HEPG Panel One

Computational Frontiers in Electricity Markets: Not Your Grandfather's Economic Dispatch

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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

$$\pi^{x}_{n(s)}(t), x \in \{P, Q, R\}$$

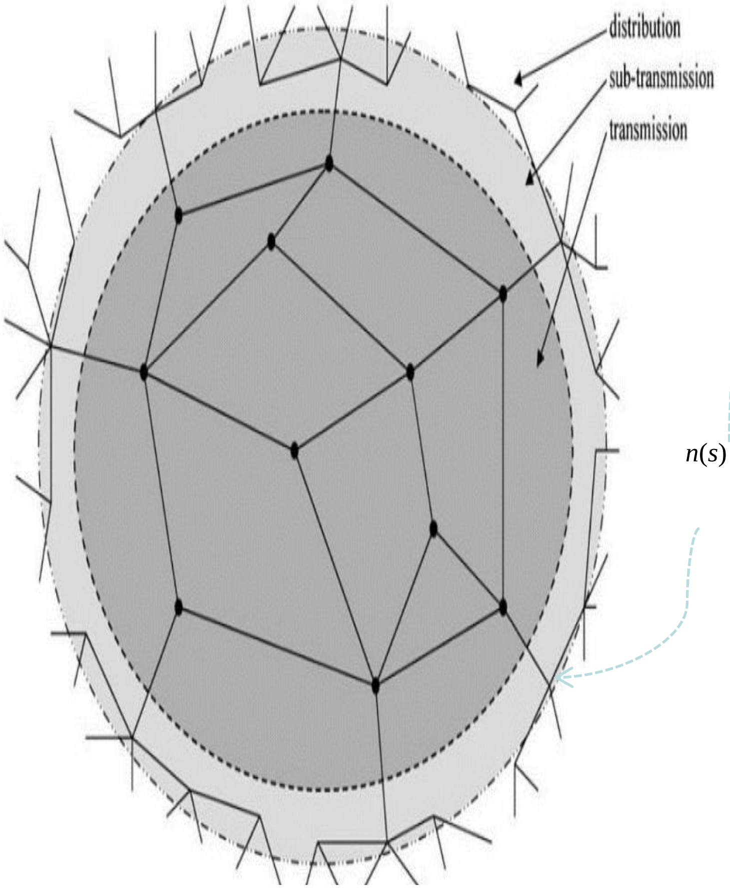


Fig. 1: Tr., Sub-tr, and Distr. Schematic

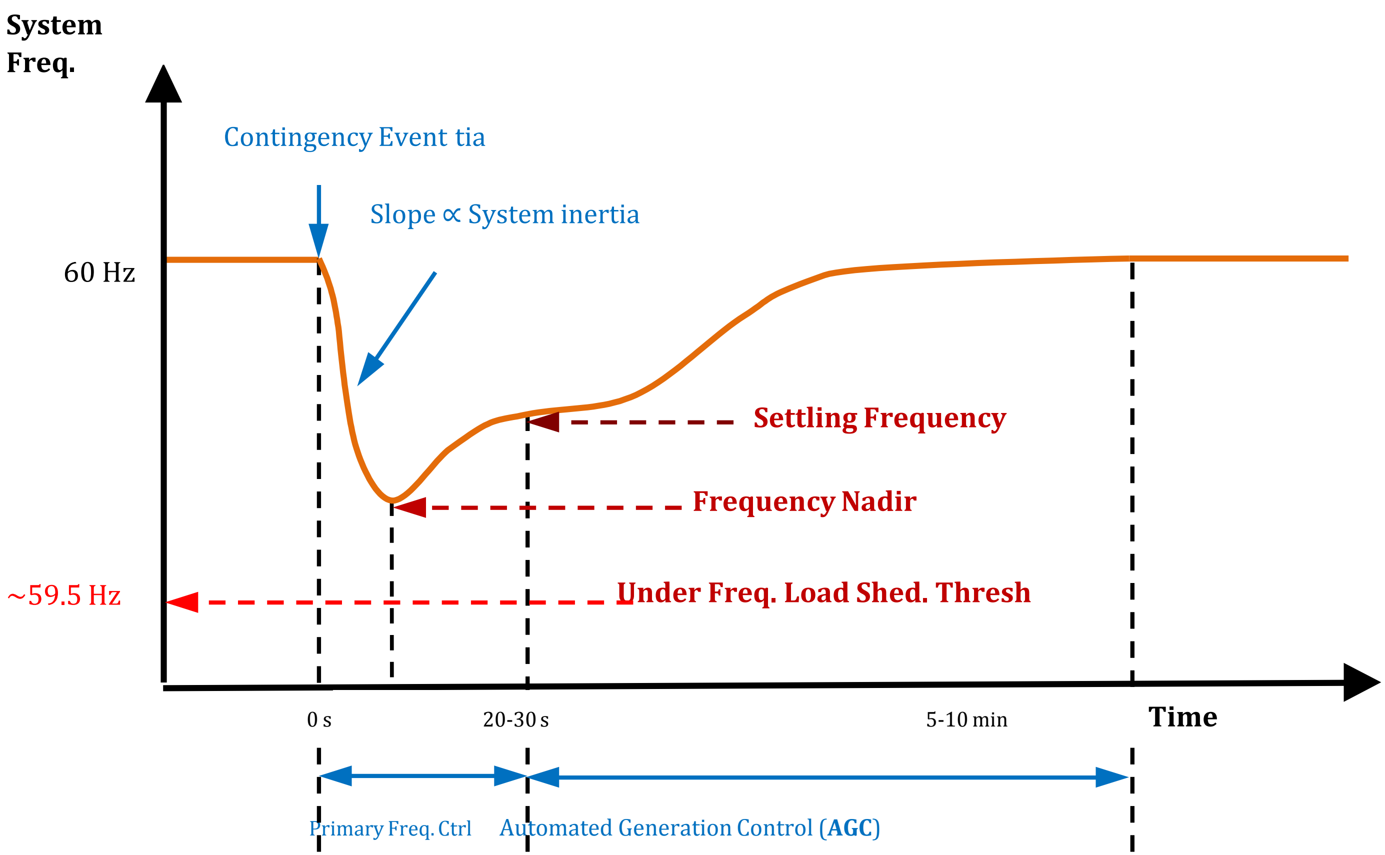
$$\pi^{P}_{n(b)}(t), \pi^{Q}_{n(b)}(t), \pi^{R}_{n(b)}(t), \mu^{R,i+1}_{n(b)}(t), \mu^{v}_{n(b)}(t)$$

Fig. 2: Distribution Feeder example

$$\frac{d\omega_j(t)}{dt} = \frac{P_{mech,j}(t) - P_{elec,j}(t)}{H_j}$$

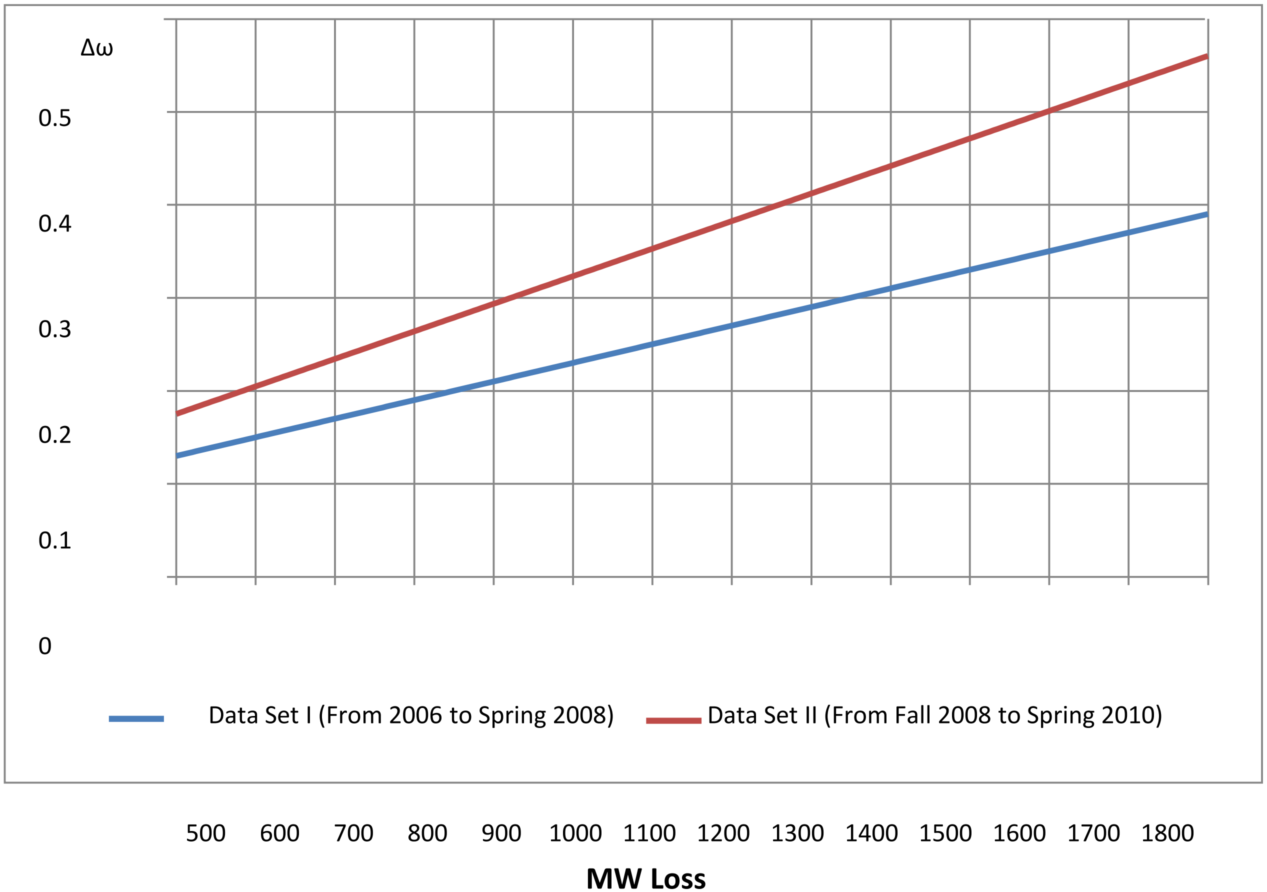
Inertia, H_j, decreases with increasing renewable integration.

$\Rightarrow$ Fast Reserve Requirements (primary and secondary) increase



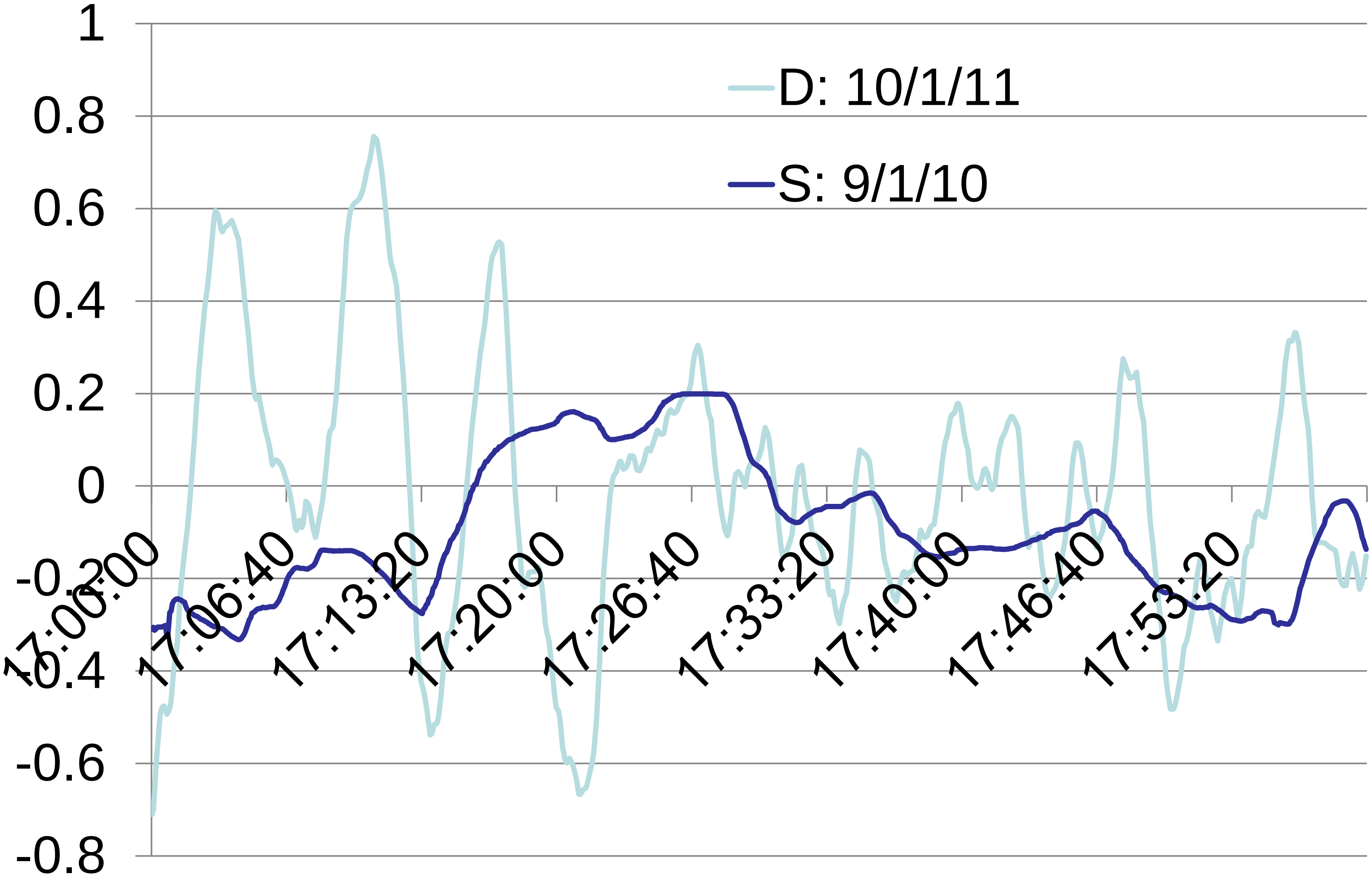
System frequency control following a loss-of-generation contingency event.

Actual Observations In ERCOT Verify Impact of Renewables!



Declining grid inertia within ERCOT interconnection from 2006 to 2010. System frequency decline is shown as a function of power loss in the system, with the red curve illustrating the loss of system inertia as a result of increased penetration of renewables.

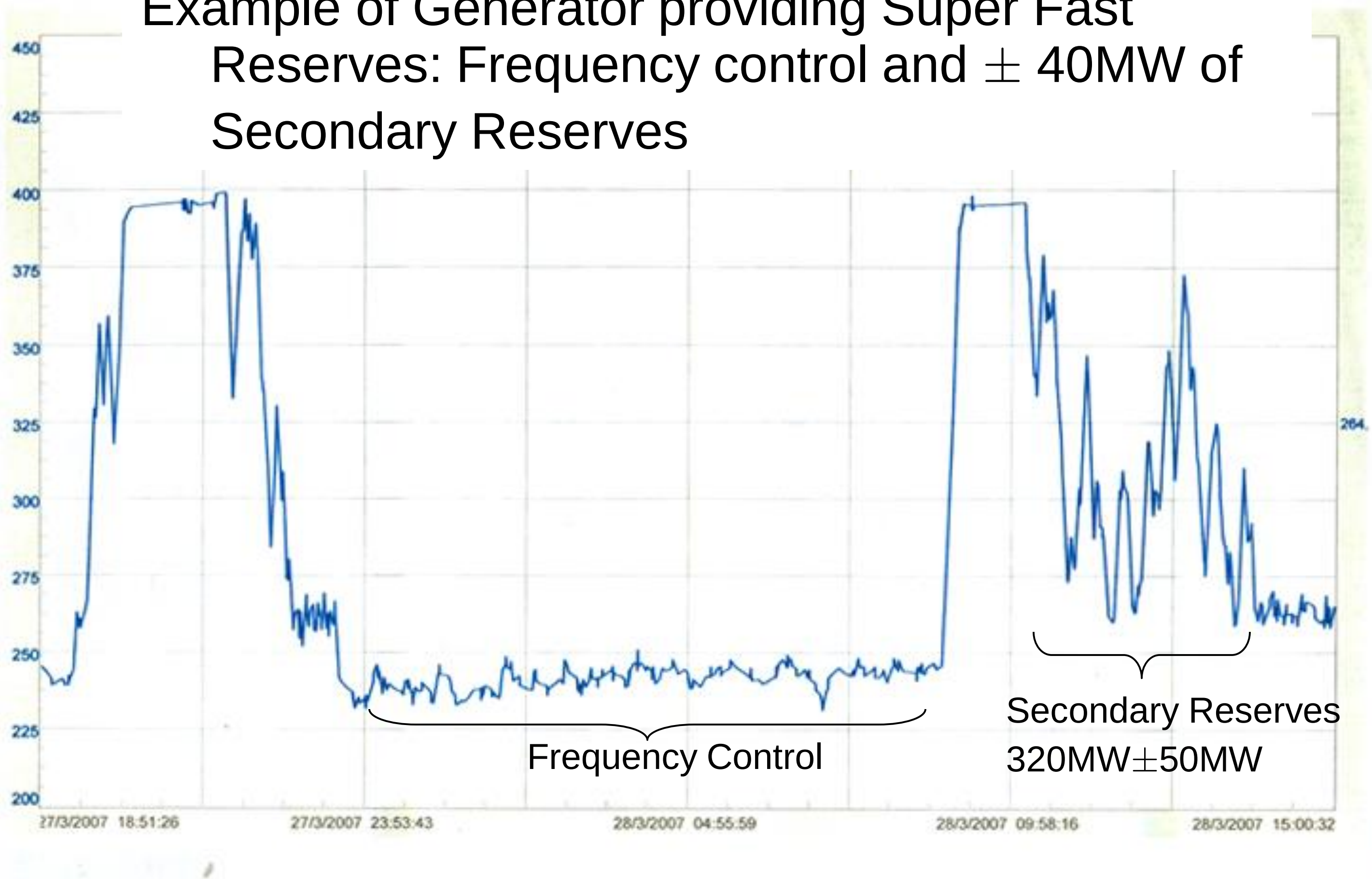
Flexible Loads Require Energy by some deadline => Capable of responding to Regulation Service Signal $D_i(t) = \bar{D}_i + y(t)\mathfrak{R}_i$



Instance of PJM Regulation Signals, $y^{dyn}(t)$ and $y^{slow}(t)$ on different days. Note: (i) random nature but (ii) energy neutrality over a relatively short period of Time

Today Generating Units are the Only RS Reserve Providers!

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



Source: Courtesy of EnThes Inc., March 2007

DER Examples and their Capabilities

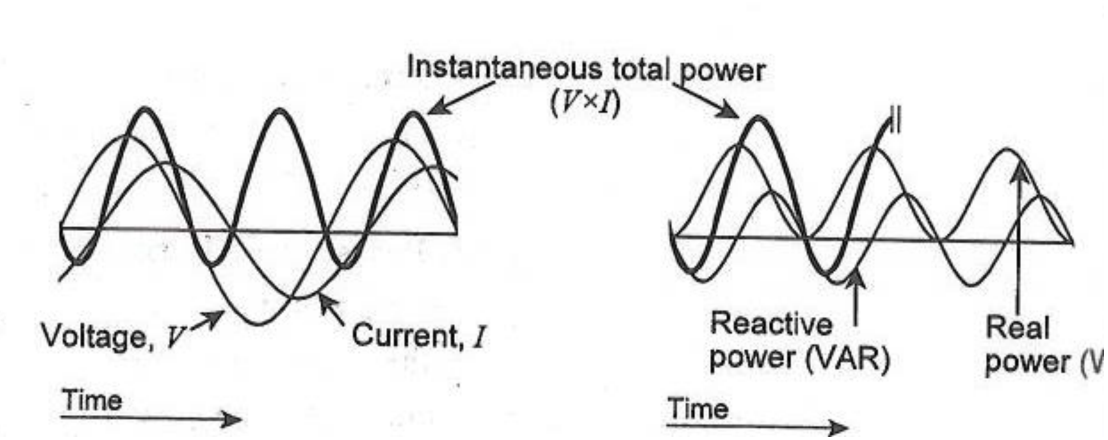
- **PV**: Distributed Non-Controllable Generation of Real Power BUT Controllable Volt/Var inverters can provide Reactive Power Compensation using excess inverter capacity
- **EV**: Storage Like Flexible Demand AND Reactive Power Compensation
- Electric **Space Conditioning**/Heat Pumps: Flexible/ Storage 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.

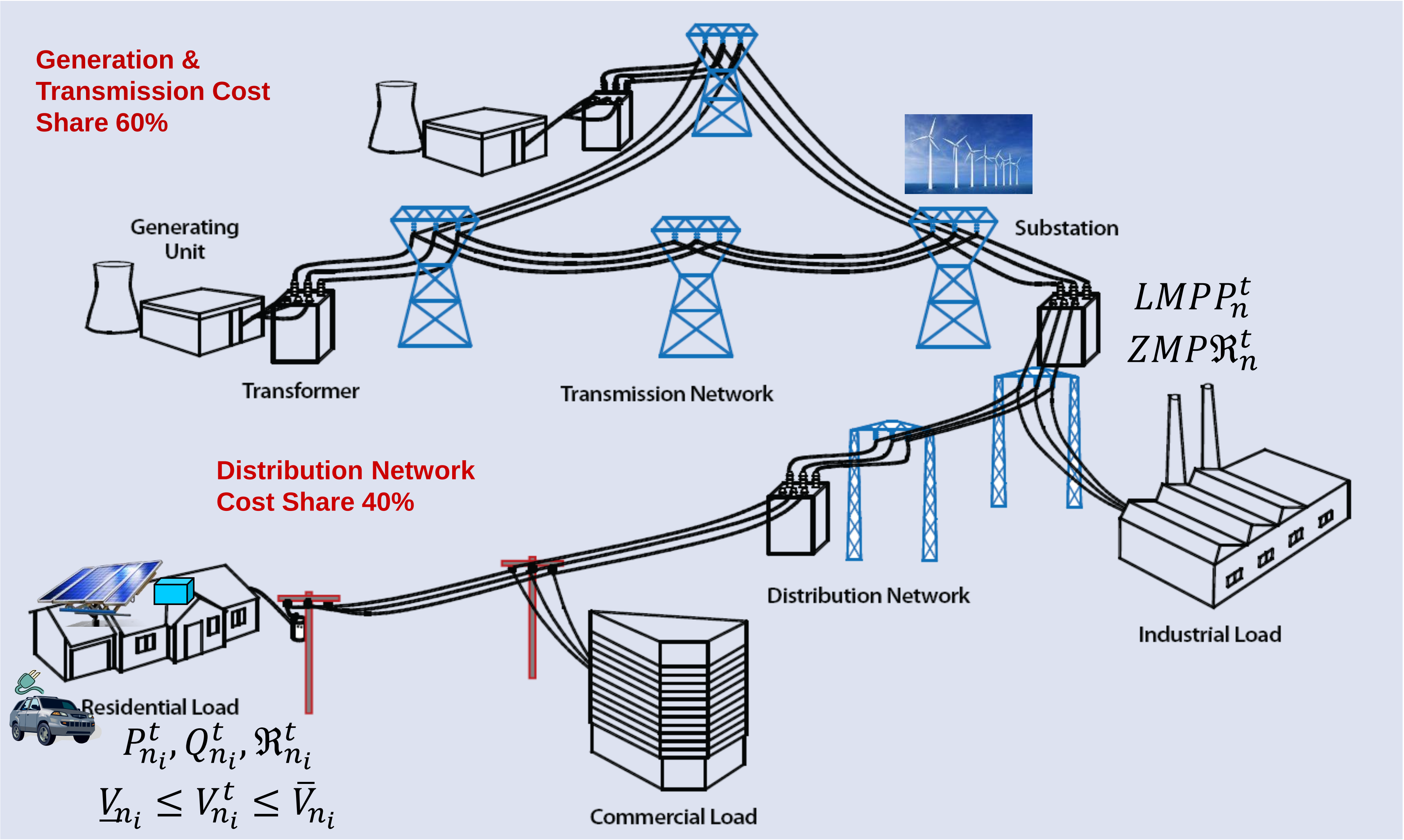
Some Distributed Loads (inductive motors, ballasts, and others)
and distribution assets (over ground and underground) **pollute**
Load flow by distorting the synchronization of Alternating Voltage and Current

This results in power **losses** and acceptable **voltage level violations**

Real and Reactive Power when Voltage and Current get out of phase



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

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

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

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

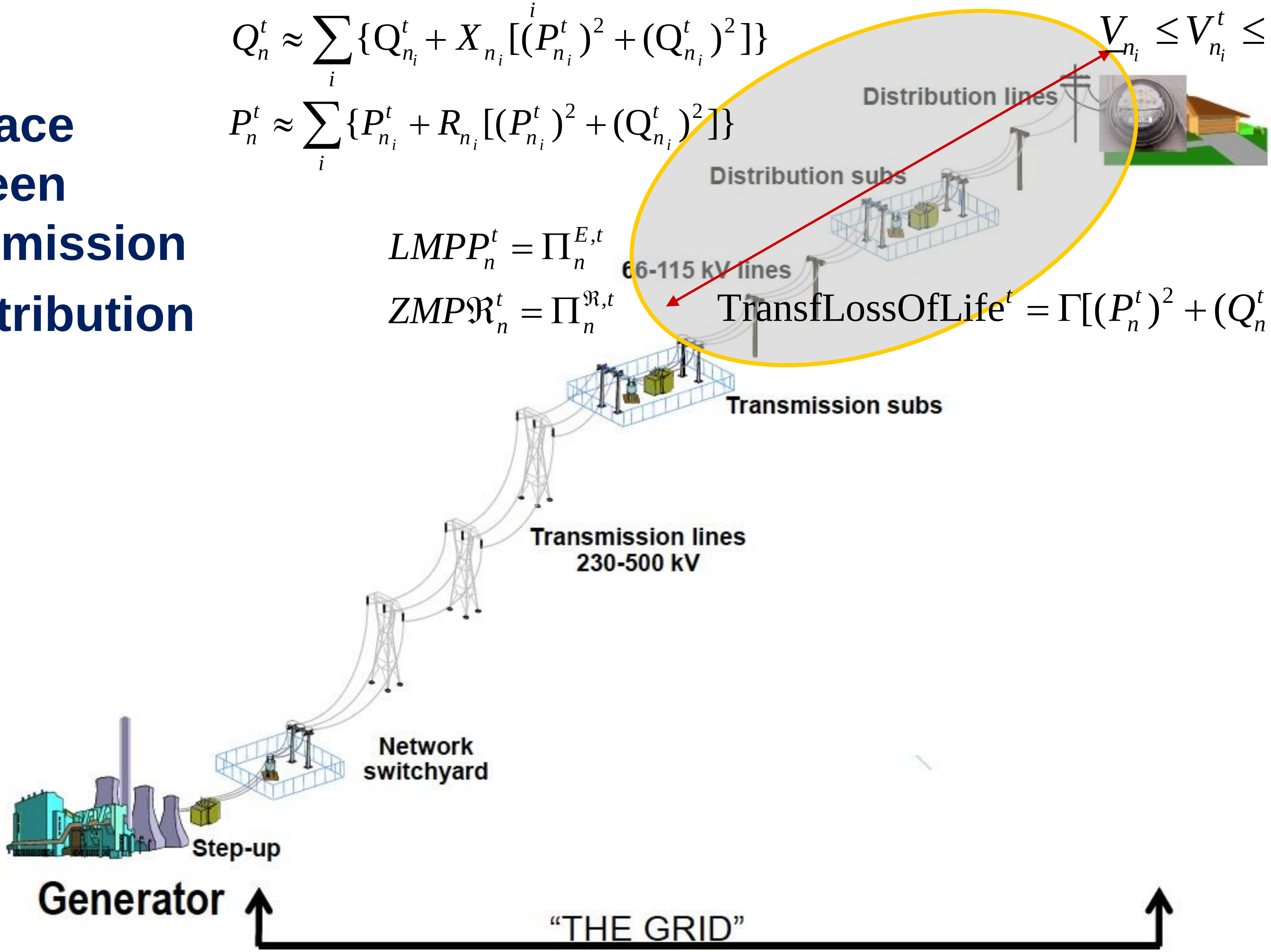
$$P_{n_i}^t, Q_{n_i}^t, \Re_{n_i}^t$$

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

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

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

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



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

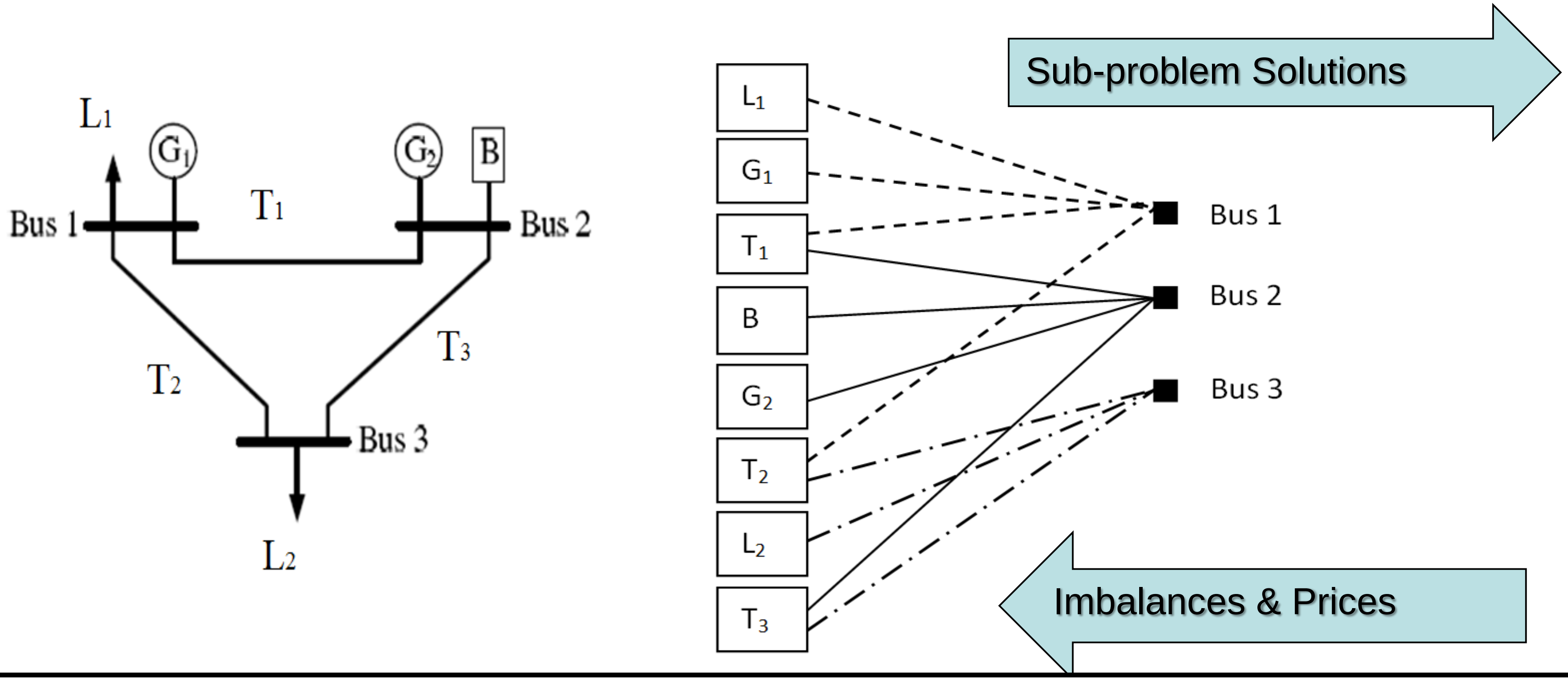
Extended Market Clearing =>
I. T&D Locational Marginal Prices (T&DLMP)
II. Scheduling of DER Capacity among Real and Reactive Power and Reserves.

- $\pi_n^x(t) \triangleq$ 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

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?

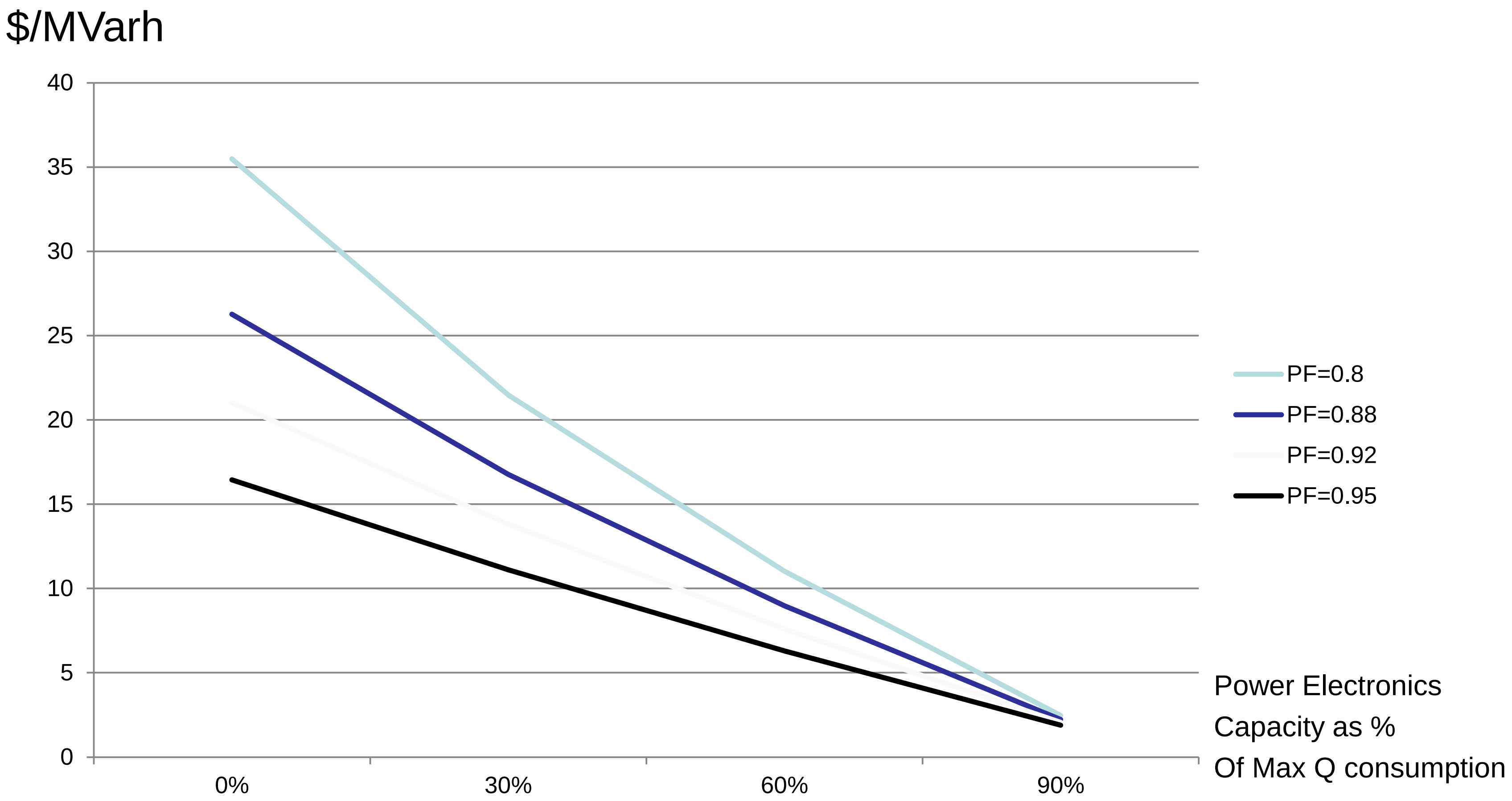
Hybrid Market Clearing Algorithm Needed

- Regional reserve requirement constraints involve multiple transmission and T-D interface busses.
- Reserve deliverability at Distribution Feeders requires (linearized) constraints involving all busses/nodes at each distribution feeder.
- Hybrid Distributed-Regionally Centralized market clearing algorithm needed.

Illustrative Numerical Results from a Day ahead Distribution Market Clearing Estimated for a 800 node Upstate NY Feeder on a Summer Day

Marginal Cost Based Charges and Income under different price information Structures				
Market Structure: Prices	Average Price No Q from DER	LMP only/ 1 Node Aggr. No Q from DER	LMP and 17 Node Aggr. No Q from DER	Full DLMP
Substation Transaction Costs	14690.28063	14565.96463	14565.96845	13088.08387
Charges to Space Conditioning	461.0024944	466.3239222	465.8748651	305.563071
Charges to EV for P	223.2177941	133.034649	133.0346451	131.2291241
Charges to Inflexible Loads	17786.03319	17704.79913	17704.2849	15103.20433
Income of EV for Q provision	0	0	0	0.236204886
Income of PV for P provision	1508.00497	1507.825229	1507.783234	1448.657325
Income of PV for Q provision	0	0	0	253.4560743
Total Charges (H=B+C+D)	18470.25348	18304.1577	18303.19441	15539.99653
Total DER income (I=E+F+G)	1508.00497	1507.825229	1507.783234	1702.349604
Net Cost of Distribution Participants (J=H-I)	16962.24851	16796.33247	16795.41118	13837.64692
Distribution Network Rent (L=J-A)	2271.967878	2230.367842	2229.442726	749.5630509

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

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…

- Hybrid bus-specific/group of busses market clearing algorithms yet to be fully proven
- 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, **Regulation issues** are still on the table
- Communication Architecture to support distributed business models still on the table, including malicious attacks.
- Observation/Anticipation/Analysis of New Participants that may/will 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……