DOE EAC Panel on Valuation and Integration of DERs

Comments on the Extension of Dynamic Power Markets to Distribution Network Participants, "Smart Power Distribution Networks: Adaptive Flexible Loads and Resources"

Washington DC, March 17, 2016

Michael Caramanis
mcaraman@bu.edu

Paradigm Shift in Power System Operation and Planning

- Power System Fundamentals: Non-Storable Electric Power + Uncertainty + Limited Control of Load Flow => Need to
  - Procure and Deploy Reserves for System Stability
  - Manage Transmission (Line overload) and Distribution (Voltage bounds and Transformer) Congestion.
- Newcomers and Generation Mix: Renewables (Centralized and Distributed) ↑, Flexible Gen. (CCGT) ↑, Inflexible Gen. (nuclear, coal) ↓, Flexible Loads (EV) ↑ Distributed Resources (GFA, Inverters) ↑, Inflexible Loads (Lights, capacity demands) ↓, Reserve Requirements ↑, Congestion and/or Equipment Loss of Life ↑ & ↓ .
- Will Familiar Pattern of **Generation** Following-Consumption and Providing-Reserves be Replaced (at Least Partly) by **Consumption**-Following-Generation and Providing-Reserves?

Some Key Issues

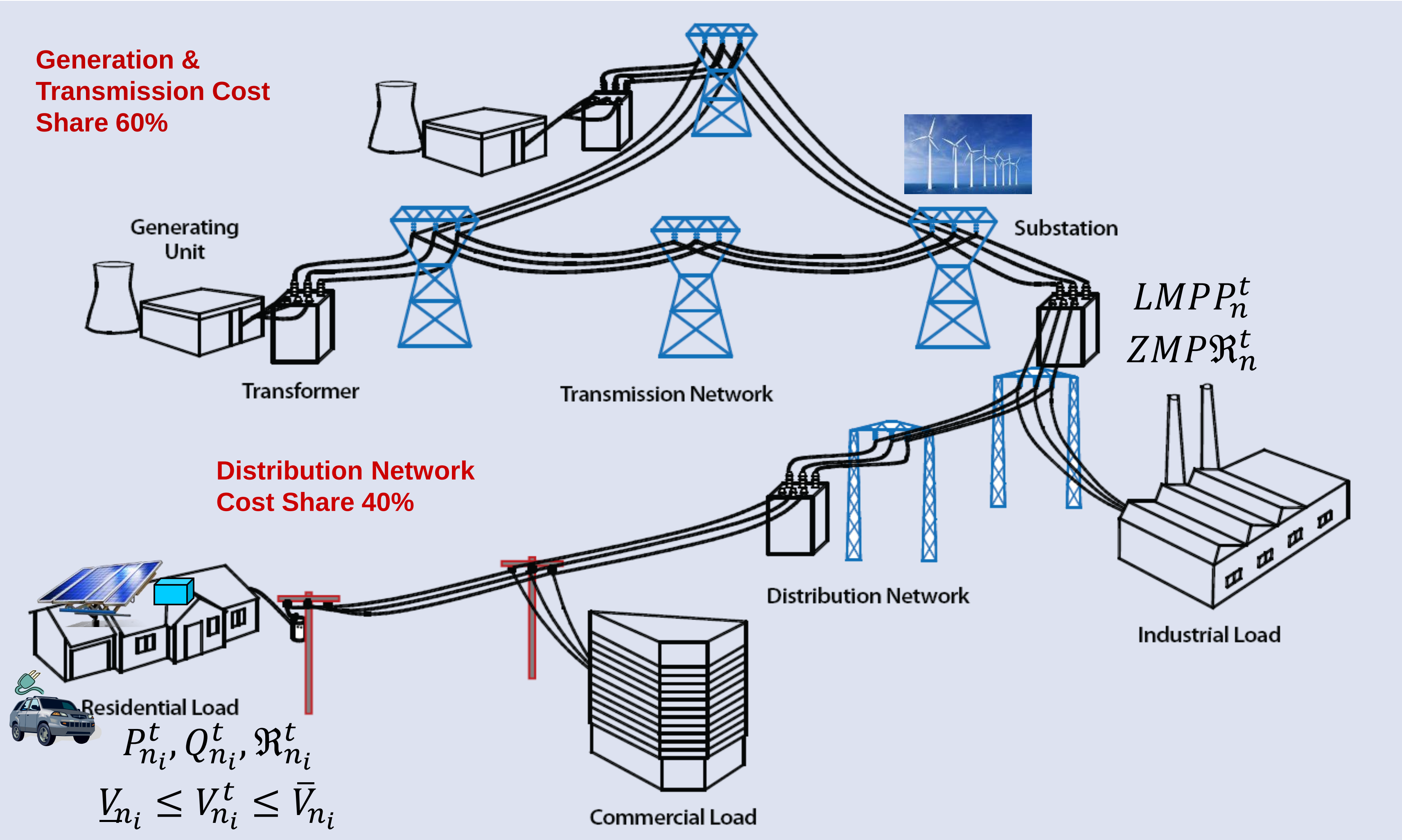
- At the transmission Network:
  - Transmission Line Congestion
  - Stability: Reserve Procurement and Deployment
- At the distribution Networks:
  - Transformer overloading
  - Losses (real and reactive power)
  - Voltage Control (real and reactive power)
- T&D interface
  - Retail Response to Transmission needs/MCs
  - Deliverability of Retail Response/Reserve Offers

DER Examples and their Capabilities

- **PV**: Distributed Non-Controllable Generation of Real Power BUT Controllable Volt/Var inverters can provide Reactive Power Compensation using excess inverter capacity
- **EV**: Storage Like Flexible Demand AND Reactive Power Compensation
- Electric **Space Conditioning**/Heat Pumps: Flexible/ Storage Like loads (precooling-preheating) with often Reactive Power Compensation capability (e.g., Var. Speed Drives)
- **Computing**: Sever farms, Data Centers
- **Duty Cycle** Appliances, Distributed Storage,…

All of the above Can promise and deploy reserves.

Incurred Cost Distribution, Congestion, Reserves, Voltage Control, Losses, Transformers, Deliverability



$LMPP_n^t = \Pi_n^{E,t}$ = Locational Marginal Price of Real Power at bus n, during hour t

$ZMP\Re_n^t = \Pi_n^{\Re,t}$ = Locational Zonal Price of Reserves at bus n $\in$ zone Z, during hour t

Interface between Transmission & Distribution

$$\Re_n^t \approx \sum_i \{\Re_{n_i}^t + 2R_{n_i} P_{n_i}^t\}$$

$$Q_n^t \approx \sum_i \{Q_{n_i}^t + X_{n_i}[(P_{n_i}^t)^2 + (Q_{n_i}^t)^2]\}$$

$$P_n^t \approx \sum_i \{P_{n_i}^t + R_{n_i}[(P_{n_i}^t)^2 + (Q_{n_i}^t)^2]\}$$

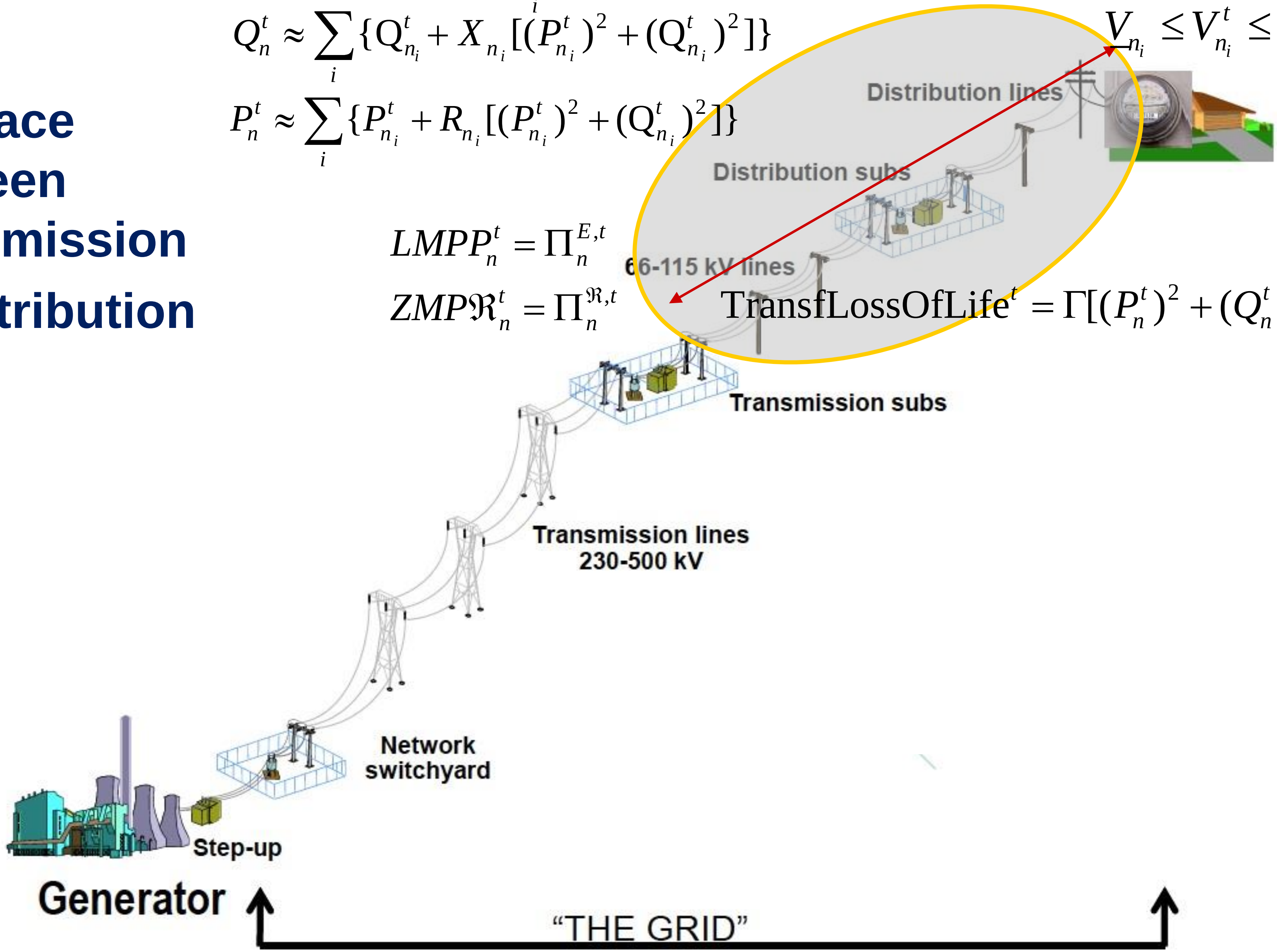
$$P_{n_i}^t, Q_{n_i}^t, \Re_{n_i}^t$$

$$\underline{V}_{n_i} \le V_{n_i}^t \le \overline{V}_{n_i}$$

$$LMPP_n^t = \Pi_n^{E,t}$$

$$ZMP\Re_n^t = \Pi_n^{\Re,t}$$

$$\text{TransfLossOfLife}^t = \Gamma[(P_n^t)^2 + (Q_n^t)^2]$$



Reactive Power Affects All Costs and Voltage magnitudes!

$$P_{n_i}, \quad Q_{n_i}$$ Real and Reactive Consumption at Distribution Network Location i below Sub-Transmission bus n

$$Q_n \approx \sum_i \{Q_{n_i} + x_{n,n_i}[(P_{n,n_i})^2 + (Q_{n,n_i})^2]\}$$ Reactive Power at Sub

$$P_n \approx \sum_i \{P_{n_i} + r_{n,n_i}[(P_{n,n_i})^2 + (Q_{n,n_i})^2]\}$$ Real Power at Sub

$$\text{Transf Loss Of Life} = \Gamma[(P_{n,n_i})^2 + (Q_{n,n_i})^2]$$

$$\underline{V}_{n_i} \le V_{n_i} \le \bar{V}_{n_i}$$ Voltage Level Control

$$\Delta V^2 \approx (V_n^t)^2 - (V_{n_i}^t)^2 \approx 2(r_{n,n_i} P_{n_i}^t + x_{n,n_i} Q_{n_i}^t)$$

Planning to Operation Practices Incorporated in Today's Power Markets are Surprising Useful (and Adaptable?)

- Generation Capacity and Transmission Congestion (FTR) Markets – <u>Years to Months</u>
- Forward Energy Commodity Markets – <u>Months</u>
- Energy and Reserve Co-Clearing Markets:
  - Day Ahead: Multiple <u>Hours</u>
  - Hour Ahead/Adjustment Market – <u>Hour</u>
- Reserve Deployment Dynamics:
  - Operating: 5 min.,
  - Regulation Service (AGC Centralized): 2-4 sec
  - Frequency Control (Decentralized): Real-Time

Extended Market Clearing =>

I. T&D Locational Marginal Prices (T&DLMP)

II. Scheduling of DER Capacity among Real and Reactive Power and Reserves.

- $\pi_n^x(t)$ □ the Marginal/Incremental cost to the Power System associated with Delivering a unit of Service x to location n at time t. **This results in optimal operating decisions**.
- x ranges over real, reactive power and reserves
- n ranges over T&D busses

LMPs : Wholesale – High Voltage -- Market Clearing (DC approximation)

$$\min_{P_n^j, R_n^j} \sum_{j,n,t} u_n^j P_n^j(t) + \sum_{j,n,t} \bar{J}_n^j(R_n^j(t))$$

subject to

$$\sum_{j,n,t} P_n^j(t) + Losses = 0 \quad \rightarrow \lambda(t); \quad \forall t \quad P_n^{j \in \text{gen}}(t) \geq 0, \; P_n^{j \in \text{dem}}(t) \leq 0$$

$$\sum_{j,n \in Z,t} R_n^j(t) \geq \Re_Z \quad \rightarrow \pi_Z^R(t); \quad \forall t$$

$$\underline{P}_{n,n'}(t) \leq P_{n,n'}^{\text{lin gap}}(t) + \sum_{\hat{n}} P_{\hat{n}}(t) \text{ShF}_{n,n'}^{\hat{n}}(t) \leq \bar{P}_{n,n'}(t) \rightarrow \underline{\mu}_{n,n'}(t), \bar{\mu}_{n,n'}(t); \; \forall t$$

$$P_n(t) = \sum_j P_n^j(t); \;\; \text{plus capacity constraints}$$

$$\text{ShF}_{n,n'}^{\hat{n}}(t) \equiv \frac{\partial P_{n,n'}}{\partial P_{\hat{n}}} \quad \text{the line flow shift factor -- linearization -- at } t$$

LMP price Relations

$$\pi_{\hat{n}}^{P}(t) = \lambda(t)(1 + \frac{\partial Losses}{\partial P_{\tilde{g}(\hat{n})}}) + \sum_{n,n'} \mu_{n,n'}(t) P_n(t) \mathrm{ShF}_{n,n'}^{\hat{n}}(t)$$

where $\mu_{n,n'}(t) \equiv [\bar{\mu}_{n,n'}(t) - \underline{\mu}_{n,n'}(t)]$

$$\pi_{\hat{n}}^{R}(t) = \pi_{Z}^{R}(t) = \max_{j,\hat{n}\in Z, R_{\hat{n}}^{j}>0} [\,|\,\pi_{\hat{n}}^{P}(t) - u_{\hat{n}}^{j}\,| + \partial \bar{J}_{\hat{n}}^{j}(R_{\hat{n}}^{j}) / \partial R_{\hat{n}}^{j}\,]$$

Proposed Distribution Market Problem formulation:

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

Minimize Over DER real, reactive power and reserves and substation voltage V_∞:
Sum over all hours. Note Sum over *t* and (*t*) argument not shown to avoid notational Clutter.

$$\pi_\infty^P P_\infty + \pi_\infty^{OC}\left(C_\infty - \sqrt{C_\infty^2 - Q_\infty^2}\right) + \pi_\infty^R \frac{P_\infty^{R,up} - P_\infty^{R,down}}{2} + c_\infty^v (v_\infty - 1)^2$$

Substation Real P

Opportunity Cost of Q at Substation

Value of Sec. Reserves at Substation

Cost of deviating from Nominal V a substation

$$+\sum_{j,b} u_b^j(X_b^j) + \sum_{j,b} \bar{J}_b^j(R_b^j) + \sum_{b,b' \in tr} \Gamma(S_{b,b'})$$

Utility (- or +) of State X at the end of hour *t*

Expected Average cost of deployment of R_b^j during hour t

Cost of Transf. life loss.

Subject to: constrains shown below

Subject to: Load Flow relations when the regulation signal y=0 *(relaxed brunch flow model)*

$$\ell_{b,b'} = \frac{P_{b,b'}^2 + Q_{b,b'}^2}{v_b} = \frac{S_{b,b'}^2}{V_b^2} \qquad \textit{current sq.} \qquad \text{(A1)}$$

$$v_{b'} = v_b - 2(r_{b,b'}P_{b,b'} + x_{b,b'}Q_{b,b'}) + (r_{b,b'}^2 + x_{b,b'}^2)\ell_{b,b'} \qquad \text{(A2)}$$

$$\sum_j P_b^j = \sum_{b'} P_{b,b'} \rightarrow \pi_b^P \qquad \text{(A3)}$$

$$\sum_j Q_b^j = \sum_{b'} Q_{b,b'} \rightarrow \pi_b^Q \qquad \text{(A4)}$$

$$P_{b,b'} + P_{b',b} = r_{b,b'}\ell_{b,b'} \qquad \textit{real losses} \qquad \text{(A5)}$$

$$Q_{b,b'} + Q_{b',b} = x_{b,b'}\ell_{b,b'} \qquad \textit{reactive losses} \qquad \text{(A6)}$$

$$\underline{v} \le v_b \le \overline{v} \rightarrow \underline{\mu}_b, \overline{\mu}_b \qquad \mu_b \equiv \overline{\mu}_b - \underline{\mu}_b \qquad \text{(A7)}$$

Subject to: Load Flow relations when the regulation signal y=1 (relaxed brunch flow model)

$$\ell_{b,b'}^{R,up} = \frac{(P_{b,b'}^{R,up})^2 + (Q_{b,b'}^{R,up})^2}{v_b^{R,up}} \tag{B1}$$

$$v_{b'}^{R,up} = v_b^{R,up} - 2(r_{b,b'} P_{b,b'}^{R,up} + x_{b,b'} Q_{b,b'}^{R,up}) + (r_{b,b'}^2 + x_{b,b'}^2)\ell_{b,b'}^{R,up} \tag{B2}$$

$$\sum_j P_b^j + \sum_j R_b^j = \sum_{b'} P_{b,b'}^{R,up} \rightarrow \pi_b^{P,up} \tag{B3}$$

$$\sum_j Q_b^{j,up} = \sum_{b'} Q_{b,b'}^{R,up} \rightarrow \pi_b^{Q,up} \tag{B4}$$

$$P_{b,b'}^{R,up} + P_{b',b}^{R,up} = r_{b,b'} \ell_{b,b'}^{R,up} \tag{B5}$$

$$Q_{b,b'}^{R,up} + Q_{b',b}^{R,up} = x_{b,b'} \ell_{b,b'}^{R,up} \tag{B6}$$

$$\underline{v} \le v_b^{R,up} \le \overline{v} \rightarrow \underline{\mu}_b^{R,up}, \overline{\mu}_b^{R,up} \tag{B7}$$

Subject to: Load Flow relations when the regulation signal y=-1 *(relaxed brunch flow model)*

$$\ell_{b,b'}^{R,down} = \frac{(P_{b,b'}^{R,down})^2 + (Q_{b,b'}^{R,down})^2}{v_b^{R,down}} \tag{C1}$$

$$v_{b'}^{R,down} = v_b^{R,down} - 2(r_{b,b'}P_{b,b'}^{R,down} + x_{b,b'}Q_{b,b'}^{R,down}) + (r_{b,b'}^2 + x_{b,b'}^2)\ell_{b,b'}^{R,down} \tag{C2}$$

$$\sum_j P_b^j - \sum_j R_b^j = \sum_{b'} P_{b,b'}^{R,down} \rightarrow \pi_b^{P,down} \tag{C3}$$

$$\sum_j Q_b^{j,down} = \sum_{b'} Q_{b,b'}^{R,down} \rightarrow \pi_b^{Q,down} \tag{C4}$$

$$P_{b,b'}^{R,down} + P_{b',b}^{R,down} = r_{b,b'}\ell_{b,b'}^{R,down} \tag{C5}$$

$$Q_{b,b'}^{R,down} + Q_{b',b}^{R,down} = x_{b,b'}\ell_{b,b'}^{R,down} \tag{C6}$$

$$\underline{v} \le v_b^{R,down} \le \overline{v} \rightarrow \underline{\mu}_b^{R,down}, \overline{\mu}_b^{R,down} \tag{C7}$$

Subject to: Device Specific Constraints

$$R_b^j \le \min(P_b^j, C_b^j - P_b^j) \quad \text{DER Secondary Reserves}$$

$$\left(P_b^j\right)^2 + \left(Q_b^j\right)^2 \le \left(C_b^j\right)^2 \quad \text{DER Reactive Power Capabilities:}$$

Note: DER Reactive Compensation can take continuous values, + or -

=>, optimal compensation is possible, UNLIKE Utility Capacitors!

$$\left(P_b^j + R_b^j\right)^2 + \left(Q_b^{j,up}\right)^2 \le \left(C_b^j\right)^2$$

$$\left(P_b^j - R_b^j\right)^2 + \left(Q_b^{j,down}\right)^2 \le \left(C_b^j\right)^2$$

State Variables, $\mathrm{X}(t)$, Dynamics (example of $\mathrm{X} \in \{\mathrm{SoC}, T\}$)

$$\mathrm{SoC}_b^{EV}(t) = \mathrm{SoC}_b^{EV}(t-1) + \eta P_b^{EV}(t)$$

$$T_b^{j,in}(t) = T_b^{j,in}(t-1) + a(V_b)P_b^j(t) - b\left[\frac{T_b^{j,in}(t-1) + T_b^{j,in}(t)}{2} - T_b^{j,out}(t)\right]$$

LMP , DLMP Relations (see next slides)

$$\pi_b^P = \pi_{\infty_s}^P \frac{\partial P_{\infty_s,\infty_{s*}}}{\partial \hat{P}_b} + \frac{\pi_{\infty_s}^{OC} Q_{\infty_s,\infty_{s*}}}{\sqrt{C_{\infty_s}^2 - Q_{\infty_s,\infty_{s*}}^2}} \frac{\partial Q_{\infty_s,\infty_{s*}}}{\partial \hat{P}_b} + \sum_{b'} \mu_{b'} \frac{\partial v_{b'}}{\partial \hat{P}_b} + \sum_{\hat{b},\hat{b}' \in tr} \frac{\partial \Gamma(\ell_{\hat{b},\hat{b}'})}{\partial \hat{P}_b}$$

$$\pi_b^Q = \pi_{\infty_s}^P \frac{\partial P_{\infty_s,\infty_{s*}}}{\partial \hat{Q}_b} + \frac{\pi_{\infty_s}^{OC} Q_{\infty_s,\infty_{s*}}}{\sqrt{C_{\infty_s}^2 - Q_{\infty_s,\infty_{s*}}^2}} \frac{\partial Q_{\infty_s,\infty_{s*}}}{\partial \hat{Q}_b} + \sum_{b'} \mu_{b'} \frac{\partial v_{b'}}{\partial \hat{Q}_b} + \sum_{\hat{b},\hat{b}' \in tr} \frac{\partial \Gamma(\ell_{\hat{b},\hat{b}'})}{\partial \hat{Q}_b}$$

$$\pi_b^R = \pi_{\infty_s}^R \frac{\partial R_{\infty_s,\infty_{s*}}}{\partial \hat{R}_b} + \sum_{b'} \mu_{b'}^{up} \frac{\partial v_{b'}^{up}}{\partial \hat{R}_b} + \sum_{b'} \mu_{b'}^{dn} \frac{\partial v_{b'}^{dn}}{\partial \hat{R}_b}$$

$$\pi_b^{Q,up} = \pi_{\infty_s}^R \frac{\partial P_{\infty_s,\infty_{s*}}^{up}}{\partial \hat{Q}_b^{up}} + \sum_{b'} \mu_{b'}^{up} \frac{\partial v_{b'}^{up}}{\partial \hat{Q}_b^{up}}$$

$$\pi_b^{Q,dn} = -\pi_{\infty_s}^R \frac{\partial P_{\infty_s,\infty_{s*}}^{dn}}{\partial \hat{Q}_b^{dn}} + \sum_{b'} \mu_{b'}^{dn} \frac{\partial v_{b'}^{dn}}{\partial \hat{Q}_b^{dn}}$$

Real Power DLMP Components

Note: Cost of modulating V_∞ modeled approximately and conservatively low

$$\pi_b^P = \pi_{\infty_s}^P \frac{\partial P_{\infty_s,\infty_{s*}}}{\partial \hat{P}_b} + \frac{\pi_{\infty_s}^{OC} Q_{\infty_s,\infty_{s*}}}{\sqrt{C_{\infty_s}^2 - Q_{\infty_s,\infty_{s*}}^2}} \frac{\partial Q_{\infty_s,\infty_{s*}}}{\partial \hat{P}_b} +$$

$$\sum_{b'} \mu_{b'} \frac{\partial v_{b'}}{\partial \hat{P}_b} + \sum_{\hat{b},\hat{b}' \in tr} \frac{\partial \Gamma(\ell_{\hat{b},\hat{b}'})}{\partial \hat{P}_b}$$

$$\text{Note:} \quad \frac{\partial P_{\infty_s,\infty_{s*}}}{\partial \hat{P}_b} = \left(1 + \frac{\partial \text{TotalPLosses}}{\partial \hat{P}_b}\right)$$

$$\frac{\partial Q_{\infty_s,\infty_{s*}}}{\partial \hat{P}_b} = \frac{\partial \text{TotalQLosses}}{\partial \hat{P}_b}$$

Reactive Power DLMP Components

Note: Cost of modulating V_∞ modeled approximately and conservatively low

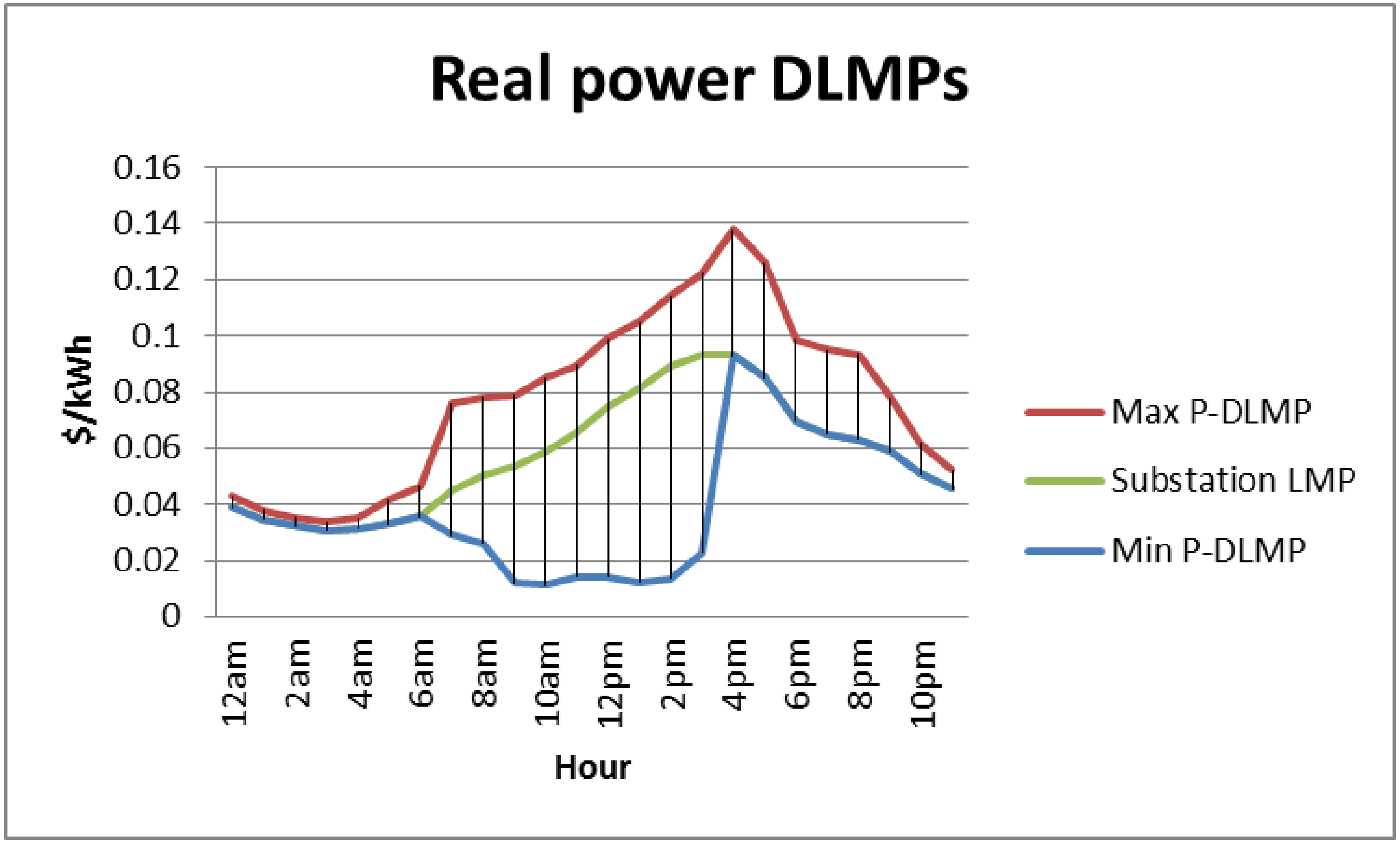
$$\pi_b^Q = \pi_{\infty_s}^P \frac{\partial P_{\infty_s,\infty_{s*}}}{\partial \hat{Q}_b} + \frac{\pi_{\infty_s}^{OC} Q_{\infty_s,\infty_{s*}}}{\sqrt{C_{\infty_s}^2 - Q_{\infty_s,\infty_{s*}}^2}} \frac{\partial Q_{\infty_s,\infty_{s*}}}{\partial \hat{Q}_b} +$$

$$\sum_{b'} \mu_{b'} \frac{\partial v_{b'}}{\partial \hat{Q}_b} + \sum_{\hat{b},\hat{b}' \in tr} \frac{\partial \Gamma(\ell_{\hat{b},\hat{b}'})}{\partial \hat{Q}_b}$$

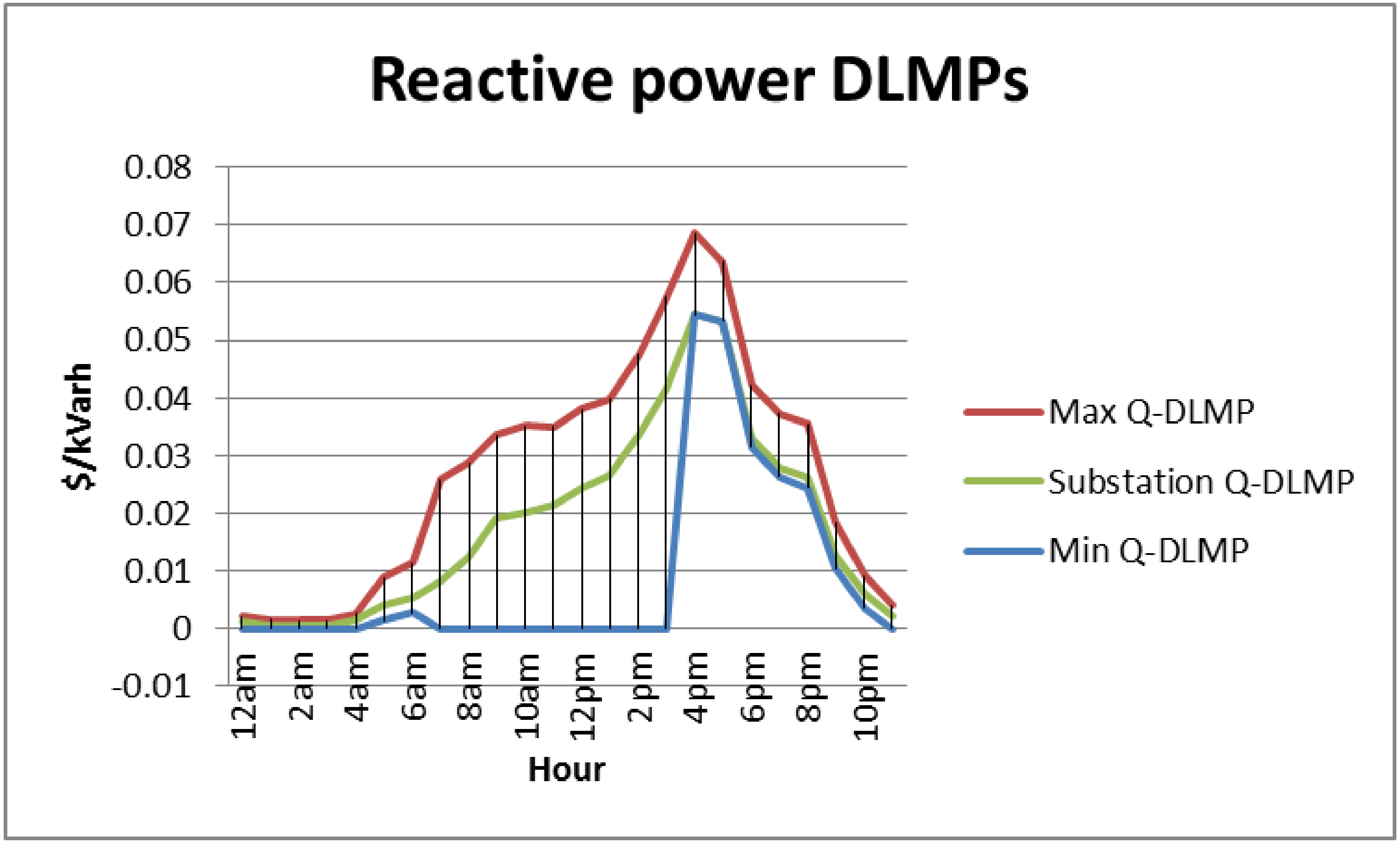
$$\text{Note:} \quad \frac{\partial P_{\infty_s,\infty_{s*}}}{\partial \hat{Q}_b} = \frac{\partial \text{TotalPLosses}}{\partial \hat{Q}_b}$$

$$\frac{\partial Q_{\infty_s,\infty_{s*}}}{\partial \hat{Q}_b} = (1 + \frac{\partial \text{TotalQLosses}}{\partial \hat{Q}_b})$$

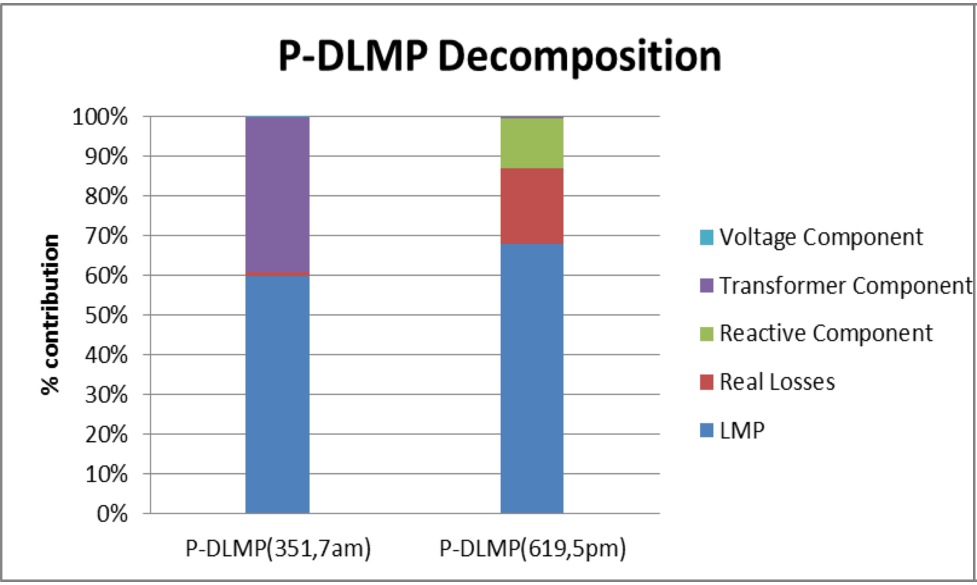
Simulation Results: Summer Peak Day Real DLMP Behavior

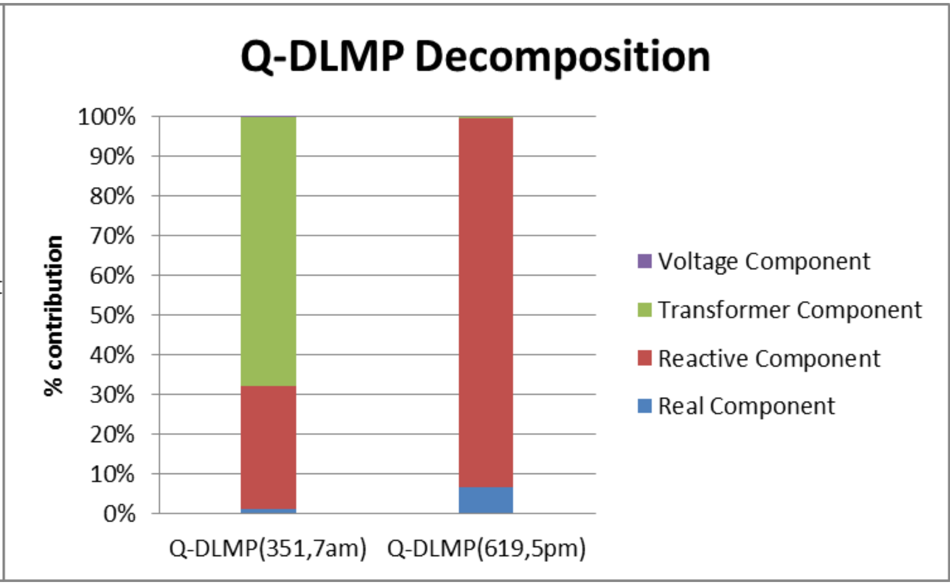


Simulation Results: Summer Peak Day Reactive DLMP Behavior



DLMP Components: Max DLMP/LMP examples





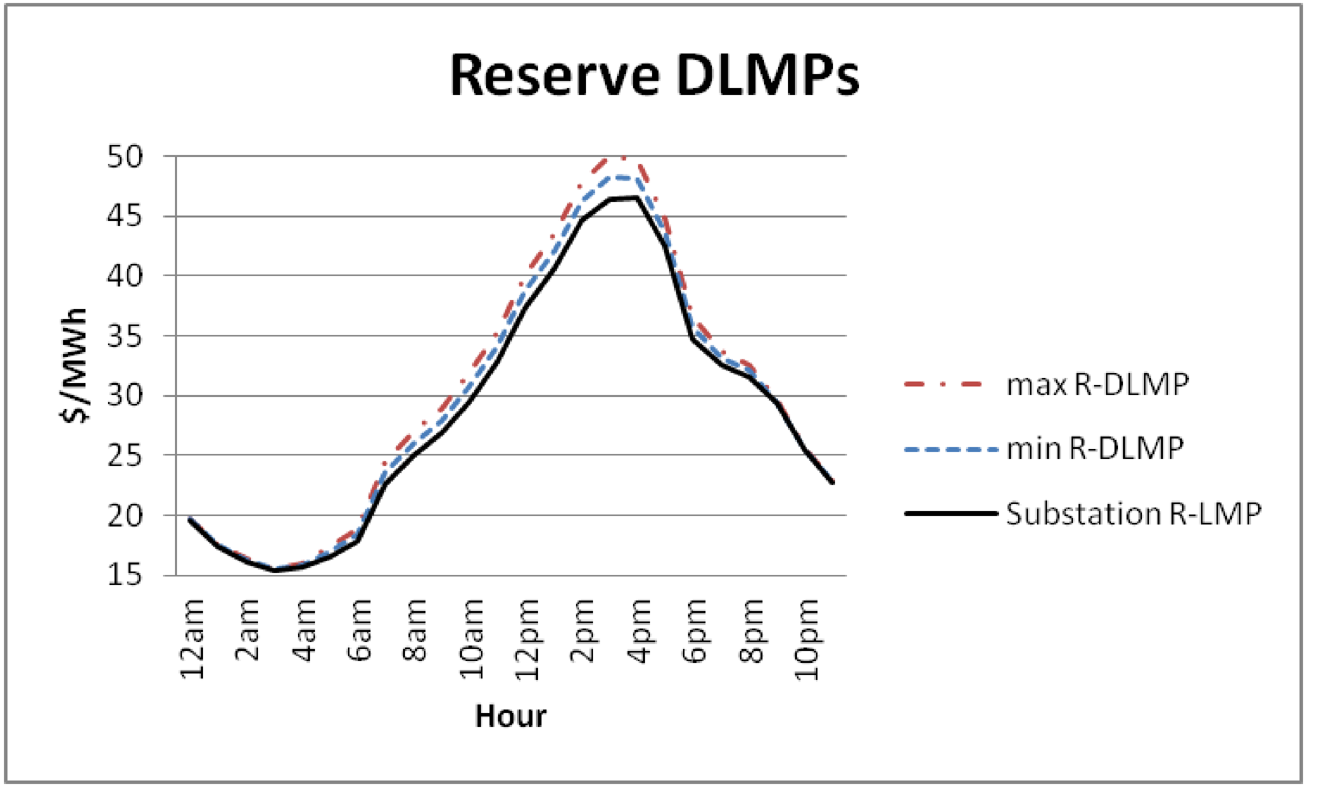
	P-DLMP(351,7am)	P-DLMP(619,5pm)		Q-DLMP(351,7am)	Q-DLMP(619,5pm)
LMP	45.1	85.04	Real Component	0.270599982	4.166960043
Real Losses	0.721599986	23.55608022	Reactive Component	7.859643732	56.97063807
Reactive Component	0.105444136	15.98801817	Transformer Comp.	17.19	0.21
Transformer Comp	29.4	0.459999999	Voltage Component	0.005611093	0
Voltage Component	0.007508159	0	TOTAL	25.32585481	61.34759811
TOTAL	75.33455228	125.0440984			

Example from Summer Peak day demonstrating that DLMPs Provide Locational Incentives and Optimal Reactive Power Compensation (negative Q is possible)

Hour 2pm					
Bus 689, V=1.1! BINDING	**PV real (kW)**	**PV reactive (kVar)**	**P-DLMP**	**Q-DLMP**	**LMP**
	4.44	-1.43	14.52	-2.87E-06	89.21
Bus 619, V=0.95, NOT Binding	**PV real (kW)**	**PV reactive (kVar)**	**P-DLMP**	**Q-DLMP**	**LMP**
	4.44	1.46	111.83	37.88	89.21

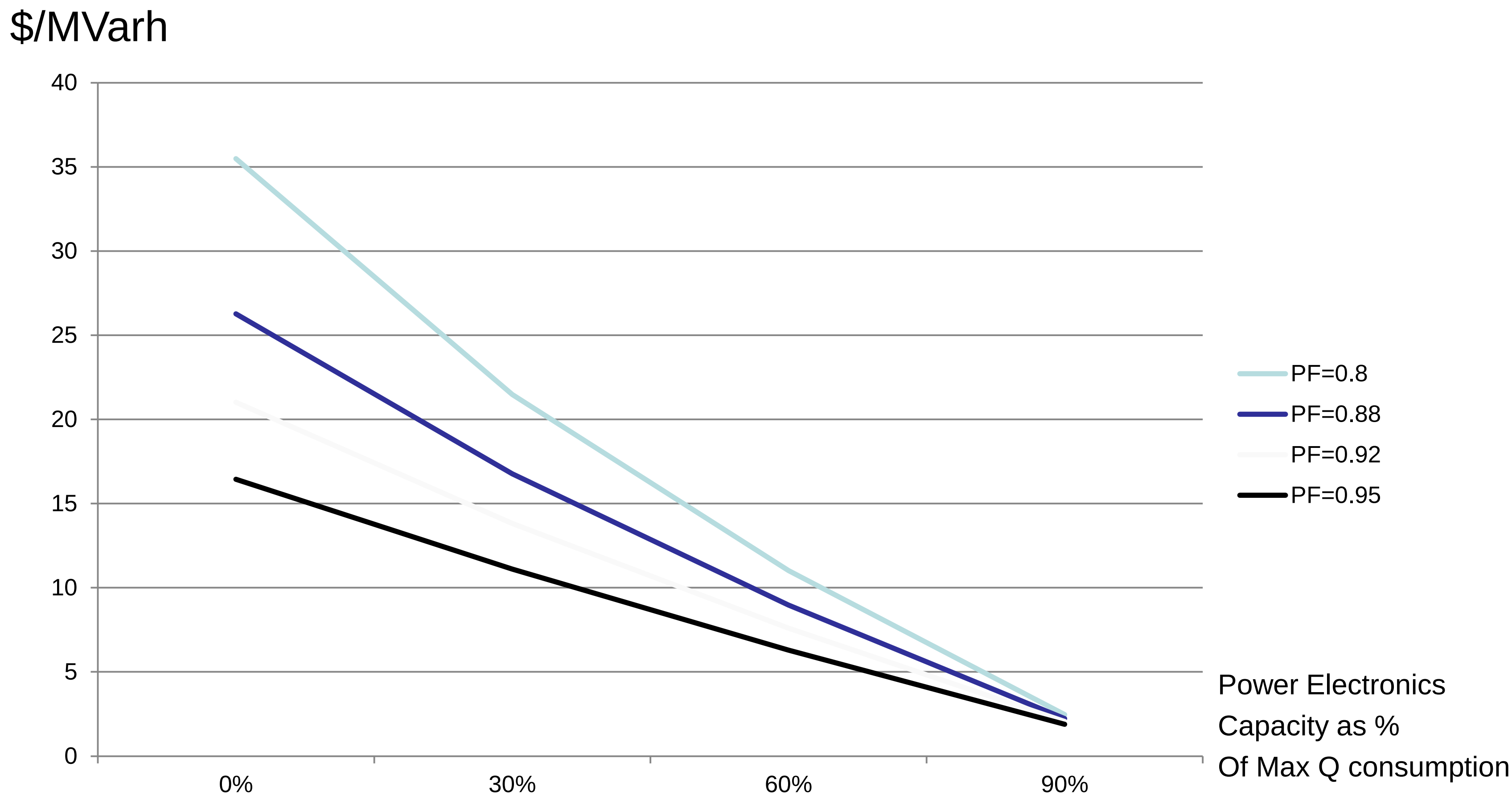
Illustrative Numerical Results: Day ahead Distribution Market Clearing of a 800 node Upstate NY Feeder on a Summer Day

	Market Structure	Average No Q from DER	LMP No Q from DER	Full DLMP
A	Substation Transaction Costs for P	13281	13172	13235
B	Substation Transaction Costs for Q	1182	1133	777
	Total **Substation Cost** A+B	**14463**	**14305**	**14013**
C	Charges to Space Conditioning for P	743	721	703
D	Charges to Space Conditioning for Q	212	188	140
	Total **Space Conditioning Charges** C+D	**955**	**909**	**843**
E	Charges to EV for P	220	127	127
F	Charges to Inflexible Loads for P	15102	15037	14869
G	Charges to Inflexible Loads for Q	2089	2027	1609
	Total **Inflexible Load Charges** F+G	**17190**	**17065**	**16478**
H	Income of EV for Q provision	0	0	134
	Net EV Charges E-H	**220**	**127**	**-8**
I	Income of PV for P provision	1494	1493	1408
J	Income of PV for Q provision	0	0	169
	Total PV Income I+J	**1494**	**1493**	**1577**
K	Total Charges (K=C+D+E+F+G)	18365	18101	17448
L	**Total DER income** (L=H+I+J)	**1494**	**1493**	**1711**
M	**Net Cost of Distribution Participants** (M=K-L)	**16871**	**16607**	**15737**
N	Distribution Network **Rent** (N=M-A-B)	**2408**	**2302**	**1724**



Minimum, Maximum and Substation Reserve DLMPs.

Size of Market for Reactive Power



Indicative Estimates of Average Price of Reactive Power against Power Electronics Capacity Penetration as a % of Maximum Hourly Reactive Power Consumed.

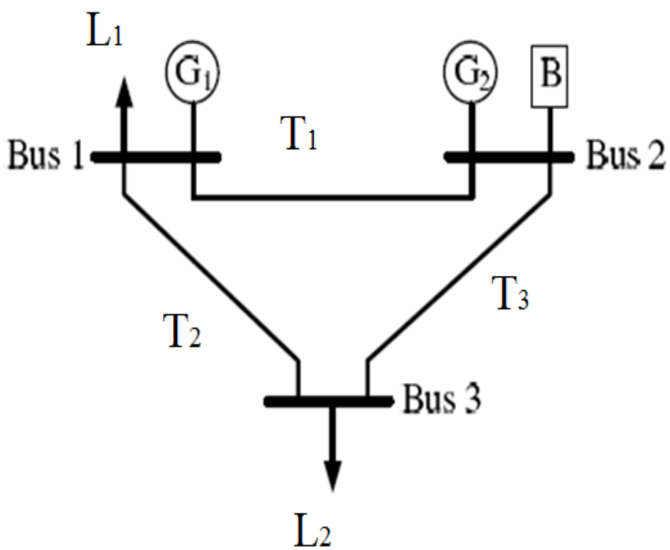
$$Q/P = \frac{\sqrt{1-PF^2}}{PF} \Rightarrow$$

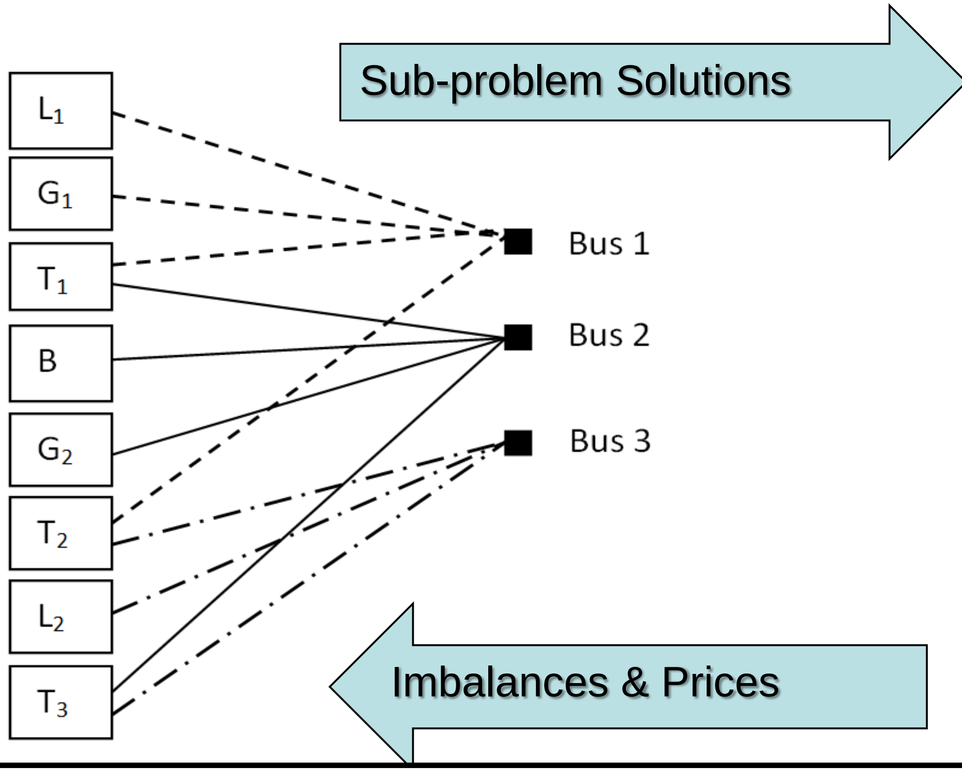
PF	.8	.88	.92	.95
Q/P	.75	.54	.426	.33

Issue: Centralized Market Clearing Approach is **Not Tractable**. Why?

- Transmission (HV) System (Real Power and Reserves)
  - Generator costs minimization and associated constraints
  - Load Flow (**DC approx. OK**) and Transmission Line Congestion
  - Regional Reserve Requirements
  - Line Losses (1.5% on average)
- Distribution Network (Real and Reactive Power and Reserves)
  - DER Cost Minimization and associated constraints **INTRACTABLE** in Centralized Model!
  - Transformer Life Degradation
  - Line Losses (6% on average)
  - Reactive Power Compensation
  - Voltage Control
  - Load Flow. **Non Linear AC** relationships required!
- BTW, why is Reactive Power not Priced in HV Markets?

ADMM, a PMP Algorithm May Achieve Network Asset and DER Objective maximization Consensus **Tractably!**.





Asynchronous/**Parallel** Sub-problem Solution:

Each device (DER and Line) solves individual sub-problem

Each Bus calculates imbalances & prices

Iterative Process, until bus violations→0

Convergence?

PMP based convergence Certificate?

Vulnerability to Malicious Communication Interception?

Distributed Market Clearing Algorithm Challenges

- Regional reserve requirement constraints involve multiple transmission and T-D interface busses.
- Reserve deliverability at Distribution Feeders must observe Voltage Constraints (Congestion) under Reserve Deployment Contingencies.
- Reactive Power Compensation must be Sensitive to Reserve Deployment Contingency Voltage Limitations.

Full T&D Market Supports Innovation!

- **Operational and Investment** Efficiencies => **Resilience of Infrastructure**
- Efficient **Supply of Fast Reserves** => Renewable Generation Integration
- Sustainable Marginal Losses Reflected in T&DLMPs=> **Distributed Adaptation** to Short term and Anticipation of Long Term Costs/Benefits
- Reactive Power Pricing allows **Dual Use** of Power Electronics => **Operational and Investment** Efficiencies (Distributed PV, EVs, Heat Pumps, New Devices and controllers…)

Open Issues Remain, However, Prospects Promising…

- Interplay of Real Power Reserves and Reactive Power provision by DERs for Reserve Deliverability Slow Voltage Constraint Dual Variables Convergence in Distributed Algorithms.
- Proof that Price Directed Dynamic DER work in practice as advertised
- **Market Deficiencies** (market power/capacity withholding, strategic behavior) must be further studied and their prevalence empirically evaluated in practice. Hence, **Regulatory issues** are still on the table
- Communication Architecture to support distributed business models still on the table, including malicious attacks.
- Will New Business Models/Entities step up to supplement/replace existing utility structures?
- New Financial Instruments for risk mitigation?
  - Hedging
  - Auctions for futures, DER reserve deliverability a la FTRs, more……