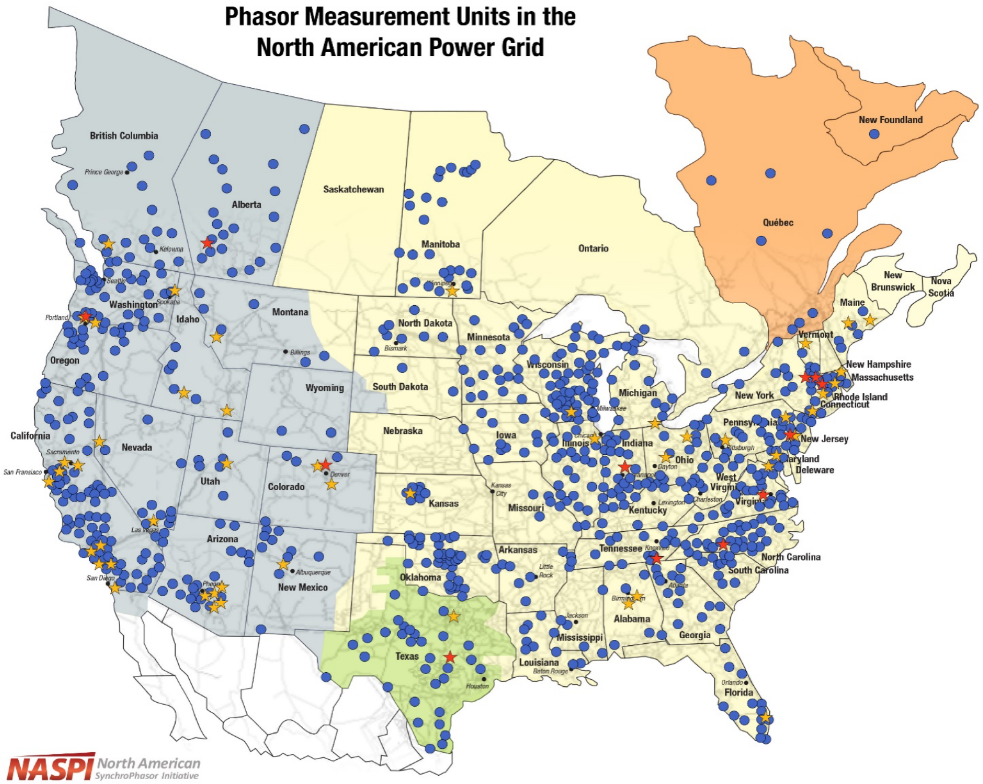
Anomaly Management in Massively Digitized Power Systems

Tong Huang

Laboratory for Information and Decision Systems (LIDS)
Massachusetts Institute of Technology (MIT)

Digitization of the Power Grid



200 → **2500**

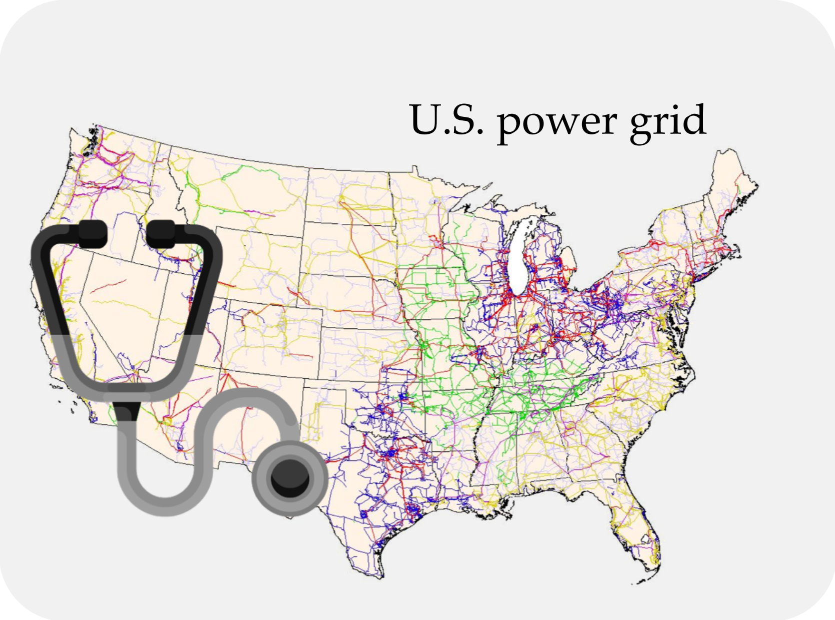
...

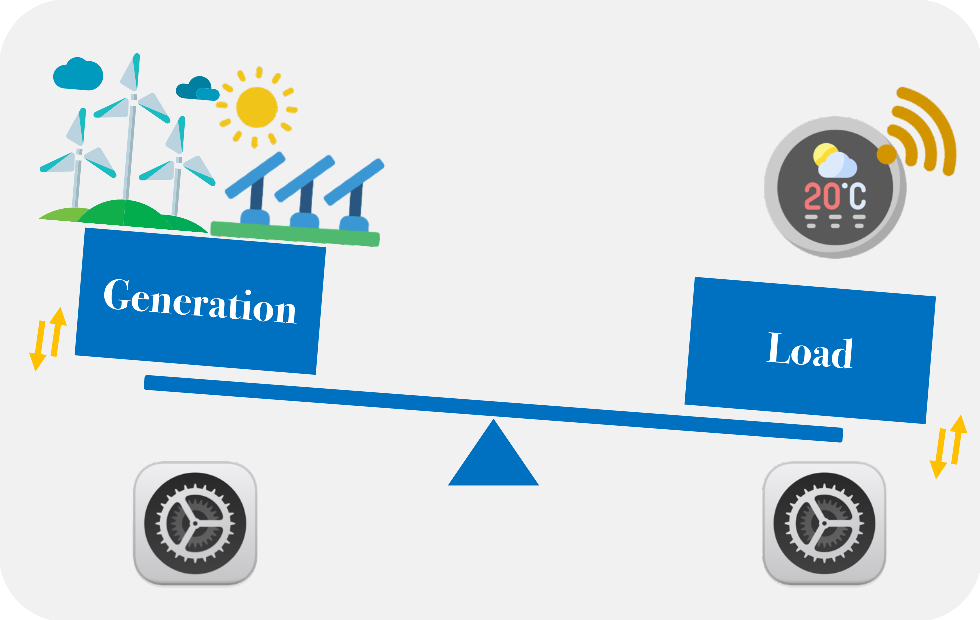
L. Xie, **T. Huang**, P. Kumar, A. Thatte, and S. Mitter, "On a Control Architecture for Future Electric Energy Systems," ***Proceedings of the IEEE***, 2022 (invited, submitted).

PC: NASPI, REenergizeCO, Enphase, SEL, Infineon, Google Nest, Belkin

Grid Digitization: Opportunities

- Massive sensors enhance grid transparency
- Edge intelligence enables load to track generation

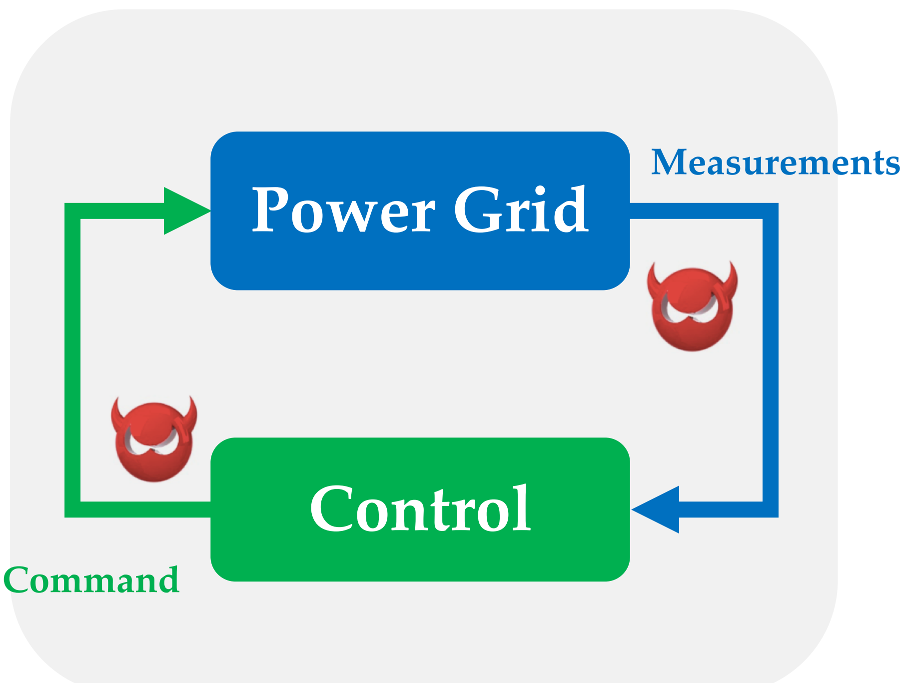




PC: https://en.wikipedia.org/wiki/North_American_power_transmission_grid

Grid Digitization: Challenges

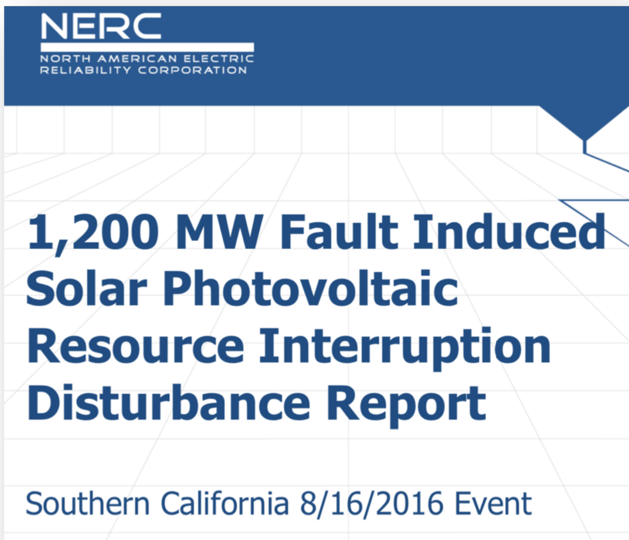
- Cyber threats



T. Huang, B. Satchidanandan, P. R. Kumar and L. Xie, "An Online Detection Framework for Cyber Attacks on Automatic Generation Control," *in IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6816-6827, Nov. 2018.

Grid Digitization: Challenges

- Cyber threats
- Physical security of the grid with inverter interfaces


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event

*"the **largest** percentage of inverter loss (~700 MW) was due to the **inverter** phase lock loop control"*

https://www.theneweconomy.com/energy/california-becomes-first-state-to-require-solar-panels-on-all-new-homes

Outline

Opportunities:

- Massive sensors enhance grid transparency
  - ***Forced oscillation localization***
- Edge intelligence enables load to track generation

Challenges:

- Cyber threats
- Physical security of the grid with inverter interfaces
  - ***Learning-based transient stability assessment***

Outline

Opportunities:

- Massive sensors enhance grid transparency
  - ***Forced oscillation localization***
- Edge intelligence enables load to track generation

Challenges:

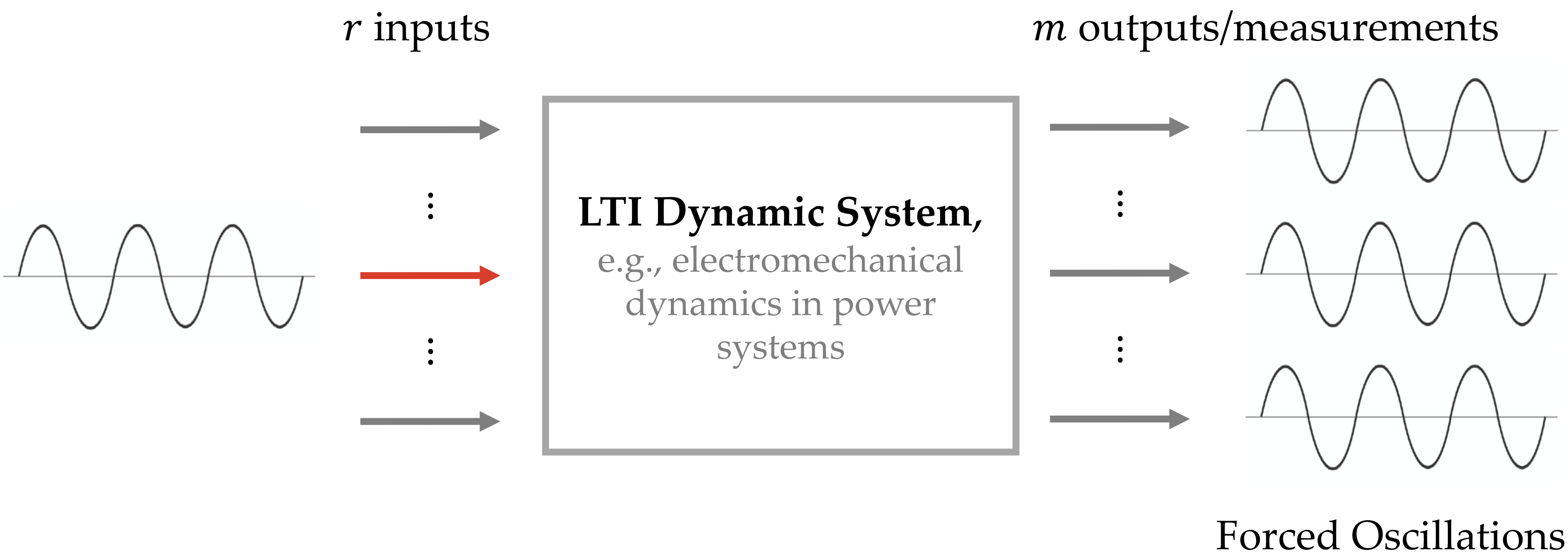
- Cyber threats
- Physical security of the grid with inverter interfaces
  - ***Learning-based transient stability assessment***

A Synchrophasor Data-driven Method for Forced Oscillation Localization under Resonance Conditions

T. Huang, N. M. Freris, P. R. Kumar and L. Xie, "A Synchrophasor Data-Driven Method for Forced Oscillation Localization Under Resonance Conditions," in *IEEE Transactions on Power Systems*, vol. 35, no. 5, pp. 3927-3939, Sept. 2020.

T. Huang, N. M. Freris, P. R. Kumar and L. Xie, "Localization of forced oscillations in the power grid under resonance conditions," *2018 52nd Annual Conference on Information Sciences and Systems (CISS)*, Princeton, NJ, USA, 2018, pp. 1-5.

Forced Oscillation Localization



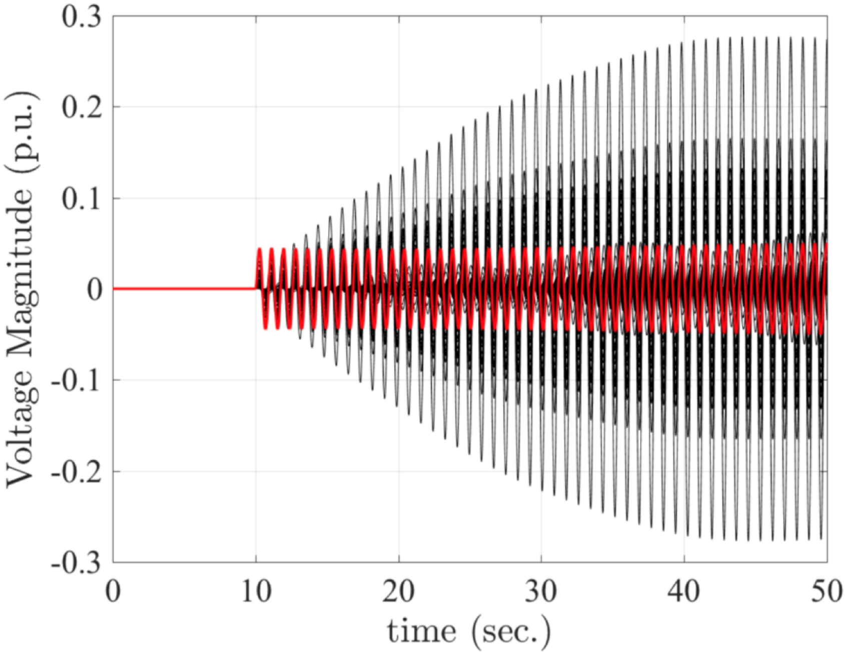
- Oscillation *source*: the input with periodic signal.
- Different measurements have different geographic locations.
- FOL: How to find the measurement near the source only by outputs?

LTI: linear time-invariant
* in the small-signal sense

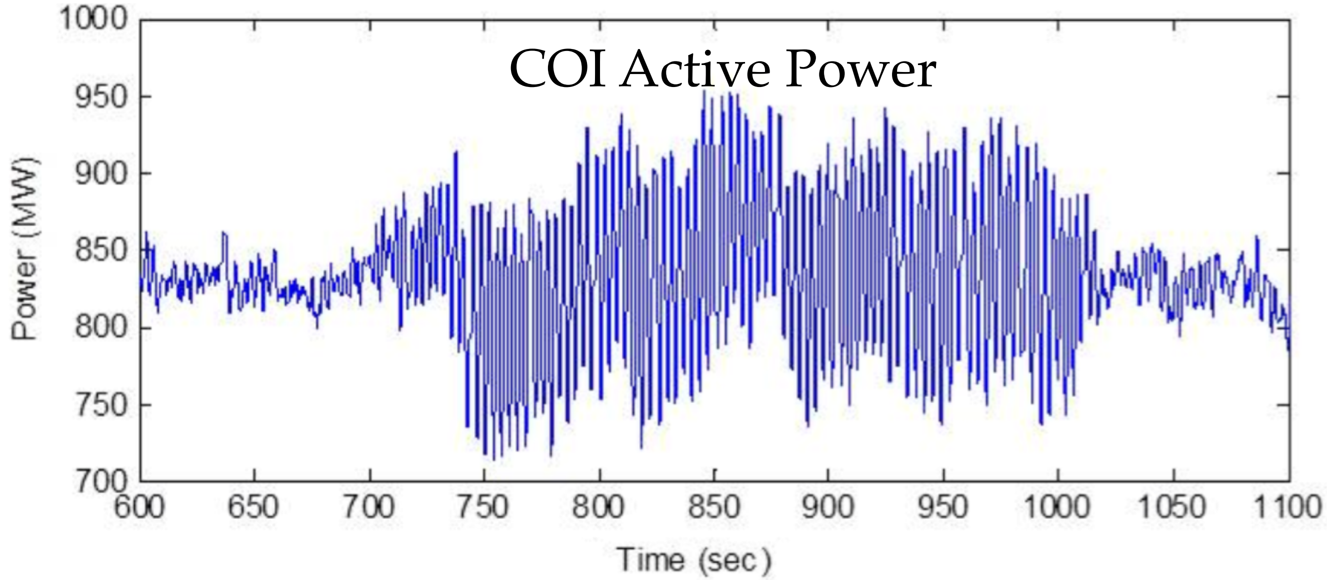
The Challenge of Source Localization

Challenges come when the injection frequency is near one of natural frequencies of the system [Mani, TPWRS'16a], [Mani, TPWRS'16b]

Red: Source measurement
Black: the rest measurements



Forced Oscillation under Resonance Condition in the Real-world Power System



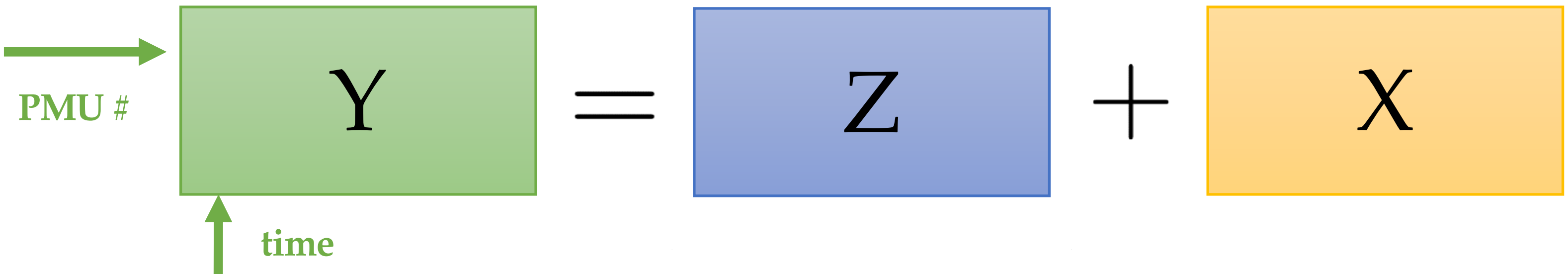
- One power plant at Nova Joffre (source) has 20 MW oscillations
- The California-Oregon Intertie (COI) has 200 MW oscillations
- The distance between these two places is 1100 miles

PC: http://www.nerc.com/pa/RAPA/rg/ReliabilityGuidelines/Reliability_Guideline_-_Forced_Oscillations_-_2017.pdf

The Challenge of Source Localization

We need to develop an approach that can locate the oscillation source even when *resonance* happens!

Problem Formulation



$$\text{rank } Z \leq r \qquad \|X\|_0 \leq p$$

How to decompose a measurement matrix Y into a *low-rank* matrix Z and a *sparse* matrix X?

T. Huang, N. Freris, P. Kumar, and L. Xie, "Localization of Forced Oscillation in the Power Grid under Resonance Conditions," *52th CISS*, 2018

Problem Formulation: Robust PCA

How to decompose a measurement matrix Y into a *low-rank* matrix Z and a *sparse* matrix X?

$$Y = Z + X$$

$$\operatorname{rank} Z \leq r$$

$$\|X\|_0 \leq p$$

- Non-convex
- r and p are unknown

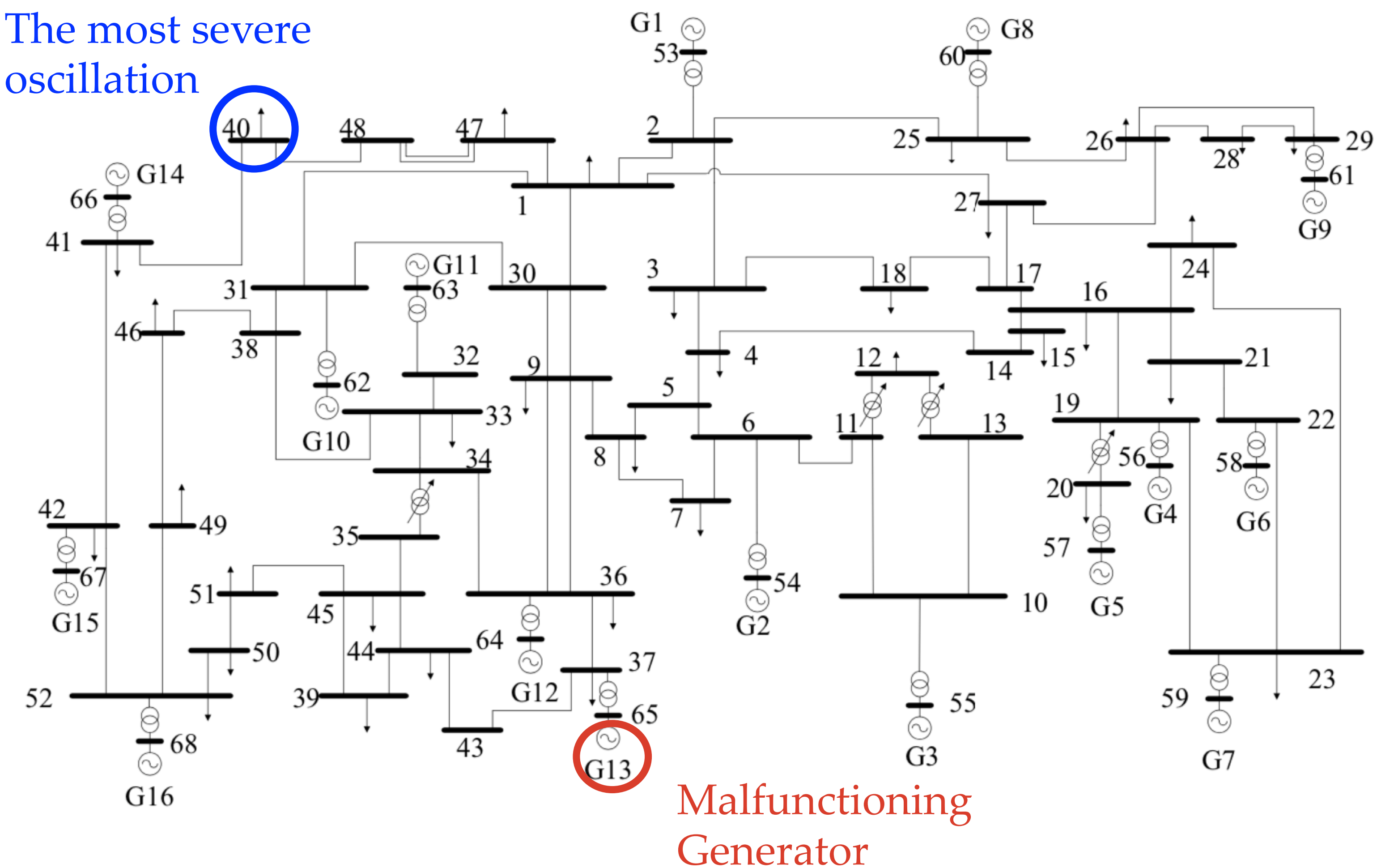
$$\min_X \|Y - X\|_\star + \lambda \|X\|_{1,1}$$

- *Convex* optimization
- No need to know r and p
- Efficient Algorithms to solve it
- $\lambda = 1/\sqrt{n_0}$, where n_0 is col. #of Y

PCA: Principal Component Analysis
Augment Lagrange Multiplier (ALM)
http://perception.csl.illinois.edu/matrix-rank/sample_code.html

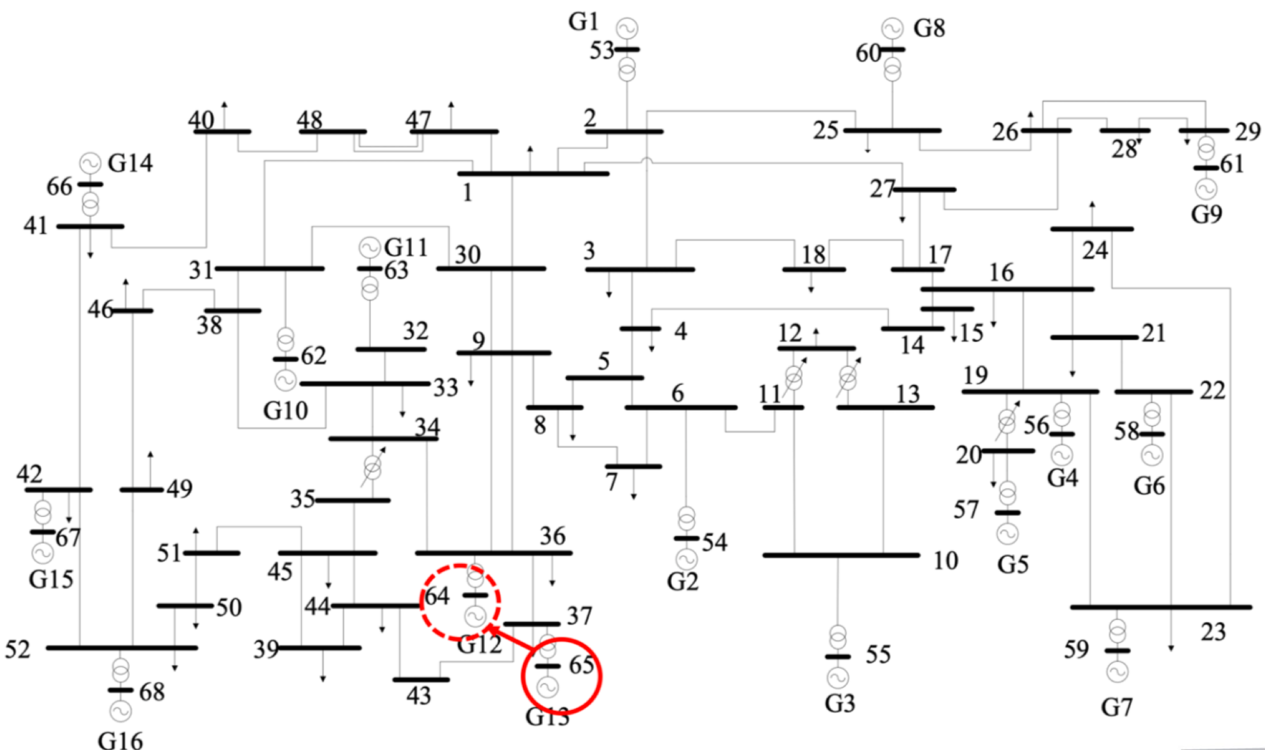
[Candes, Li, Ma, Wright, JACM'11]
[Lin, Liu, and Su, NIPS'11]
[CISS'18]

FO Localization in the Power Grid



- 44 *counter-intuitive* cases

Performance in the 68-bus Systems



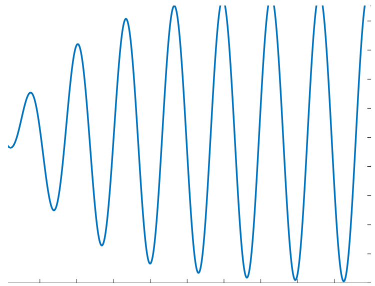
- Over ***97.73%*** (43/44) accuracy
- Search space is narrowed
- Collaboration with ERCOT

ERCOT: Electric Reliability Council of Texas

FO Localization: One Possible Interpretation

Physical Analysis

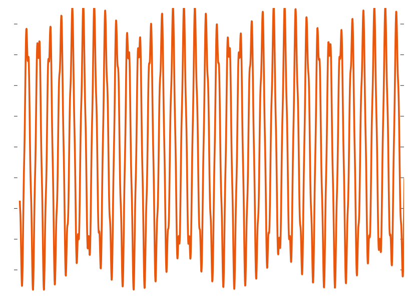
$$y_k(t) =$$



Resonance

"Rank 2"

$+$



Resonance-free

Source location info.

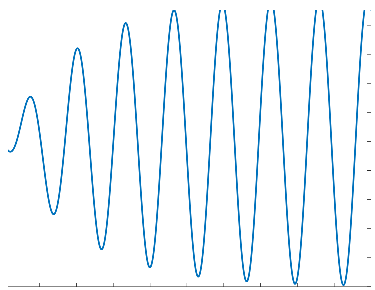
Theorem: *For a linear time-invariant dynamical system, the resonance matrix has rank 2.*

T. Huang, N. Freris, P. R. Kumar and L. Xie, "A Synchrophasor Data-driven Method for Forced Oscillation Localization under Resonance Conditions," *IEEE Transactions on Power Systems.*

FO Localization: One Possible Interpretation

Physical Analysis

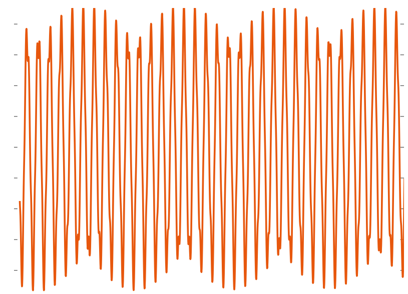
$$y_k(t) =$$



Resonance

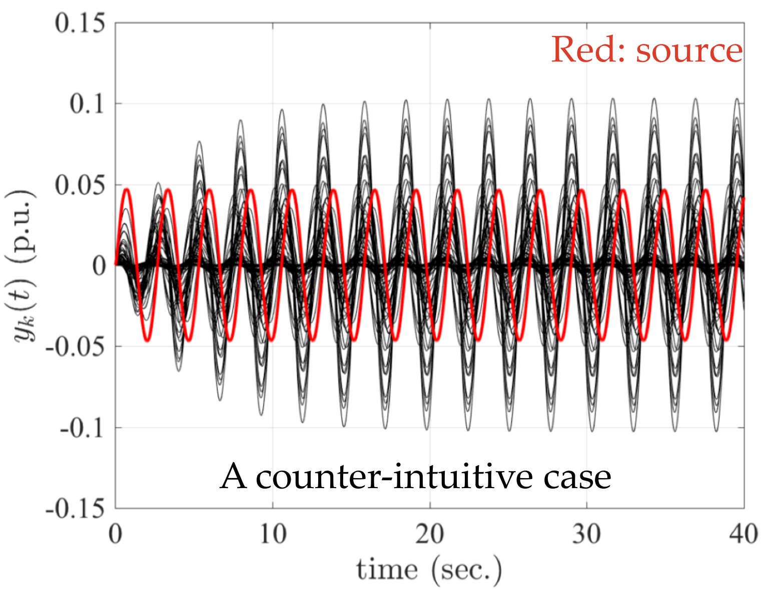
"Rank 2"

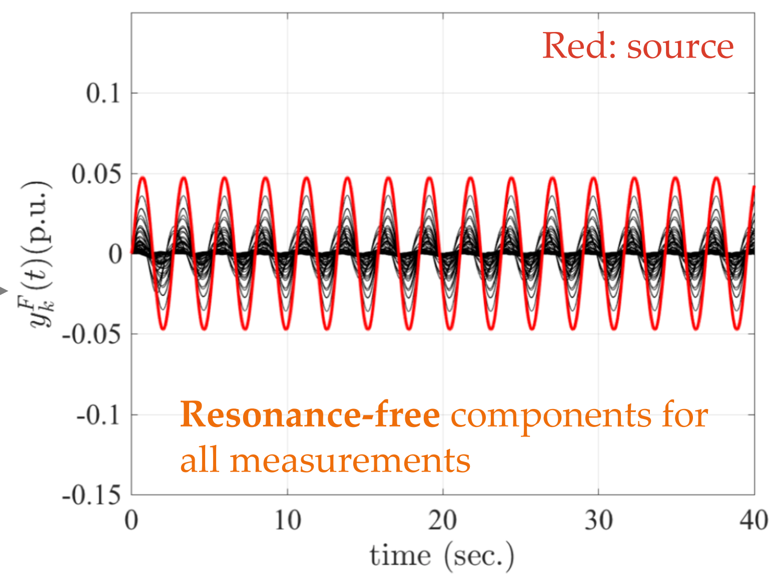
$$+$$



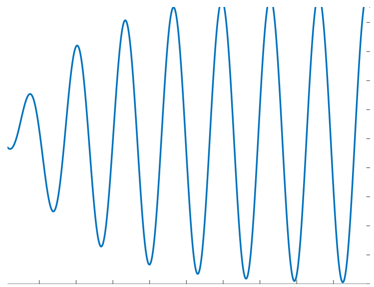
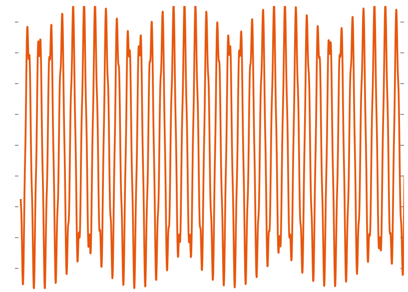
Resonance-free

Source location info.





FO Localization: One Possible Interpretation

$$y_k(t) =$$  $$+$$ 

Resonance

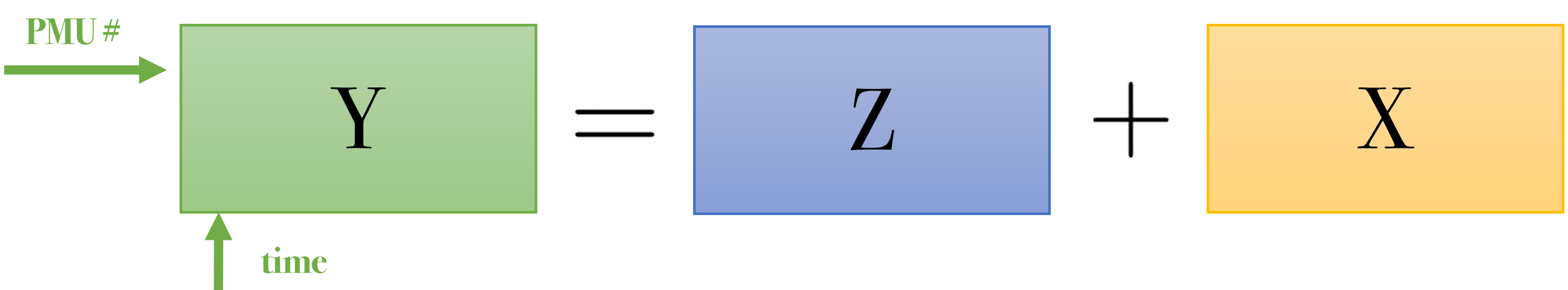
Resonance-free

"Rank 2"

Source location info.

Physical Analysis

Purely Data-driven method



$$\text{rank } Z \leq r \qquad \|X\|_0 \leq p$$

Remarks

- Source localization is formulated as a matrix decomposition problem.
- RPCA is used for matrix decomposition.
- Performance validation based on simulation and real-world data.
- One possible interpretation of the method

Outline

Opportunities:

- Massive sensors enhance grid transparency
  - ***Forced oscillation localization***
- Edge intelligence enables load to track generation

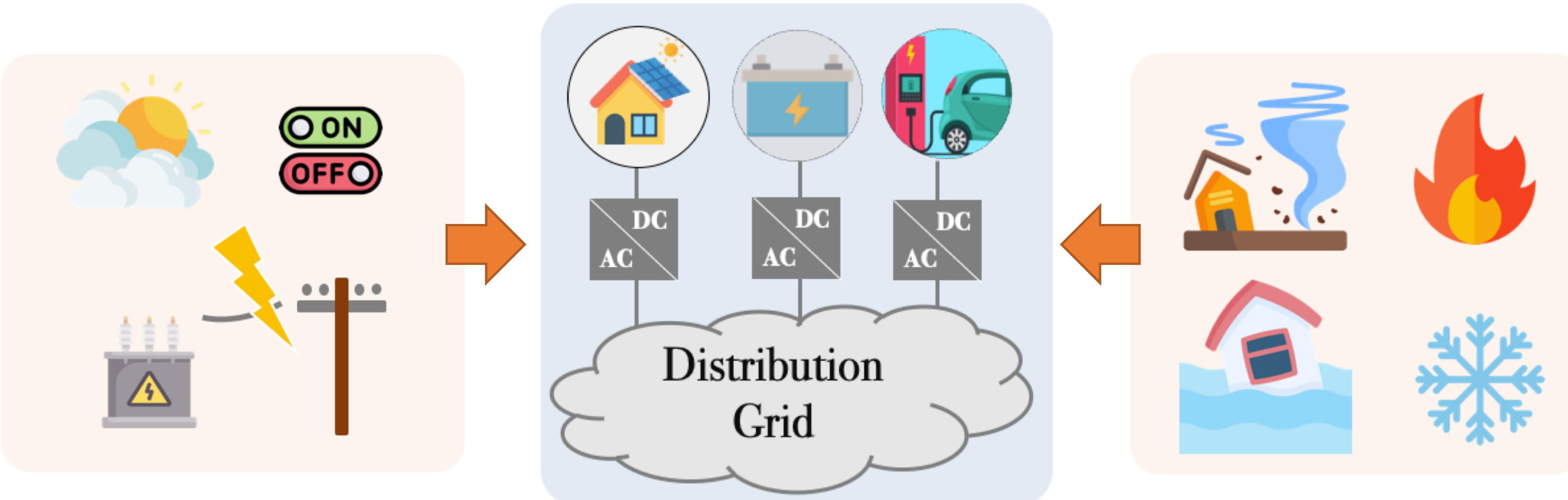
Challenges:

- Cyber threats
- Physical security of the grid with inverter interfaces
  - ***Learning-based transient stability assessment***

A Neural Lyapunov Approach to Assessing Transient Stability of Networked Microgrids

- **T. Huang**, S. Gao, and L. Xie, “A Neural Lyapunov Approach to Assessing Networked Microgrids Transient Stability,” *IEEE Transactions on Smart Grid,* vol. 13, no. 1, pp. 106-118, Jan. 2022
- **T. Huang**, H. Sun, K. J. Kim, D. Nikovski and L. Xie, "A Holistic Framework for Parameter Coordination of Interconnected Microgrids against Disasters," *IEEE Power & Energy Society General Meeting (PESGM),* Montreal, QC, Canada, 2020, pp. 1-5. **(Best Paper Award)**
- **T. Huang**, S. Gao, X. Long, and L. Xie, “A neural Lyapunov approach to transient stability assessment in interconnected microgrids,” in *Proceedings of the 54th Hawaii International Conference on System Sciences (HICSS)*, 2021, p. 3330. **(Best Paper Award)**

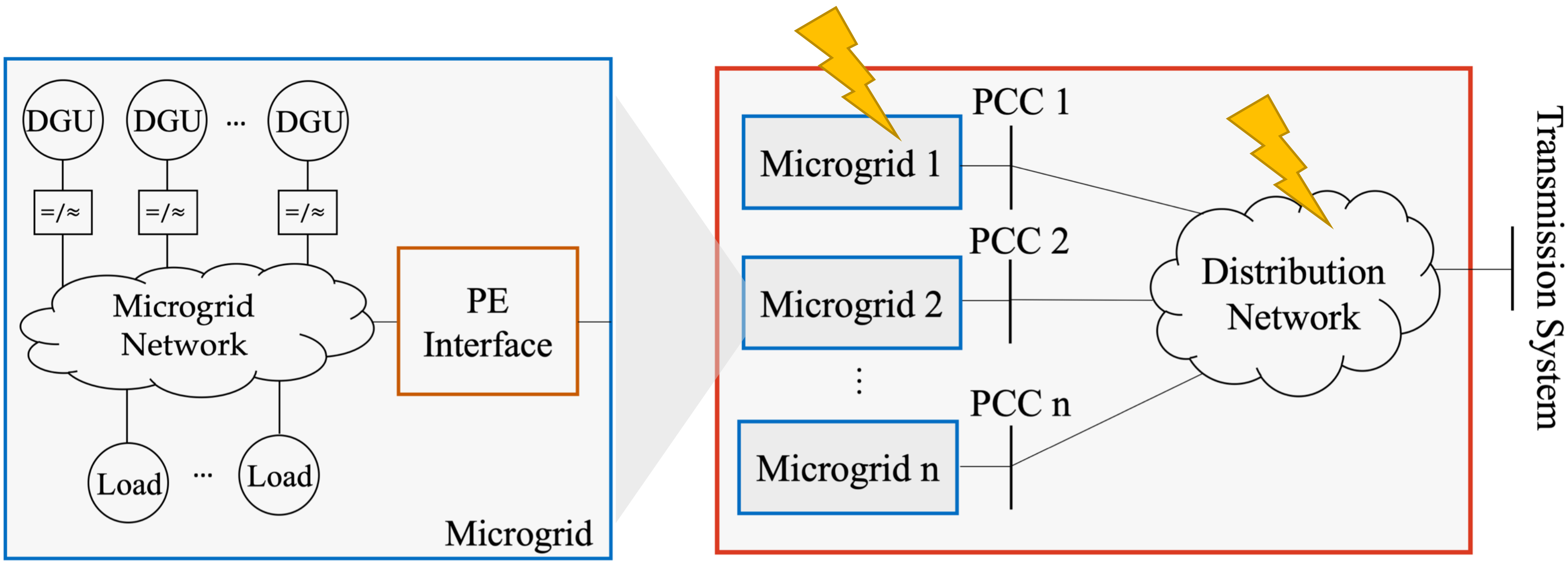
Disturbances in Distribution Systems



How to assess grid robustness to *disturbances*?

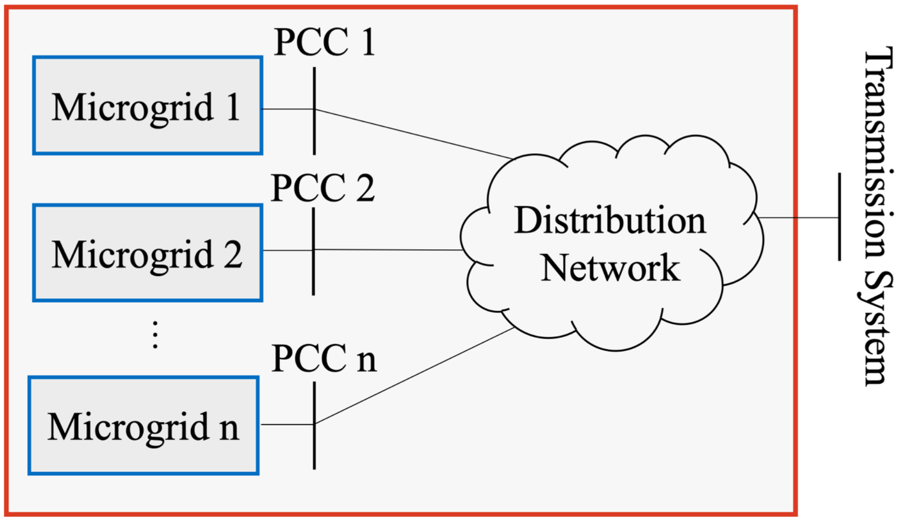
Physical Architecture of Future Distribution Systems

- Future distribution system: networked microgrids
- Disturbances: operation modes; network



DGU: distributed generation unit
PCC: point of common coupling

Interface Dynamics



PCC: point of common coupling
DSO: distribution system operator

Microgrid Interface Dynamics

$$T_{ai}\dot{\delta}_i + \delta_i - \delta_i^* = D_{ai}(P_i^* - P_i)$$
$$T_{Vi}\dot{V}_i + V_i - V_i^* = D_{Vi}(Q_i^* - Q_i),$$

Network Constraint

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x})$$

$$P_i = V_i^2 G_{ii} + \sum_{k \neq i} V_i V_k Y_{ik} \sin(\delta_i - \delta_k - \theta_{ik} + \pi/2),$$
$$Q_i = -V_i^2 B_{ii} + \sum_{k \neq i} V_i V_k Y_{ik} \sin(\delta_i - \delta_k - \theta_{ik}), \forall i,$$

[Zhang, Xie, TPWRS'16], [Kolluri, TPWRS'17], [Siva, Xie, ACC'20]

H. Ren, R. R. Jha, A. Dubey and N. N. Schulz, "Extremum-Seeking Adaptive-Droop for Model-Free and Localized Volt-VAR Optimization," in *IEEE Transactions on Power Systems*, 2022.

Is the system stable? How large are the disturbances that the system can tolerate?

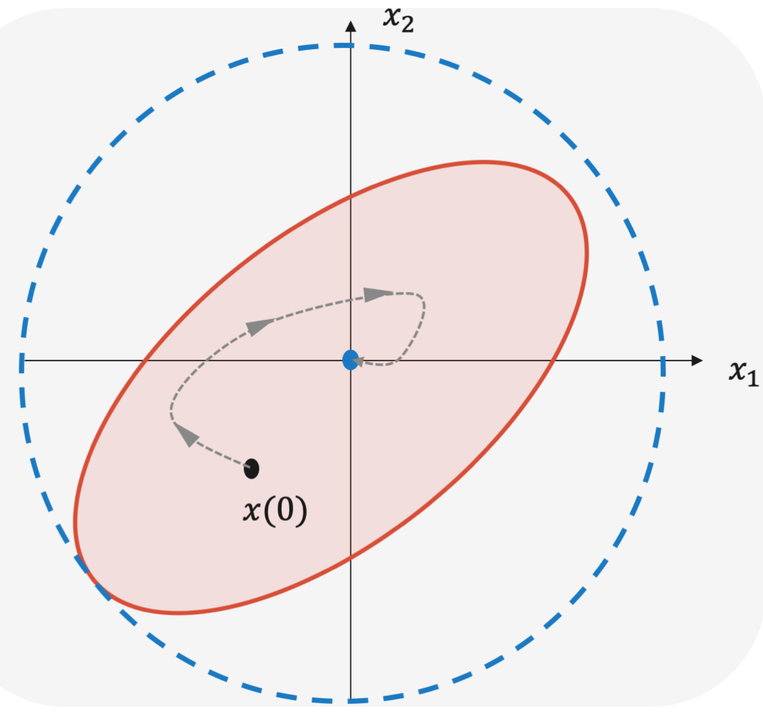
Security Region Estimation

- Stability certification
- Security region
- *How to find a Lyapunov function? Can we learn it?*

$\forall R > 0, \exists r > 0,$
$\|\boldsymbol{x}(\mathbf{0})\| < r$

- $\forall t \geq 0, \|\boldsymbol{x}(t)\| < R$
- $\boldsymbol{x}(t) \to \mathbf{0}$ as $t \to \infty$

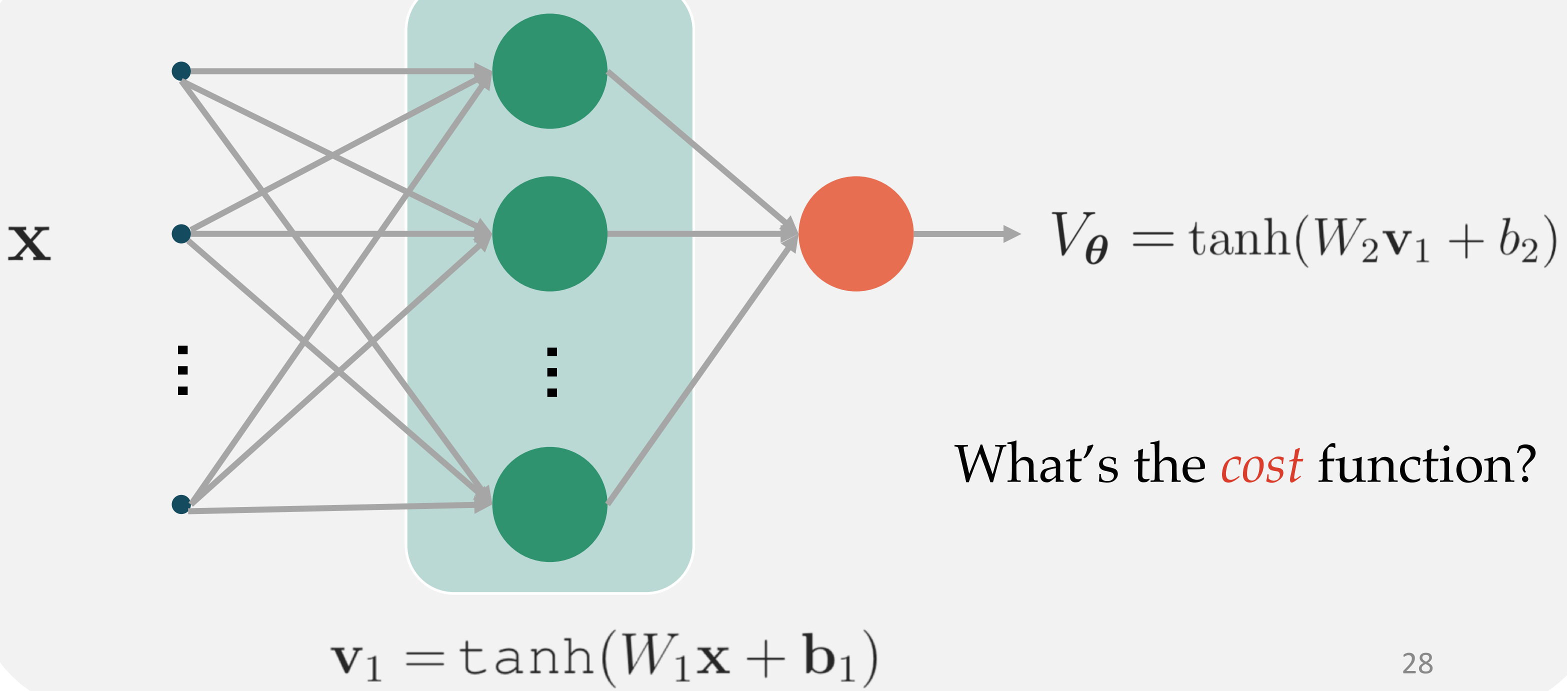
Def.: $V(\boldsymbol{x})$ is a Lyapunov function in D_u if
- V is positive definite in D_u
- $\dot{V}$ is negative definite in D_u



PC: https://en.wikipedia.org/wiki/Aleksandr_Lyapunov

Lyapunov Neural Network

- The LF is assumed to be ***neural network***-structured
- How to tune parameters of NN such that it behaves like a Lyapunov function?



What's the *cost* function?

Empirical Lyapunov Risk

$$L_N(\boldsymbol{\theta}) = \frac{1}{N}\sum_{i=1}^{N}\left(\max(-V_{\boldsymbol{\theta}}(\boldsymbol{x}_i), 0) + \max\left(\dot{V}_{\boldsymbol{\theta}}(\boldsymbol{x}_i), 0\right)\right)$$

Penalty arises when

V(x) < 0 Time derivative > 0

[Chang, Gao, NeurIPS 2019]

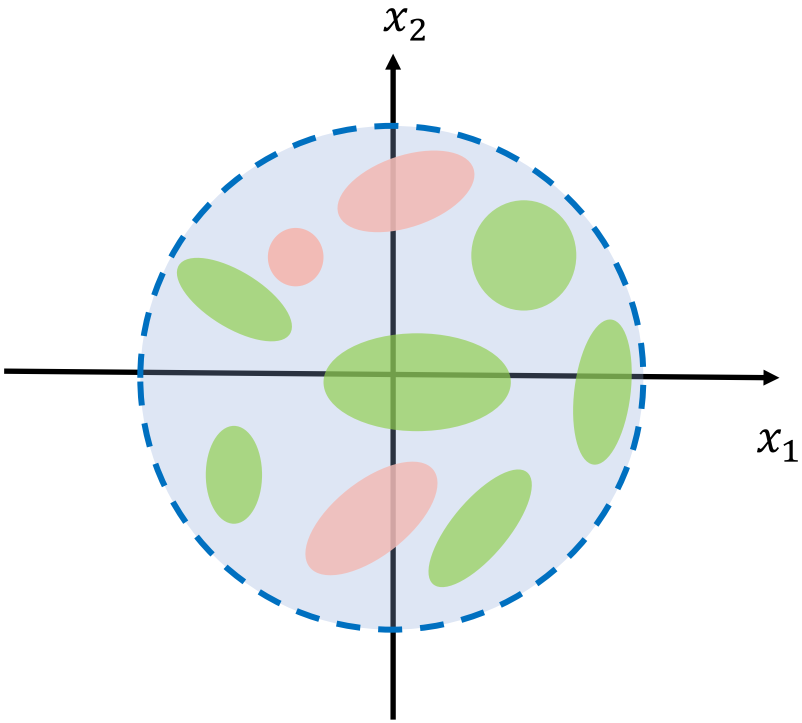
Empirical Risk Minimization

- Draw N random samples

$$\min_{\boldsymbol{\theta}} L_N(\boldsymbol{\theta})$$

- Gradient descent algorithm

- Is this enough? No!



Valid region

Random samples selected

Counterexamples

Augment of Training Samples

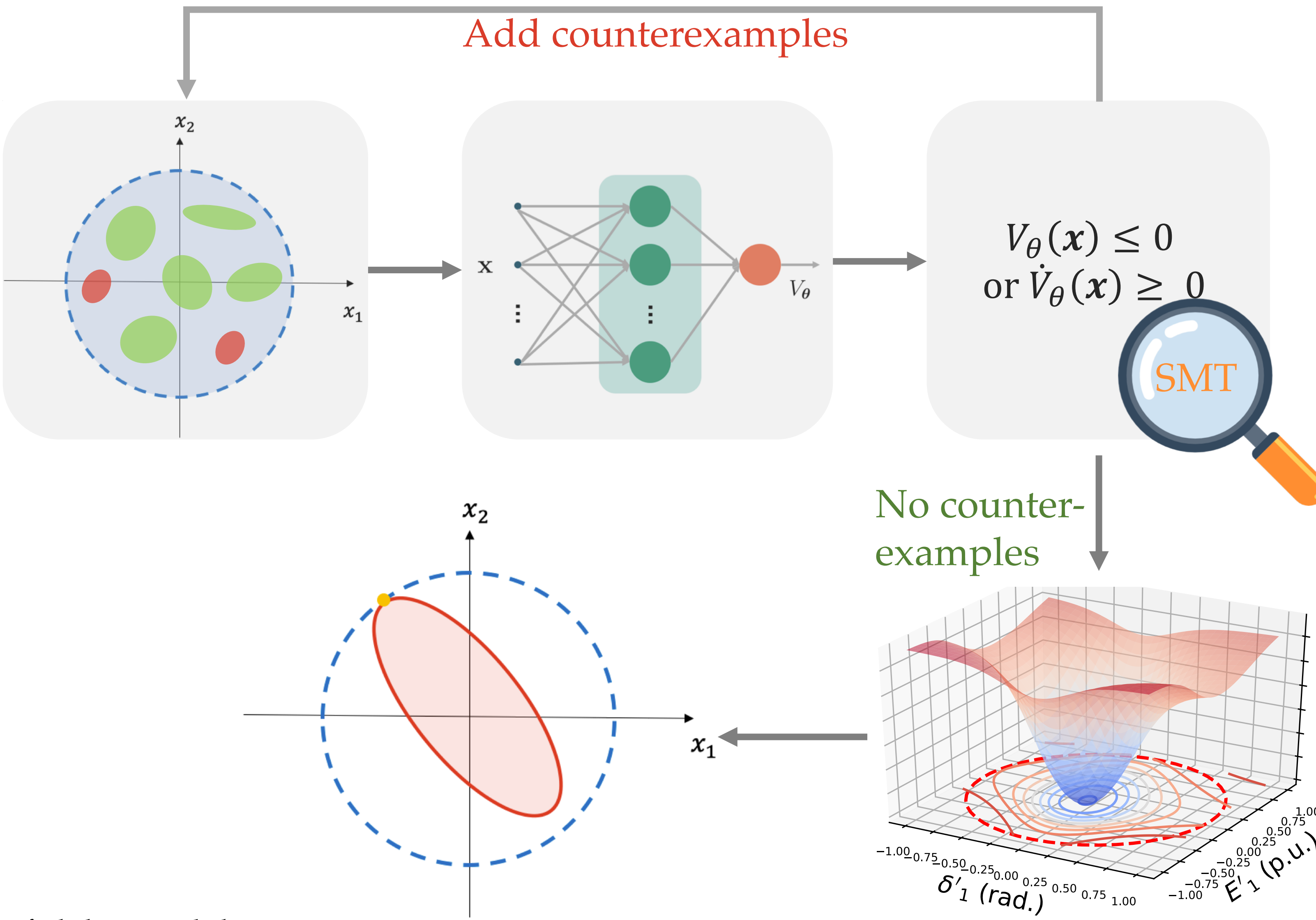
- $\boldsymbol{x} \in \mathcal{D} \backslash \{0\}$ is a counterexample, if

$$V_\theta(\boldsymbol{x}) \leq 0 \text{ or } \dot{V}_\theta(\boldsymbol{x}) \geq 0$$

- How to check satisfiability
  - SMT solver [Gao, IJCAR'12, NeurlPS'19], [Barrett, HMC'18]

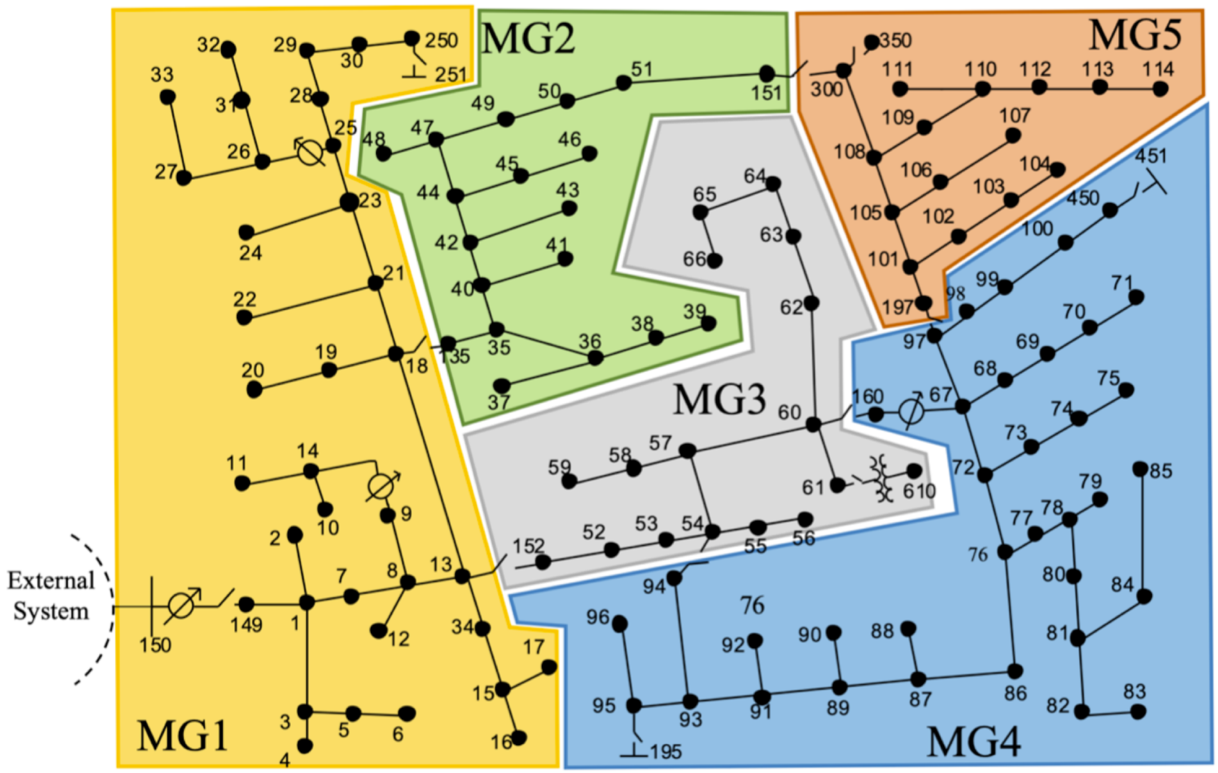
SMT: Satisfiability Modulo Theories

Implementation



SMT: Satisfiability Modulo Theories

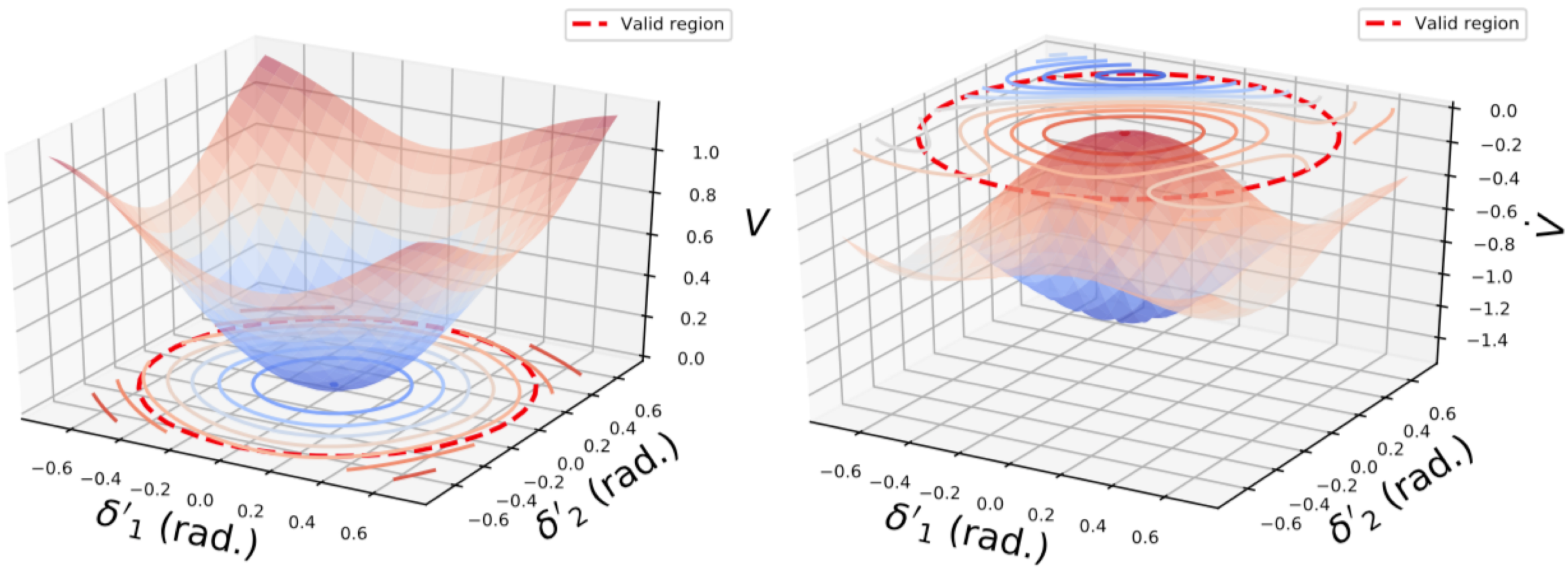
Case Study: IEEE 123-node Test Feeder



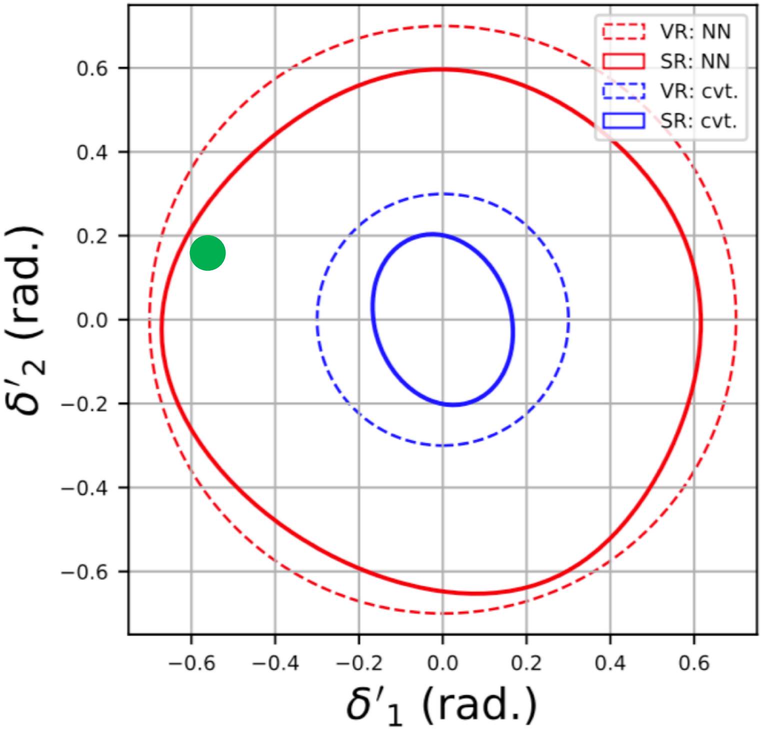
- Microgrid 5 enters the islanded mode
- Assess the stability of the rest four microgrids

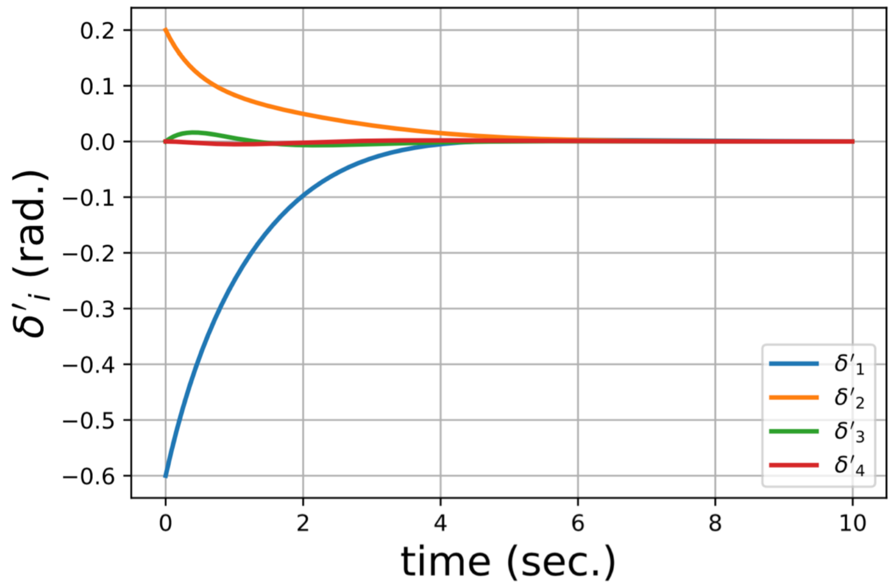
$$\{\boldsymbol{x} \in D \mid V_{\mathrm{NN}}(\boldsymbol{x}) < 0.69\}$$

123-node: Visualization of Lyapunov Function



123-node: Comparison Study





Neural Nets

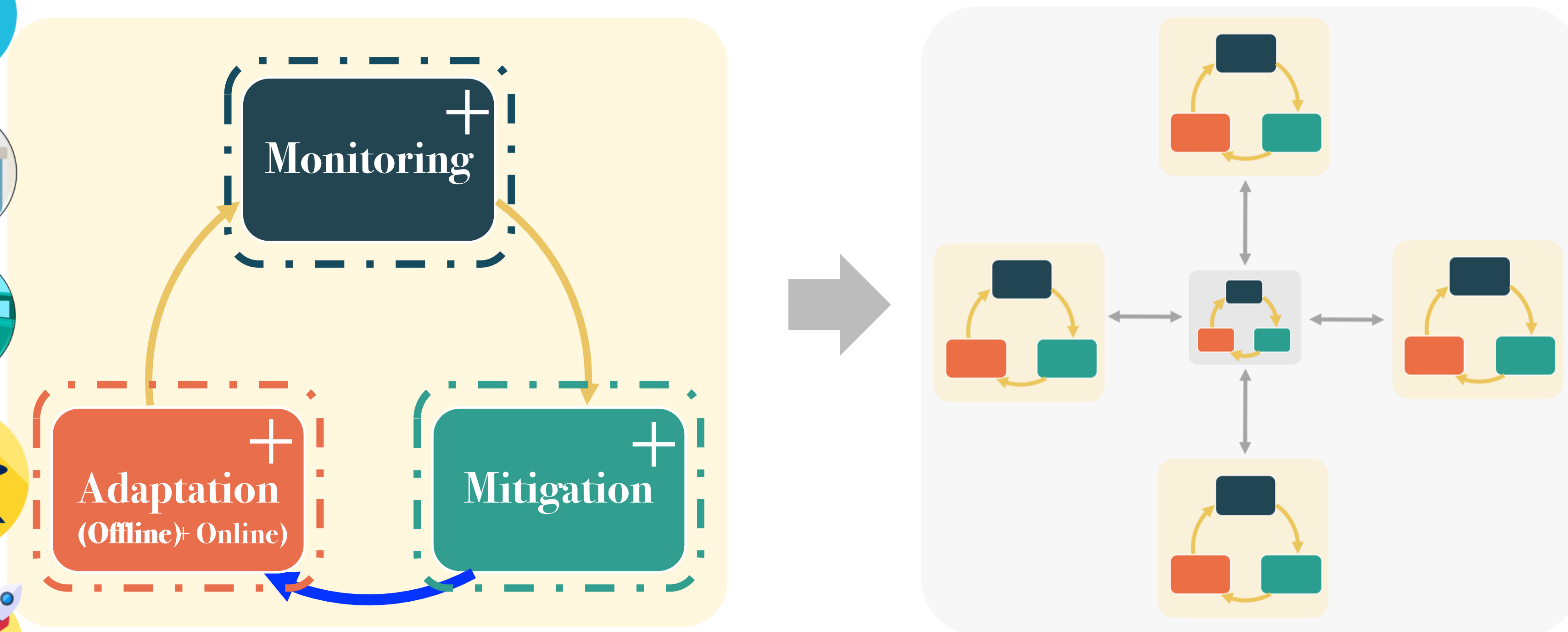
Conventional Approach

[Chiang, TCS'89]

Summary

- **Opportunities** and **challenges** in massively digitized grid
- Physically interpretable approach to **forced oscillation localization**
- Learning-based framework for **transient stability assessment** of networked microgrids

Future Energy Management System (EMS)

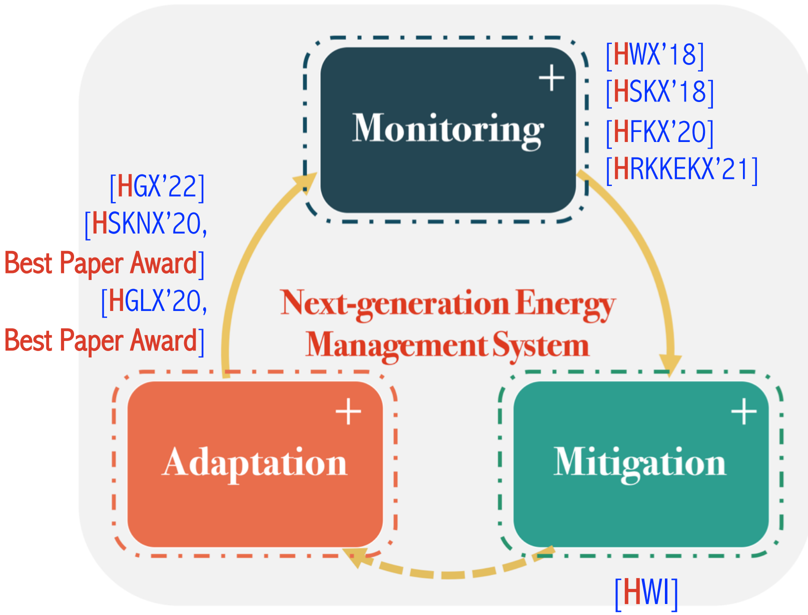


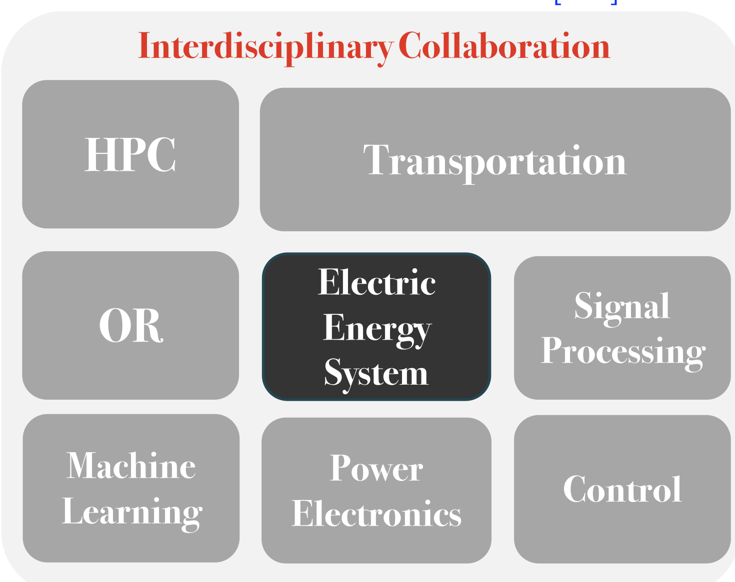
Design Philosophy

- Enriching EMS functions
- Distributed Implementation

[Dy-Liacco, TPWRS'67]

Scalable Solutions to Carbon-neutral Transition of Electric Energy Systems





Key References

[HWX'18] **T. Huang**, M. Wu and L. Xie, "Prioritization of PMU Location and Signal Selection for Monitoring Critical Power System Oscillations," in TPWRS, 2018.

[HSKX'18] **T. Huang**, B. Satchidanandan, P. R. Kumar and L. Xie, "An Online Detection Framework for Cyber Attacks on Automatic Generation Control," in TPWRS, 2018.

[HFKX'20] **T. Huang**, N. Freris, P. R. Kumar and L. Xie, "A Synchrophasor Data-driven Method for Forced Oscillation Localization under Resonance Conditions," TPWRS. 2020.

[HGX'22] **T. Huang**, S. Gao, and L. Xie, "A Neural Lyapunov Approach to Assessing Networked Microgrids Transient Stability," TSG, 2022.

[HRKKEKX'21] **T. Huang**, J. Ramos-Ruiz, W. Ko, J. Kim, P. Enjeti, P. Kumar, and L. Xie, "Enabling Secure Peer-to-peer Energy Transaction through Dynamic Watermarking in Future Distribution Grids," in IEEE Electrification Magazine, 2021.

[HFKX'18] **T. Huang**, N. Freris, P. R. Kumar and L. Xie, "Localization of forced oscillations in the power grid under resonance conditions," in CISS 2018.

[HSKNX'20] **T. Huang**, H. Sun, K. J. Kim, D. Nikovski and L. Xie, "A Holistic Framework for Parameter Coordination of Interconnected Microgrids against Disasters," PESGM, 2020, (Best Paper Award)

[HGLX'20] **T. Huang**, S. Gao, X. Long, and L. Xie, "A neural Lyapunov approach to transient stability assessment in interconnected microgrids," in HICSS 2020. (Best Paper Award)

[HWREKX'20] **T. Huang**, B. Wang, J. Ramos-Ruiz, P. Enjeti, P. R. Kumar, and L. Xie, "Detection of Cyber Attacks in Renewable-rich Microgrids Using Dynamic Watermarking," in PESGM 2020.

[XHKTM'22] L. Xie, **T. Huang**, P. Kumar, A. Thatte, and S. Mitter, "On a Control Architecture for Future Electric Energy Systems," *Proceedings of the IEEE* (invited submitted).

[XSZHB'22] L. Xie, Y. Sun, X. Zheng, **T. Huang**, and T. Bruton, "Massively Digitized Power Grid: Opportunities and Challenges from Use-inspired AI," *Proceedings of the IEEE* (invited, submitted).

[HWI] **T. Huang**, D. Wu, and M. Ilic, "Observer-based Corrective Control for Cyber Attacks in Power Electronic-interfaced Microgrids," MIT Working Paper

Tong Huang, tongh@mit.edu

References

- [TPWRS'17] **T. Huang**, M. Wu and L. Xie, "Prioritization of PMU Location and Signal Selection for Monitoring Critical Power System Oscillations," in *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 3919-3929, July 2018.
- [TPWRS'18] **T. Huang**, B. Satchidanandan, P. R. Kumar and L. Xie, "An Online Detection Framework for Cyber Attacks on Automatic Generation Control," in *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6816-6827, Nov. 2018.
- [TPWRS'19] **T. Huang,** N. Freris, P. R. Kumar and L. Xie, "A Synchrophasor Data-driven Method for Forced Oscillation Localization under Resonance Conditions," *IEEE Transactions on Power Systems,* vol. 35, no. 5, pp. 3927-3939, Sept. 2020.
- [TSG'21] **T. Huang**, S. Gao, and L. Xie, "A Neural Lyapunov Approach to Assessing Networked Microgrids Transient Stability," submitted to *IEEE Transactions on Smart Grid*.
- [CISS'18] **T. Huang,** N. Freris, P. R. Kumar and L. Xie, "Localization of forced oscillations in the power grid under resonance conditions," in 52nd CISS, March 2018, pp. 1–5.
- [PESGM'20-1] **T. Huang**, H. Sun, K. J. Kim, D. Nikovski and L. Xie, "A Holistic Framework for Parameter Coordination of Interconnected Microgrids against Disasters," IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, 2020, pp. 1-5. **(Best Paper Award)**
- [HICSS'21] **T. Huang**, S. Gao, X. Long, and L. Xie, "A neural Lyapunov approach to transient stability assessment in interconnected microgrids," in Proceedings of the 54th Hawaii International Conference on System Sciences (HICSS), 2021, p. 3330. **(Best Paper Award)**
- [PESGM'20-2] **T. Huang**, B. Wang, J. Ramos-Ruiz, P. Enjeti, P. R. Kumar, and L. Xie, "Detection of Cyber Attacks in Renewable-rich Microgrids Using Dynamic Watermarking," in IEEE PES General Meeting 2020

References

- [Trudnowski, TPWRS'08] D. J. Trudnowski, J. W. Pierre, N. Zhou, J. F. Hauer and M. Parashar, "Performance of Three Mode-Meter Block-Processing Algorithms for Automated Dynamic Stability Assessment," in *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 680-690, May 2008.
- [Tate, Overbye, TPWRS'08] J. E. Tate and T. J. Overbye, "Line Outage Detection Using Phasor Angle Measurements," in *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1644-1652, Nov. 2008.
- [Xie, Chen, Kumar, TPWRS'14] L. Xie, Y. Chen and P. R. Kumar, "Dimensionality Reduction of Synchrophasor Data for Early Event Detection: Linearized Analysis," in *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 2784-2794, Nov. 2014.
- [Wang, Turitsyn TPWRS'16] X. Wang et al., "Data-driven diagnostics of mechanism and source of sustained oscillations," IEEE Trans. on Power Systems, 2016.
- [Candes Li, Ma, Wright, JACM'11] E. J. Cande`s, X. Li, Y. Ma, and J. Wright, "Robust Principal Component Analysis?" Journal of the ACM (JACM), vol. 58, no. 3, p. 11.
- [Lin, Liu, Su, NIPS'11] Zhouchen Lin, Risheng Liu, and Zhixun Su, Linearized Alternating Direction Method with Adaptive Penalty for Low Rank Representation, NIPS 2011.
- [Maslennikov, et al, PESGM'16] S. Maslennikov et al., "A test cases library for methods locating the sources of sustained oscillations," in IEEE PESGM, July 2016, pp. 1–5.
- [Dy-Liacco, TPWRS'67] T. Dy-Liacco, "The adaptive reliability control system," in *IEEE Transactions on Power Apparatus and Systems*, vol. 86, no. 5, May 1967.
- [Chiang, TCS'89] H.-D. Chiang, "Study of the existence of energy functions for power systems with losses," IEEE Trans. Circuits Syst., vol. 36, no. 11, pp. 1423–1429, Nov. 1989.

References

- [Maslennikov, et al, IJEPES 2017] S. Maslennikov et al., “Dissipating energy flow method for locating the source of sustained oscillations,” IJEPES, 2017.
- [Ghiga, et al., TPD 2018] R. Ghiga et al., “Phasor measurement unit test under interference conditions,” IEEE Trans. on Power Delivery, vol. 33, no. 2, 2018.
- [Kolluri, TPWRS’17] R. R. Kolluri, I. Mareels, T. Alpcan, M. Brazil, J. de Hoog and D. A. Thomas, "Power Sharing in Angle Droop Controlled Microgrids," in IEEE Transactions on Power Systems, vol. 32, no. 6, pp.
- [Zhang, Xie, TPWRS’16] Y. Zhang and L. Xie, “A transient stability assessment framework in power electronic-interfaced distribution systems,” IEEE Transactions on Power Systems, vol. 31, no. 6, pp. 5106–5114, 2016.
- [Siva, Xie, ACC’20] S. Sivaranjani, E. Agarwal, L. Xie, V. Gupta and P. Antsaklis, "Mixed Voltage Angle and Frequency Droop Control for Transient Stability of Interconnected Microgrids with Loss of PMU Measurements," 2020 American Control Conference (ACC), Denver, CO, USA, 2020
- [Chang, Gao, NeurIP’19] Y. Chang, N. Roohi, S. Gao, “Neural Lyapunov Control,” Advances in Neural Information Processing Systems 32, 2019.
- [Gao, IJCAR’12] S. Gao, J. Avigad, and E. M. Clarke, “δ-complete decision procedures for satisfi- ability over the reals,” in International Joint Conference on Automated Reasoning, pp. 286–300, Springer, 2012.
- [Barrett, HMC’18] Handbook of Model Checking (Chapter 11), *Springer International Publishing*, 2018
- [Ilic’18] M. Ilic, and R. Jaddivada, “Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems,” Annual Reviews in Control, 2018.