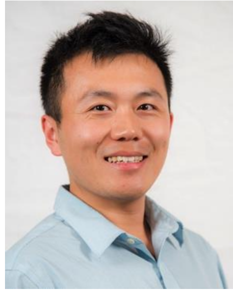
# *Controlling Smart Inverters using Proxies: A Chance-Constrained DNN-based Approach*

Sarthak Gupta, Ming Jin, and Vassilis Kekatos
(kekatos@vt.edu)

*Thursday, July 20, 2023*

*Orlando, Florida*

*Panel on Machine Learning Applications in Power Distribution System Operation*



Sarthak Gupta
(C3.AI)

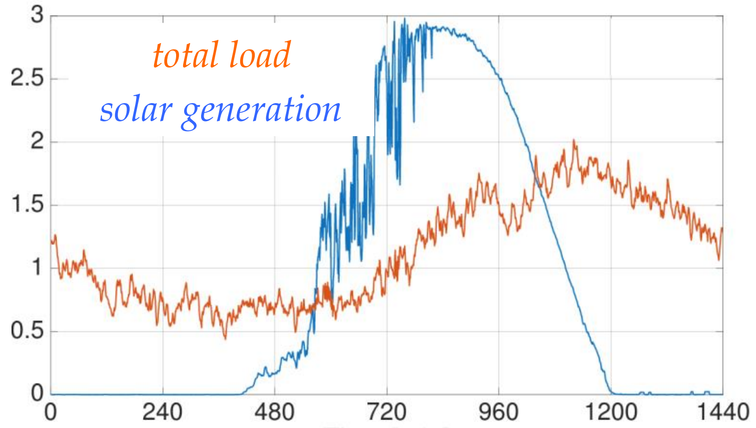
Ming Jin
(VT)

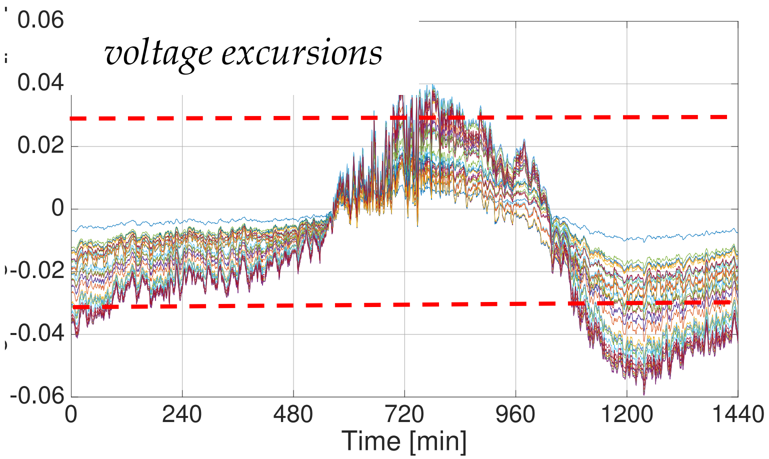
***Acknowledgements***

NSF-1751085
NSF-1923221

# Motivation

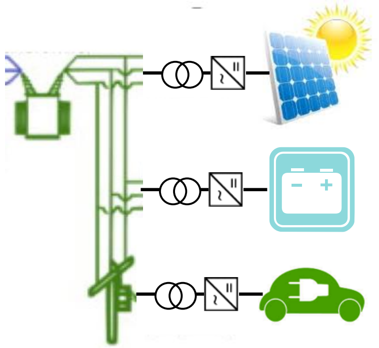
- Voltage fluctuations due to solar and other DERs



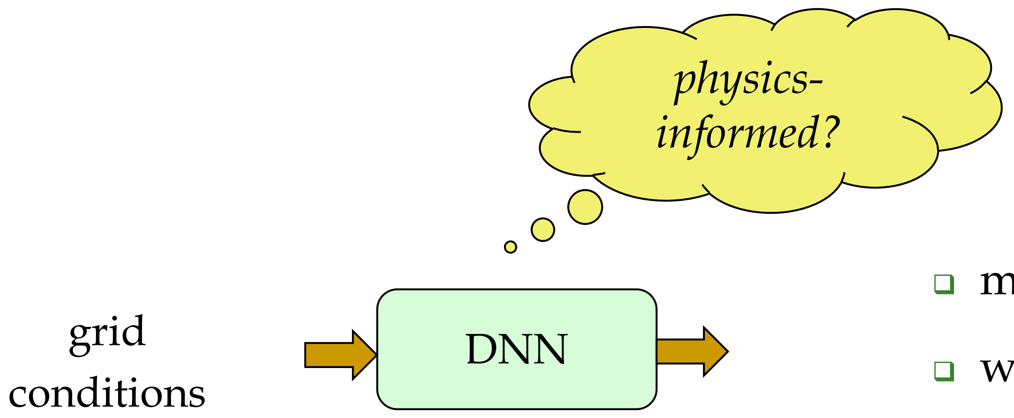

- Inefficiency of voltage control devices

- Reactive power control using smart inverters

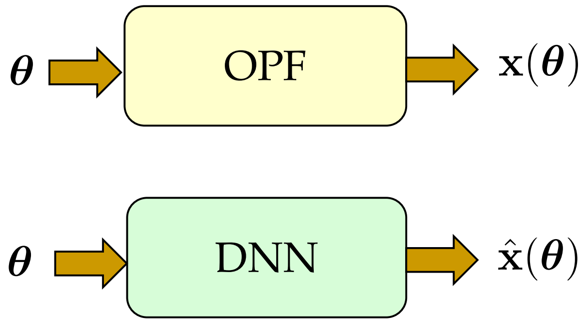


- Deep learning to expedite optimal DER dispatch

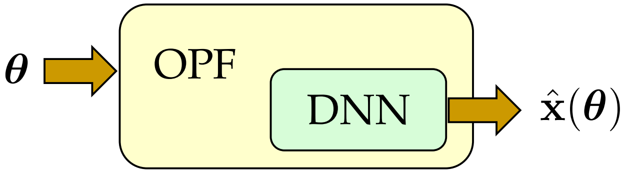
# Learning for OPF




- minimizers [Wang-Yu-Gao+'19], [Zhang-Deghanpour-Wang+'21]
- warm-starts and linearization [Zamzam-Baker'20]
- binding constraints [Guha'19], [Deka-Misra'19], [Chen-Zhang'20]



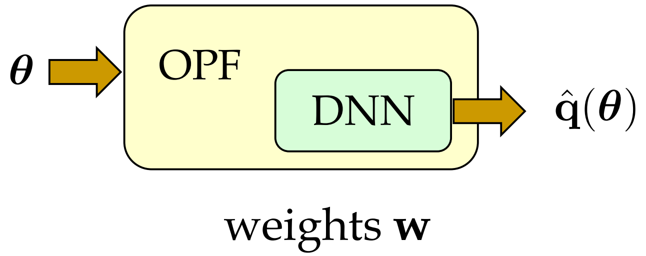

*OPF-then-Learn*




*OPF-and-Learn*

# *OPF-and-Learn*

- Decide VAR inverter setpoints via *control rules or policies*




- *Key idea:* incorporate DNN into OPF

$$\begin{aligned} \mathbf{q}_{\boldsymbol{\theta}} = \arg\min_{\mathbf{q}\in\mathcal{Q}} \; & \ell(\mathbf{q};\boldsymbol{\theta}) \\ \text{s.to } & \mathbf{v}(\mathbf{q};\boldsymbol{\theta}) \in \mathcal{V} \end{aligned}$$

$\Rightarrow$

$$\begin{aligned} \mathbf{q} = \arg\min_{\mathbf{q}\in\mathcal{Q}} \; & \mathbb{E}\left[\ell(\mathbf{q};\boldsymbol{\theta})\right] \\ \text{s.to } & \mathbf{E}\left[\mathbf{v}(\mathbf{q};\boldsymbol{\theta})\right] \in \mathcal{V} \end{aligned}$$

$\Rightarrow$

$$\begin{aligned} \mathbf{q}(\boldsymbol{\theta}) = \arg\min_{\mathbf{q}(\boldsymbol{\theta})\in\mathcal{Q}} \; & \mathbb{E}[\ell(\mathbf{q}(\boldsymbol{\theta});\boldsymbol{\theta})] \\ \text{s.to } & \mathbb{E}[\mathbf{v}(\mathbf{q}(\boldsymbol{\theta});\boldsymbol{\theta})] \in \mathcal{V} \end{aligned}$$

- Benefits from *OPF-and-Learn* scheme
  - no need for OPF labels
  - uncertain grid conditions

# OPF-and-Learn training

- Solve with stochastic primal-dual updates [Eisen-Zhang-Chamon-Lee-Ribeiro'19]

$$\mathbf{w}_{t+1} := \left[\mathbf{w}_t - \mu\left(\nabla_{\mathbf{w}}\ell_t - \boldsymbol{\lambda}_t^\top \nabla_{\mathbf{w}}\mathbf{v}_t\right)\right]_{\mathcal{Q}}$$

$$\boldsymbol{\lambda}_{t+1} := [\boldsymbol{\lambda}_t + \mu\mathbf{v}_t]_+$$

enforced
with tanh

- How to compute gradients?

$$\nabla_{\mathbf{w}}\mathbf{v} = \nabla_{\mathbf{u}}\mathbf{v} \cdot \nabla_{\mathbf{q}}\mathbf{u} \cdot \nabla_{\mathbf{w}}\mathbf{q}$$

inverse function
theorem

$$\nabla_{\mathbf{s}}\mathbf{u} = (\nabla_{\mathbf{u}}\mathbf{s})^{-1}$$

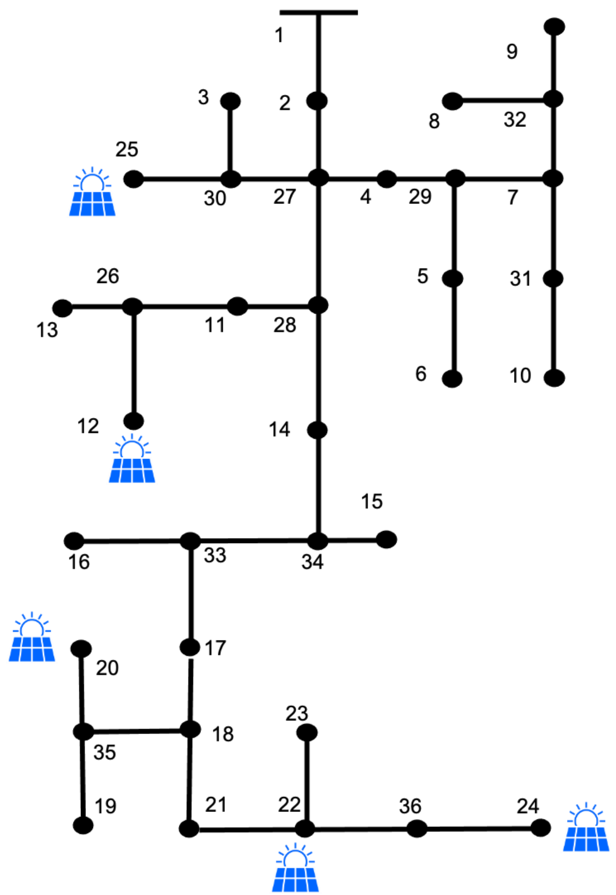
DNN back-propagation

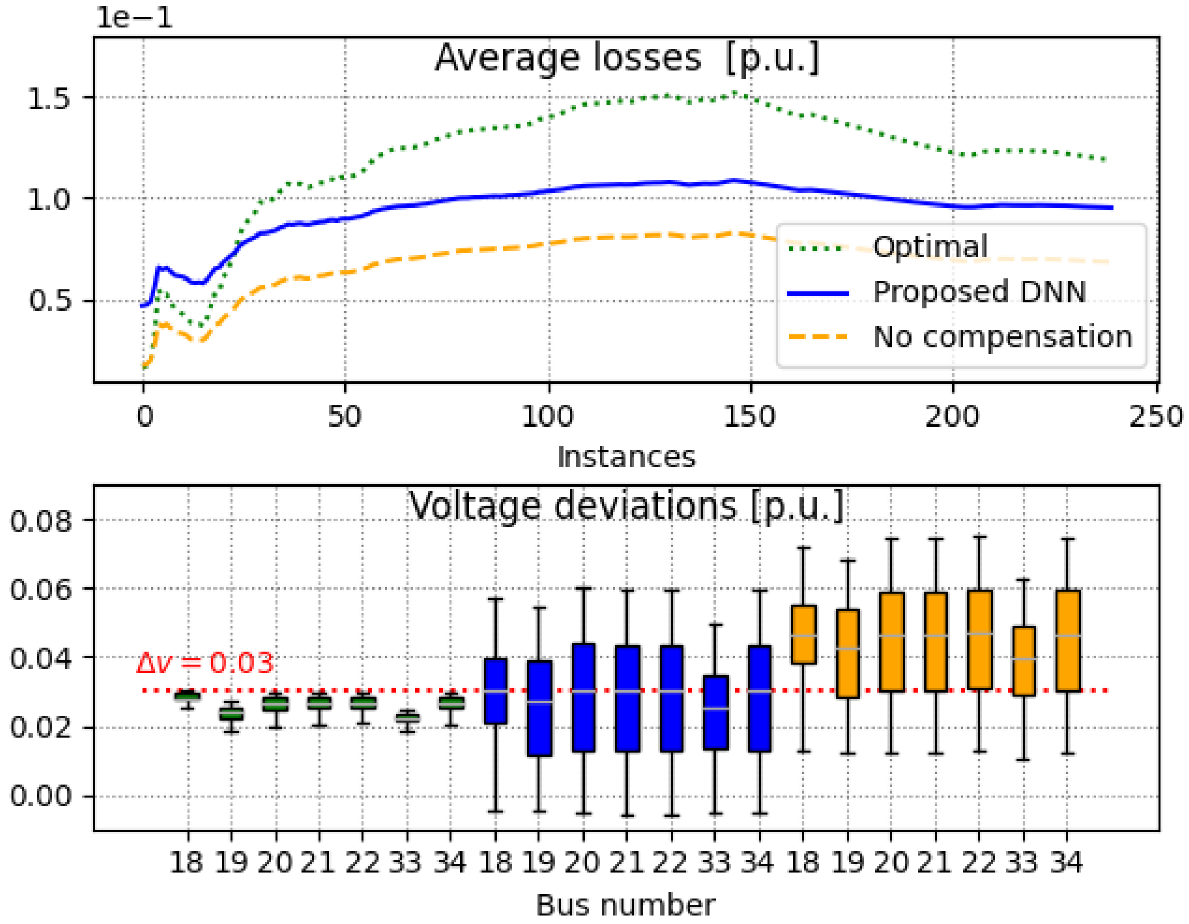
- What if you don't have the feeder model, but a *digital twin*?

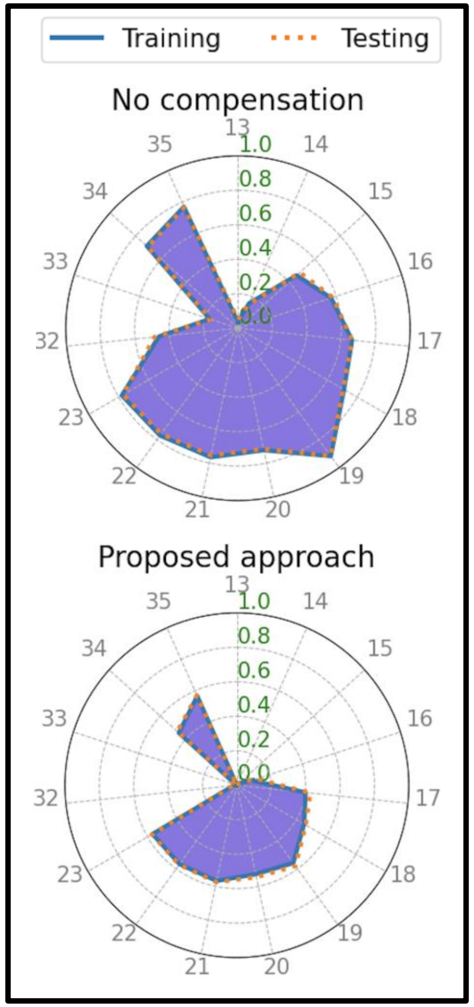
$$\hat{\nabla}_{\mathbf{q}}\mathbf{v} = \frac{\mathbf{v}(\mathbf{q} + \epsilon\check{\mathbf{q}}; \boldsymbol{\theta}) - \mathbf{v}(\mathbf{q} - \epsilon\check{\mathbf{q}}; \boldsymbol{\theta})}{2\epsilon}\check{\mathbf{q}}^\top$$

lazy differentiation

# Average formulation



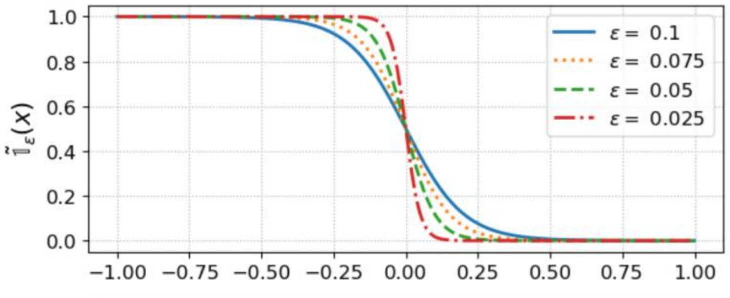




voltage violation probability per node

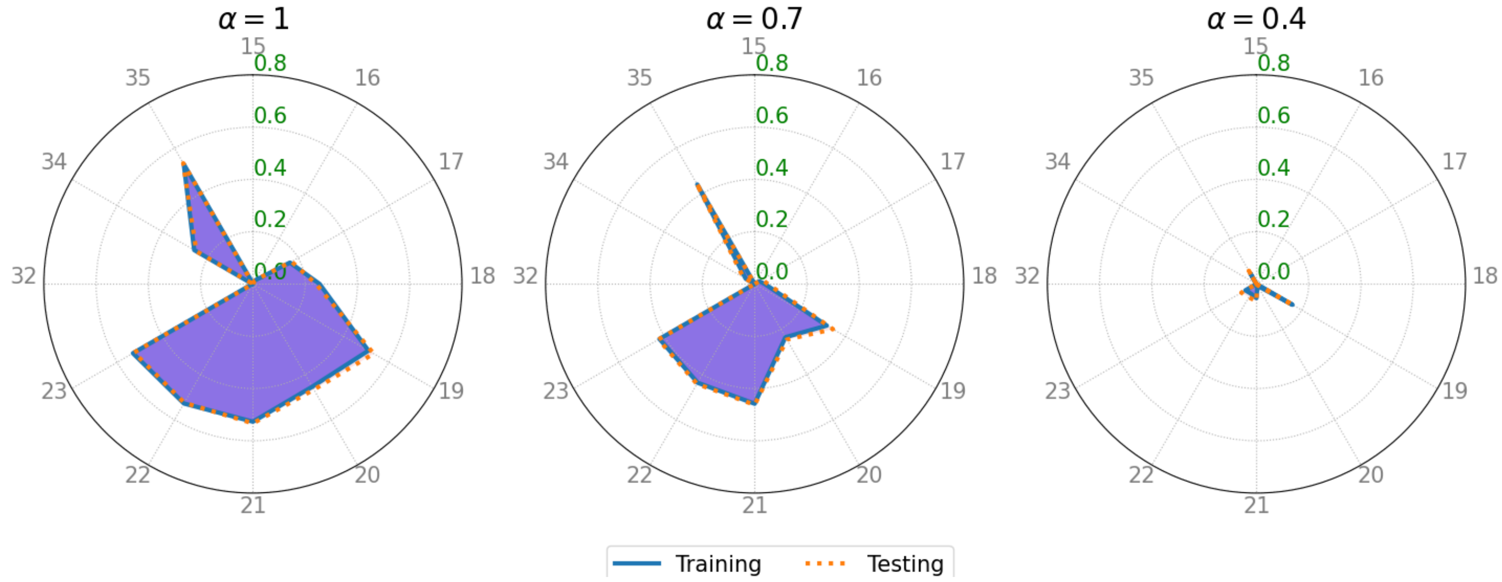
# Probabilistic formulation

$$\mathbb{E}[v_n] \le \bar{v}_n \quad \longrightarrow \quad \Pr(v_n \ge \bar{v}_n) \le \alpha \quad \longrightarrow \quad \mathbb{E}\left[[z_n + \bar{v}_n - v_n]_+\right] \le \alpha z_n \quad \longrightarrow$$

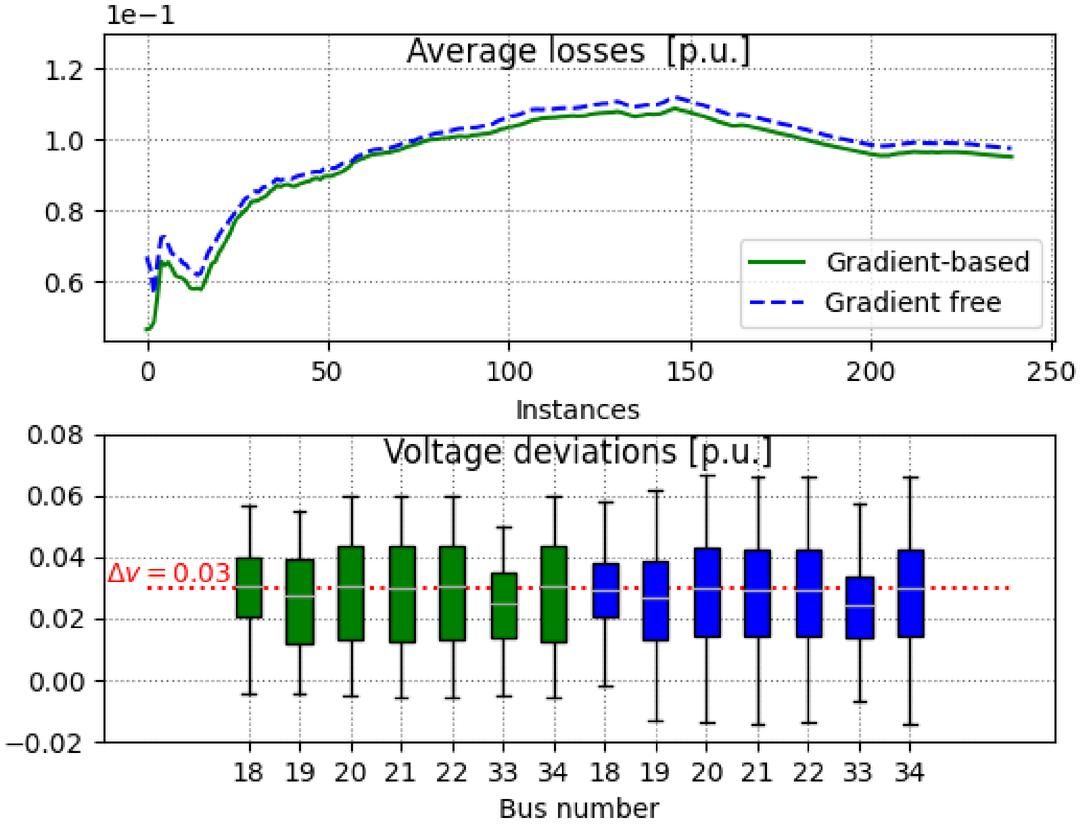
average constraint — non-convex chance constraint — convex restriction [Nemirovski-Shapiro'07]



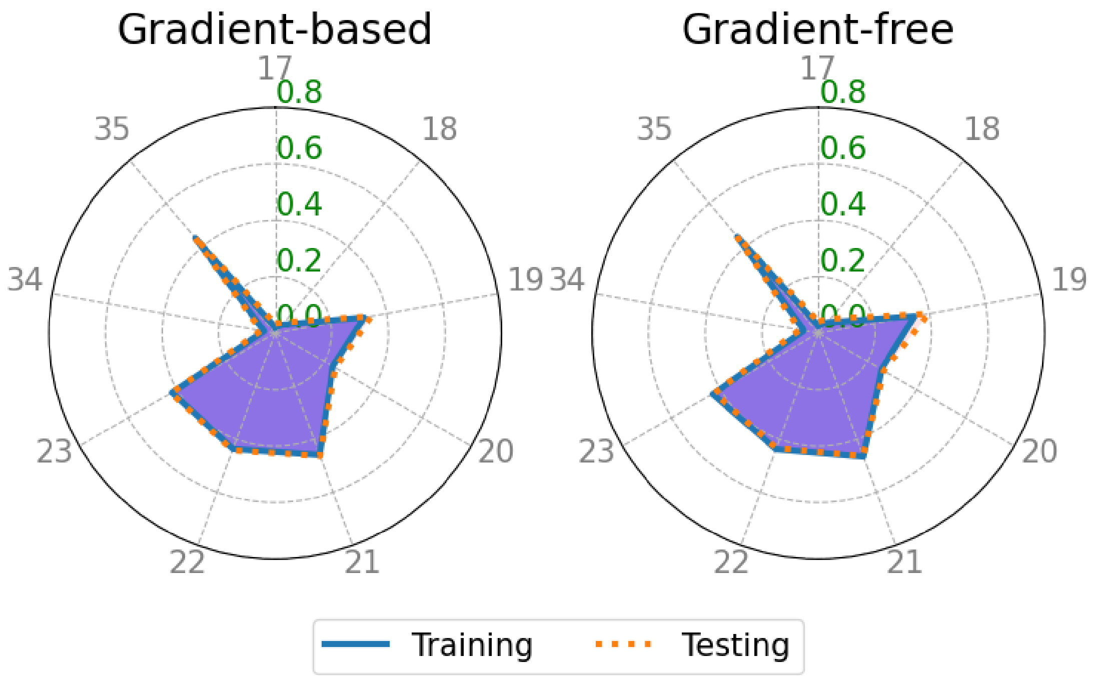

- Constraint can be handled by *OPF-and-Learn* framework with minimal increase in complexity



# Gradient-free learning



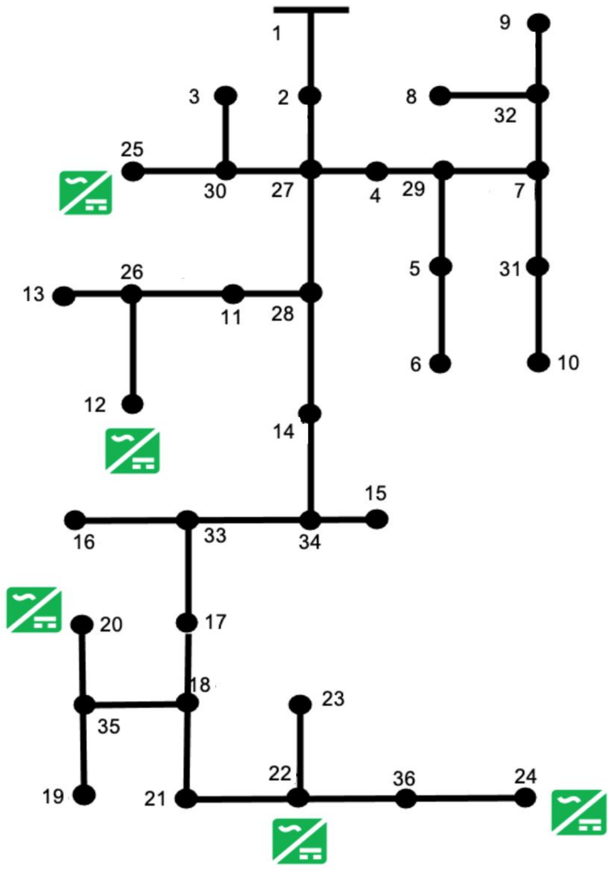

*average formulation*

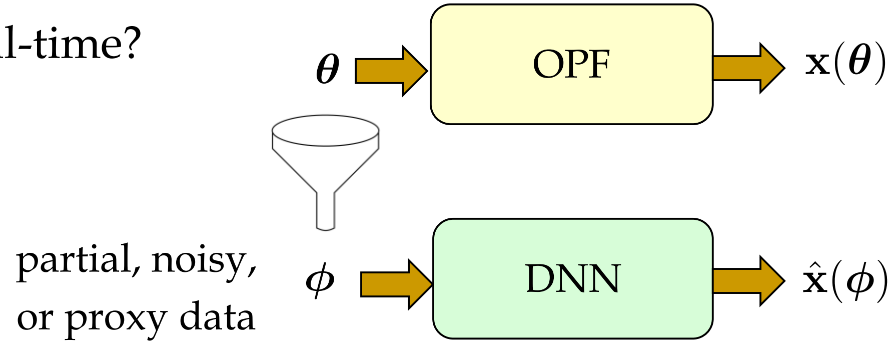


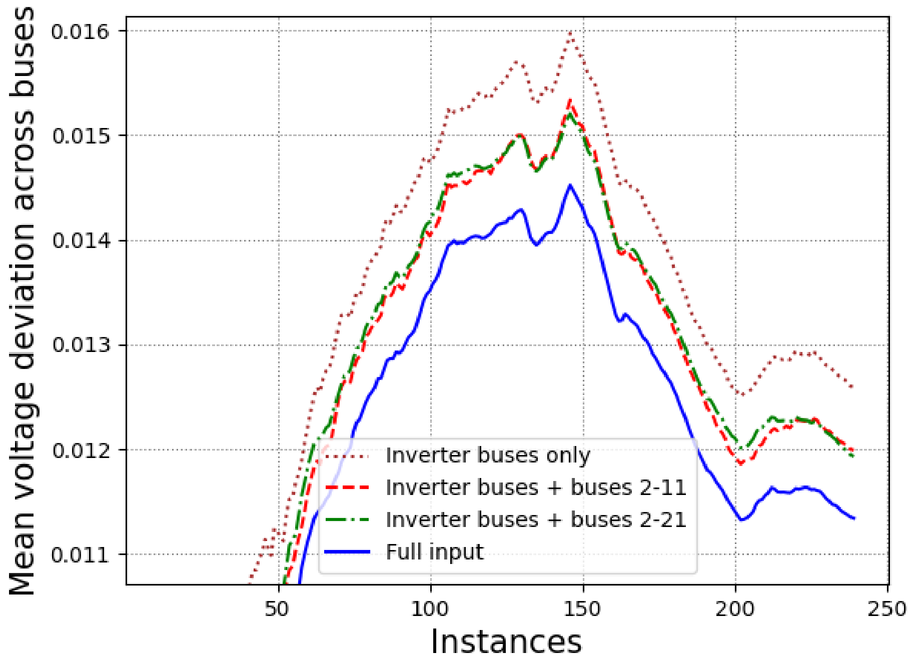

*probabilistic formulation*

# OPF with proxies

- *What if* grid conditions are not fully known in real-time?



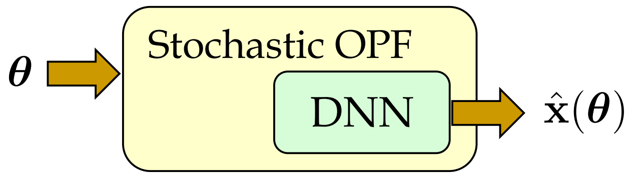



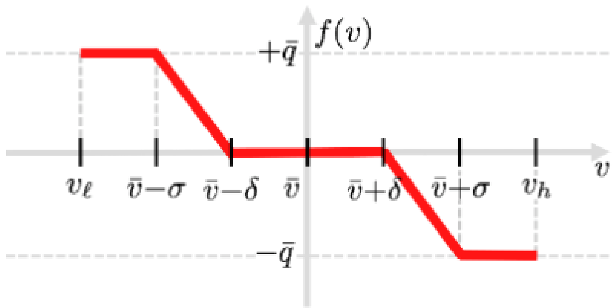
# Conclusions

*OPF-and-Learn*

- ☑ train DNN through stochastic OPF
- ☑ OPF with proxy inputs
- ☑ digital twin for lazy differentiation




*Thank You!*




- ❑ VVR rules to reduce imbalance
- ❑ solve OPF on a data budget

S. Gupta, V. Kekatos, and M. Jin, "Controlling Smart Inverters using Proxies: A Chance-Constrained DNN-based Approach," *IEEE Trans. on Smart Grid,* March 2022.