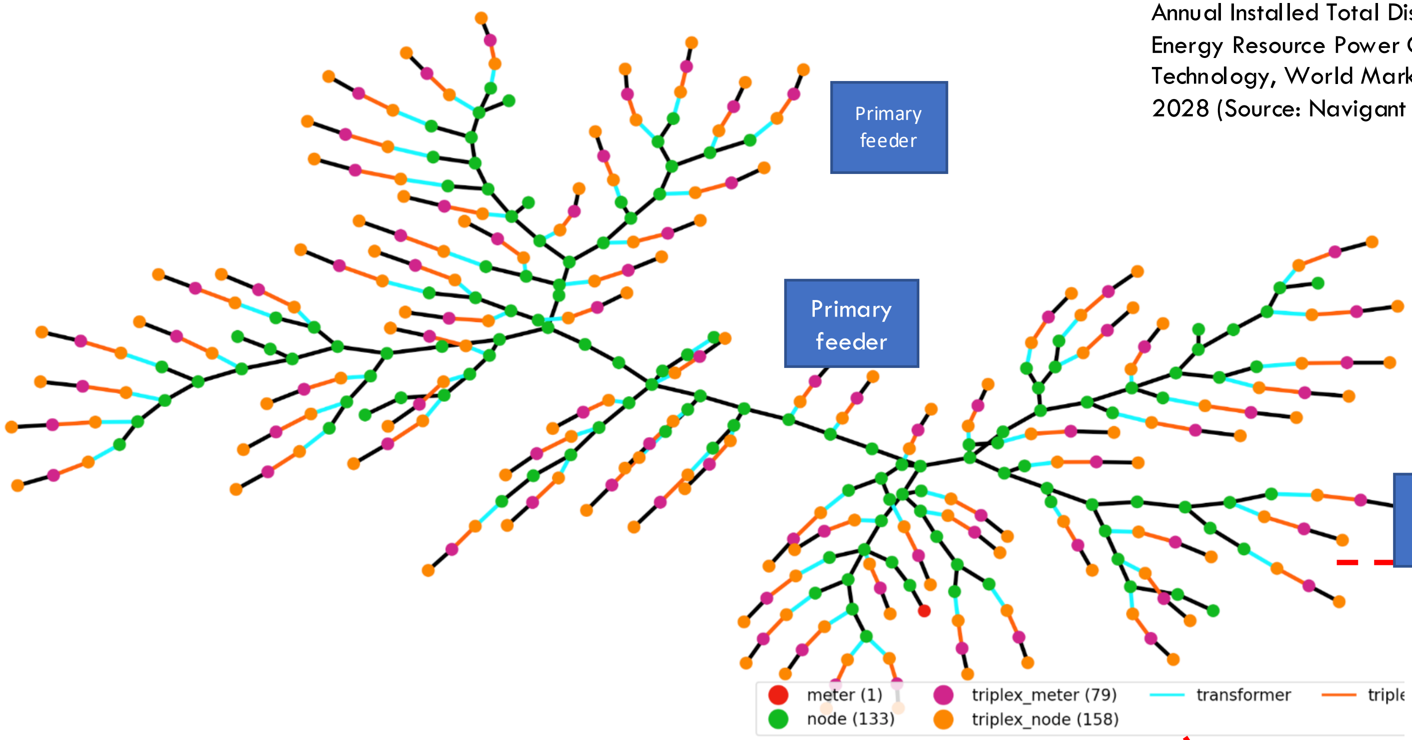
Local retail electricity markets for distribution grid services

Wednesday, August 16, 2023

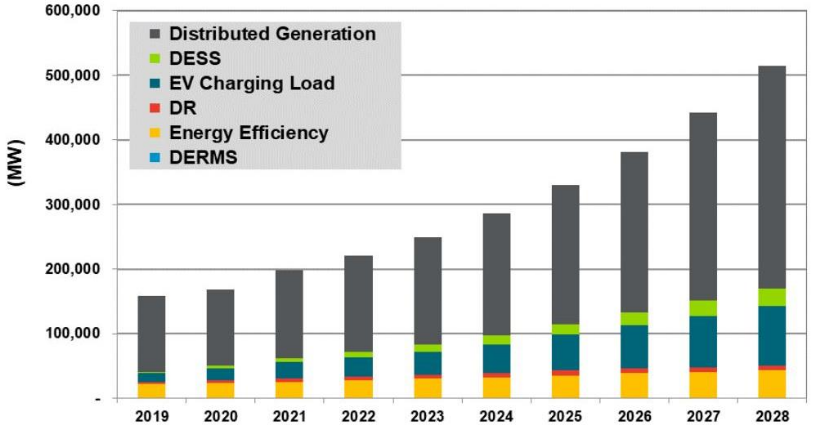
Vineet J Nair, Anuradha Annaswamy
jvineet9@mit.edu

Active-Adaptive Control Laboratory
Department of Mechanical Engineering, MIT

Optimization challenging with billions of end-point control

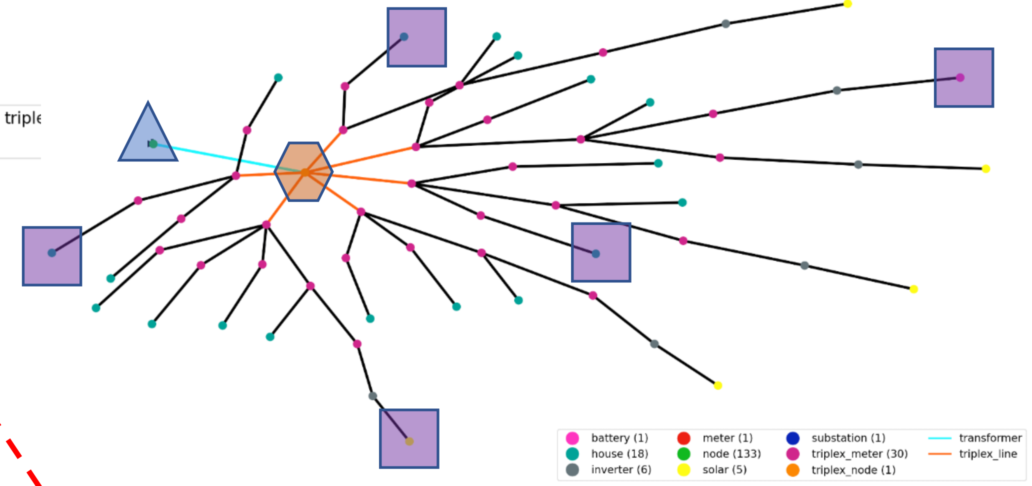


Annual Installed Total Distributed Energy Resource Power Capacity by Technology, World Markets: 2019-2028 (Source: Navigant Research)



Increasing DER penetration

Secondary feeder



Consumer feeder

400 Secondary Feeders

1000 IoT devices
100 PVs (531.5 KW)
200 batteries

Typical distribution grid with many distributed energy resources (DER) (modified IEEE-123 node feeder)

Source: PNNL Gridlab-D Modeling Team

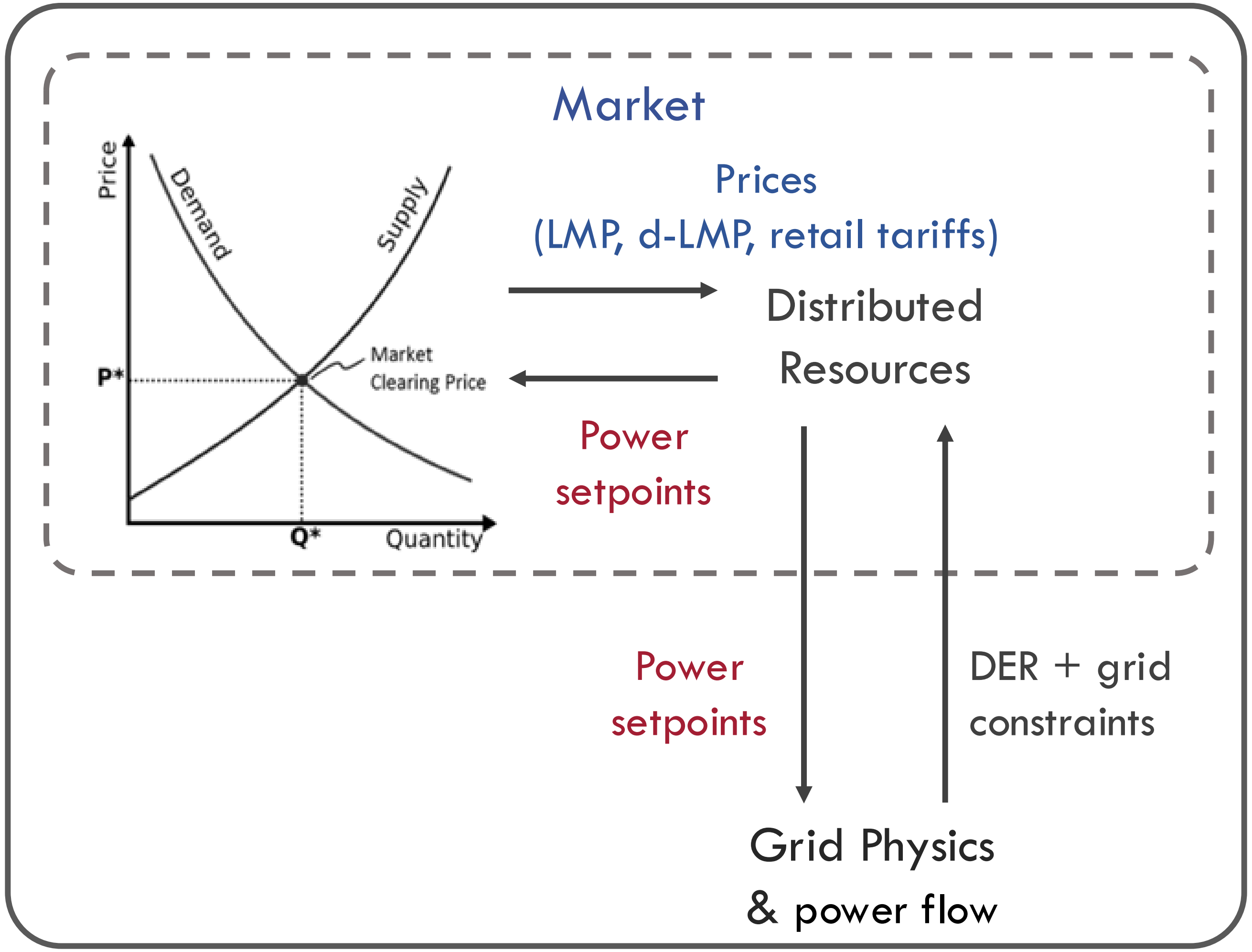
Overall approach based on Transactive Energy

Transactive Energy uses service-based value of power to influence desired behaviours from various autonomous, independent agents at the grid edge, at fast timescales

Efficient integration of Distributed Energy Resources possible with a transactive design:

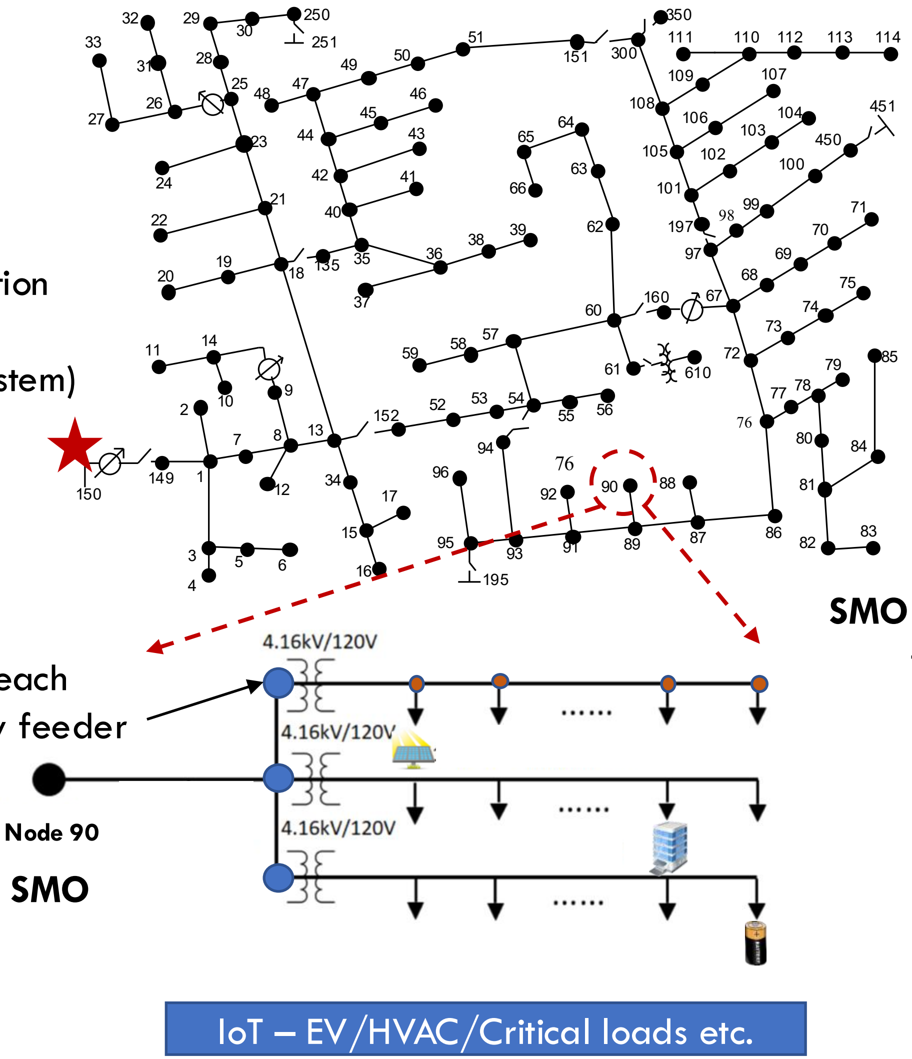
- Flexible loads (thermostats, water heaters)
- Distributed generation (rooftop solar, wind)
- Storage (EVs, batteries)

Transactive Energy



A suite of hierarchical local electricity markets (LEM)

DSO at substation (Connection to transmission system)

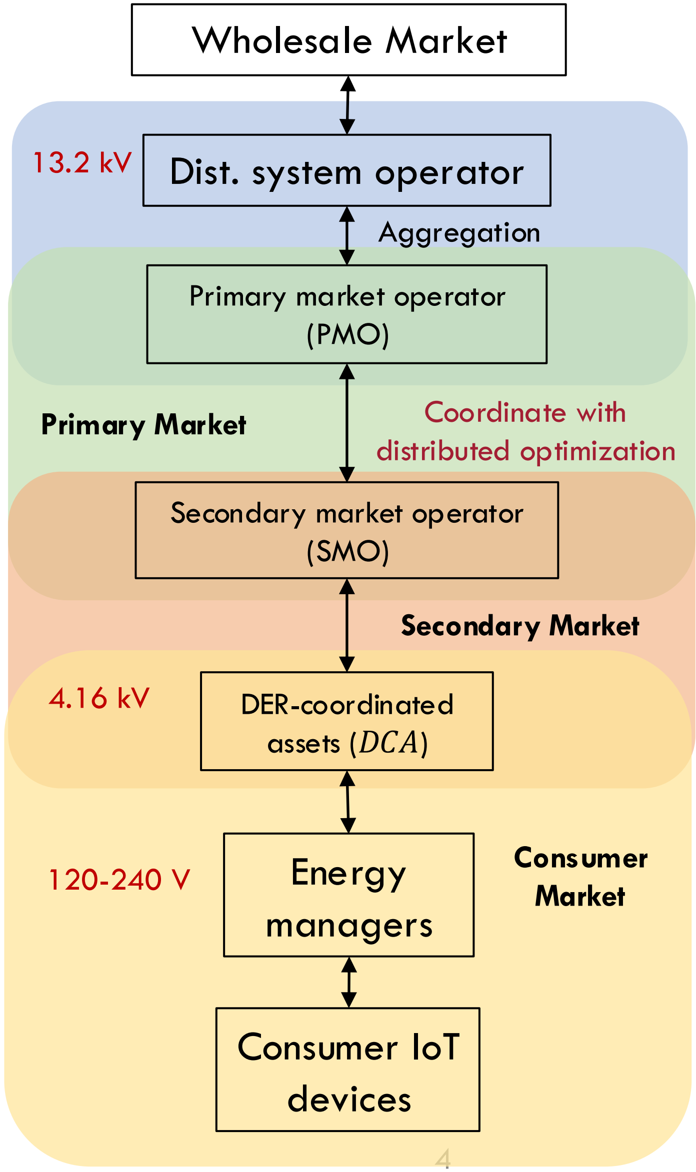


Primary feeder radial distribution network

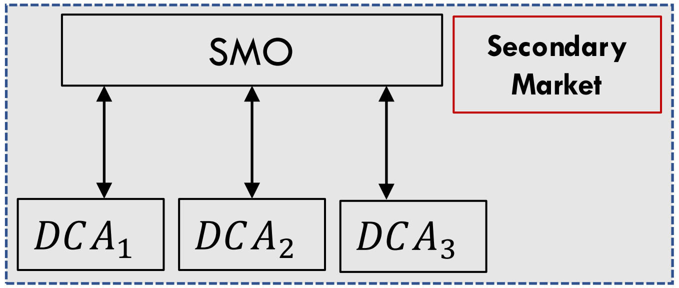
PMO for each primary feeder

SMO for each primary feeder node

DCA for each secondary feeder

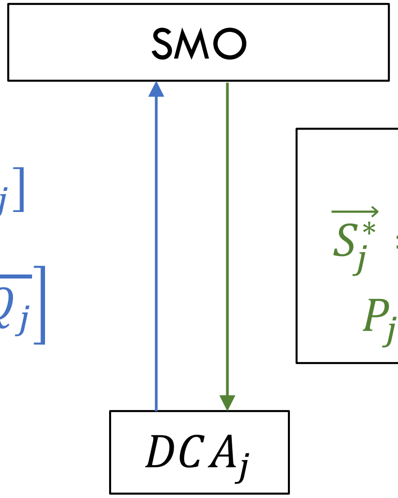


Secondary market: Flexibility in bids



Bid $\overrightarrow{B_j} = [P_j^0, Q_j^0, \Delta P_j, \Delta Q_j]$

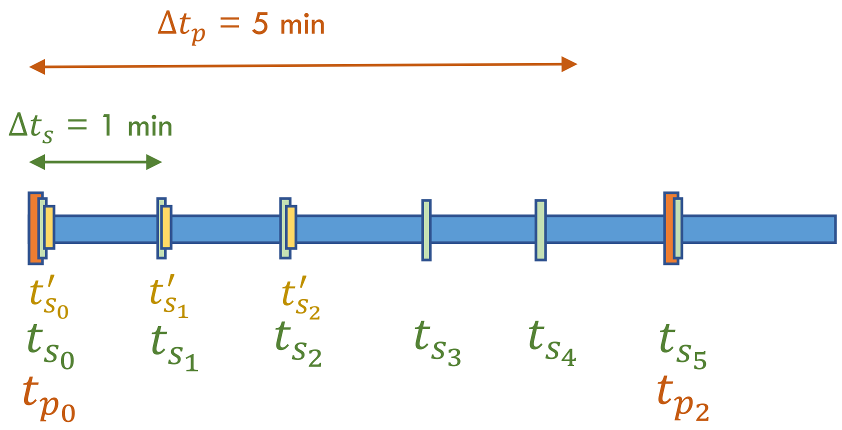
$\Delta P_j = [\underline{P_j}, \overline{P_j}], \Delta Q_j = [\underline{Q_j}, \overline{Q_j}]$

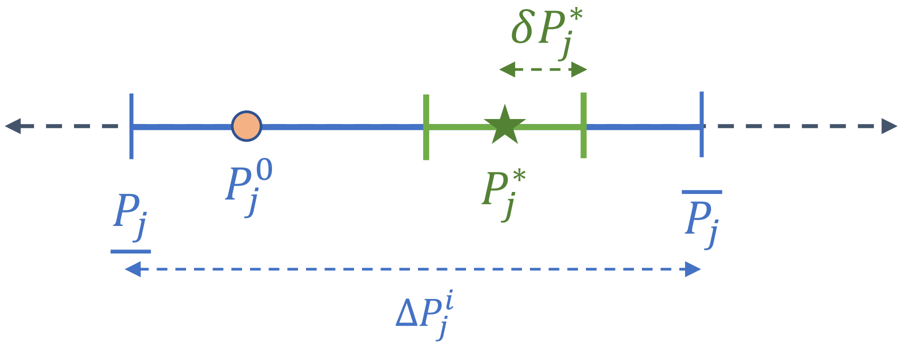


Cleared solution

$\overrightarrow{S_j^*} = [P_j^*, Q_j^*, \delta P_j^*, \delta Q_j^*, \mu_j^{P*}, \mu_j^{Q*}]$

$P_j = P_j^G - P_j^L, Q_j = Q_j^G - Q_j^L$





1. t_{s_0}: **Bidding** for $[t_{s_0}, t_{s_1}]$ period based on load/generation forecasts
2. t'_{s_0}: **Scheduling** (market clearing) for $[t_{s_0}, t_{s_1}]$
3. t_{s_1}: **Settlements** (financial transactions) for $[t_{s_0}, t_{s_1}]$

aac LAB

SM constraints

- Operational active (and reactive) power limits: $\delta P_j, \delta Q_j \geq 0$

$$\underline{P_j} + \delta P_j \leq P_j \leq \overline{P_j} - \delta P_j,\ \underline{Q_j} + \delta Q_j \leq Q_j \leq \overline{Q_j} - \delta Q_j$$

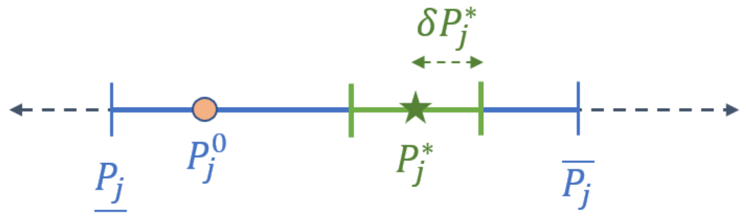
- Real-time tariff constraints: $0 \leq \mu_j^P, \mu_j^Q \leq \overline{\mu}$
- Power balance between lower (SMO) & upper (PMO) levels:

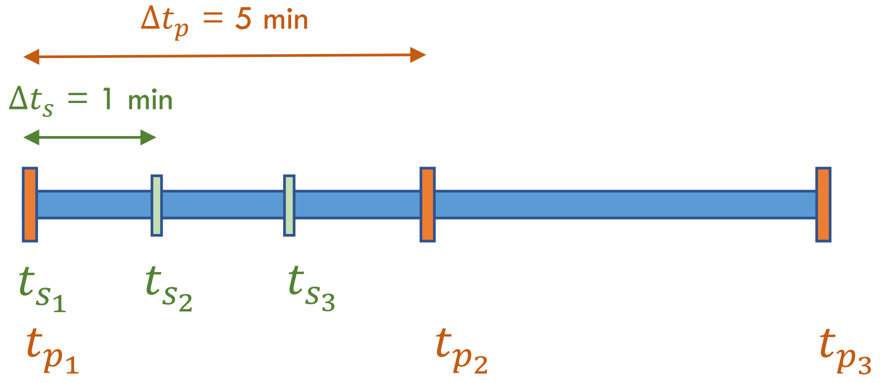
$$\sum_j P_j(t_s) = P^*(t_p),\ \sum_j Q^*(t_s) = Q^*(t_p)$$

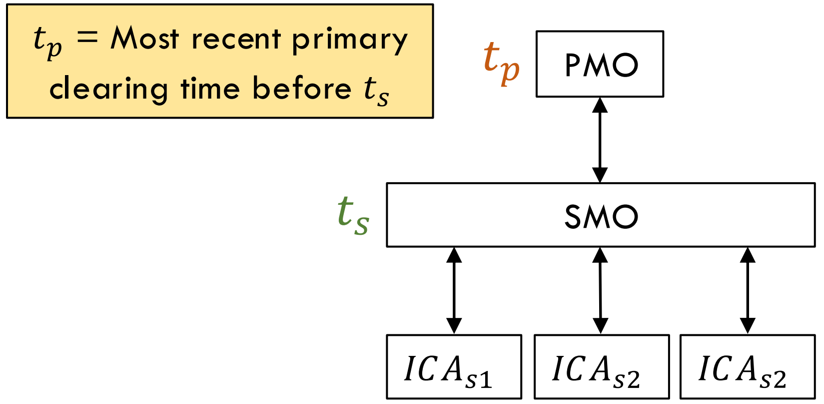
- Budget constraint: SMO must break-even over a time horizon

$$\sum_{t_p} \sum_{t_s} \sum_j \left(\mu_j^P P_j + \mu_j^Q Q_j\right) \Delta t_s \leq \sum_{t_p} \left(\mu^{P^*} P^* + \mu^{Q*} Q^*\right) \Delta t_p$$

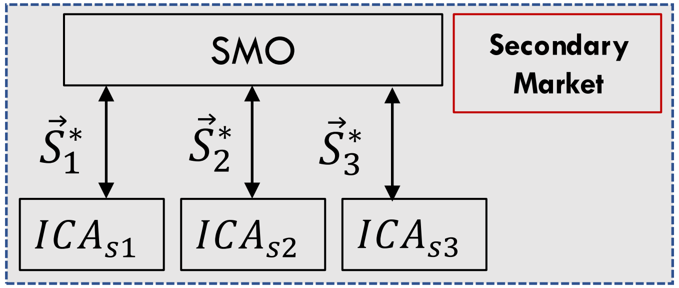
- Commitment score $0 \leq C_j \leq 1$ measures reliability
  - Reward (or penalize) DCAs for fulfilling (or violating) contracts







Secondary market: Optimization problem



- SMO i maximizes social welfare
- Multi-objective, constrained optimization at each time instant

$$\min_{\vec{S}_j^i} \sum_{j \in \mathcal{N}_{J,i}} \{f_{j,1}^i, f_{j,2}^i, f_{j,3}^i, f_{j,4}^i\}$$

$$f_{1,j}^i \succ f_{2,j}^i \succ f_{3,j}^i \succ f_{4,j}^i$$

Maximize aggregate reliability

$$f_{j,1} = -C_j^i((P_j^i - P_j^{i0})^2 + (Q_j^i - Q_j^{i0})^2)$$

Allocate larger share of flexibility to more reliable assets

Minimize net cost to SMO

$$f_{j,2}^i = \mu_j^{iP} P_j^i + \mu_j^{iQ} Q_j^i$$

Maximize aggregate flexibility

$$f_{j,3}^i = -(\delta P_j^i + \delta Q_j^i)$$

Minimize disutility to ICA_{sj}

$$f_{j,4}^i = \beta_j^{iP}(P_j^i - P_j^{i0})^2 + \beta_j^{iQ}(Q_j^i - Q_j^{i0})^2$$

$$\min_{\vec{S}_j^i} F_k = \sum_{j \in \mathcal{N}_{J,i}} f_{j,k}^i(\vec{S}_j^i) \ \forall\, k = 1,2,3,4$$

$$\text{s.t. } f_{j,\ell}^i(\vec{S}_j^i) \le (1+\epsilon) \sum_{j \in \mathcal{N}_{J,i}} f_{j,\ell}^i(\vec{S}_j^{i*}) = (1+\epsilon) F_\ell^*,$$

$$\forall\, \ell = 1, 2, \ldots, k-1, \ k > 1$$

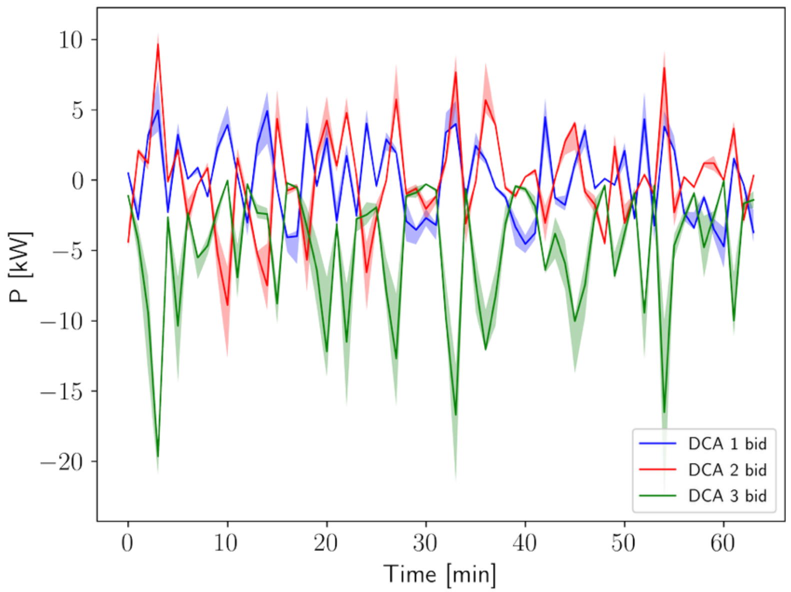
and all other constraints

- Use hierarchical approach to solve multi-objective problem
- Successively optimize each objective in descending order of importance

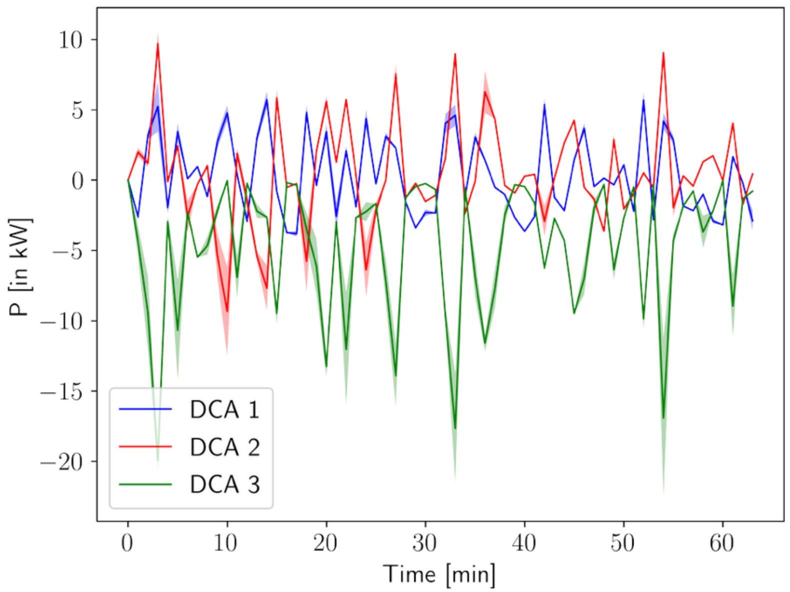
Nair, Venkataramanan, Haider, Annaswamy, IEEE Transactions on Smart Grid, 2022.

Secondary market (SM) clearing & scheduling

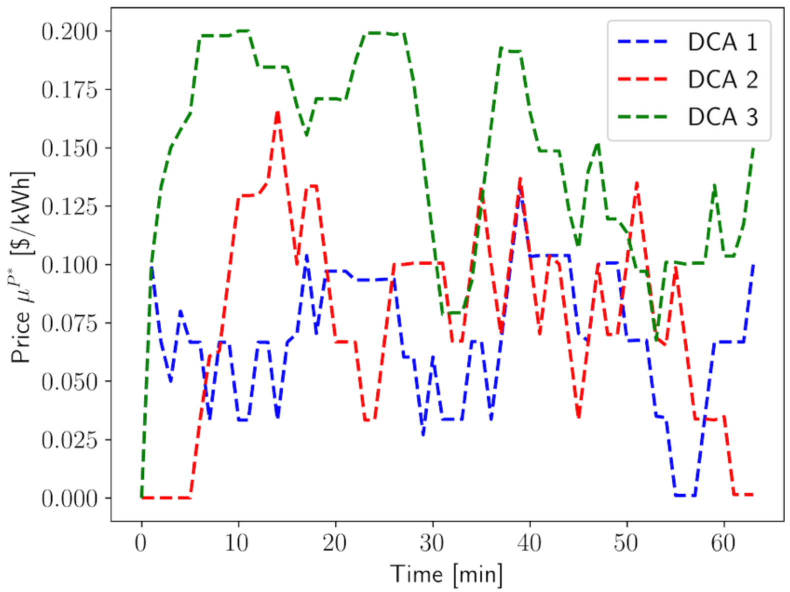
DCA bids into SM at node 7



DCA schedules from SMO 7

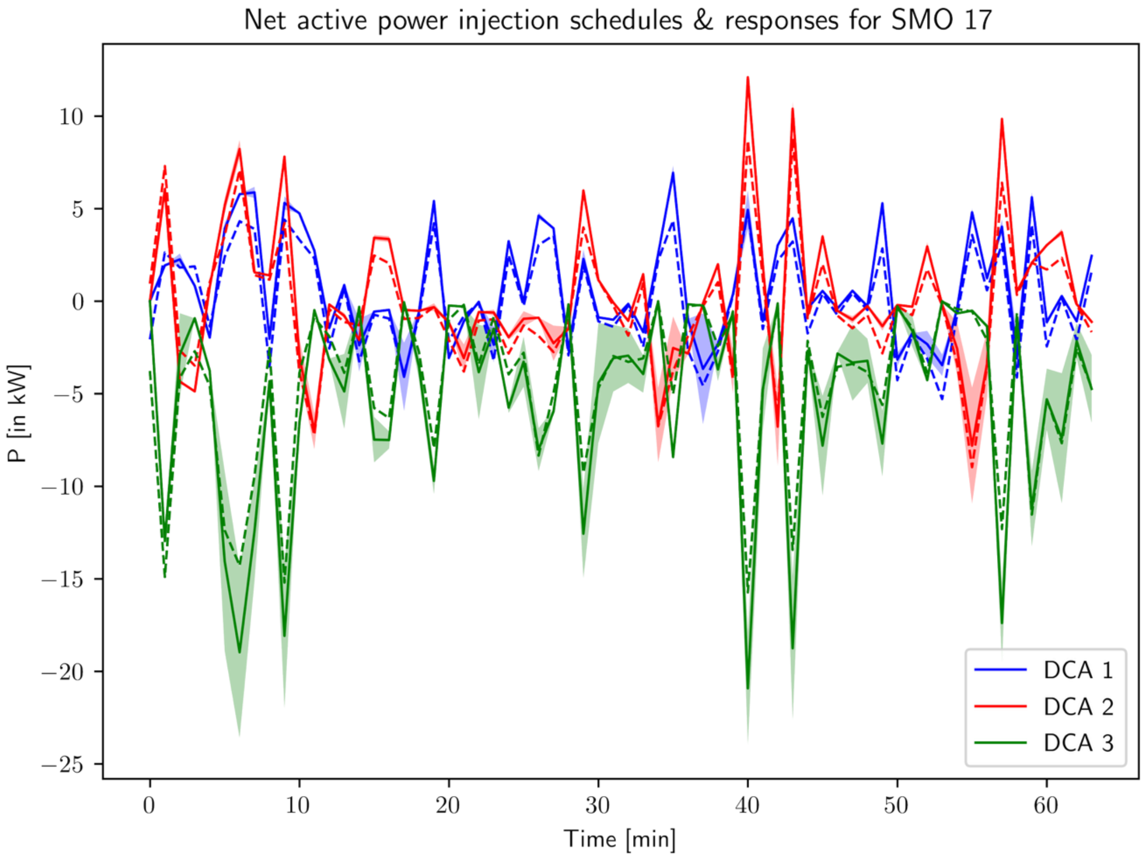


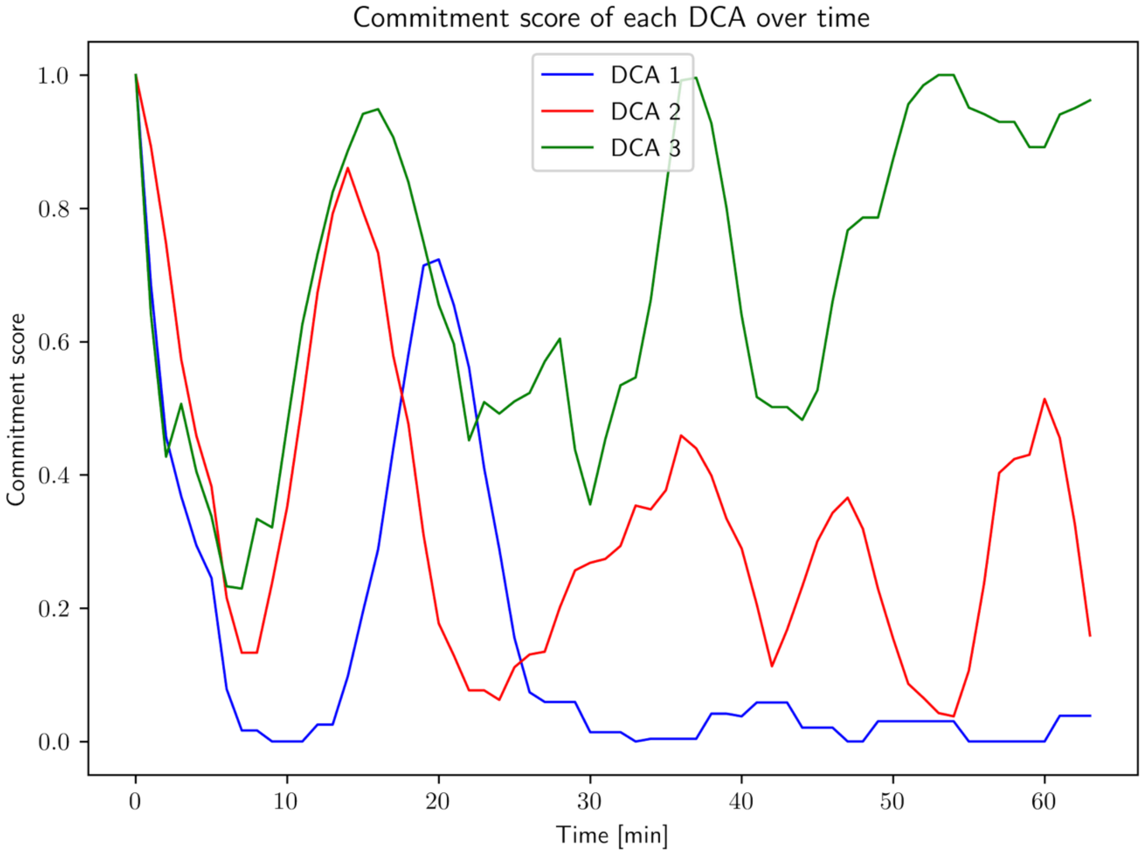
Local retail tariffs



Weighted rolling mean to reduce price volatility while ensuring budget balance: $\widetilde{\mu_j^P} = \frac{\Sigma_{t_s}^{t_s+\Delta t_p} \mu_j^P P_j}{\Sigma_{t_s}^{t_s+\Delta t_p} P_j} \quad \forall\ DCA\ j$

Actual responses of DCAs → Update commitment scores





Connecting secondary market to primary

- Extend secondary market to unbalanced case → Model all variables as 3-phase
- Before each primary clearing period, SMO i aggregates 3-phase schedules across all its DCA_j^i from latest secondary clearing
- SMO uses this combined solution to bid into primary market

$$P_i^{\phi,0}(t_p) = \sum_{j \in \mathcal{N}_{J,i}} P_j^{i,\phi^*}(t_p) \ \forall \ \phi \in \{a, b, c\}$$

$$\Delta P_i^{\phi} = \left[\underline{P_i^{\phi}}, \overline{P_i^{\phi}}\right] = \left[\sum_{j \in \mathcal{N}_{J,i}} P_j^{i,\phi^*} - \delta P_j^{i,\phi^*}, \sum_{j \in \mathcal{N}_{J,i}} P_j^{i,\phi^*} + \delta P_j^{i,\phi^*}\right]$$

- Given bids → Solve ACOPF at primary level using dual ascent-based distributed proximal atomic coordination (PAC) algorithm

Nair, Venkataramanan, Haider, Annaswamy, IEEE Transactions on Smart Grid, 2022.

Current Injection (CI) model

For unbalanced, multiphase, radial/meshed distribution networks

Complex/polar coordinates

$$\min_{(I,V,S)} f(I,V,S)$$

$$I = YV$$ ← KCL & KVL combined (Ohm's law)

$$S = VI^H$$ ← Power balance

$$\underline{V} \leq |V| \leq \bar{V}$$

$$\underline{S} \leq S \leq \bar{S}$$

$$|I_{ij}| \leq \overline{I_{ij}} \quad \forall ij \in E$$

Cartesian coordinates

$$\min_{x} f(x)$$

$$I^R = \mathrm{Re}(YV)$$

$$I^I = \mathrm{Im}(YV)$$

← Nodal current injections

$$P_i^\phi = V_i^{\phi,R} I_i^{\phi,R} + V_i^{\phi,I} I_i^{\phi,I} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

$$Q_i^\phi = -V_i^{\phi,R} I_i^{\phi,I} + V_i^{\phi,I} I_i^{\phi,R} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

} Nonconvex bilinear equality constraints

$$\underline{V_i^{\phi}}^2 \leq \left(V_i^{\phi,R}\right)^2 + \left(V_i^{\phi,I}\right)^2 \leq \overline{V_i^\phi}^2 \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

Nonconvex voltage ring constraint

$$\underline{P_i^\phi} \leq P_i^\phi \leq \overline{P_i^\phi} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

$$\underline{Q_i^\phi} \leq Q_i^\phi \leq \overline{Q_i^\phi} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

$$\left(I_{ij}^R\right)^2 + \left(I_{ij}^I\right)^2 \leq \overline{I_{ij}}^2 \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

All variables modelled for each phase $\phi \in \{a, b, c\}$ of each node

Ferro, G. (2020). Competitive and Cooperative Approaches to the Balancing Market in Distribution Grids (Doctoral dissertation, PhD thesis, Universita degli studi di Genova).
Ferro, G. et al. (2020). A distributed approach to the Optimal Power Flow problem for unbalanced and mesh networks. 21st IFAC World Congress, 2020.
*Ferro, G. et al. (2022). A Current Injection Based Method for Unbalanced and Meshed Distribution Networks. Under preparation.

CI model: McCormick envelopes (MCE) convex relaxation

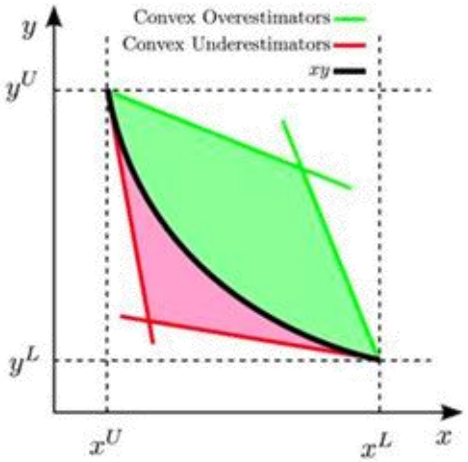
$$P_j = Re\left(V_j I_j^*\right) = Re(V_j)Re(I_j) + Im(V_j)Im(I_j)$$
$$Q_j = Im\left(V_j I_j^*\right) = -Re(V_j)Im(I_j) + Im(V_j)Re(I_j)$$

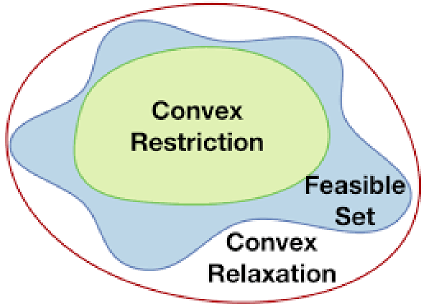
Create a convex constraint, using McCormick Envelopes

Consider bilinear form: $w = xy$

Defined over set: $S \subset \mathbb{R}^3 = \left\{x, y : x \in \left[\underline{x}, \overline{x}\right], y \in \left[\underline{y}, \overline{y}\right]\right\}$

Then we introduce a new variable, w, and we define MCE envelope as:





$$
\begin{aligned}
&(5a)\ w \geq \underline{x}y + x\underline{y} - \underline{x}\,\underline{y} \\
&(5\text{b})\ w \geq \overline{x}y + x\overline{y} - \overline{x}\,\overline{y} \\
&(5\text{c})\ w \geq \underline{x}y + x\overline{y} - \underline{x}\,\overline{y} \\
&(5\text{d})\ w \geq \overline{x}y + x\underline{y} - \overline{x}\,\underline{y}
\end{aligned}
$$

Thus, we can relax the power balance constraints as:

$$P = a + b$$
$$Q = -c + d$$

$\underline{V^R} \leq V_r \leq \overline{V^R}$	and	$\underline{V^I} \leq V^I \leq \overline{V^I}$
$\underline{I^R} \leq I_r \leq \overline{I^R}$	and	$\underline{I^I} \leq I^I \leq \overline{I^I}$

Iterative preprocessing to set tight V & I bounds → More accurate convex relaxation

And corresponding MCE constraints on $\{a, b, c, d\}$

McCormick, G.P. "Computability of global solutions to factorable nonconvex programs: Part i - convex underestimating problems." Mathematical Programming. 1976
*Ferro, G. et al. (2022). A Current Injection Based Method for Unbalanced and Meshed Distribution Networks. Under preparation.

Apply 3-phase PM + SM for primary voltage regulation

1. Regulate voltage about set points:
   $|V| = 1\,p.u. \rightarrow V_i^{\phi,R^*} = 1,\ V_i^{\phi,I^*} = 0$

$$f^{Volt,\phi}(x) = \sum_{i\in\mathcal{I}}\sum_{\phi\in\mathcal{P}}\left[\left(V_i^{\phi,R} - V_i^{\phi,R^*}\right)^2 + \left(V_i^{\phi,I} - \bar{V}_i^{\phi,I^*}\right)^2\right]$$

2. Minimize line losses

$$f^{Loss,\phi}(x) = \sum_{ij\in\mathcal{E}}\sum_{\phi\in\mathcal{P}} R_{ij}|I_{ij}^{\phi}|^2 = R_{ij}\left(I_{ij}^{\phi,R^2} + I_{ij}^{\phi,I^2}\right)$$

3. Minimize disutility

$$f^{Disutil,\phi}(x) = \beta_i^P(P_i^{L,\phi} - P_i^{L0,\phi})^2 + \beta_i^Q(Q_i^{L,\phi} - Q_i^{L0,\phi})^2$$

4. Minimize generation costs

$$f^{Volt,\phi}(x) = \sum_{i\in\mathcal{I}}\sum_{\phi\in\mathcal{P}}\begin{cases}\alpha_i^{P,\phi}P_i^{G,\phi} + \alpha_i^{Q,\phi}Q_i^{G,\phi}, & \\ \lambda_i^P P_i^{G,\phi} + \lambda_i^Q Q_i^{G,\phi}, & \text{if } i \text{ is PCC}\end{cases}$$

Overall social welfare objective function

$$\min_y f^{S-W}(x) = w_1 f^{Disutil,\phi}(x) + w_2 f^{Gen-Cost,\phi}(x) + w_3 f^{Volt,\phi}(x) + w_4 f^{Volt,\phi}(x)$$

- Multobjective optimization
  $w_1 + w_2 + w_3 + w_4 = 1, 0 \le w_i \le 1$
- All quantities (P, Q, V, I, R) in p.u.
  → Similar magnitude terms
- Adjust relative weights based on priority
- Can extend to other grid service applications e.g. Conservation voltage reduction (CVR)

aac LAB

Accurately pricing different grid services

Dual variables of equality constraints
→ Decompose distribution locational marginal price (dLMP)

$$\min_x f(x)$$

KCL & KVL combined (Ohm's law)

$$\begin{cases} I^R = \mathrm{Re}(YV) \\ I^I = \mathrm{Im}(YV) \end{cases}$$

Value of voltage support $\mathrm{Re}(\lambda_V)$

$I = YV$ complex

Power balance

$$\begin{cases} P_i^\phi = V_i^{\phi,R} I_i^{\phi,R} + V_i^{\phi,I} I_i^{\phi,I} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P} \\ Q_i^\phi = -V_i^{\phi,R} I_i^{\phi,I} + V_i^{\phi,I} I_i^{\phi,R} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P} \end{cases}$$

P & Q "energy" prices λ_P, λ_Q

$$\underline{V_i^{\phi}}^2 \leq \left(V_i^{\phi,R}\right)^2 + \left(V_i^{\phi,I}\right)^2 \leq \overline{V_i^{\phi}}^2 \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

$$\underline{P_i^\phi} \leq P_i^\phi \leq \overline{P_i^\phi} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

$$\underline{Q_i^\phi} \leq Q_i^\phi \leq \overline{Q_i^\phi} \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

$$(I_{ij}^R)^2 + (I_{ij}^I)^2 \leq \overline{I_{ij}}^2 \quad \forall i \in \mathcal{N}, \phi \in \mathcal{P}$$

aac LAB

Price decomposition → Value of grid services

$$\mathcal{L} = f^{obj}(x) + \lambda_P^\intercal P_{balance} + \lambda_Q^\intercal Q_{balance} \quad + \lambda_I^\intercal (I - YV) + \lambda_{ineq}^\intercal (RHS_{ineq} - LHS_{ineq})$$

$$\lambda_I^\intercal (I - YV) \equiv \lambda_V^\intercal (ZI - V) = \lambda_V^\intercal (Y^{-1} I - Y^{-1} YV) = \lambda_V^\intercal Y^{-1} (I - YV)$$

$$\implies \lambda_I^\intercal = \lambda_V^\intercal Y^{-1} \implies \lambda_V = Y^\intercal \lambda_I$$

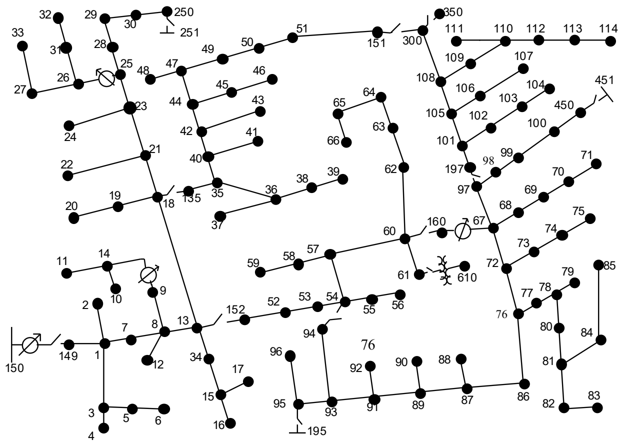
$$\frac{\partial \mathcal{L}}{\partial V} = \frac{\partial f^{obj}(x)}{\partial V} - \lambda_I^\intercal Y = \frac{\partial f^{obj}(x)}{\partial V} - \lambda_V$$

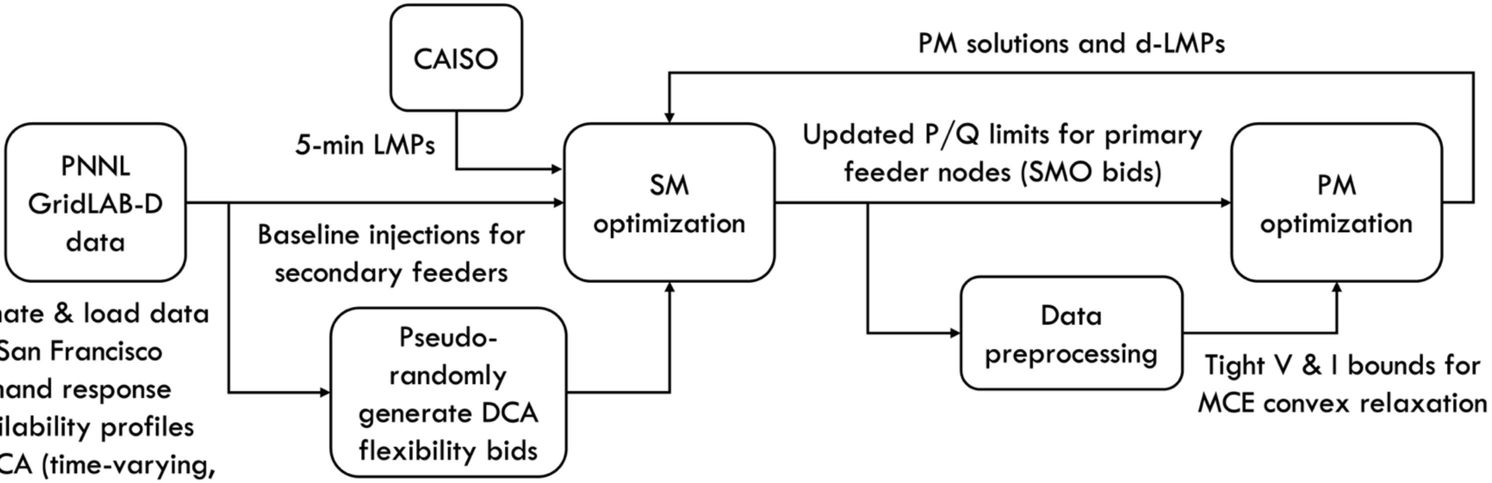
$$\text{At optimality } \frac{\partial \mathcal{L}}{\partial V^*} = \frac{\partial f^{obj}}{\partial V^*} - \lambda_V = 0 \implies \frac{\partial f^{obj}}{\partial V^*} = \lambda_V^*$$

Cost of satisfying voltage constraints (in terms of degrading objective function)

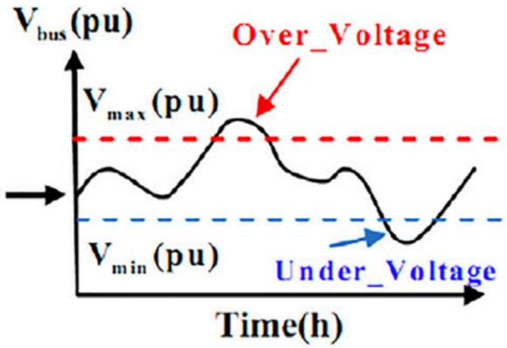
Co-simulation of primary + secondary markets

Data from modified
IEEE-123 GridLAB-D model





- Climate & load data for San Francisco
- Demand response availability profiles for CA (time-varying, up to 50%)

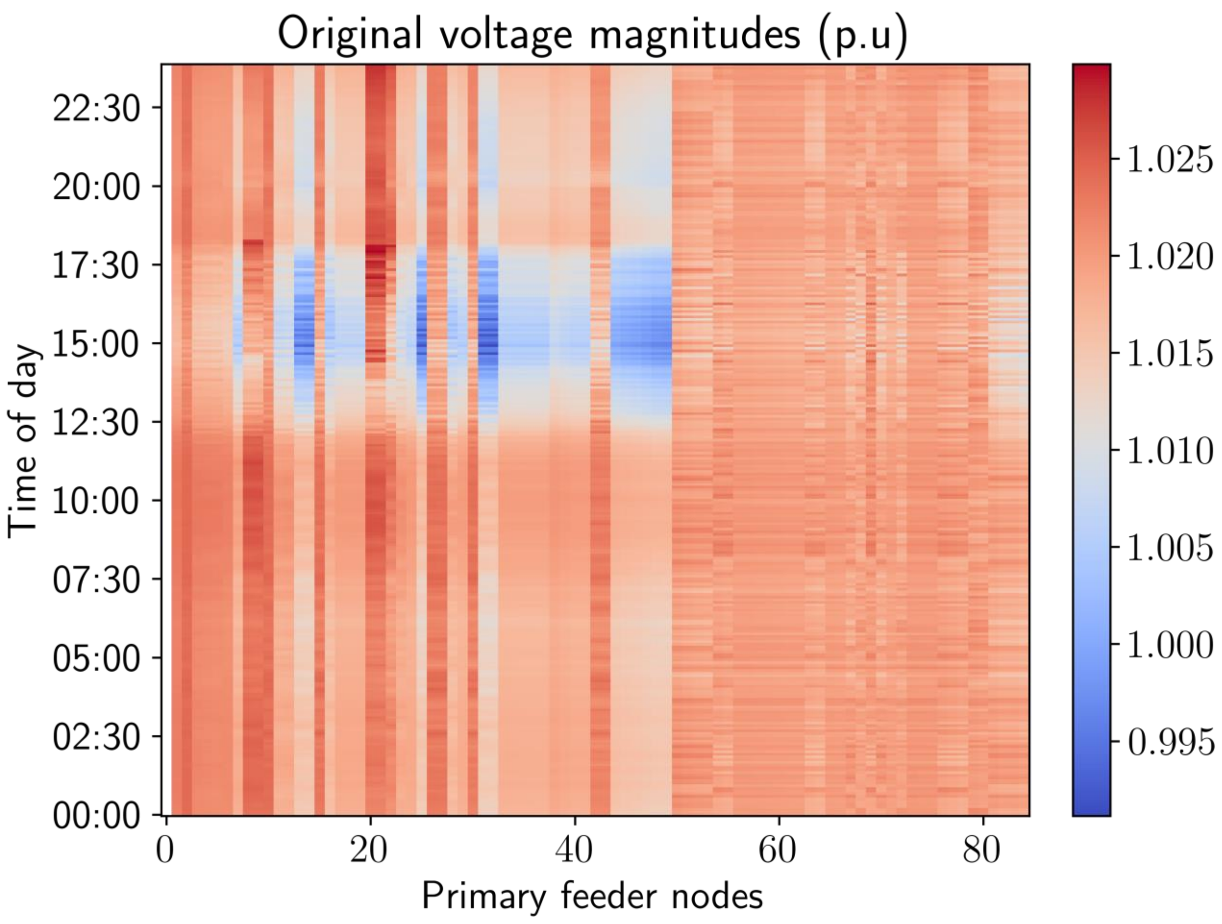


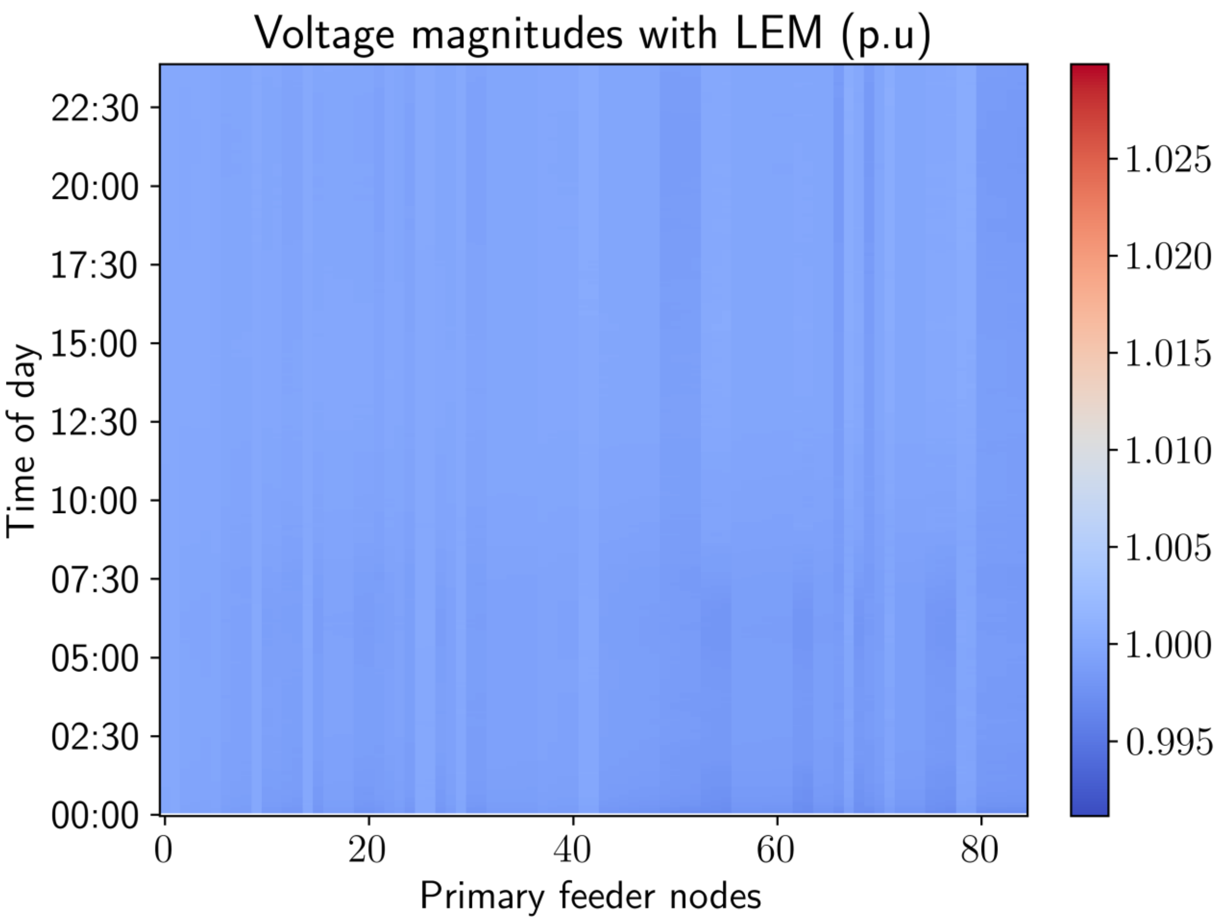
- Accelerated by parallelizing independent SM clearings
- Mitigate voltage issues common in low-medium voltage distribution grids, e.g.
  - High PV output → Over-voltage
  - Demand spikes from HVAC → Under-voltage

Type	Number	Capacity
DERs	380	1,745.8 kVA (~**44%**)
PVs	207	880.84 kVA
Batteries	173	865 kVA
Spot loads	85	3,985.7 kVA
Houses	1008	4-10 kW (variable)
Flexible loads	1-2 per house	10-50% flexibility (variable)

LAB

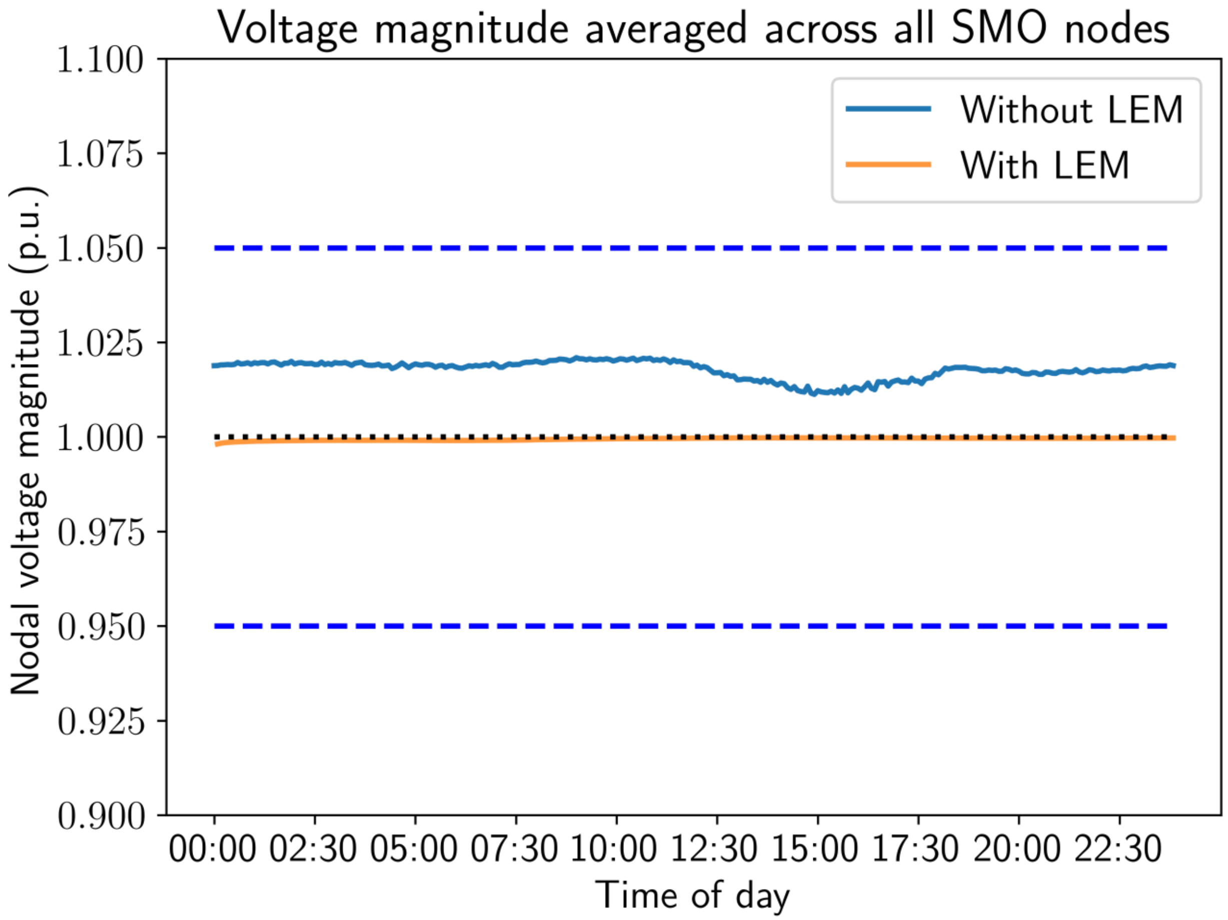
Numerical simulation results: Improved voltage profile

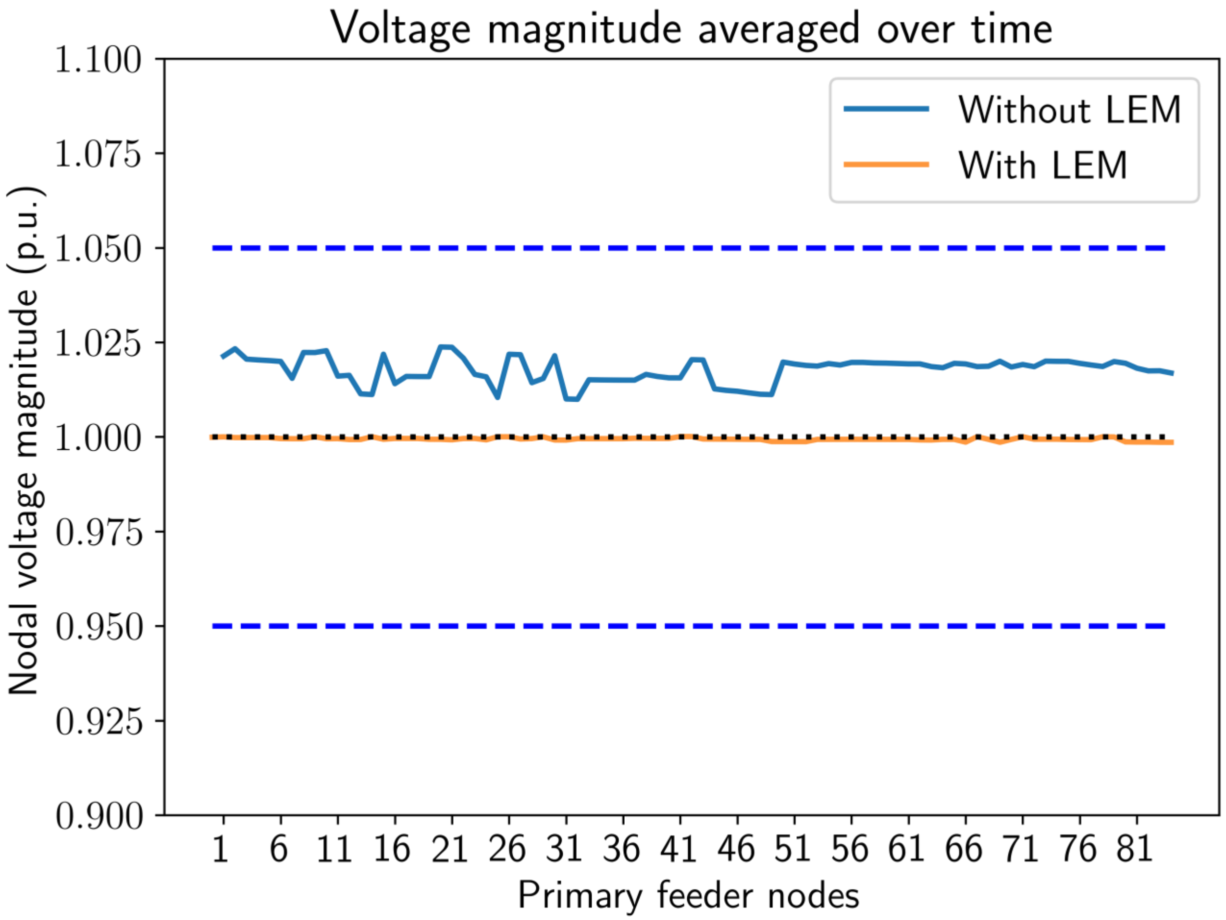




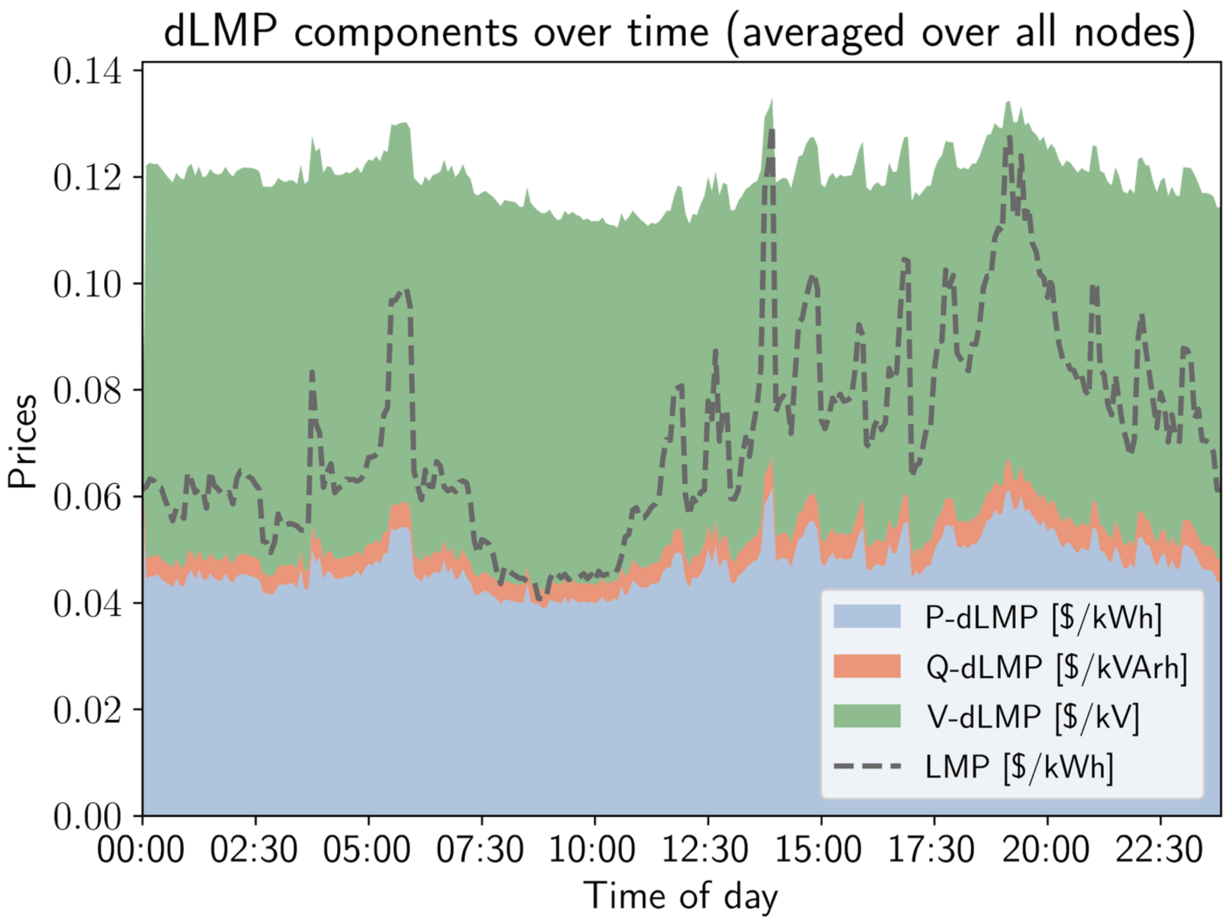
LEM (SM + PM) improves overall voltage profile → More uniform + closer to 1 p.u.

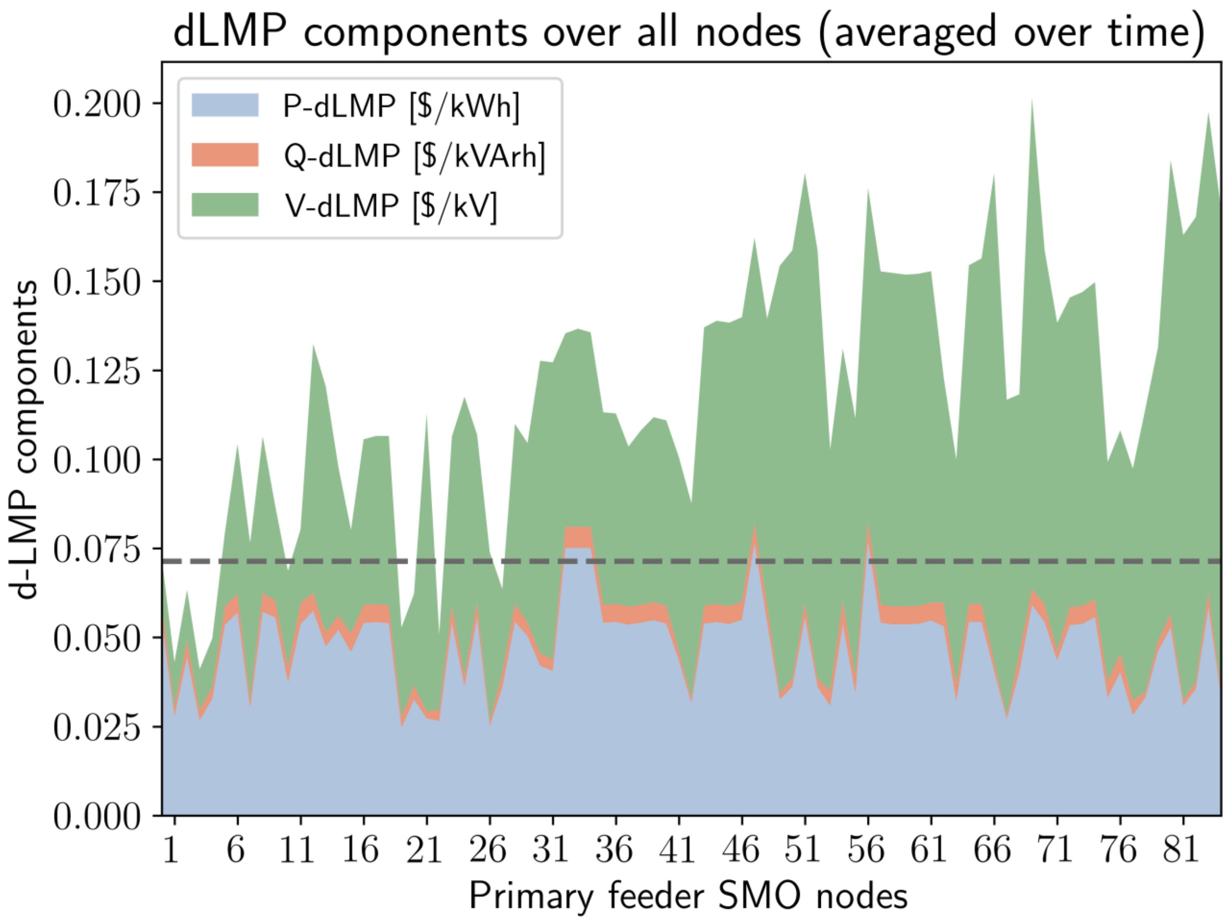
Average voltages over space and time





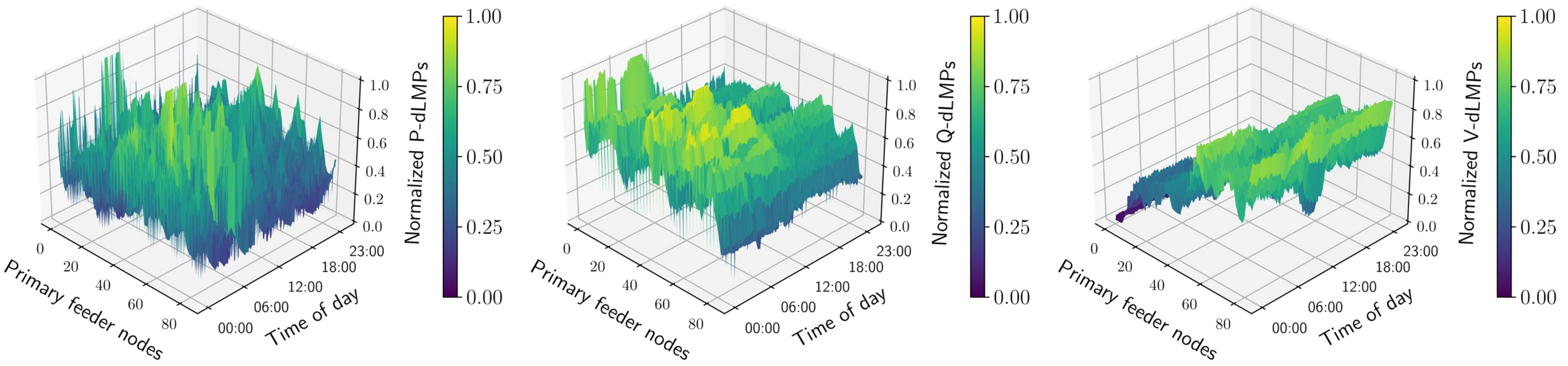
d-LMP component variations





aac LAB

Spatial-temporal distributions & cost comparison



- Average bundled tariff for PG&E (Aug 2022) = 33.72 ¢/kWh
- Weighted average d-LMP for LEM = 5.38 ¢/kWh
- *Caveat:* Our rate does not include additional maintenance/infrastructure costs, delivery charges etc.

$$\lambda_{eq} = \left(\lambda_P^* P^* + \lambda_Q^* Q^* + \bar{\lambda}_V^* \Delta V^*\right) / P^*$$

$$\Delta V^* = \left|V^{R^*} - 1\right| + \left|V^{I^*}\right|$$

Conclusions

- Developed local hierarchical retail market structure applicable to general types of networks using current injection model
- Market structure coordinates DERs to provide valuable grid services like voltage control & compensates them
  - Upper level (Primary): Accounts for AC power physics, interacts with wholesale energy market and transmission network
  - Lower level (Secondary): Accounts for consumer preferences (utility, costs, flexibilities, commitment reliabilities) & budget constraints
- SMO coordinates DERs & effectively leverages flexibility to lower network-wide costs → Lower electricity prices

[1] Nair, Annaswamy, "Local retail markets for distribution grid services." 7th IEEE Conference on Control Technology and Applications (CCTA), 2023.
[2] Nair, Venkataramanan, Haider, Annaswamy, "A Hierarchical Local Market for a DER-Rich Grid Edge." IEEE Transactions on Smart Grid, 2022.
[3] Srivastava, Haider, Nair, Venkataramanan, Annaswamy, Srivastava, "Voltage regulation in distribution grids: A survey". Annual Reviews in Control, 2023.

APPENDIX

Commitment scores

- Commitment score for each ICA_s
- SMO rewards ICA_s for fulfilling bilateral contracts, penalizes violations → Measure of commitment reliability
- Normalized deviations of actual ICA_s P/Q injections from cleared setpoints

$$e_j^P(t_s) = \left[\!\left[\hat{P}_j > \overline{P}_j^{i^*}\right]\!\right]\left(\hat{P}_j - \overline{P}_j^{i^*}\right) + \left[\!\left[\hat{P}_j < \underline{P}_j^{i^*}\right]\!\right]\left(\underline{P}_j^{i*} - \hat{P}_j\right) + \left[\!\left[\underline{P}_j^{i^*} \leq \hat{P}_j \leq \overline{P}_j^{i^*}\right]\!\right] \max\left(\hat{P}_j - \overline{P}_j^{i^*}, \underline{P}_j^{i^*} - \hat{P}_j\right)$$

- Normalize by true solution & across all ICA_{sj} for the SMO:

$$\widetilde{e_j^P}(t_s) = \frac{e_j^P(t_s)}{|P_j^*(t_s)|} \Rightarrow \widetilde{e^{iP}}(t_s) = \frac{\mathbf{e^{iP}}(t_s)}{\|\mathbf{e^{iP}}(t_s)\|}$$

- Update score for each ICA_s at every timestep:

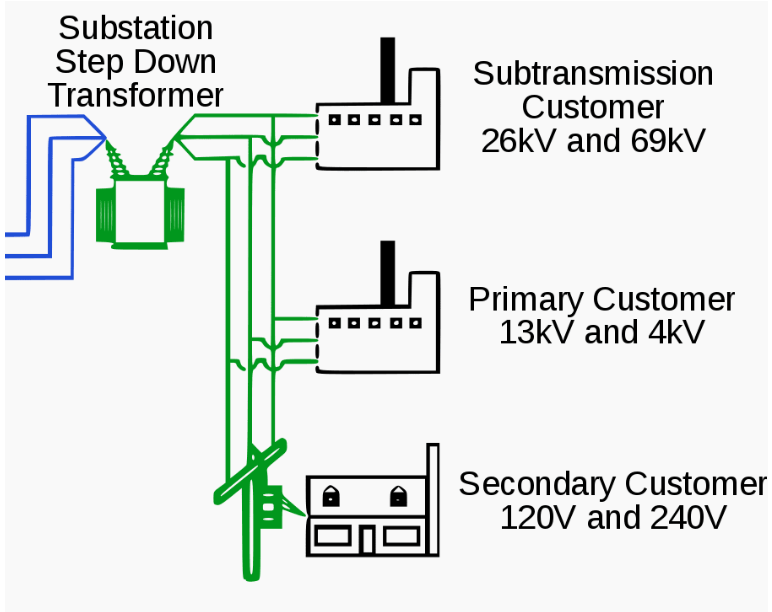
$$C_j(t_s) = \begin{cases} 1 & \text{if } t_s = 0 \\ C_j(t_s - 1) - \frac{\widetilde{e_j^P}(t_s) + \widetilde{e_j^Q}(t_s)}{2} & \text{if } t_s > 0 \end{cases}$$

→ Clip/scale values

$\Rightarrow 0 \leq C_j(t_s) \leq 1 \; \forall \; t_s$

LAB

Distribution system models



Power Systems Models Designed for Transmission Network

Distribution Grid:

Mixed topologies: Meshed and radial

Unbalanced networks

- Lines are not transposed – lines are unbalanced
- Have many single, two, & three-phase lines
- Unbalanced loads

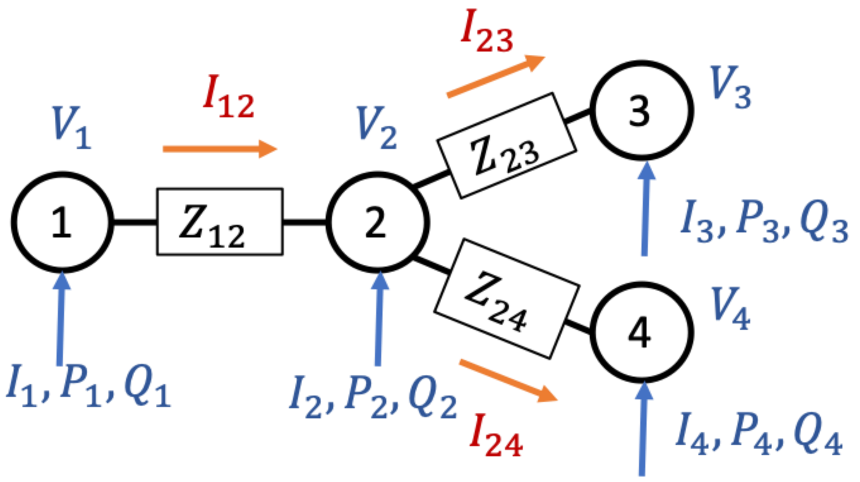
Emerging features:

- High DER penetration along grid's edge
- Energy injection into the grid (DG and storage)

Want power systems model with:

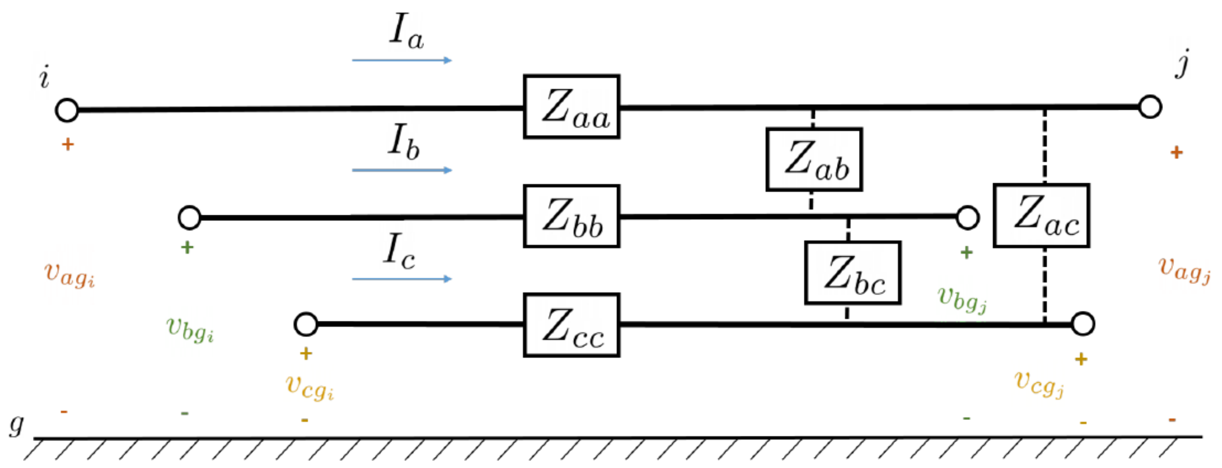
- **Applicability:** To unbalanced and meshed networks
- **Simplicity:** Linear constraints better than quadratic constraints
- **Computational tractability:** Applicable to large networks with limited pre/post-processing time

Review: Notation



Notation

- Nodal variables: Current injections, voltages, power injection (P & Q)
- Line variables: Current flow
- Each line has series impedance, $Z_{ij} = R_{ij} + X_{ij}i$



3-phase impedance matrix

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Iterative preprocessing to obtain tight V/I bounds

- Need tight bounds on nodal current injections and voltage bounds
- Tighter convex relaxation → More accurate results
- Use iterative, sequential bound tightening approach
- Solve series of simpler optimization problems to find lower/upper bounds

e.g., to find $\overline{I^R}$

$$\max_{\{P,Q,v,\delta\}} h_1(P,Q,v,\delta)$$

$$\underline{\delta} \leq \delta \leq \overline{\delta}$$ Voltage phase angle

$$\underline{v} \leq v \leq \overline{v}$$ Voltage magnitude

$$\underline{P} \leq P \leq \overline{P}$$

$$\underline{Q} \leq Q \leq \overline{Q}$$

$$h_1 = I^R = \mathrm{Re}\left[\left(\frac{P + jQ}{v e^{j\delta}}\right)^H\right] = \frac{P\cos(\delta)}{v} + \frac{Q\sin(\delta)}{v}$$

e.g., to find $\overline{V^I}$

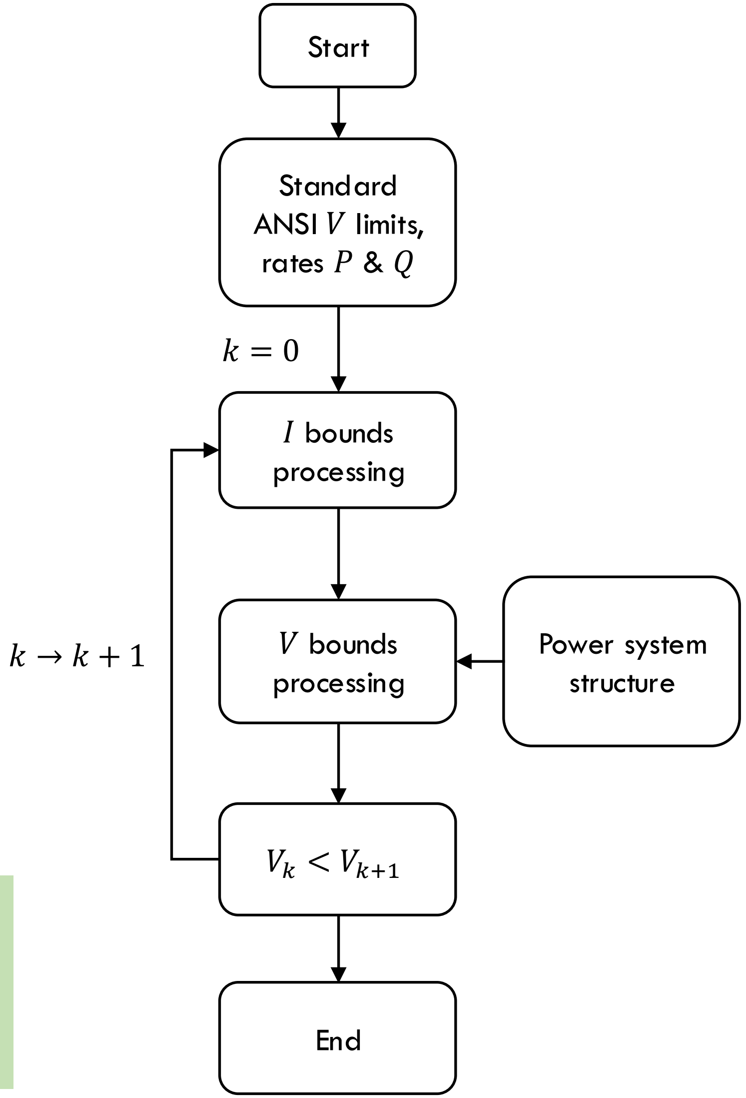
$$\max_{\{V_i^I, I_i^R, I_i^I\}} V_i^I$$

$$V_i^I = \mathbf{R}_{il} I_{l'}^I - \mathbf{X}_{il} I_{l'}^R$$

$$\underline{I_l^R} \leq I_l^R \leq \overline{I_l^R}$$

$$\underline{I_l^I} \leq I_l^I \leq \overline{I_l^I}$$

- Can derive closed form analytical solutions
- Solutions also satisfy nonconvex voltage ring constraint



Ferro, G. (2020). *Competitive and Cooperative Approaches to the Balancing Market in Distribution Grids* (Doctoral dissertation, PhD thesis, Universita degli studi di Genova).
*Ferro, G. (2022). *A Current Injection Based Method for Unbalanced and Meshed Distribution Networks.* Under preparation.