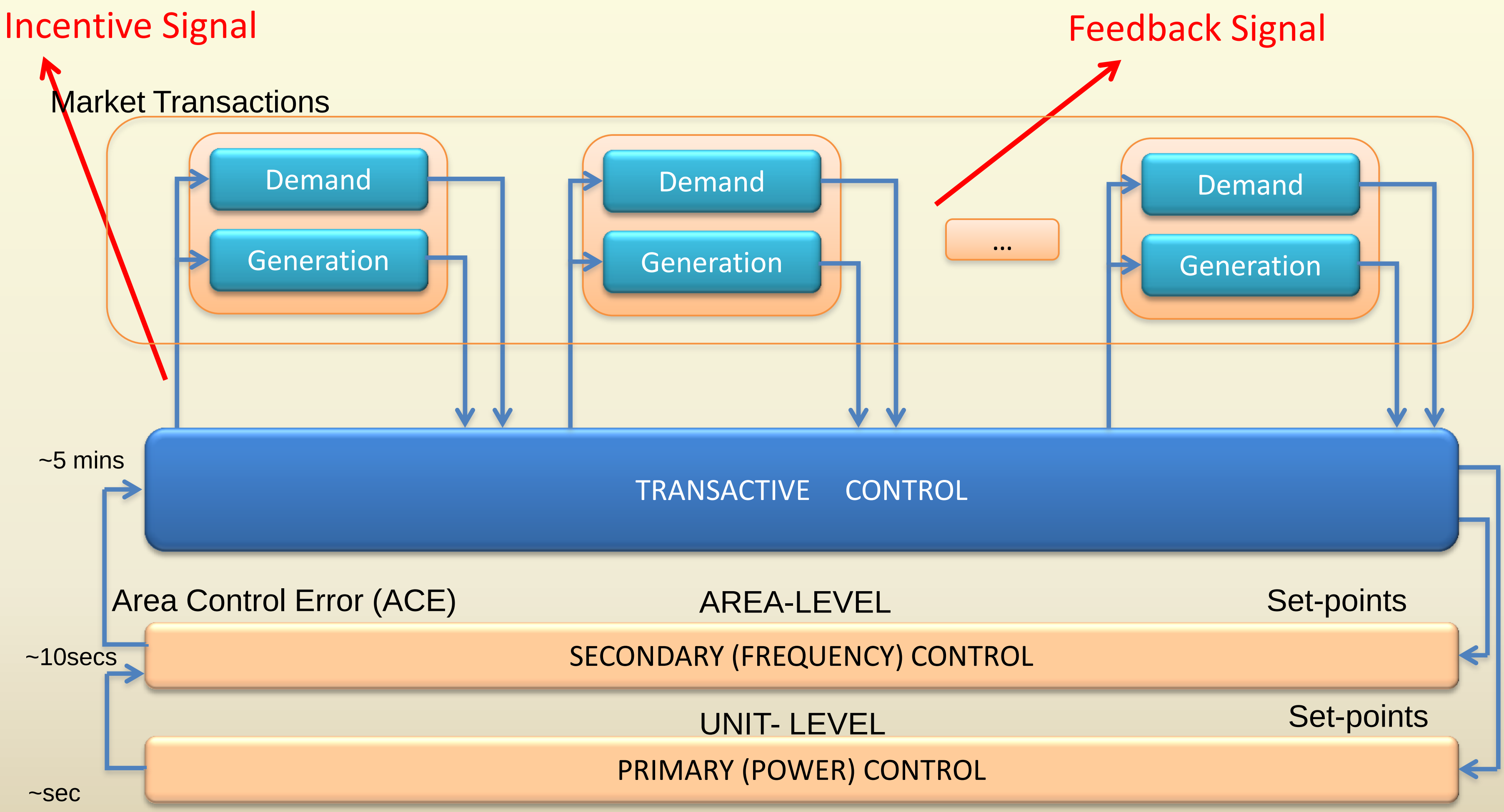
The use of dynamic market mechanism to send an incentive signal and receive a feedback signal within the power system's node structure

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

Transactive Control → Control architecture that coordinates

- ➢ Market Transactions
- ➢ Active Control at the AGC level with Regulation Demand Response

Transactive Control Framework*



* A. Kiani, A.M. Annaswamy, and T. Samad, "A Hierarchical Transactive Control Architecture for Renewables Integration in Smart Grids." HYCON Workshop, Brussels, 2012.

Primary Level

$$\begin{bmatrix} \dot{x}_G \\ \dot{x}_L \\ \varepsilon \dot{P}_G \\ \varepsilon \dot{P}_L \end{bmatrix} = \begin{bmatrix} A_G & 0 & -c_G & 0 \\ 0 & A_L & 0 & c_L \\ Y_{GG}E_G & Y_{GL} & -I & 0 \\ Y_{LG}E_L & Y_{LL} & 0 & -I \end{bmatrix} \begin{bmatrix} x_G \\ x_L \\ P_G \\ P_L \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \phi_G \\ \phi_L \end{bmatrix} + \begin{bmatrix} b_G & 0 \\ 0 & b_L \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_{ref} \\ P_L^{ref} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \Delta_G \\ \Delta_L \\ 0 \\ 0 \end{bmatrix}$$

- time scale t

$$x_G = \begin{bmatrix} \omega_G \\ \delta \\ \vdots \end{bmatrix} \qquad z_p = \begin{bmatrix} P_G \\ P_L \end{bmatrix} \qquad u[k] = \begin{bmatrix} \omega_{ref}[k] \\ P_L^{ref}[k] \end{bmatrix}$$

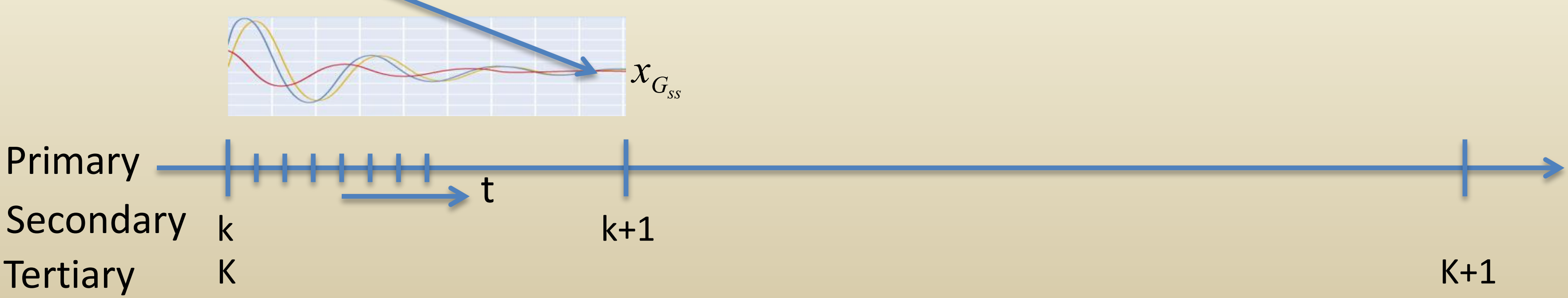
f : *Tie - Line flow*

Δ : *uncertainty*

$$0 = Ax_{p_{ss}}[k] + Bz_{p_{ss}}[k] + Fu[k] + \Delta_{p_{ss}}$$

$$0 = Cx_{p_{ss}}[k] + Dz_{p_{ss}}[k] + f_{p_{ss}}[k] + \Delta f_{p_{ss}}$$

Steady state



Secondary Level

$$0 = Ax_{p_{ss}}[k] + Bz_{p_{ss}}[k] + Fu[k] + \mathrm{D}_{p_{ss}}$$
$$0 = Cx_{p_{ss}}[k] + Dz_{p_{ss}}[k] + f_{p_{ss}}[k] + \mathrm{D}f_{p_{ss}}$$

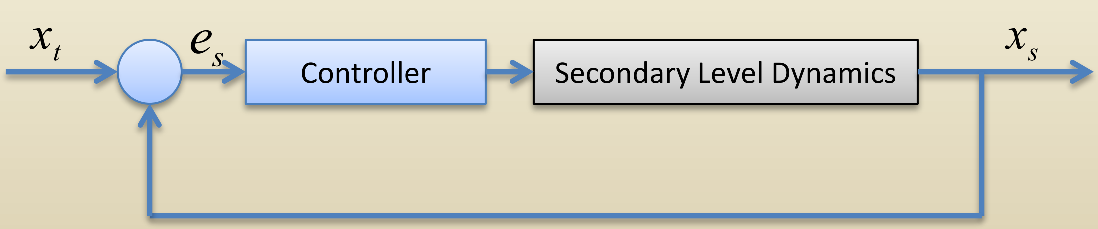
ß

$$x_s[k+1] = x_s[k] + B_s u_s[k] + C_s \mathrm{D}_s[k]$$

$$x_s[k] : W_{G_{ss}} \qquad u_s[k] : u[k+1] - u[k]$$

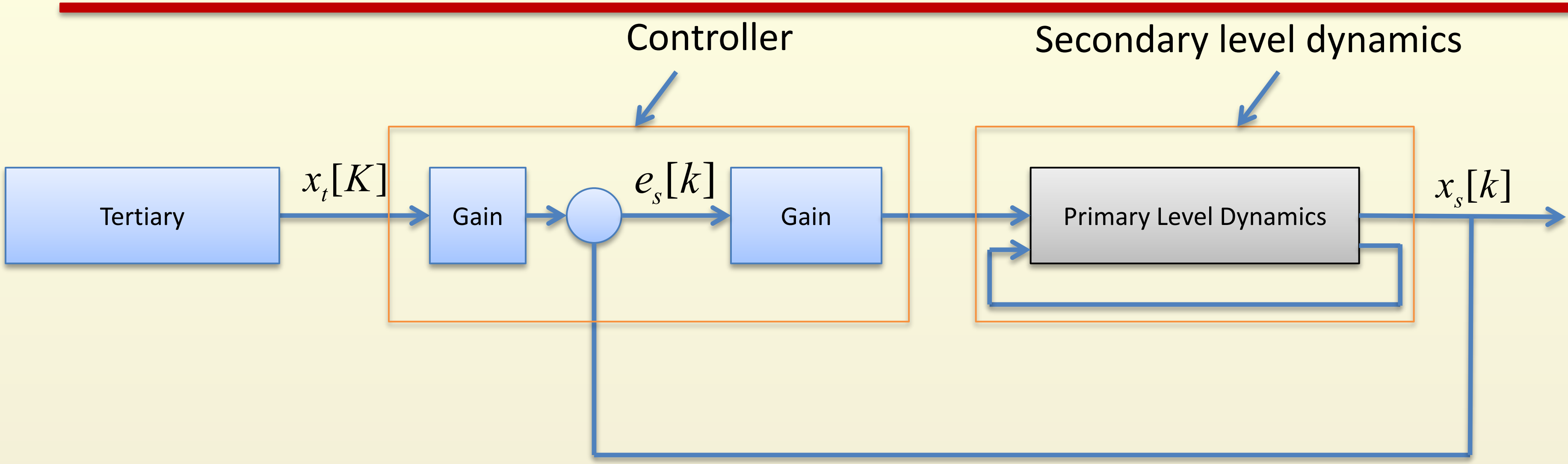
$\mathrm{D}_s[k]$: Uncertainty in generation, load, and tie-line flow

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



$e_s = x_s - x_t$: Area Control Error (ACE)

Tertiary Level

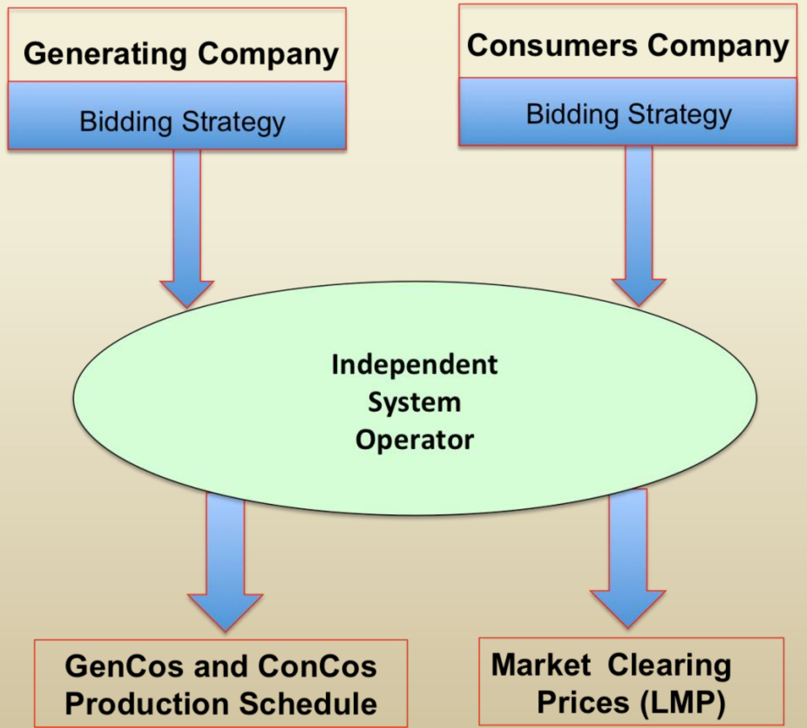


How do we design the Tertiary Level?

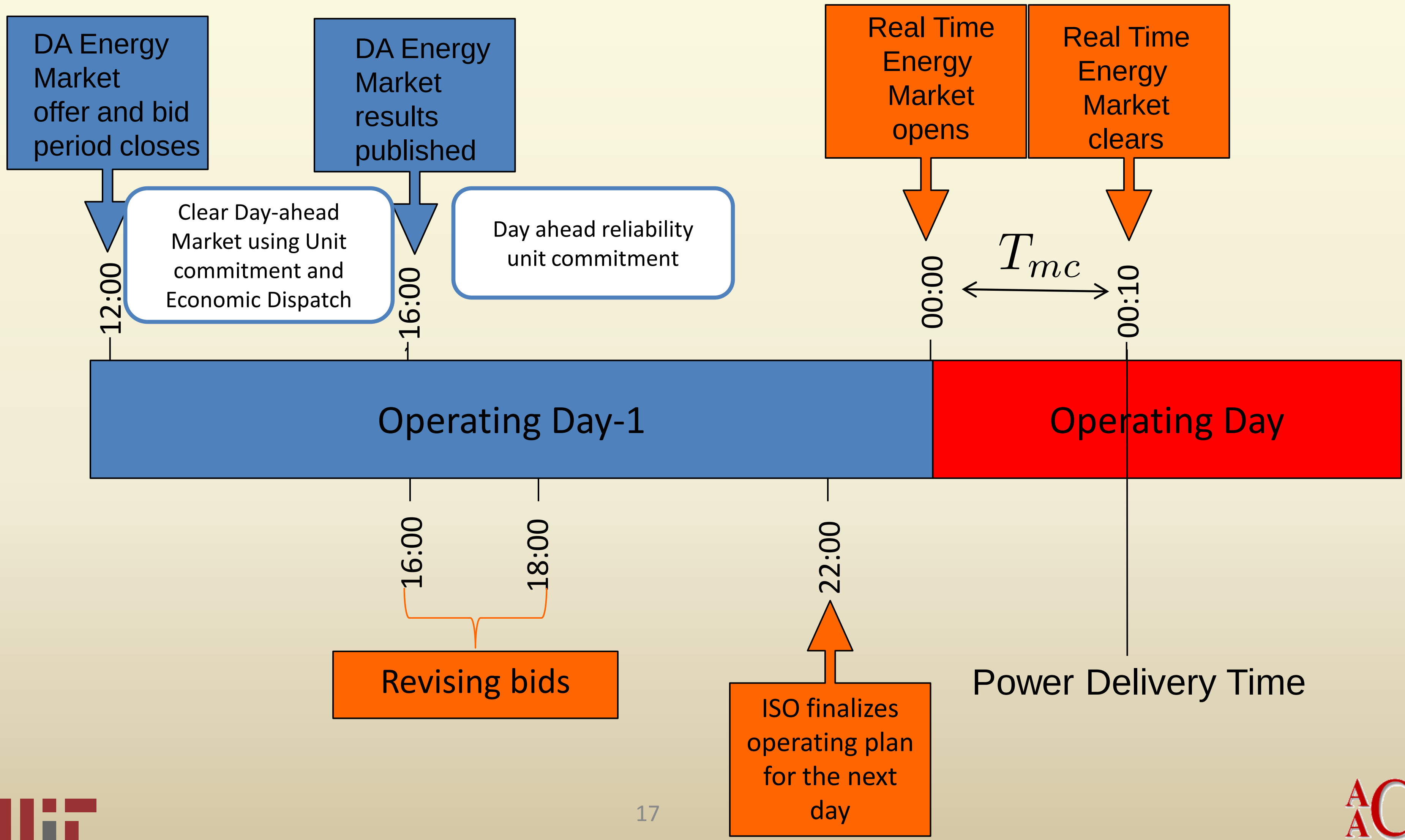
Electricity Market

- 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)

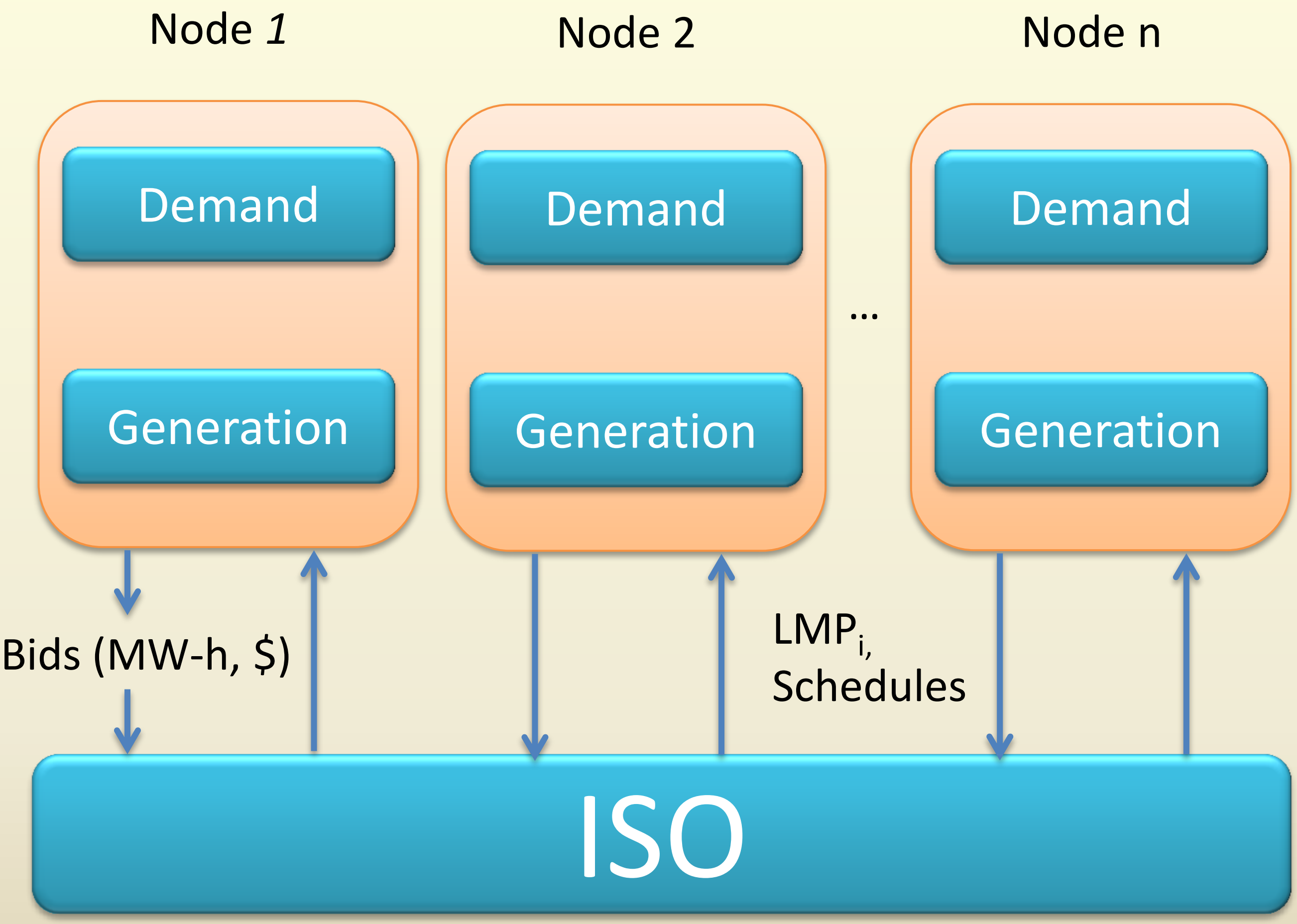
Wholesale Market →

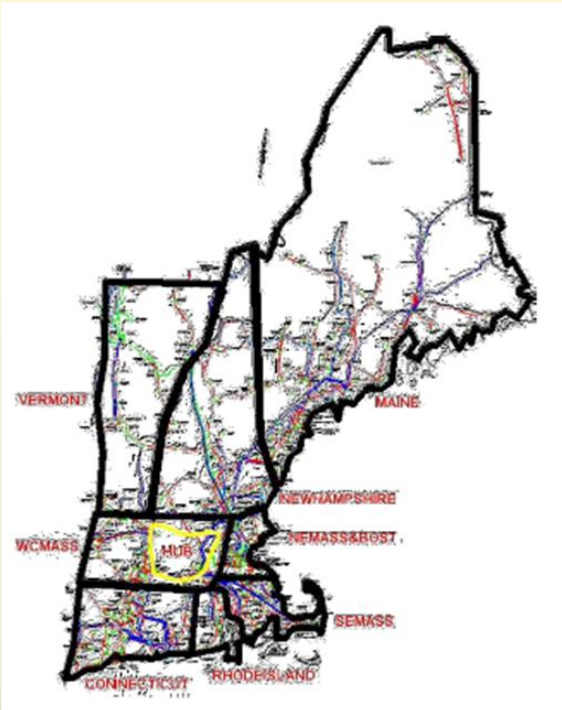


Wholesale Market: A Dynamic System



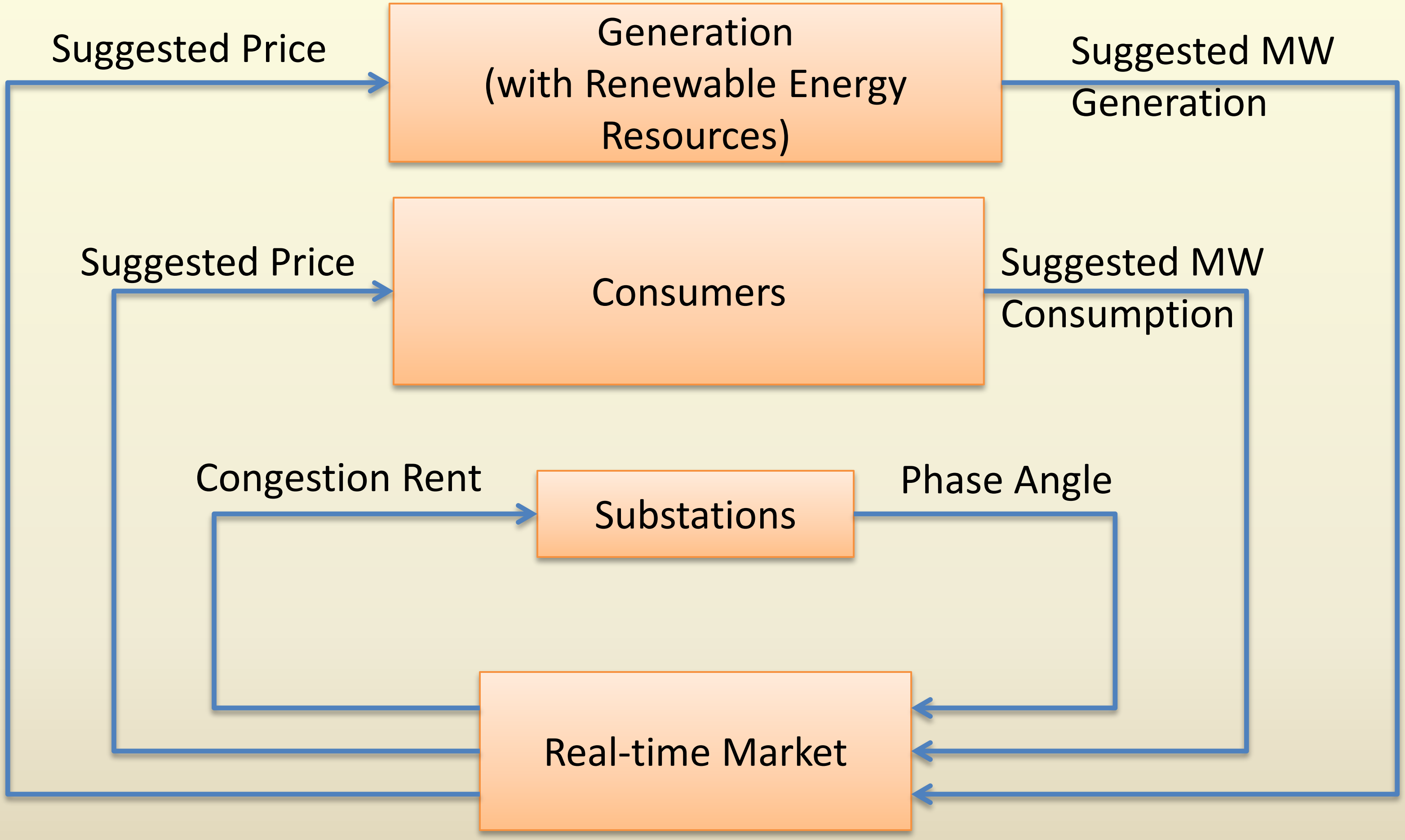
Market Mechanisms - LMP





Nodes in New England, USA

Top Layer: A Dynamic Market Mechanism

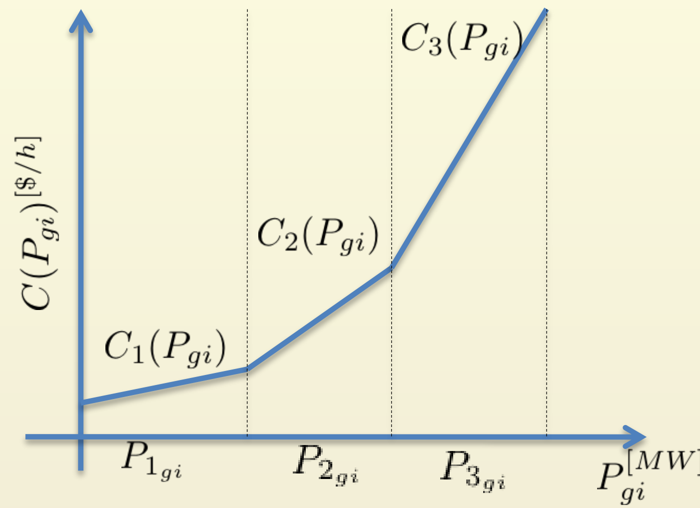


1. Equilibrium under constant flux.
2. GenCos and ConCos adjust their power level using a recursive process.
3. Price is a Public Signal that guides all entities to adjust efficiently.

Modeling of Generating Company

- ρ: market price ~ Locational Marginal Price at market equilibrium.
- The cost function of each generators unit is

$$C(P_{g_i}) = b_{g_i} P_{g_i} + \frac{c_{g_i}}{2} P_{g_i}^2$$



A dynamic model, for suppler $i = 1, \ldots, M$ can be shown as

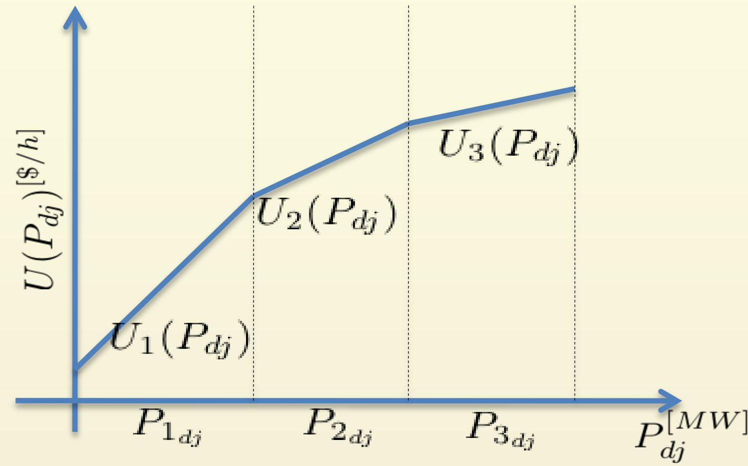
$$P_{g_{i_{k+1}}} = P_{g_{i_k}} + k_{p_{g_i}} (\rho_{n(i)_k} - c_{g_i} P_{g_{i_k}} - b_{g_i})$$

That is, if a generator observes a market price $\rho_{n(i)_k}$ above the marginal cost $c_{g_i} P_{g_{i_k}} + b_{g_i}$ will expand production until the marginal cost of production equals the price.

Modeling of Consumers Company

- $P_{n(i)_k} = c_{d_j} P_{d_{j_k}} + b_{d_j}$: marginal benefit of P_{d_j}
- Consumer utility function:

$$U(P_{d_j}) = b_{d_j} P_{d_j} + \frac{c_{d_j}}{2} P_{d_j}^2$$



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

$$P_{d_{j_{k+1}}} = P_{d_{j_k}} + k_{P_{d_j}} (c_{d_j} P_{d_{j_k}} + b_{d_j} - \rho_{n(j)_k})$$

i.e. Demand P_{d_j} 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

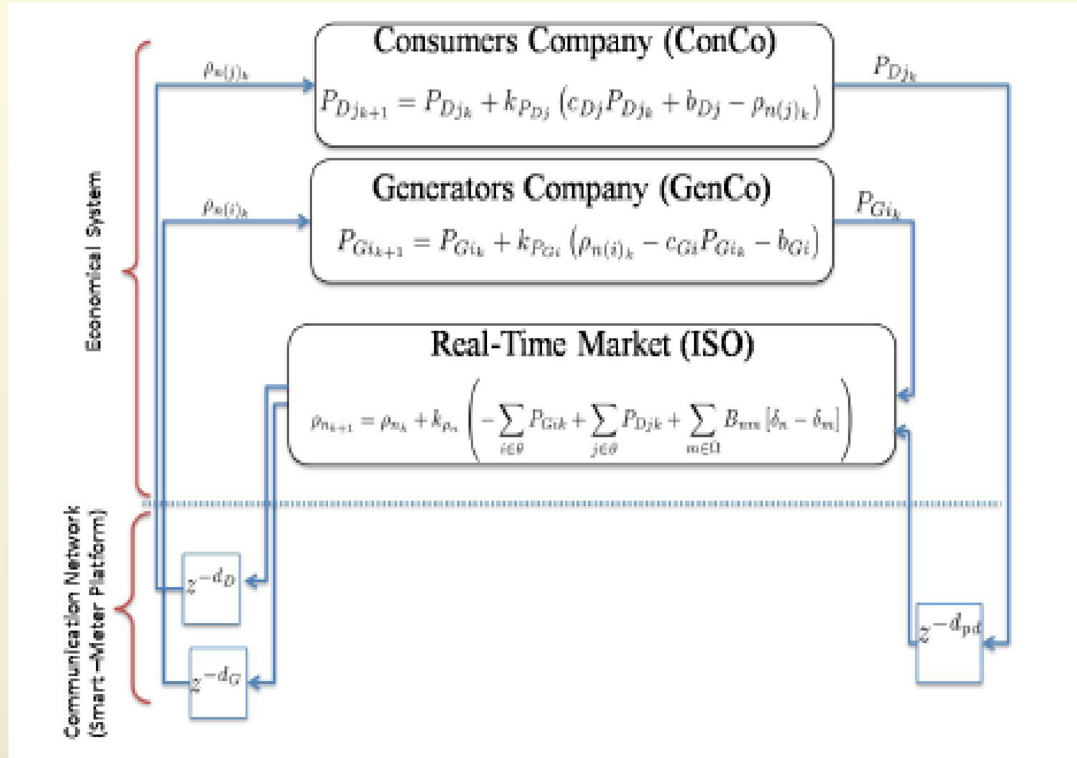
$$E_k = \left(-\sum_{i \in \theta} P_{g_{i_k}} + \sum_{j \in \theta} P_{d_{j_k}} + \sum_{m \in \Omega_n} B_{nm} \left[\delta_n - \delta_m \right] \right)$$

- 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**.



$$\min f(x) \quad \text{s.t} \quad g(x) = 0 \quad h(x) < P$$

Distributed Gaming →

$$x_i(K+1) = \overline{x}_i(K) - hk_x \nabla_x L(\overline{x}_i(K), \overline{\rho}_i(K), \overline{\mu}_i(K))$$
$$\rho_i(K+1) = \overline{\rho}_i(K) - hk_\rho \nabla_\rho L(\overline{x}_i(K), \overline{\rho}_i(K), \overline{\mu}_i(K))$$
$$\mu_i(K+1) = \overline{\mu}_i(K) - hk_\mu \left[\nabla_x L(\overline{x}_i(K), \overline{\rho}_i(K), \overline{\mu}_i(K))\right]_\mu^+$$

Dynamic Market Mechanism (contd.)

The overall dynamic model:

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

$$x_t = \left[\{P_G\}_i \quad \{P_D\}_j \quad \{\delta\}_n \quad \{\rho\}_n\right]^T_{(n)\times 1}$$

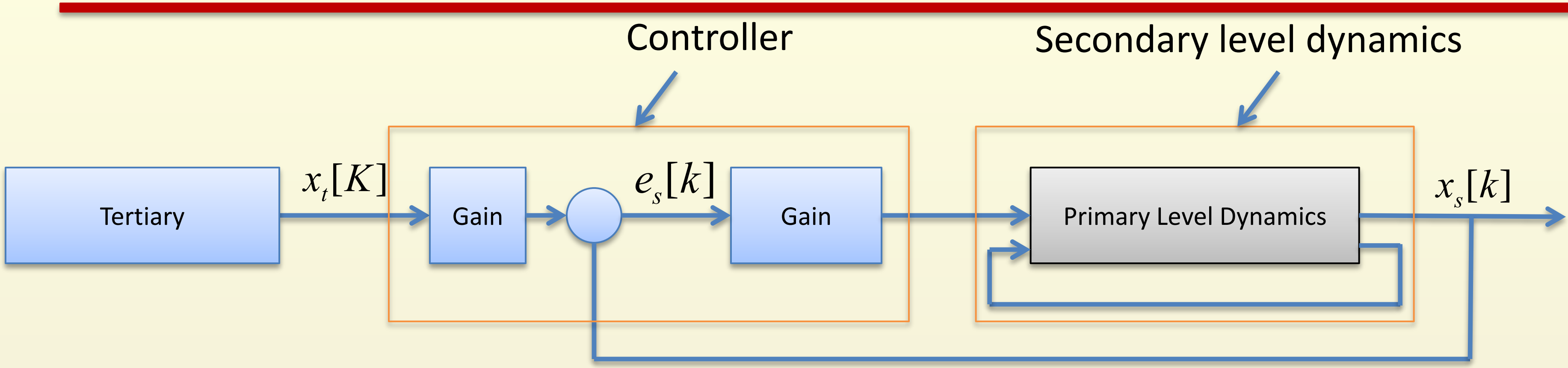
$$A = \begin{bmatrix} -k_g c_g & 0 & 0 & k_g A_g^T \\ 0 & k_d c_d & 0 & -k_d A_d^T \\ 0 & 0 & 0 & k_\delta Y^T \\ -k_\rho A_g & k_\rho A_d & k_\rho Y & 0 \end{bmatrix}$$

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

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

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

Interconnections



$$\sum_{PRI}: \begin{cases} \dot{x}_p = (A+E_p)x_p(t) + Bz_p(t) + Fu[k] \\ \varepsilon \dot{z}_p = Cx_p(t) + Dz_p(t) + \phi_p(t) \end{cases}$$

$$\sum_{SEC}: \quad x_s[k+1] = (\tilde{A}_s + C_sE_s)x_s[k] + B_sL_tx_t[K]$$

$$\sum_{TER}: \quad x_t[K+1] = \tilde{A}_t x_t[K] + hk_pE_te_s[K] + b$$

$$e_s[k+1] = x_s[k+1] - R_tx_t[K]$$

$$\Im_{PRI}: u[k+1] = u[k] - L_sx_s[k] + L_tx_t[K]$$

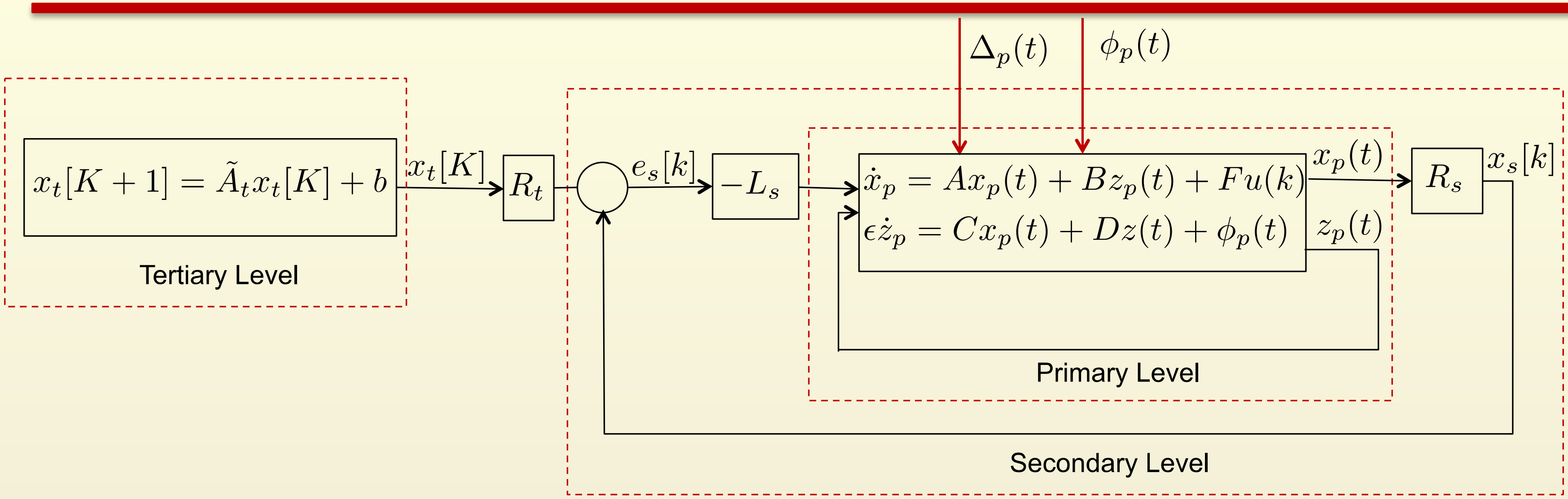
$$\Im_{SEC}: e_s[k+1] = (\tilde{A}_s + C_sE_s)e_s[k] + C_sE_sR_sx_t[K]$$

$$x_p = \begin{bmatrix} \omega_G \\ \vdots \end{bmatrix}$$

$$x_s = \begin{bmatrix} \omega_{G_{ss}} \\ \vdots \end{bmatrix}$$

$$u = \begin{bmatrix} \omega_{ref} \\ P_L^{ref} \end{bmatrix}$$

Transactive Control: Lower Levels



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

$$\Sigma_{Pri} : \begin{cases} \dot{x}_p = (A + E_p)x_p(t) + Bz_p(t) + Fu(k) \\ \epsilon\dot{z}_p = Cx_p(t) + Dz_p(t) + \phi_p(t) \end{cases}$$

$$\mathscr{I}_{Pri} : \quad u[k+1] = u[k] - L_s x_s[k] + L_t x_t[K]$$

$$\Sigma_{Sec} : \quad x_s[k+1] = (\tilde{A}_s + C_s E_s)x_s[k] + B_s L_t x_t[K]$$

$$\mathscr{I}_{Sec} : \quad e_s[k+1] = (\tilde{A}_s + C_s E_s)e_s[k] + C_s E_s R_t x_t[K]$$

$$\Sigma_{Ter} : \quad x_t[K+1] = \tilde{A}_t x_t[K] + hk_\rho E_t e_s[K] + b$$

Transactive Control: Stability*

If the transactive control is such that

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

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

$$|\lambda_i(\tilde{A}_t)| < 1 \text{ for all } \; i = 1, ...n_t, \quad (1c)$$

where λ_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 ϵ^* such that for all $h \in (0, h^*)$ and $\epsilon \in (0, \epsilon^*)$, the equilibrium $O = (x_{p_{ss}}, x_s^*, e_s^*, x_t^*)$ of the overall hierarchical Transactive control is asymptotically stable.

* A. Kiani and A.M. Annaswamy, "A Hierarchical Transactive Control Architecture for Renewables Integration in Smart Grids," CDC 2012, Maui, Hawaii.

Transactive control architecture

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

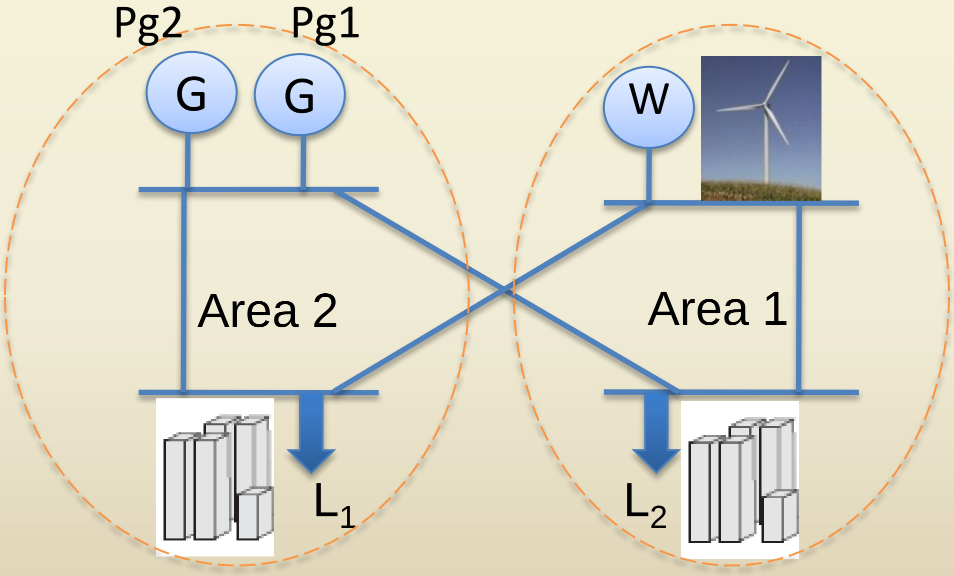
- Incentive Signal: Ex. Dynamic Pricing
- Feedback Signal:
  - Adjustable Demand (Market Level)
    - (Price Responsive, and Regulation Responsive)
  - Area Control Error (Secondary Level)
  - Governor Control (Primary Level)

Transactive Control ⟶ Control architecture that coordinates

- ➢ Market Transactions
- ➢ Active Control at the AGC level with Regulation Demand Response

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:

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

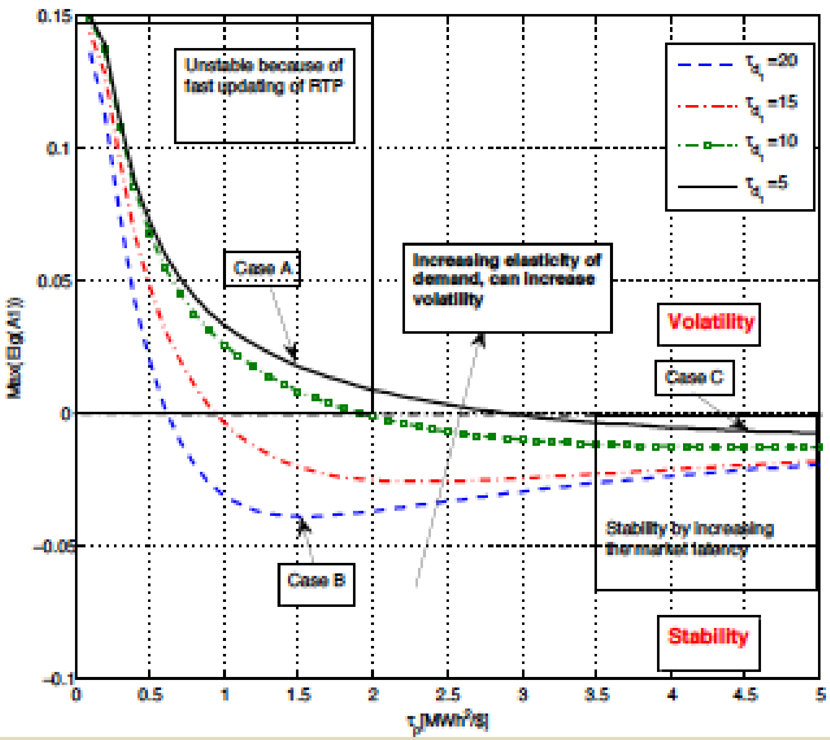
k_{d1} = k_{d2} = 0.3; demand time constants

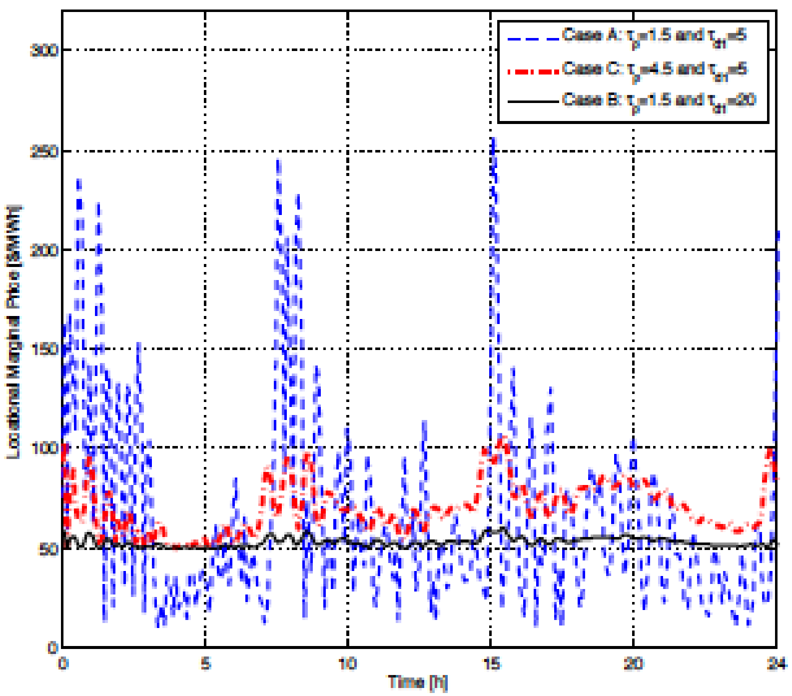
k = 0:7; LMP time constant (market time constant)

Market Stability & Volatility

Volatility: With increased demand-elasticity (k_d)

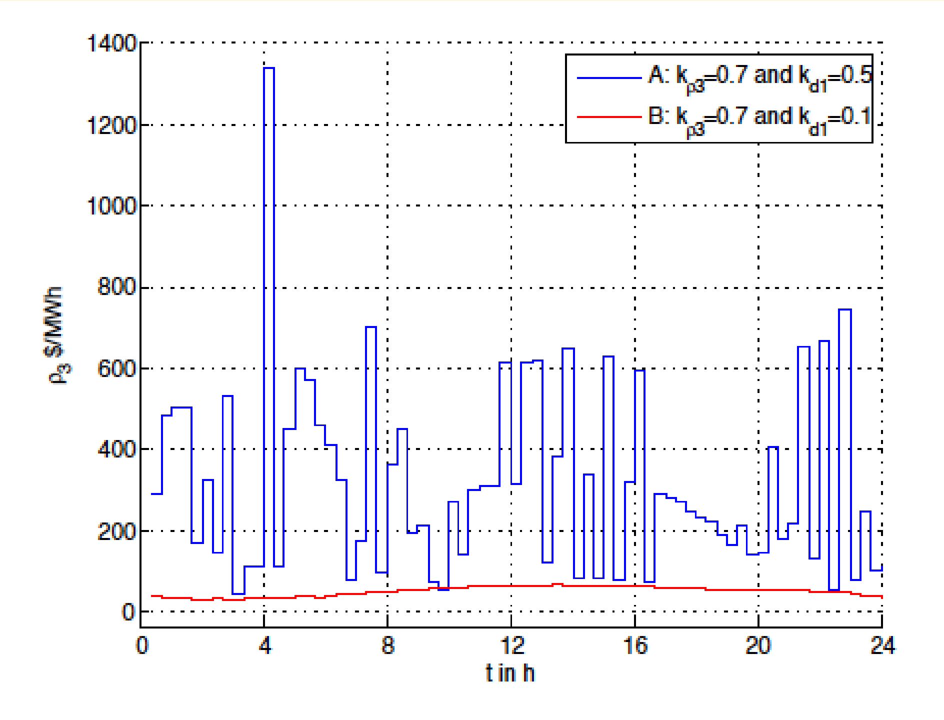
Stability: With increased latency (k_ρ)



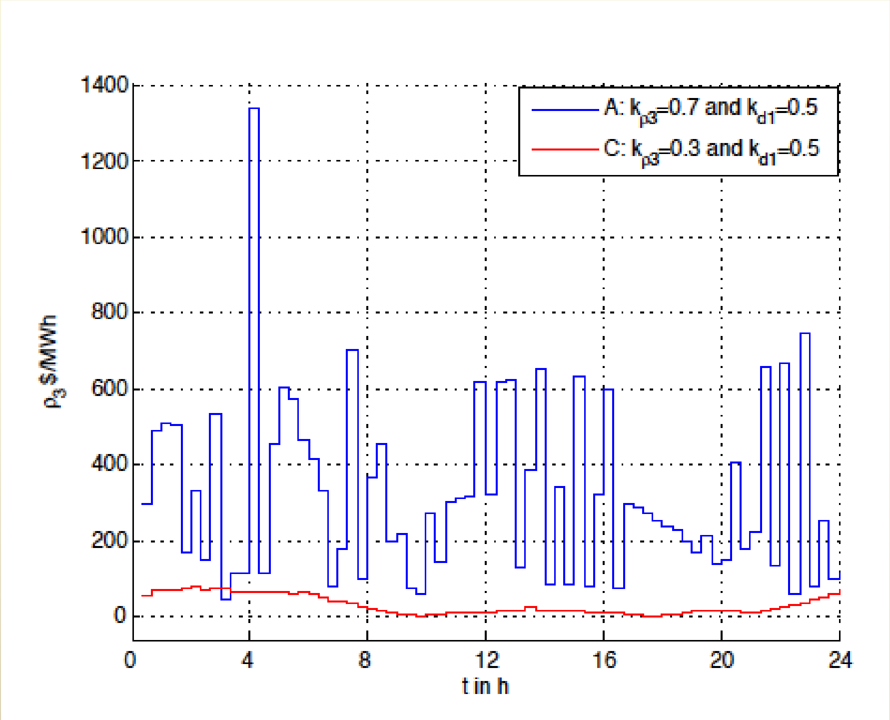


Simulation Results: Market Stability & Volatility

Volatility: With increased demand-elasticity (k_d)



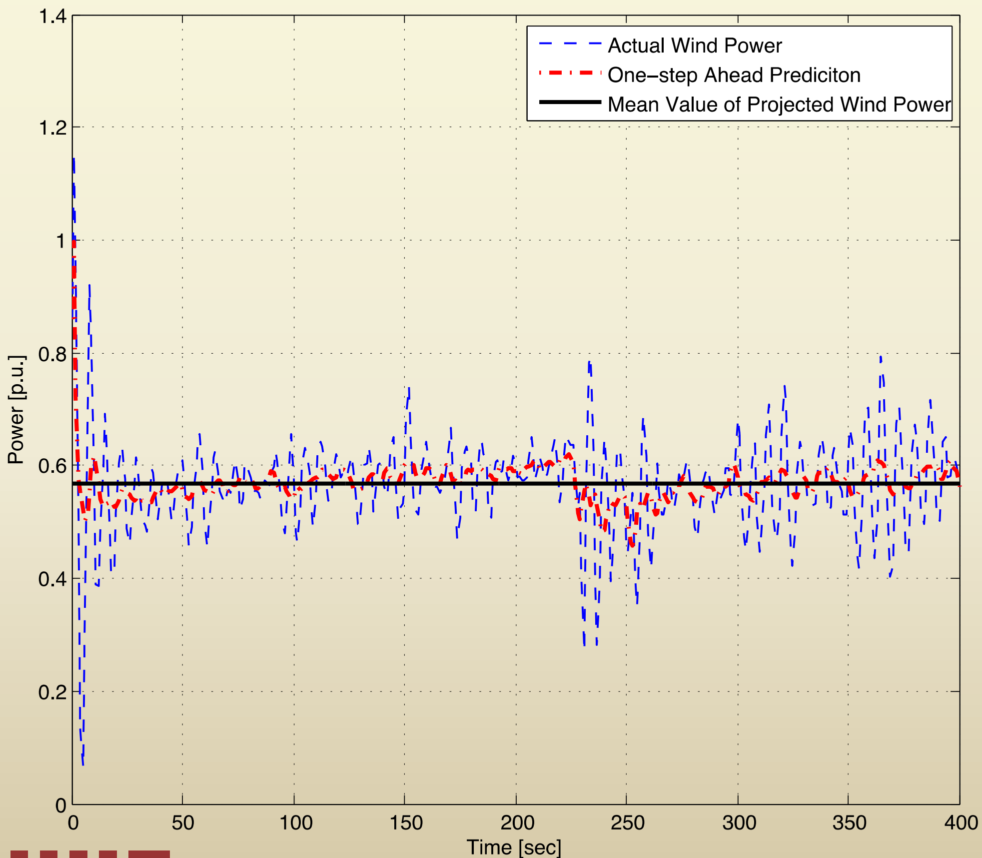
Stability: With increased latency (k_ρ)

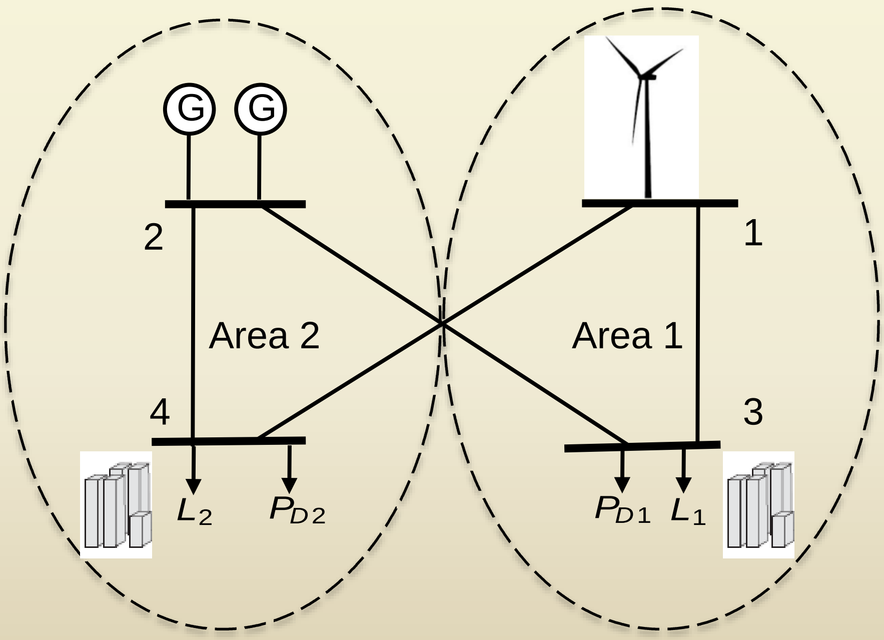


Simulation Results

Wind Properties:

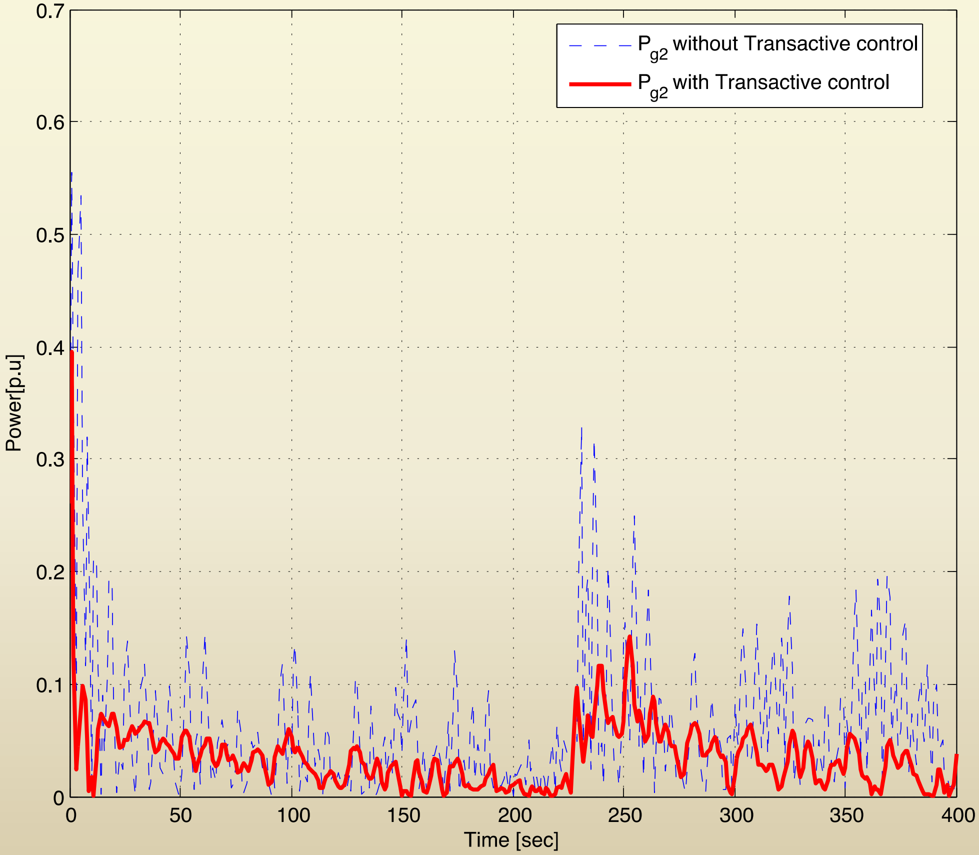
- : Actual Wind Power
- : Mean value of the projected wind. → Current Market Practice
- : ARMA model of the actual wind power. → With Transactive Control



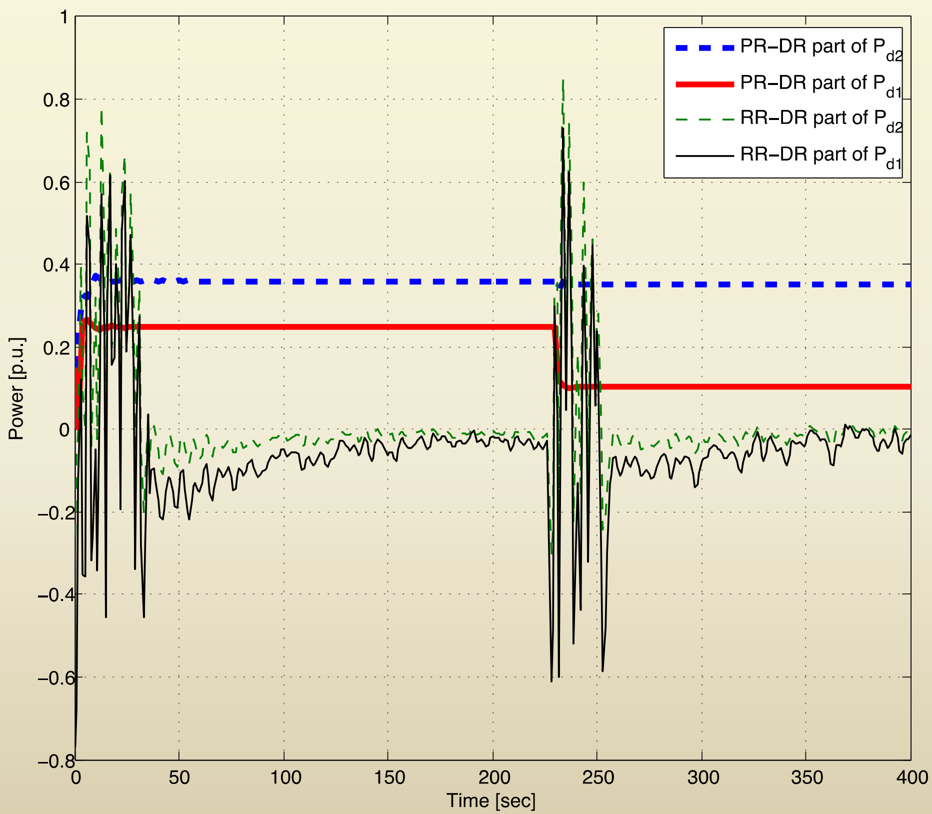


Simulation Results: Effect of Wind Uncertainty

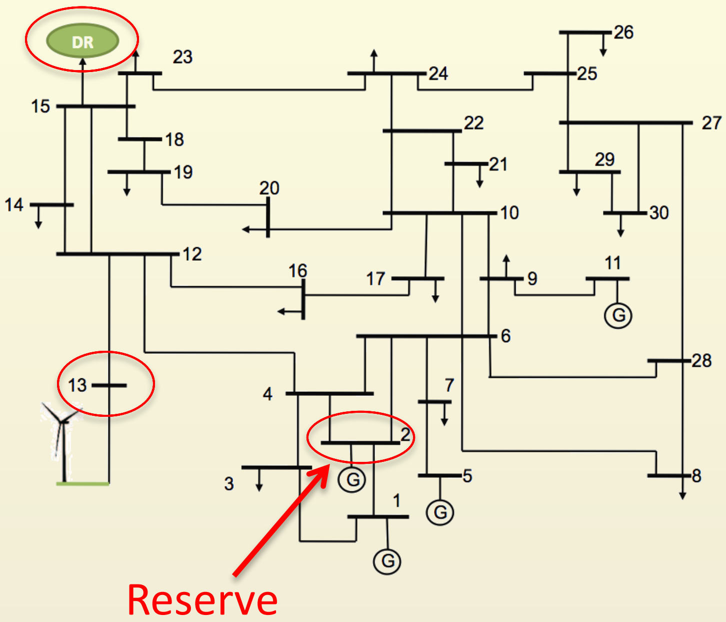
Less reserve is required.



Hierarchical coordination

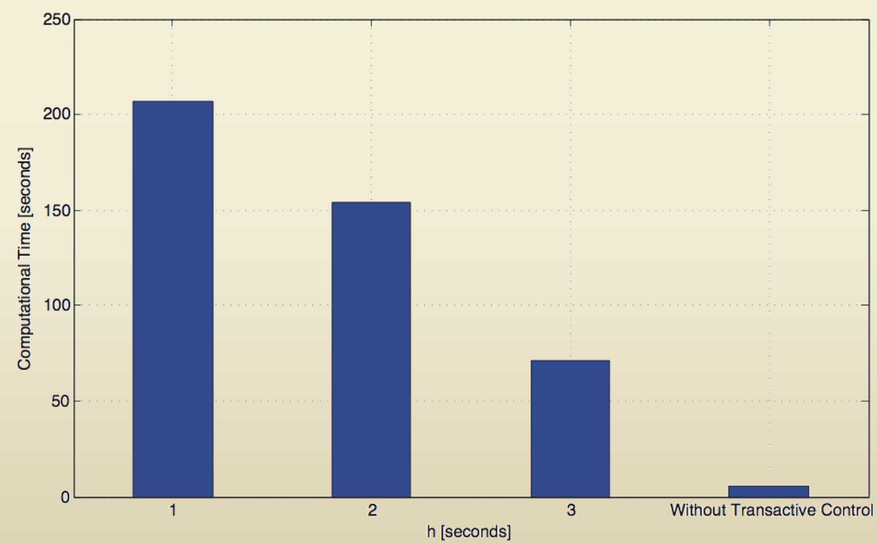


Simulation Results: IEEE 30 bus Case



Name	$P_{G_i}^{min}$ MW	$P_{G_i}^{max}$ MW	k_{P_G} $MW/\$$	c_G $\$/MW^2h$	b_G $\$/MWh$
P_{g_1}	0	100	0.012	0.28	47.2
P_{g_2}	0	100	0.02	0.55	53.8
P_{g_5}	0	150	0.06	0.25	40
$P_{g_{11}}$	0	150	0.06	0.25	40
$P_{g_{13}}$	0	100	0.02	0.015	10

Algorithm	Generation Cost $\sum_{i=1}^{5} C_{G_i}(P_{Gi})$	Reserve Cost $C_{G_2}(P_{G2})$	Social Welfare S_W
With Transactive Control	\$/h 3040.1	\$/h 827.2	\$/h 134.2
Without Transactive Control	\$/h 3980.8	\$/h 1342.8	\$/h 97.8



Summary

- Transactive Control
  - Dynamic Market Mechanisms
  - Integrated Secondary and Primary Control
- Case Studies

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IEEE VISION FOR SMART GRID
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John McDonald
Eduardo Mojica-Nava
Alexis Legbedji Motto
Lucy Pao
Alessandra Parisio
Adrian Pinder
Michael Polis
Mardavij Roozbehani
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Tariq Samad
Jakob Stoustrup

Thank You!