Power Market Participation of Flexible Loads and Reactive Power Providers: Real Power, Reactive Power, and Regulation Reserve Capacity Pricing at T&D Networks

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CISE

Outline

- How can Flexible Loads Provide Fast Reserves
- How do Distribution Network Injections Differ From Transmission System Bus Injections?
- Current Market Bidding Rules Motivate Flexible Distributed Loads to Exercise Strategic Behavior Resulting in a Hierarchical Game
- Conditions for Hierarchical Game to Converge
- Revised Bidding Rules Remove Strategic Behavior Incentives and Allow ISO/“DNO” to Clear Market in a Socially Optimal Manner
- Detailed Distribution Market Pricing Real and Reactive Power

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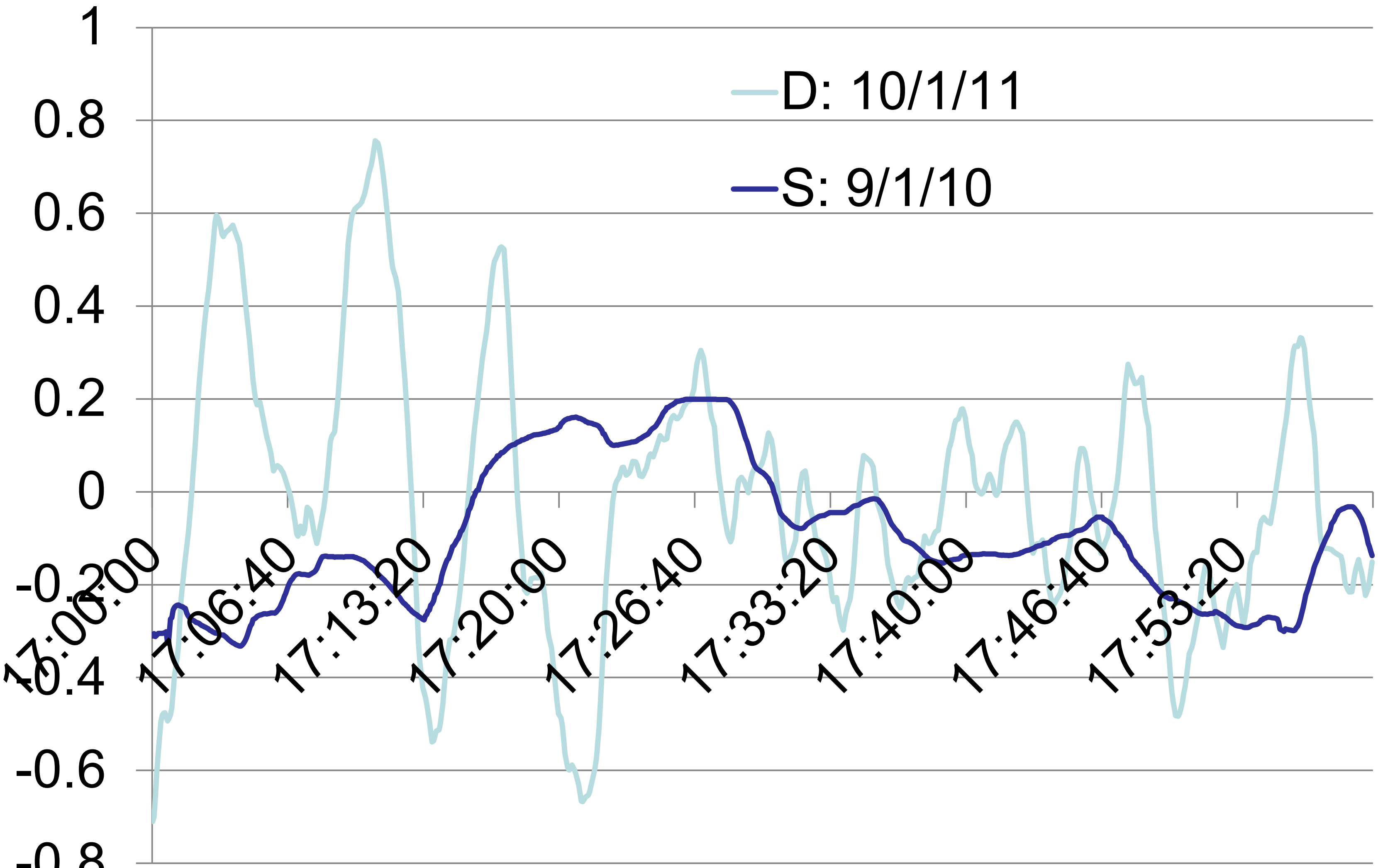
Generation and Demand Share Functional Characteristics that are Key to the Efficient and reliable Operation of the Electricity Grid

Characteristic	Generation	Demand
Dispatchability-Schedulability Low/Med/High	Wind, Run of Riv /Neuclear, L.E.P,/ HydroFossil	Capacity Loads, dependent on env. e.g.,Light/ Ind. Energy Loads Aluminum idle/Schedulable production of electr. energy intensive storable products (gas liquif.)
Flexibility Low/med/high	No Ramp – steady output e.g., nucl, min gen, start up cost and delay/ Inertia and medium storage/high ramp-low inertia large storage	Thermal or work inertia (Allum. Smelter)/Enegy Demand with small storage to capacity ratio (HVAC)/ Large storage to capacity ratio (ice, molten salt, batteries in Evs)
Forecastaility Low/Med/High	Wind, Solar. RoR Hydro/reliable fossil/unreliable fossil	Inflexible loads (lighting cooking)/Weather dependent/scheduled loads
Voltage Control	Synchronous Generators with dynamic Var compensators, DC-AC Converters	Distributed Power Electronics accompanying EVs. HVAC, Roof top PV.

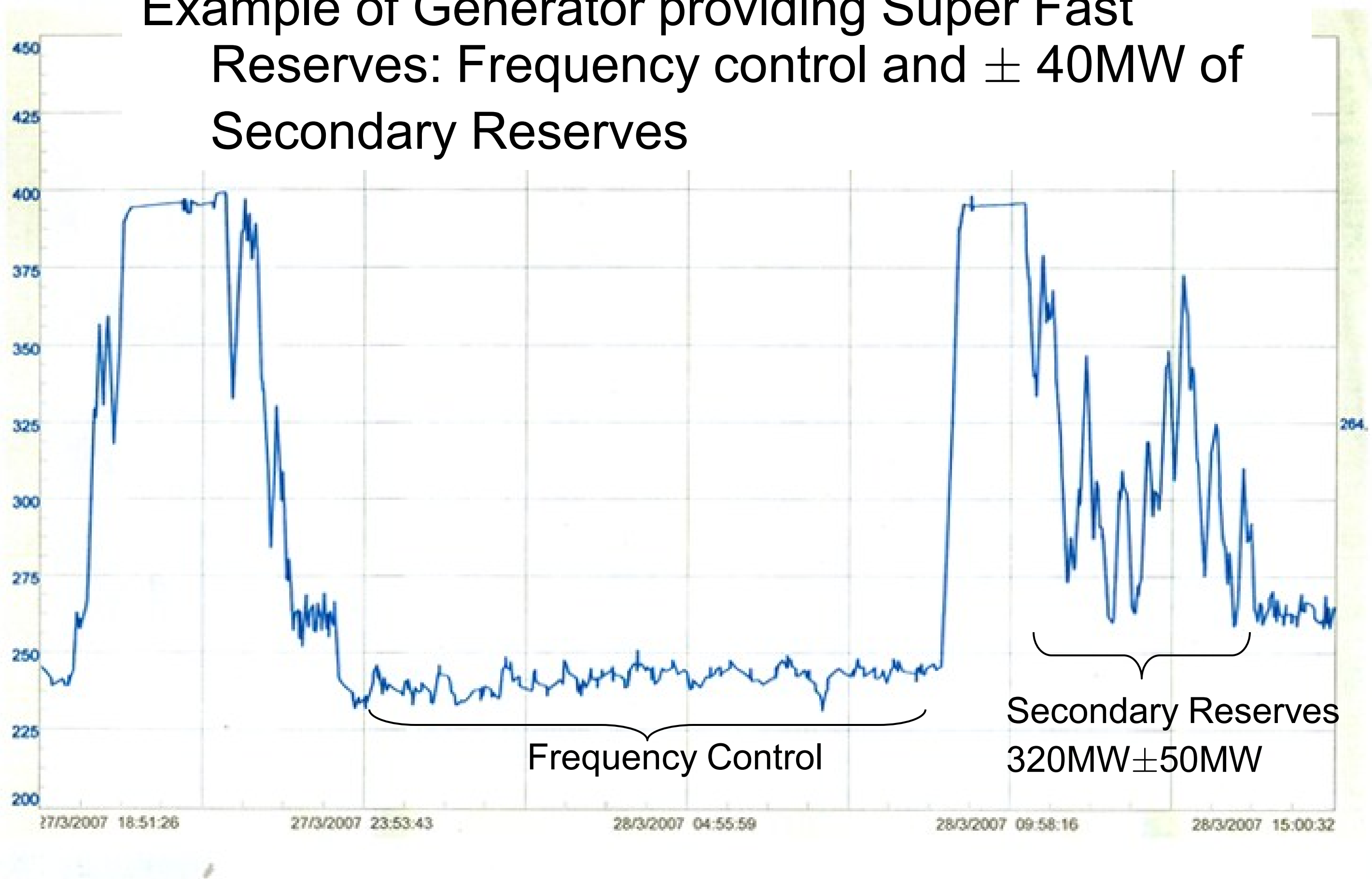
Flexible Loads Require Energy by some deadline => Capable of Regulation Reserves



Instance of PJM Regulation Signal, $y(t)$. Note Constant Average over relatively short period of Time

Today Generating Units are Only Reserve Providers

Example of Generator providing Super Fast Reserves: Frequency control and ± 40MW of Secondary Reserves



Source: Courtesy of EnThes Inc., March 2007

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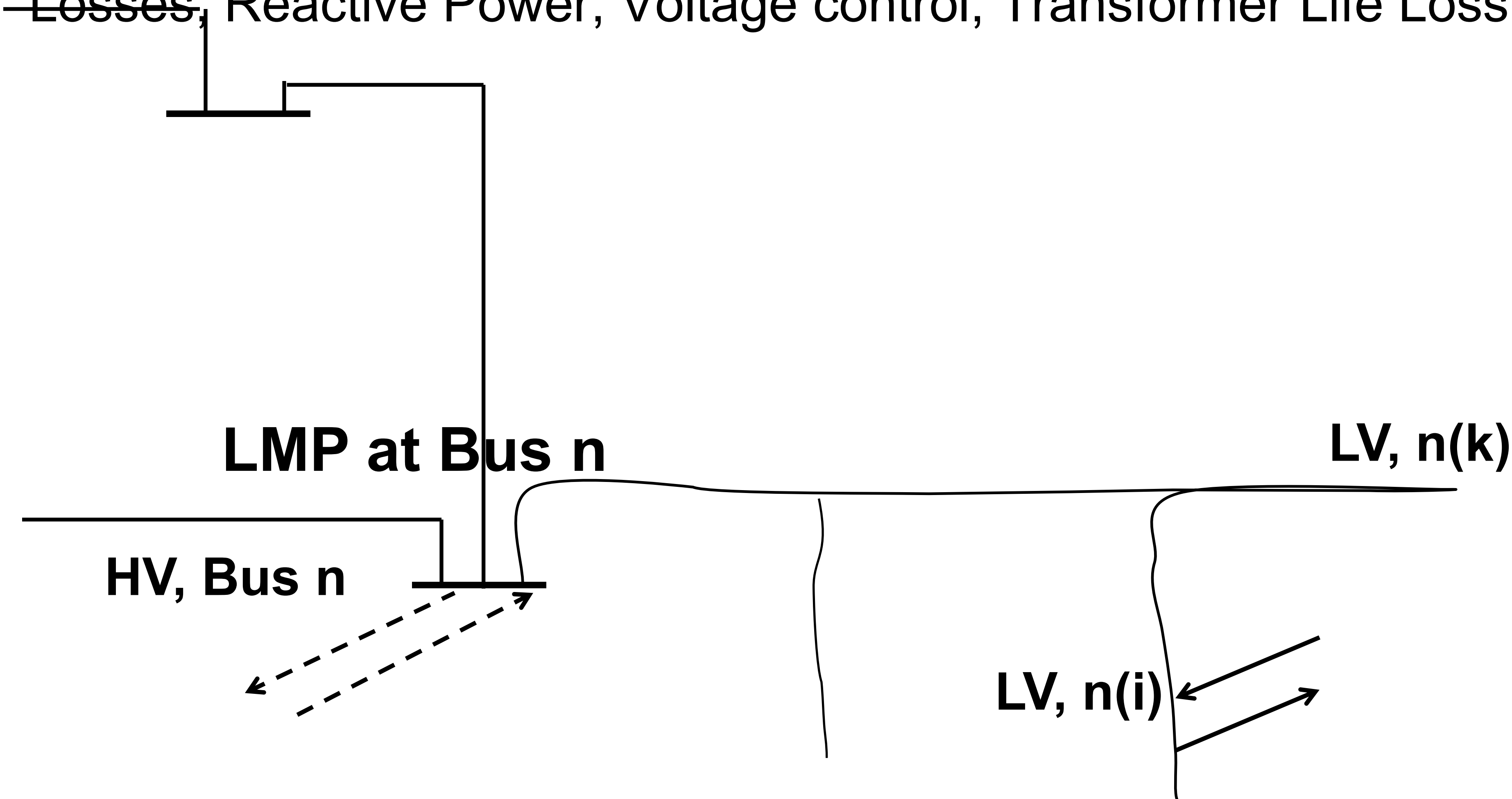
Distribution Network Low Voltage Bus Marginal Cost Based Dynamic Prices (DLMP) Result from Augmenting Transmission System High Voltage Prices (LMP) by Marginal cost of: Line ~~Losses~~, Reactive Power, Voltage control, Transformer Life Loss



DLMP at n(i)=$m_{n(i)}$(LMP at n)+…Where $m_{n(i)}$=(1+ML at n(i))…

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Examples of Flexible Loads: State Dynamics Determine Preferences

- Distributed PHEV Charging

$$^{F_j}x_{n(i)}^{t} = {}^{F_j}x_{n(i)}^{t-1} - {}^{F_j}d_{n(i)}^{t} + {}^{F_j}\hat{\omega}_{n(i)}^{t}$$

$$^{F_j}x_{n(i)}^{\text{dep time}} = 0$$

- Centralized Pumped Storage Hydro Units

$$^{psh}x_{n(p)}^{t} = {}^{psh}x_{n(p)}^{t-1} + \eta_{n(p)}^{p} p_{n(p)}^{t} - \eta_{n(p)}^{g} g_{n(p)}^{t} - \eta_{n(p)}^{r} \, {}^{R}g_{n(p)}^{t}$$

$$^{psh}x_{n(p)}^{0} = {}^{psh}x_{n(p)}^{24}$$

Strategic Flexible PHEV Load Behavior

$$\min_{{}^{F_j}d^t_{n(i)},\ {}^{F_j,R}d^t_{n(i)},\forall j,t} \sum_{j,t} \{ \underset{{}^{E}\boldsymbol{\lambda}^t_n,\ {}^{R}\boldsymbol{\lambda}^t_n,\ m^t_{n(i)}}{E} [\left(m^t_{n(i)}\ {}^{E}\lambda^t_n\right) {}^{F_j}d^t_{n(i)}$$

$$-\left(m^t_{n(i)}\ {}^{R}\lambda^t_n\right) {}^{F_j,R}d^t_{n(i)}] + {}^{F_j}U^t_{n(i)}({}^{F_j}x^t_{n(i)})\}$$

$s.t.$

$${}^{F_j}x^t_{n(i)} = {}^{F_j}x^{t-1}_{n(i)} - {}^{F_j}d^t_{n(i)} + {}^{F_j}\hat{\omega}^t_{n(i)}$$ e.g., state dyn of EV dem.

$${}^{F_j}d^t_{n(i)} \geq {}^{F_j,R}d^t_{n(i)}$$ up/dn nature of Reg. Res.

$$\sum_j [{}^{F_j}d^t_{n(i)} + {}^{F_j,R}d^t_{n(i)}] \leq \hat{C}^t_{n(i)}$$ Local Constraint

Use of Current Bidding Rules to Self Schedule

Bid Energy ${}^{F_j}d_{n(i)}^{t*} - {}^{F_j,R}d_{n(i)}^{t*}$ at a very high price

Bid Energy $2\,{}^{F_j,R}d_{n(i)}^{t*}$ at energy price $\sim\left(m_{n(i)}^{t}\,{}^{E}\lambda_n^t\right)$

and Regulation Service Rate at 0.

Using the Current Bidding Rules. Bids described on the previous slide, induce the ISO/DSO to almost surely Schedule Energy and Reserves to the * values, and thus effectively self dispatch.

$$\max_{{}^{c}d^{t}_{n(i)},\, g^{t}_{n(\gamma)},\, {}^{R}g^{t}_{n(\gamma)},\, \forall t} \sum_{t,i,\gamma} \left({}^{c}u^{t}_{n(i)}\, {}^{c}d^{t}_{n(i)} - \bar{c}^{t}_{n(\gamma)} g^{t}_{n(\gamma)} - \bar{r}^{t}_{n(\gamma)}\, {}^{R}g^{t}_{n(\gamma)} \right)$$

$s.t.$

$$\sum_{n(\gamma)} g^{t}_{n(\gamma)} - \sum_{n(i),j} {}^{F_j}d^{t*}_{n(i)} - \sum_{n(i)} {}^{c}d^{t}_{n(i)}$$

$$-\sum_{n(i)} \frac{\beta_{n(i)}}{2} \Big(\sum_{j} {}^{F_j}d^{t*}_{n(i)} + {}^{c}d^{t}_{n(i)}\Big)^2 = 0,\ \forall t \Rightarrow {}^{E,u}\lambda^{t}_{n}$$

$$\sum_{n(\gamma)} {}^{R}g^{t}_{n(\gamma)} + \sum_{j,n(i)} {}^{F_j,R}d^{t*}_{n(i)} + \sum_{n(i)} \Delta Loss_{n(i)} \geq {}^{c}R^{t}\ \forall t \Rightarrow {}^{R,u}\lambda^{t}_{n}$$

& other capacity and ramp constr. for conv. gen. and dem.

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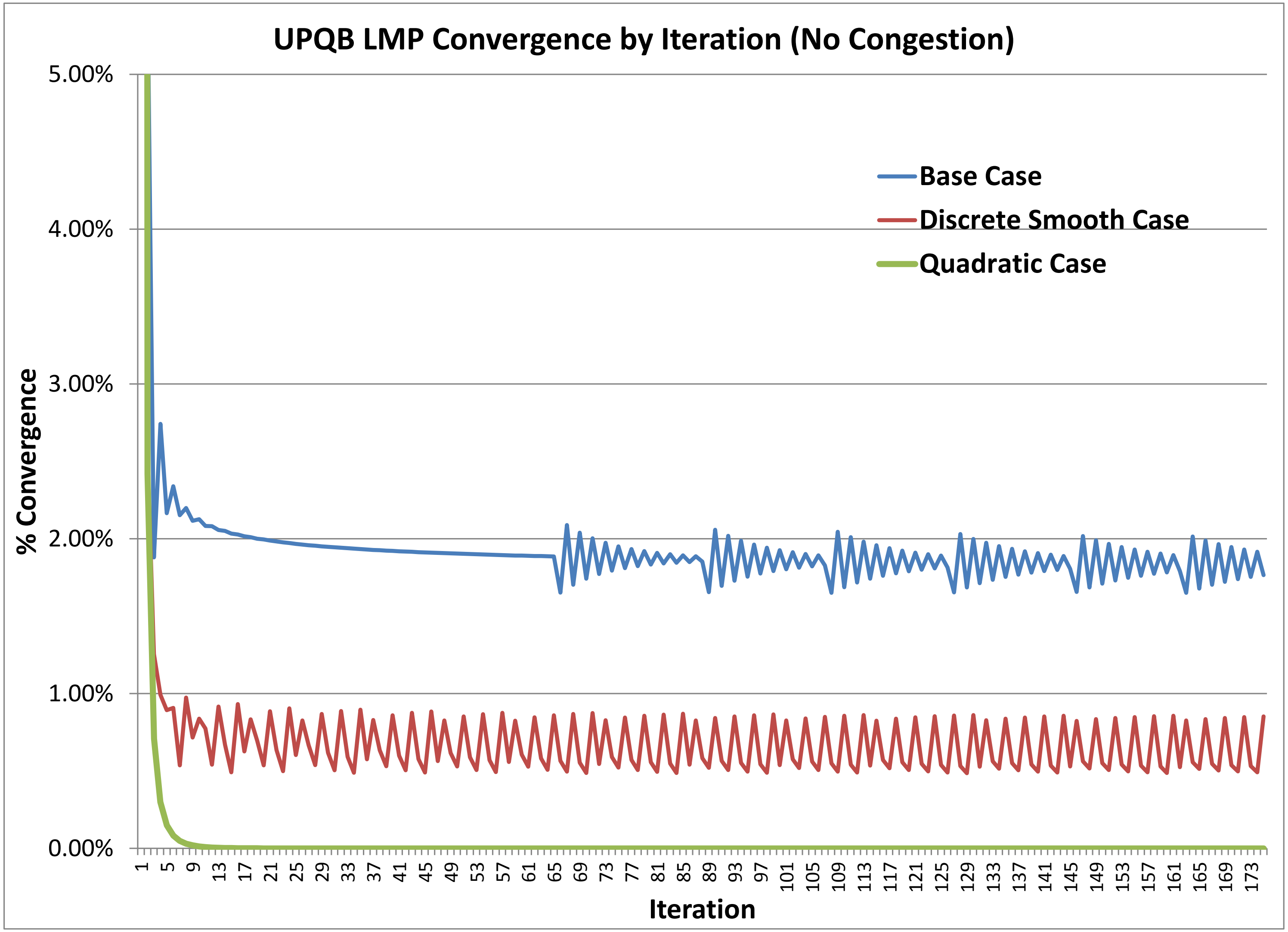
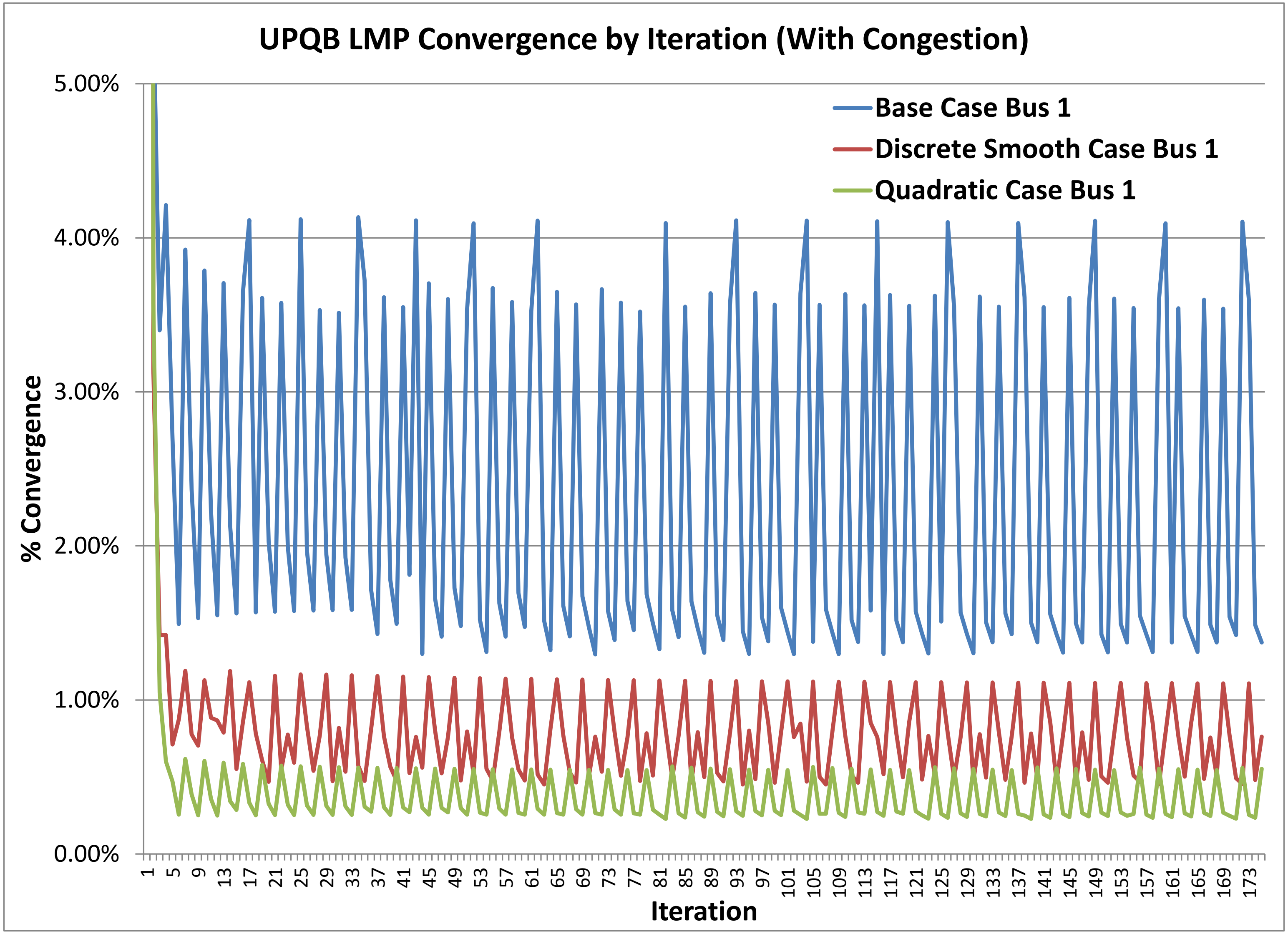
Hierarchical Game Dynamics

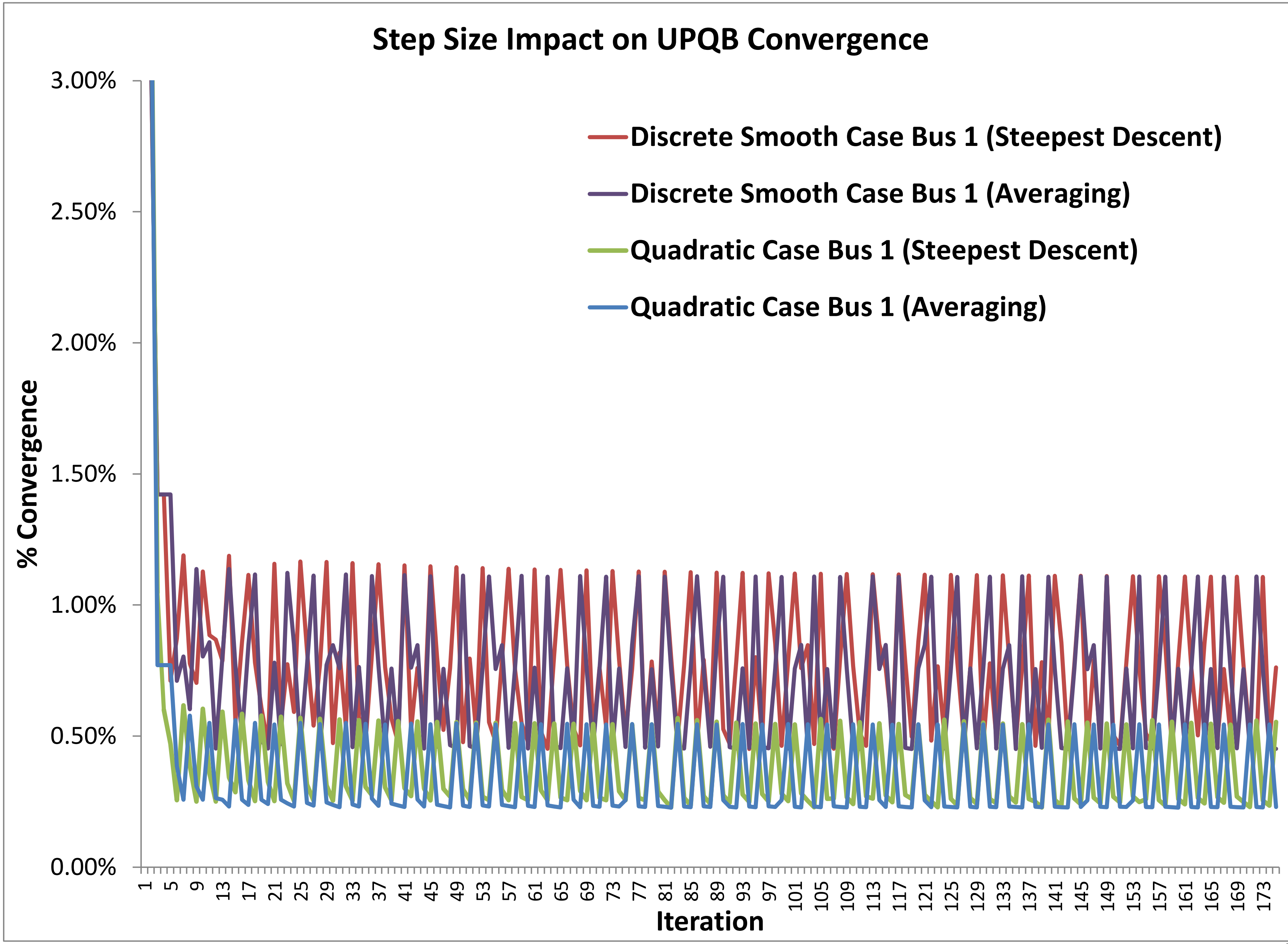
- Undamped Oscillations when Flex Load Updates Clearing Price Estimates Myopically to Most Recent ex-post ISO/DMO value
- Convergence to stable equilibrium when Flex Load Updates Clearing Price Estimates Factoring in History, for example sets them Equal to their Time Average



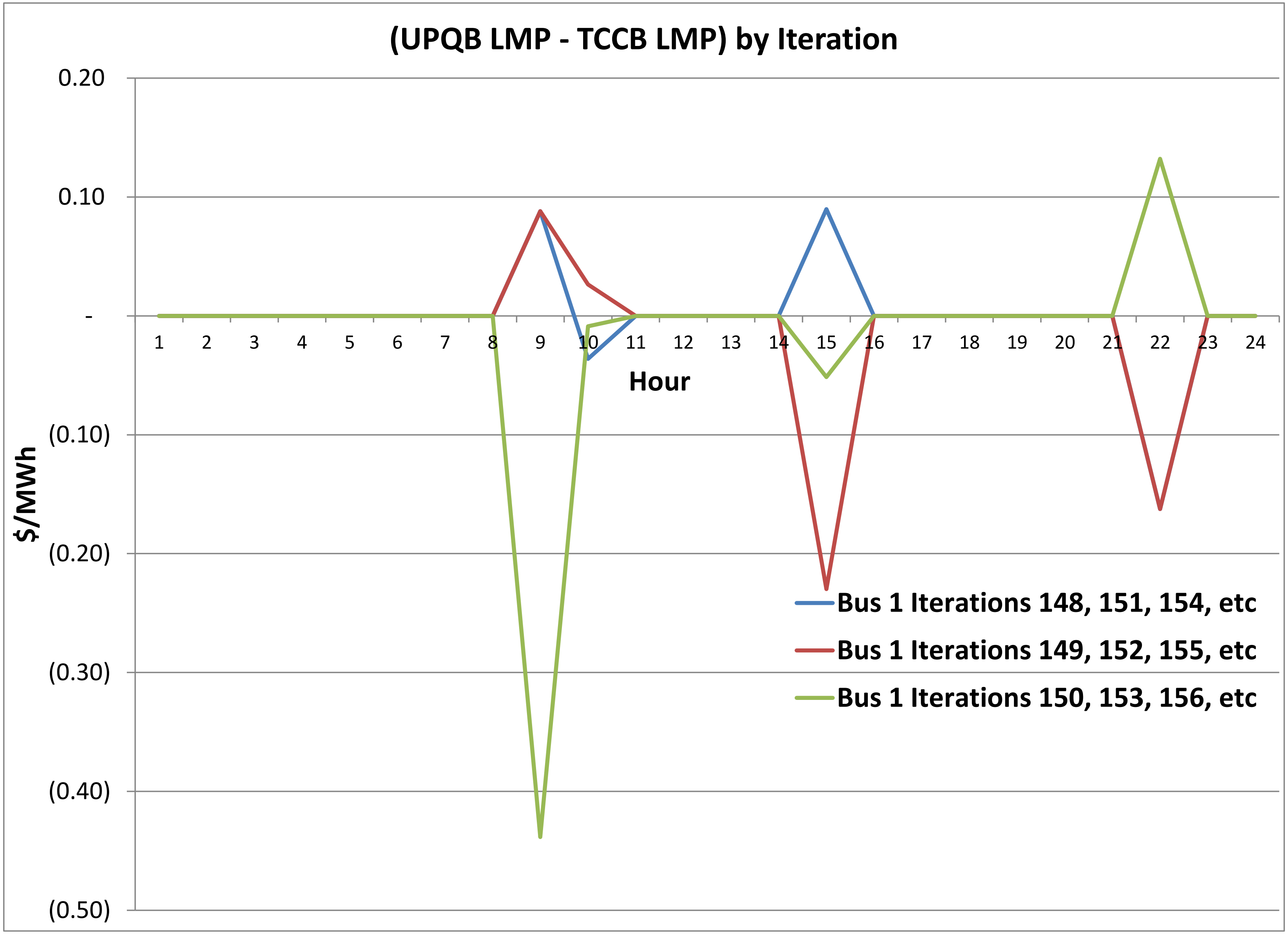
UPQB LMP Convergence by Iteration (No Congestion)
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
% Convergence
Base Case
Discrete Smooth Case
Quadratic Case
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
77
81
85
89
93
97
101
105
109
113
117
121
125
129
133
137
141
145
149
153
157
161
165
169
173
Iteration



UPQB LMP Convergence by Iteration (With Congestion)
Base Case Bus 1
Discrete Smooth Case Bus 1
Quadratic Case Bus 1
% Convergence
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
77
81
85
89
93
97
101
105
109
113
117
121
125
129
133
137
141
145
149
153
157
161
165
169
173
Iteration



Step Size Impact on UPQB Convergence
Discrete Smooth Case Bus 1 (Steepest Descent)
Discrete Smooth Case Bus 1 (Averaging)
Quadratic Case Bus 1 (Steepest Descent)
Quadratic Case Bus 1 (Averaging)
% Convergence
Iteration
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%



(UPQB LMP - TCCB LMP) by Iteration
0.20
0.10
-
(0.10)
(0.20)
(0.30)
(0.40)
(0.50)
$/MWh
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Bus 1 Iterations 148, 151, 154, etc
Bus 1 Iterations 149, 152, 155, etc
Bus 1 Iterations 150, 153, 156, etc

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Under New Bidding Rule allowing Flex Load to Express True Utility, ISO/DNO will Solve

$$\max_{{}^{c}d^{t}_{n(i)}, g^{t}_{n(\gamma)}, {}^{R}g^{t}_{n(\gamma)}, {}^{F_j}d^{t}_{n(i)}, {}^{F_j,R}d^{t}_{n(i)}, {}^{W}g^{t}_{n(\gamma)} \forall t,\gamma,i,\tau} \sum_{t,\gamma,\iota} [\, {}^{c}u^{t}_{n(i)} \, {}^{c}d^{t}_{n(i)}$$

$$- \bar{c}^{t}_{n(\gamma)} g^{t}_{n(\gamma)} - \bar{r}^{t}_{n(\gamma)} \, {}^{R}g^{t}_{n(\gamma)} - {}^{F_j}U^{t}_{n(i)}({}^{F_j}x^{t}_{n(i)})] \quad s.t.$$

$$\sum_{n(\gamma)} g^{t}_{n(\gamma)} - \sum_{n(i),j} {}^{F_j}d^{t}_{n(i)} - \sum_{n(i)} {}^{c}d^{t}_{n(i)} -$$

$$\sum_{n(i)} \frac{\beta_{n(i)}}{2} (\sum_{j} {}^{F_j}d^{t}_{n(i)} + {}^{c}d^{t}_{n(i)})^2 = 0, \quad \forall t \quad \Rightarrow {}^{E,x}\lambda^{t}_{n}$$

$$\sum_{n(\gamma)} g^{t}_{n(\gamma)} - \sum_{n(i),j} {}^{F_j}d^{t}_{n(i)} - \sum_{n(i)} {}^{c}d^{t}_{n(i)} -$$

$$\sum_{n(i)} \frac{\beta_{n(i)}}{2} (\sum_{j} {}^{F_j}d^{t}_{n(i)} + {}^{c}d^{t}_{n(i)})^2 = 0, \quad \forall t \quad \Rightarrow {}^{E,x}\lambda^{t}_{n}$$

$${}^{F_j}x^{t}_{n(i)} = {}^{F_j}x^{t-1}_{n(i)} - {}^{F_j}d^{t}_{n(i)} + {}^{F_j}\hat{\omega}^{t}_{n(i)} \quad \forall n(i) \text{ Flex Load Dynamics}$$

& other Local $n(i)$ and System constraints

Complex Bid ISO/DNO Market Clearing Achieves Hierarchical Game Equilibrium

- Theorem:
  - First order Optimality Conditions
  - Complementary Slackness, and
  - Feasibility Conditions

  Coincide if we combine Hierarchical game problems and compare to ISO/DSO problem,

  Except when Flex loads dominate in a Distr. Location (competitive assumption fails?)

$$\nabla_{{}^{F_j}d^t_{n(i)}} \pounds_{ISO} = \left(1+\beta_{n(i)}\left({}^{c}d^t_{n(i)}+\sum_j {}^{F_j}d^t_{n(i)}\right)\right){}^{E}\lambda^t_n$$

$$-{}^{R}\lambda^t_n \beta^t_{n(i)} {}^{F_j,R}d^t_{n(i)} + \alpha^{t,j}_{n(i)} + \mu^{t,j}_{n(i)} + \varsigma^{t,\tau}_{n(i)} = 0$$

Additional term in ISO/DNO problem

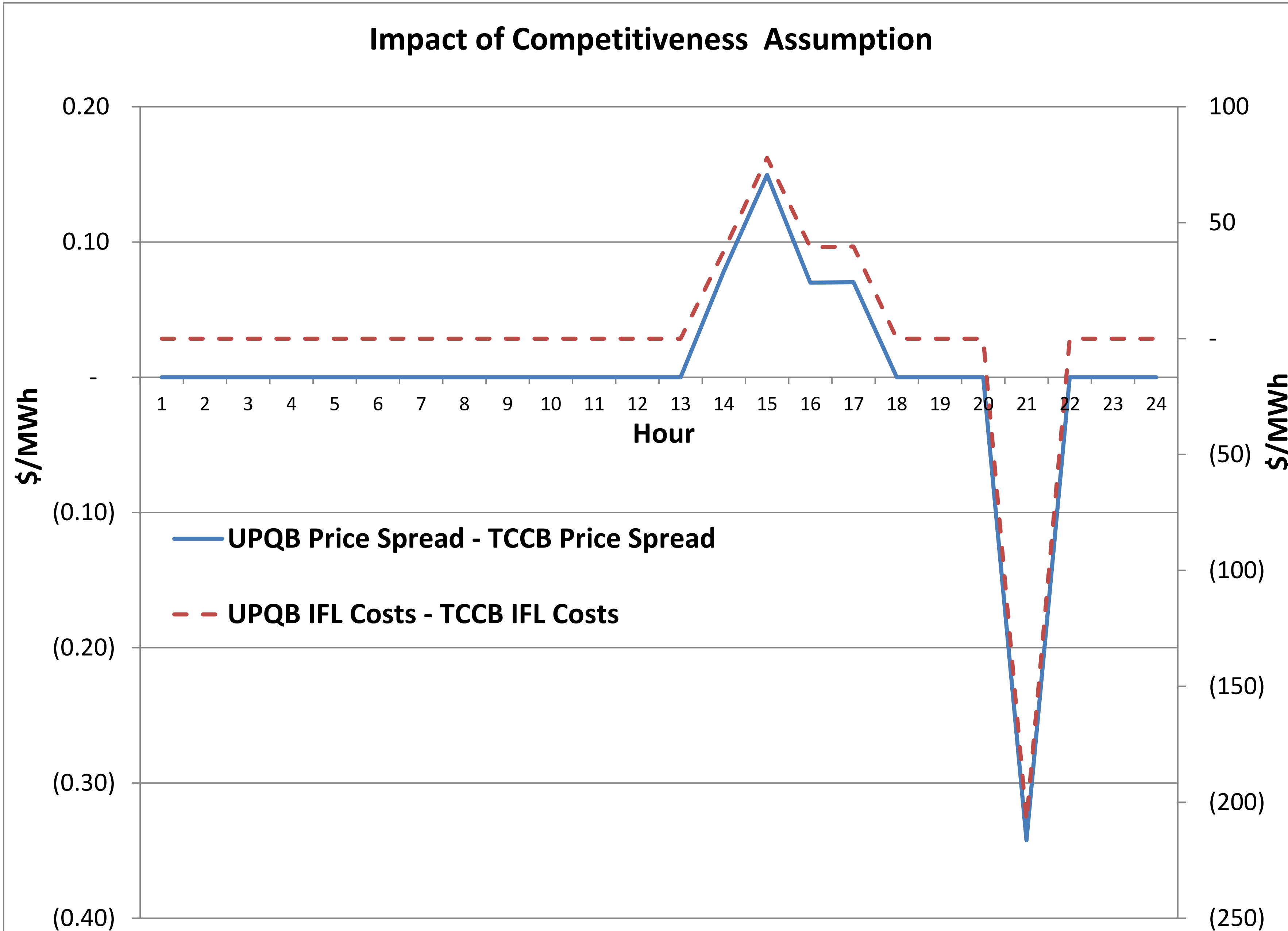
$$\nabla_{{}^{F_j}d^t_{n(i)}} \pounds_{ISO} = \left(1 + \beta_{n(i)}\left({}^{c}d^t_{n(i)} + \sum_j {}^{F_j}d^t_{n(i)}\right)\right){}^{E}\lambda^t_n$$

$$- {}^{R}\lambda^t_n \beta^t_{n(i)} \; {}^{F_j,R}d^t_{n(i)} + \alpha^{t,j}_{n(i)} + \mu^{t,j}_{n(i)} + \varsigma^{t,\tau}_{n(i)} = 0$$

Becomes negligible, i.e. $\rightarrow 0$ as

$$\frac{{}^{F_j,R}d^t_{n(i)}}{{}^{F_j}d^t_{n(i)} + {}^{c}d^t_{n(i)}} \rightarrow 0$$

or as the relative size of flex load Reg. Res. Transactions $\rightarrow 0$


Impact of Competitiveness Assumption
0.20
0.10
-
(0.10)
(0.20)
(0.30)
(0.40)
$/MWh
100
50
-
(50)
(100)
(150)
(200)
(250)
$/MWh
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
UPQB Price Spread - TCCB Price Spread
UPQB IFL Costs - TCCB IFL Costs

Conclusion

- Flexible Loads at Distribution Level may participate in Expanded ISO/DNO Centrally Cleared Power Market bringing significant benefits, particularly w.r.t. Sustainable Renewable Generation Integration to the Grid
- Expanded ISO/DNO-Operated Power Market Clearing is Practical from Information and Computational Tractability Point of view.
- Inclusion of Other Important Distribution Network Costs, such as Reactive Power Compensation and Voltage Control is also Practical.

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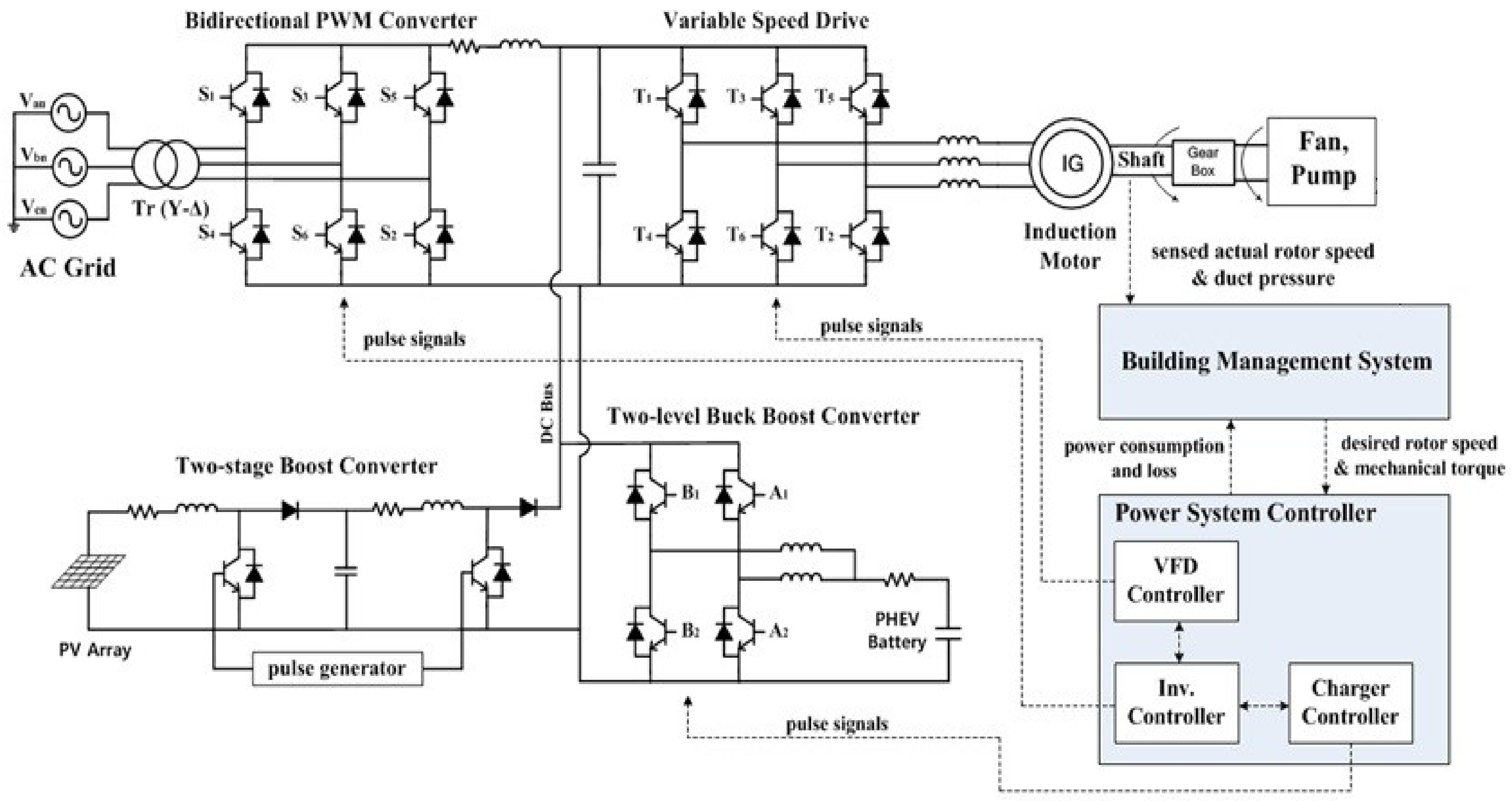
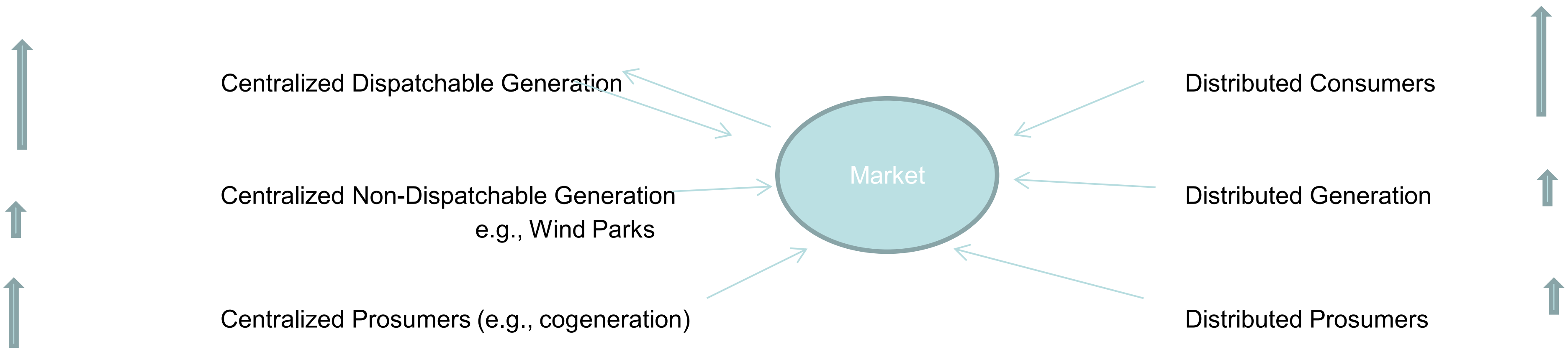
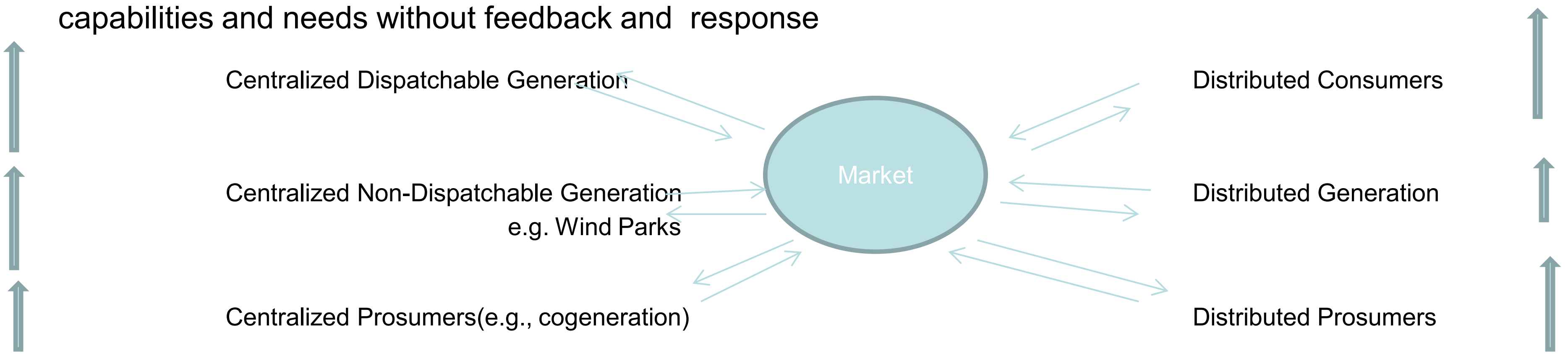
Ex. of Var. Speed HVAC - PV Collaboration: Action in the small by Distr. Flex. Loads



Load and Other Resources May Participate fully in Future Distribution Markets:

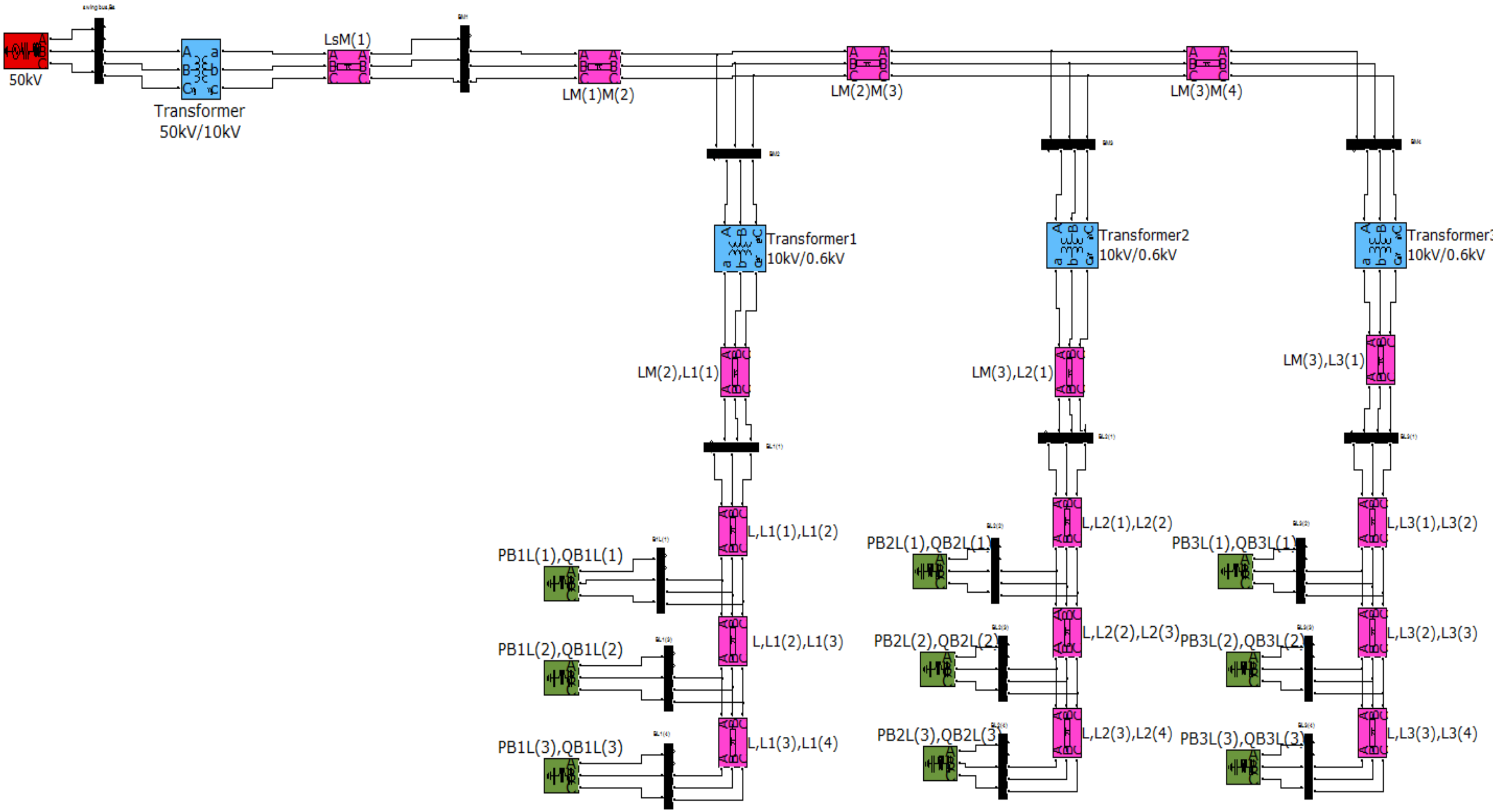


Current market: Only Centralized generation is a full market participant. All others communicate their capabilities and needs without feedback and response



Future Market: Many more non-dispatchable cedtralized generators, distributed generators and prosumers. On the distributed side, “feedback” renders Non-Dispatchable generation and distributed consumers-producers (prosumers) full market participants

Example of a Radial Distribution Network: One Medium Voltage Branch is Shown with three feeders, each with three building loads. Substation is the Slack Bus



Distribution Market Problem formulation:

Minimize **Utility Loss, Real and React. Power Cost (incl Losses), Asset Life Loss, and Volt. Control Cost *s.t.* Load Flow , Capac., Volt. Magnitude Const**

Minimize

$$\sum_m \left[\sum_i c^P_{g_i,m} P^{g_i}_m - \sum_i u^{d_i}_m P^{d_i}_m \right] + \pi^P_\infty P_{\infty,b_M(1)} + \pi^P_\infty \left(C_\infty - \sqrt{C^2_\infty - Q^2_{\infty,b_M(1)}} \right) + \sum_{f_{m,n}} \frac{\Gamma_{f_{m,n}} tM_{f_{m,n}}}{\tau_{f_{m,n}}} + c^V_\infty \left(V_\infty - 1 \right)^2$$

Subject to

$$P_{m,n} = V_m^2 G_{m,n} - V_m V_n G_{m,n} \cos(A_m - A_n) - V_m V_n B_{m,n} \sin(A_m - A_n), \forall (m,n)$$

$$Q_{m,n} = -V_m^2 B_{m,n} + V_m V_n B_{m,n} \cos(A_m - A_n) - V_m V_n G_{m,n} \sin(A_m - A_n), \forall (m,n)$$

$$P_m = \sum_n P_{m,n}, \forall m$$

$$Q_m = \sum_n Q_{m,n}, \forall m$$

$$S_{m,n} = \sqrt{P^2_{m,n} + Q^2_{m,n}}, \forall (m,n)$$

$$0 \le (P^{g_i}_b)^2 + (Q^{g_i}_b)^2 \le (C^{g_i}_b)^2$$

$$Q^{d_i}_b = P^{d_i}_b \sin(\arccos(A^{d_i}_b))$$

Distribution Market Problem formulation (cont.)

$$-\sqrt{(C_b^{e_i})^2-(P_b^{e_i})^2} \le Q_b^{e_i} \le \sqrt{(C_b^{e_i})^2-(P_b^{e_i})^2}, \forall e_i$$

$$P_b^{e_i} = \begin{cases} 0, if\ e_i\ is\ s\tan d-alone \\ <0, if\ e_i\ is\ associated\ with\ d_i \\ >0, if\ e_i\ is\ associated\ with\ g_i \end{cases}$$

$$\sum_i P_b^{g_i} + \sum_i P_b^{e_i} - \sum_i P_b^{d_i} = P_b, \forall b \neq \infty$$

$$\sum_i Q_b^{g_i} + \sum_i Q_b^{e_i} - \sum_i Q_b^{d_i} = Q_b, \forall b \neq \infty$$

$$\Gamma_{f_{b,m}} = \exp\left(\frac{15000}{383} - \frac{15000}{273+\theta_{f_{b,m}}^H}\right), \forall f_{b,m}$$

$$\theta_{f_{b,m}}^H = \theta^A + k_{1,f_{b,m}} + k_{2,f_{b,m}} S_{b,m}^2, \forall f_{b,m}$$

$$\underline{V_b} \le V_b \le \overline{V_b}, \forall b$$

$$A_\infty = 0$$

Distribution Market Benefits

- Marginal Losses Reflected in DLMPs=>Demand Adaptation
- Reactive Power Pricing motivates Dual Use of Power Electronics whose presence is expected to Become Ubiquitous while accompanying Distributed Clean Generation (e.g., PV) installations and Flexible Loads (e.g., EVs, Heat Pumps)
- Marginal Voltage Control Cost Reflected in DLMPs =>Demand Adaptation
- Distribution Asset Degradation Marginal Costs Reflected in DLMPs =>Demand Adaptation
- Full Distr. Net Price Unbundling =>Distr. Net Rent