Using Smart Meter and PMU Data for Load Inference

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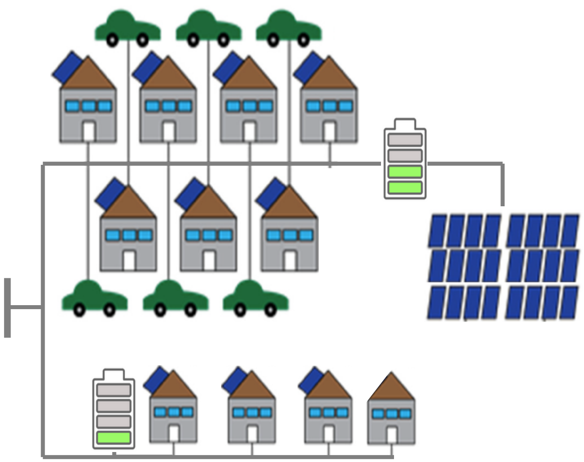
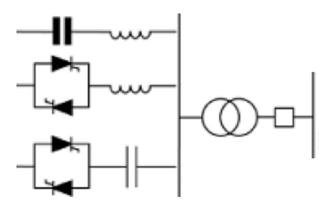
Learning loads in distribution grids

- Reduced observability due to sheer extent and limited metering infrastructure

- However, load estimates needed for grid optimization, billing, and energy theft detection



- Leverage smart meter data and smart inverters



Problem statement and prior work

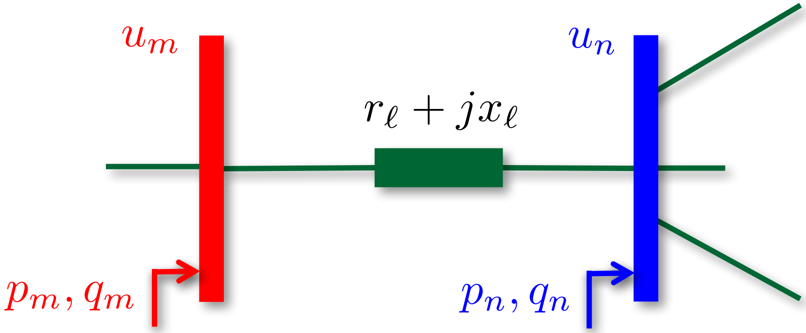
Load learning: *Given* ***readings*** *from a set of metered (controllable) buses* $\mathcal{M}$, *recover the system state and hence the power injections at non-metered buses* $\mathcal{O}$.

- Collected readings
  - *passively collected* (smart meter and sychrophasor (PMU) data)
  - *actively collected* through grid probing

- For sufficiently rich (pseudo)measurement sets, solve as D-PSSE [Dzafic-Jabr-Pal et al'13], [Klauber-Zhu'15], [Gomez-Exposito et al'15]
- Linear estimator if grid is equipped with micro-PMUs [A. von Meier'15]
- Meter placement in distribution grids [Lui-Ponci'14]
- Probing transmission grids for estimating oscillation modes [Trudnowski-Pierre'09]
- System identification in DC microgrids [Angjelichinoski-Scaglione '17]

Linearized distribution flow model

- Single-phase radial grid with *N+1* nodes and *N* lines



- Approximate LDF model [Baran-Wu'89], [Bolognani-Dorfler'15], [Deka et al'17]

$$\mathbf{u} \simeq \mathbf{R}\mathbf{p} + \mathbf{X}\mathbf{q}$$
$$\boldsymbol{\theta} \simeq \mathbf{X}\mathbf{p} - \mathbf{R}\mathbf{q}$$

nodal voltage phasor $V_n = |V_n|e^{j\theta_n}$

$u_n := |V_n|^2 - |V_0|^2$

- The inverses of *(***R***,***X***)* are reduced graph Laplacian matrices

Passive load learning

- Partition data into metered and non-metered buses

$$\begin{bmatrix}\mathbf{u}_{\mathcal{M}}\\ \mathbf{u}_{\mathcal{O}}\end{bmatrix} = \begin{bmatrix}\mathbf{R}_{\mathcal{M},\mathcal{M}} & \mathbf{R}_{\mathcal{M},\mathcal{O}}\\ \mathbf{R}_{\mathcal{M},\mathcal{O}}^{\top} & \mathbf{R}_{\mathcal{O},\mathcal{O}}\end{bmatrix}\begin{bmatrix}\mathbf{p}_{\mathcal{M}}\\ \mathbf{p}_{\mathcal{O}}\end{bmatrix} + \begin{bmatrix}\mathbf{X}_{\mathcal{M},\mathcal{M}} & \mathbf{X}_{\mathcal{M},\mathcal{O}}\\ \mathbf{X}_{\mathcal{M},\mathcal{O}}^{\top} & \mathbf{X}_{\mathcal{O},\mathcal{O}}\end{bmatrix}\begin{bmatrix}\mathbf{q}_{\mathcal{M}}\\ \mathbf{q}_{\mathcal{O}}\end{bmatrix} + \boldsymbol{\eta}$$

- Model for smart meter data

$$\mathbf{u}_{\mathcal{M}} - \mathbf{R}_{\mathcal{M},\mathcal{M}}\mathbf{p}_{\mathcal{M}} - \mathbf{X}_{\mathcal{M},\mathcal{M}}\mathbf{q}_{\mathcal{M}} = [\mathbf{R}_{\mathcal{M},\mathcal{O}} \;\; \mathbf{X}_{\mathcal{M},\mathcal{O}}]\begin{bmatrix}\mathbf{p}_{\mathcal{O}}\\ \mathbf{q}_{\mathcal{O}}\end{bmatrix} + \boldsymbol{\eta}_{\mathcal{M}}$$

- Model for synchrophasor data

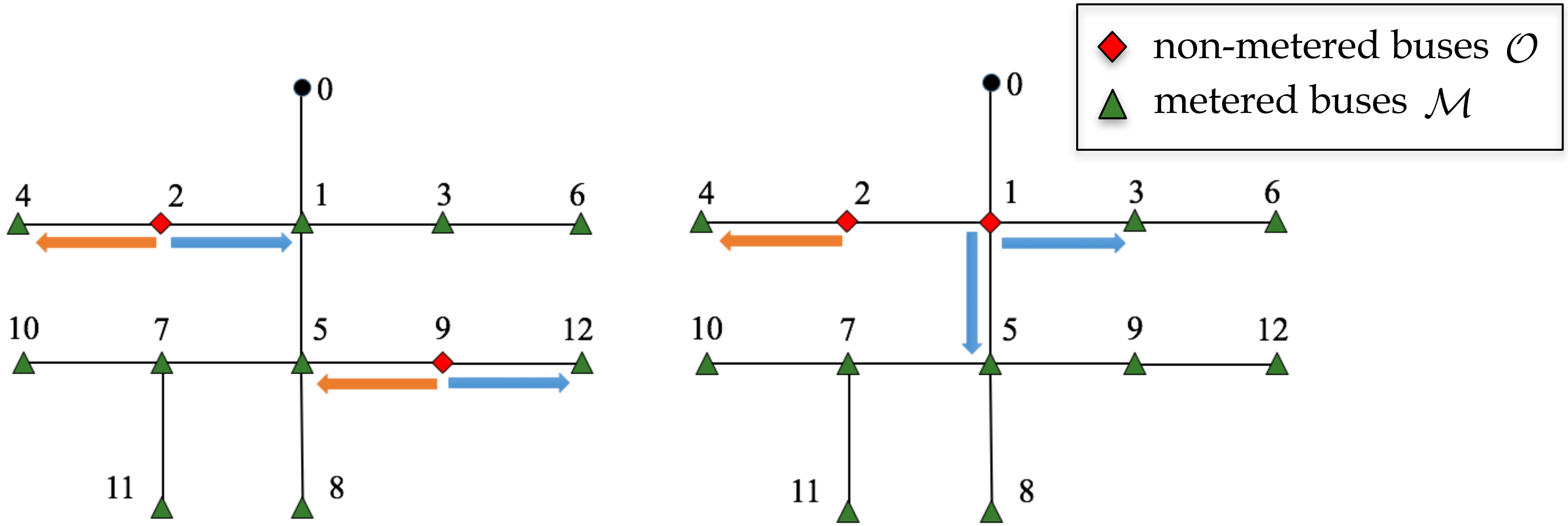
$$\begin{bmatrix}\mathbf{u}_{\mathcal{M}} - \mathbf{R}_{\mathcal{M},\mathcal{M}}\mathbf{p}_{\mathcal{M}} - \mathbf{X}_{\mathcal{M},\mathcal{M}}\mathbf{q}_{\mathcal{M}}\\ \boldsymbol{\theta}_{\mathcal{M}} - \mathbf{X}_{\mathcal{M},\mathcal{M}}\mathbf{p}_{\mathcal{M}} + \mathbf{R}_{\mathcal{M},\mathcal{M}}\mathbf{q}_{\mathcal{M}}\end{bmatrix} = \begin{bmatrix}\mathbf{R}_{\mathcal{M},\mathcal{O}} & \mathbf{X}_{\mathcal{M},\mathcal{O}}\\ \mathbf{X}_{\mathcal{M},\mathcal{O}} & -\mathbf{R}_{\mathcal{M},\mathcal{O}}\end{bmatrix}\begin{bmatrix}\mathbf{p}_{\mathcal{O}}\\ \mathbf{q}_{\mathcal{O}}\end{bmatrix} + \boldsymbol{\epsilon}_{\mathcal{M}}$$

- Non-metered injections can be uniquely recovered via least-squares if regression matrices are full column-rank

Identifiability with passive load learning

***Proposition 1**: Given **smart meter data** on $\mathcal{M} = \mathcal{M}_1 \cup \mathcal{M}_2$, the injections at $\mathcal{O}$ are identifiable if every bus in $\mathcal{O}$ is connected to unique buses in $\mathcal{M}_1$ and $\mathcal{M}_2$.*

***Proposition 2**: Given **PMU data** on $\mathcal{M}$, the injections at $\mathcal{O}$ are identifiable if every bus in $\mathcal{O}$ is connected to a unique bus in $\mathcal{M}$.*



Key ideas

- Partition reduced (resistive) Laplacian $\mathbf{L} := \mathbf{R}^{-1} = \begin{bmatrix} \mathbf{L}_{\mathcal{M},\mathcal{M}} & \mathbf{L}_{\mathcal{M},\mathcal{O}} \\ \mathbf{L}_{\mathcal{M},\mathcal{O}}^\top & \mathbf{L}_{\mathcal{O},\mathcal{O}} \end{bmatrix}$

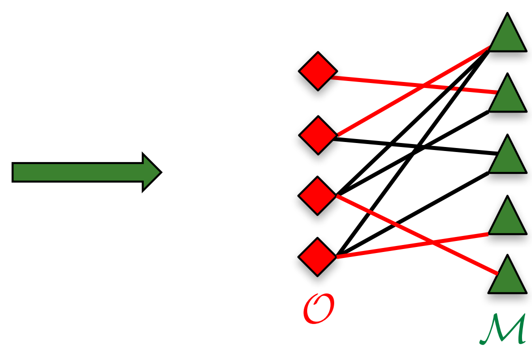
- Rank of Schur complement $\text{rk}(\mathbf{L}) = \text{rk}(\mathbf{L}_{\mathcal{M},\mathcal{M}}) + \text{rk}(\mathbf{L}_{\mathcal{O},\mathcal{O}} - \mathbf{L}_{\mathcal{M},\mathcal{O}}^\top \mathbf{L}_{\mathcal{M},\mathcal{M}}^{-1} \mathbf{L}_{\mathcal{M},\mathcal{O}})$

- Matrix inversion lemma and Sylvester's inequality

$$\mathbf{R}_{\mathcal{M},\mathcal{O}} = -\mathbf{L}_{\mathcal{M},\mathcal{M}}^{-1} \mathbf{L}_{\mathcal{M},\mathcal{O}} (\mathbf{L}_{\mathcal{O},\mathcal{O}} - \mathbf{L}_{\mathcal{M},\mathcal{O}}^\top \mathbf{L}_{\mathcal{M},\mathcal{M}}^{-1} \mathbf{L}_{\mathcal{M},\mathcal{O}})^{-1}$$

- Matrix $\mathbf{L}_{\mathcal{M},\mathcal{O}}$ is *generically* invertible iff there exists a perfect matching in the bipartite graph defined by its sparsity pattern [Tutte'47]

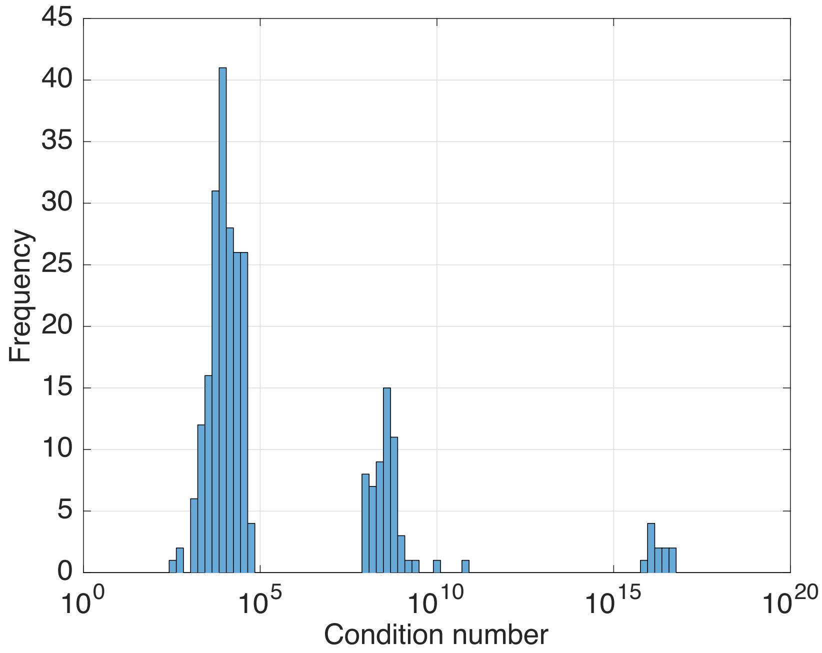
$$\mathbf{L}_{\mathcal{M},\mathcal{O}} = \begin{bmatrix} 0 & * & * & * \\ * & 0 & * & 0 \\ 0 & * & 0 & * \\ 0 & 0 & 0 & * \\ 0 & 0 & * & 0 \end{bmatrix}$$



- Perfect matching as max-flow problem; analysis holds for radial multiphase too

W. T. Tutte, "The factorization of linear graphs," *Journal of the London Mathematical Society*, 1947
Ford and Fulkerson, "Maximal flow through a network," *Canadian J. of Mathematics*, 1956

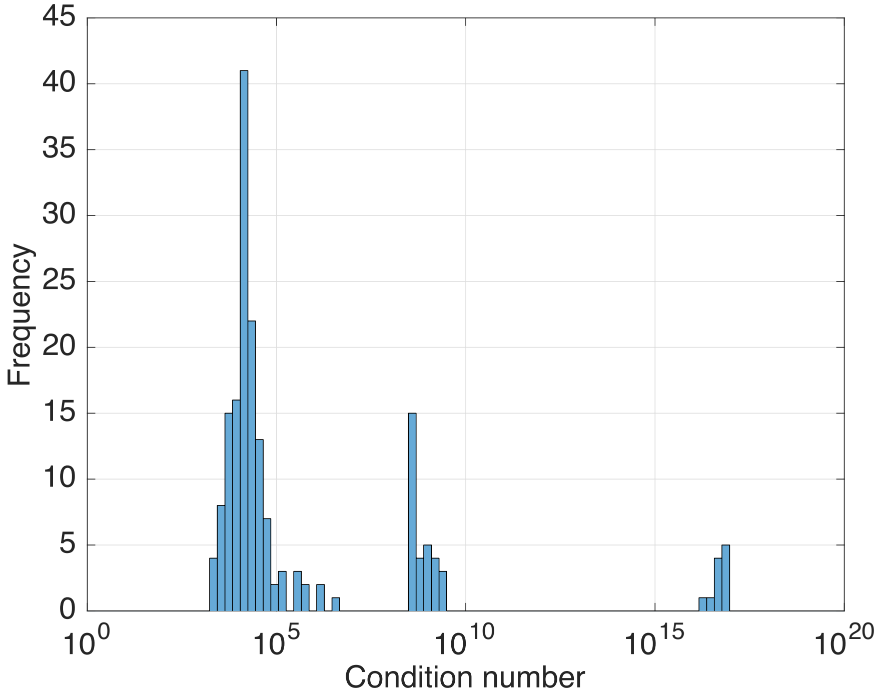
Identifiable setups with smart meter data



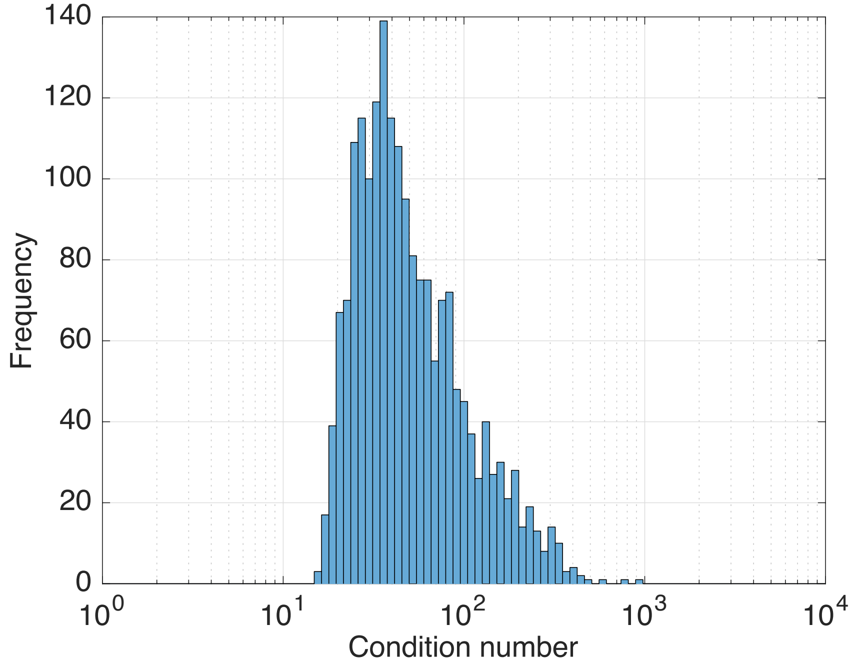
IEEE 123-bus network with $|\mathcal{O}| = 4$

IEEE 123-bus network with $|\mathcal{O}| = 10$

and 10 added lines (meshed)

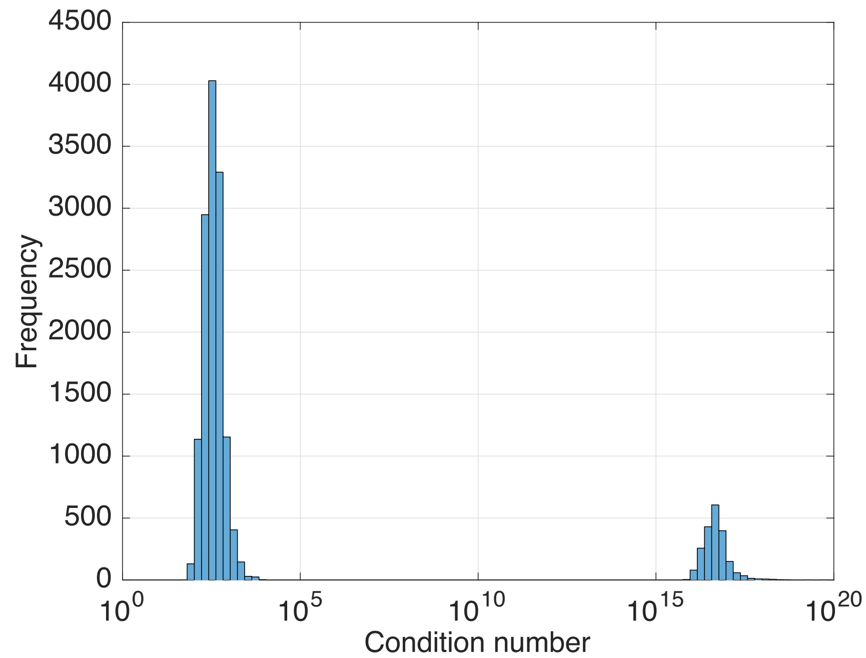


Identifiable setups with PMUs



IEEE 123-bus network with $|\mathcal{O}| = 4$

IEEE 123-bus network with $|\mathcal{O}| = 10$



Similar results for weakly meshed networks

Load learning through grid probing

Time $t = 1$: Record data $\{u_n^1, p_n^1, q_n^1\}_{n \in \mathcal{M}}$ associated with state $\mathbf{v}_1$

Time $t = 2$

- Probe *nonlinear physical system* by perturbing power injections at controllable buses [how?]
- Record data $\{u_n^2, p_n^2, q_n^2\}_{n \in \mathcal{M}}$ associated with state $\mathbf{v}_2 \neq \mathbf{v}_1$

Repeat say every second for $t = 1, \ldots, T$ each separated by say 5 secs, over 5 mins

$$p_n(\mathbf{v}_t) = \hat{p}_n^t \quad \forall n \in \mathcal{M}$$
$$q_n(\mathbf{v}_t) = \hat{q}_n^t \quad \forall n \in \mathcal{M}$$
$$u_n(\mathbf{v}_t) = \hat{u}_n^t \quad \forall n \in \mathcal{M}$$

$t = 1, \ldots, T$

- Exploit the fact that $\{p_n^t, q_n^t\}_{n \in \mathcal{O}}$ remain *invariant* during probing

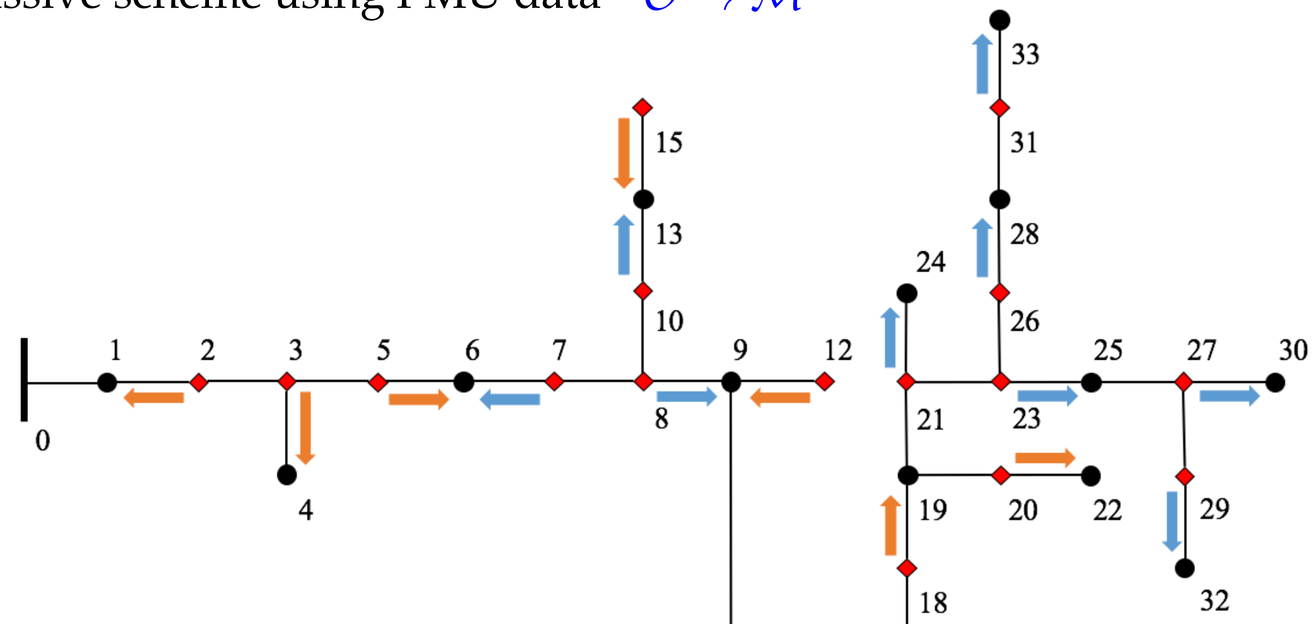
$$p_n(\mathbf{v}_t) = p_n(\mathbf{v}_{t+1}) \quad \forall n \in \mathcal{O}$$
$$q_n(\mathbf{v}_t) = q_n(\mathbf{v}_{t+1}) \quad \forall n \in \mathcal{O}$$

$t = 1, \ldots, T-1$

Identifiability through grid probing

Theorem: *If* $\mathcal{O}$ *can be partitioned into T/2 subsets such that each can be matched to* $\mathcal{M}$, then *the states* $\{\mathbf{v}_t\}_{t=1}^{T}$ *and the injections at* $\mathcal{O}$ *are locally identifiable.*

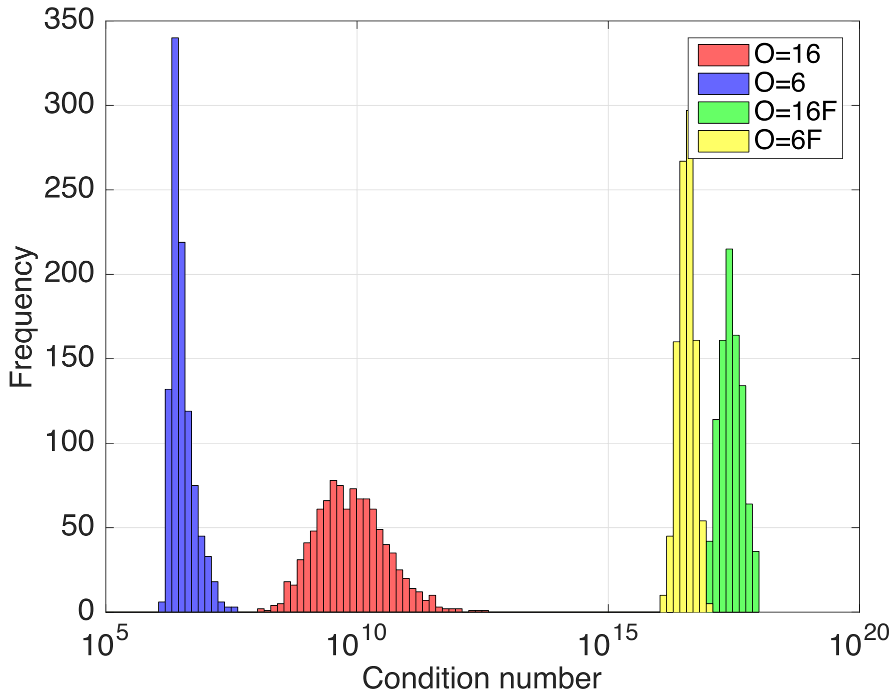
- $T = 1$:passive scheme with smart meter data
- $T = 2$:passive scheme using PMU data $\quad \mathcal{O} \rightarrow \mathcal{M}$



IEEE 34-bus feeder: $T = 4, |\mathcal{O}| = 18$

S.Bhela, V. Kekatos, and H. Veeramachameni, “Enhancing observability in distribution grids using smart meter data,” *IEEE Trans. on Smart Grid*, (early access) 2018.

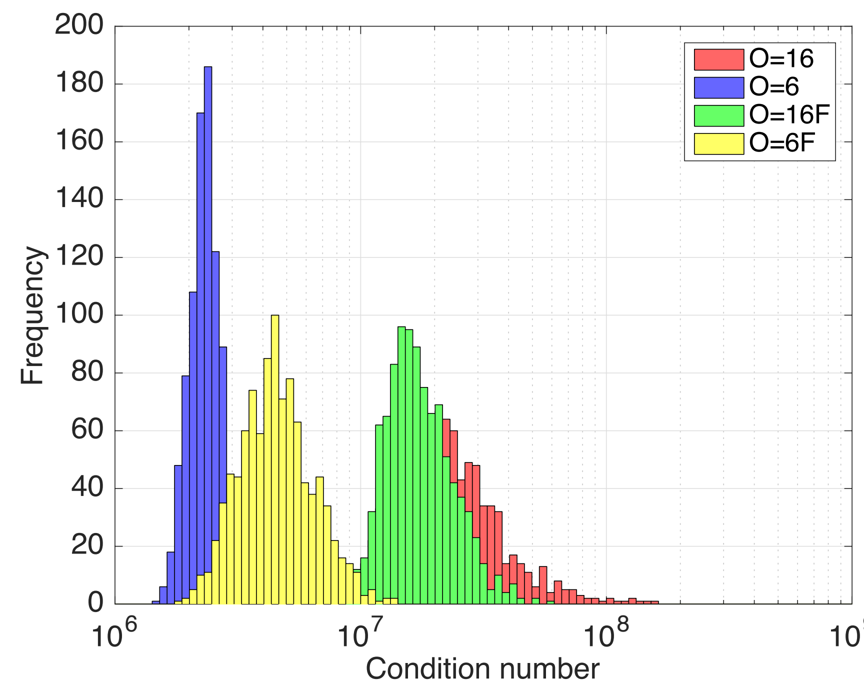
Numerical tests (Jacobian condition numbers)



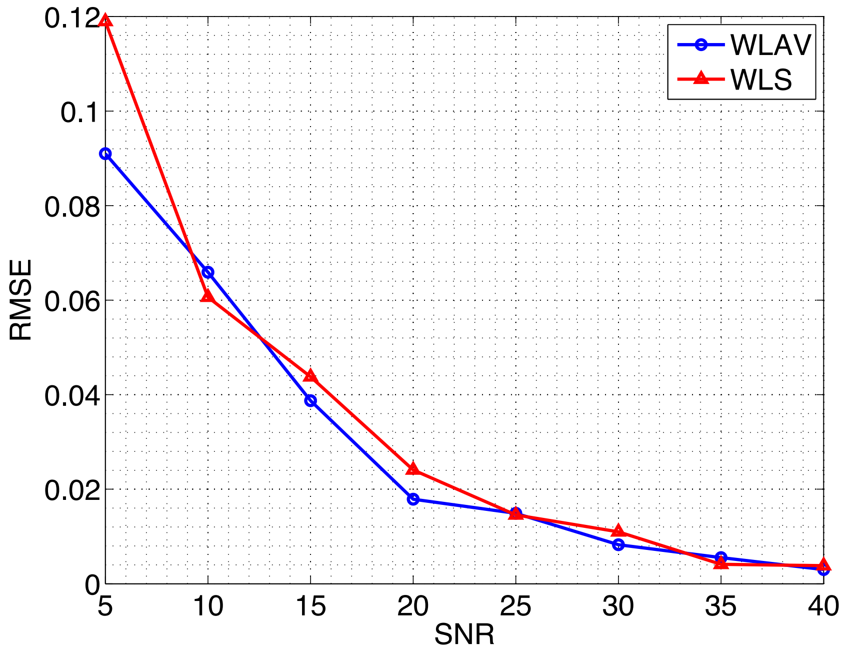
condition numbers of CPF Jacobians for random states

IEEE 34-bus feeder: $T = 2$

IEEE 34-bus feeder: $T = 4$

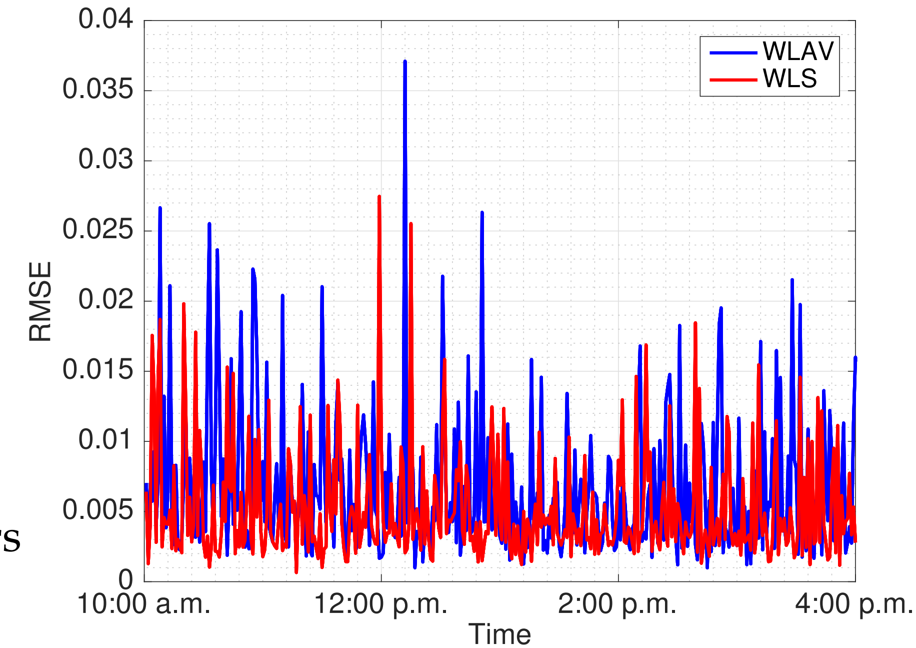


Numerical tests with synthetic and real data



- State RMSE for CPSSE $(T = 2)$

- Actual load/solar data (Pecan St.)
- RMSE on system state over one day
- Probing by changing pf in smart inverters



Conclusions

Passive injection learning

- Identifiability for single-phase radial grids smart meter and PMU data
- Simple LS solver using LDF model
- No time coupling; timescale depends on data

Active injection learning

- Inverter data collected via intentional probing
- Identifiability for possibly meshed and polyphase grids
- Improvements with increasing T
- Optimal probing design? PMU data? Line flow data?
- Probing for topology identification?

Thank You!