A Neural Lyapunov Approach to Transient Stability Assessment in Interconnected Microgrids

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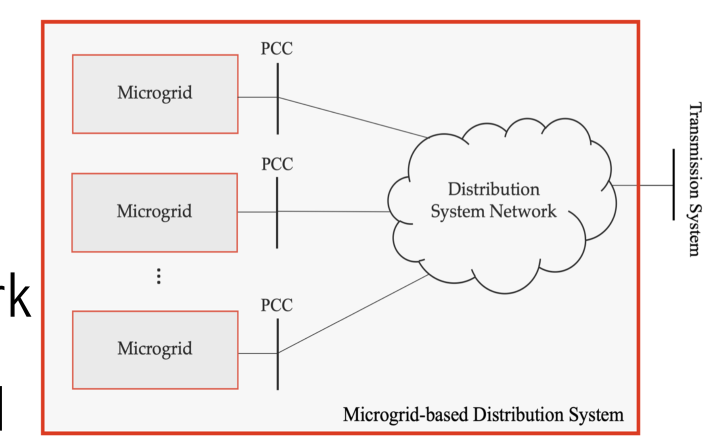
Key Innovations

- We develop a novel transient stability assessment tool for networked microgrids using a machine learning-based Neural Lyapunov method.
- The tool can address the networked microgrids with lossy lines.
- The tool can provide a less conservative characterization of the security region, compared with conventional methods based on quadratic Lyapunov functions.

Background & Motivation

- Future distribution system: networked microgrids
- Disturbances: operation modes; network
- Transient stability assessment is critical for both planners & operators.



DGU: distributed generation unit
PCC: point of common coupling

Interface Dynamics

- PCC: power-electronic interface for simplifying the control tasks of DSO and achieving power sharing
- Interface dynamics depend on control strategies.
- Frequency/angle droop control

Microgrid Interface Dynamics

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

Network Constraints

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

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

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

Security Region Estimation

- Stable certification: Lyapunov function (LF)
- Security region estimation with Lyapunov function

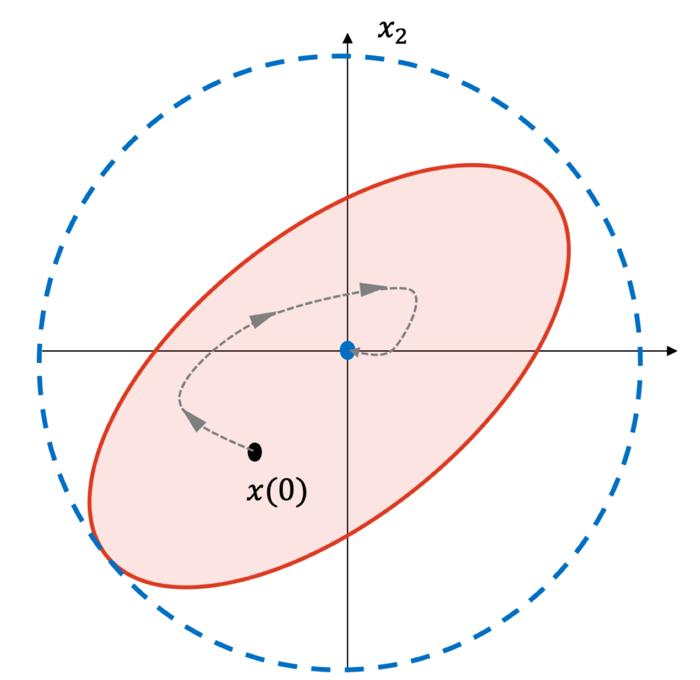
Definition 1 *If, in a ball $D_R := \{\mathbf{x} \mid \|\mathbf{x}\|_2^2 \le R^2\}$, there exists a continuous differentiable scalar function V such that*

- *V is positive definite in D_R,*
- *$\dot{V}$ is negative definite in D_R*

then the equilibrium point $\mathbf{o}'$ is asymptotically stable, and the function V is called a Lyapunov function.

Definition 2 *A region $\mathcal{R} \subseteq \mathbb{R}^{m'}$ is a security region if*

$$\mathbf{x}(0) \in \mathcal{R} \implies \mathbf{x}(\infty) = \mathbf{0}_{m'} \wedge \forall t > 0 (\mathbf{x}(t) \in \mathcal{R}).$$



How to find a Lyapunov Function? Can we learn it?

Neural Lyapunov Approach

"Learning"

- The LF is assumed to be neural network-structured
- A neural network is a function
- Inputs: state variables x; output: V(x); hidden layer(s) and output layer
- How to tune the weights and bias of the NN such that the NN behaves like a Lyapunov function?
- Minimizing the following cost function via gradient decent algorithm

$$L_{N,\rho}(\theta) = \frac{1}{N}\sum_{i=1}^{N}\Big(\max(-V_\theta(x_i), 0) + \max(\nabla_f V_\theta(x), 0)\Big)$$

Penalty arises when $V(x) < 0$ or time derivative > 0

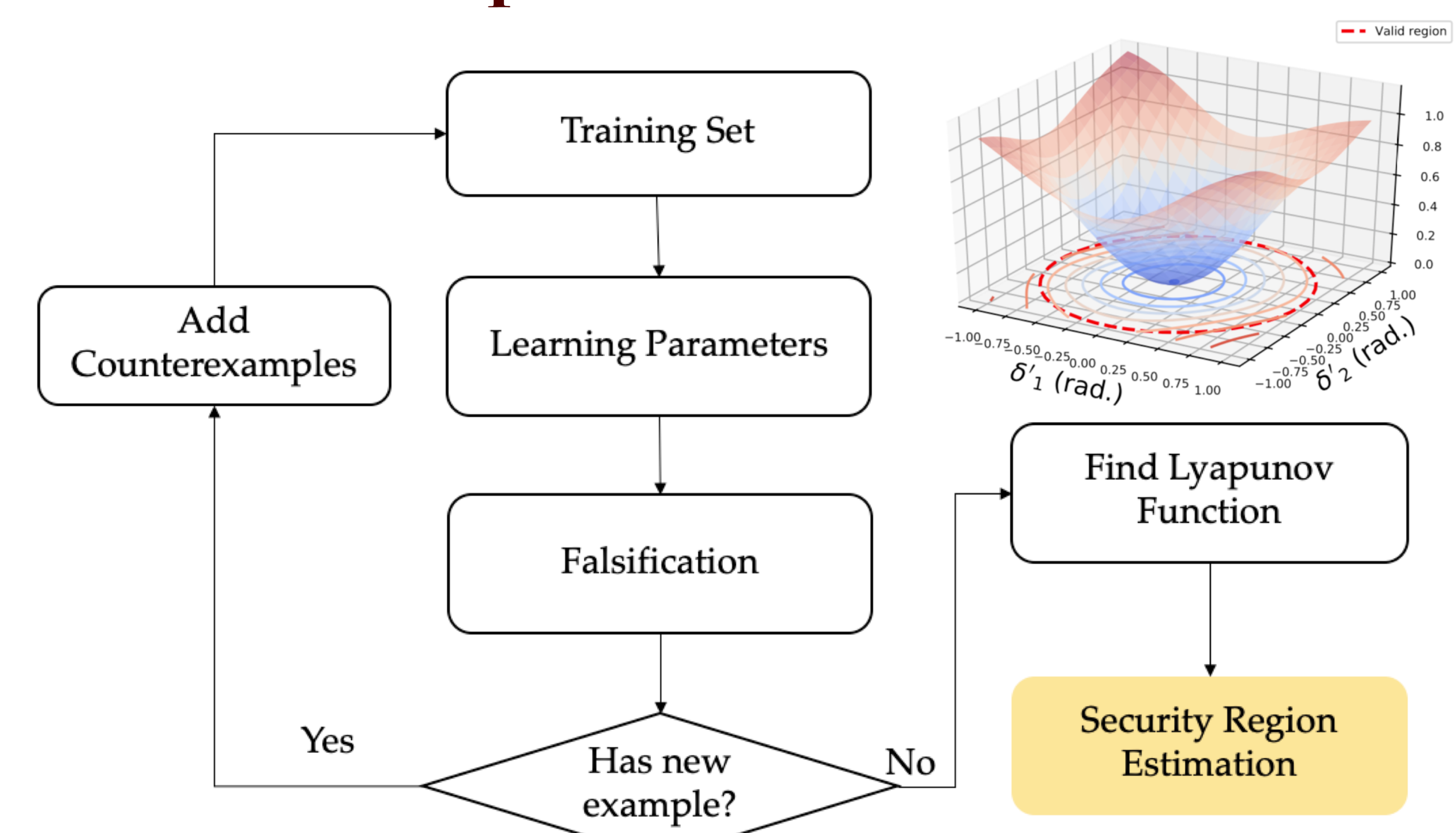
"Falsification"

- For all $x \in \mathcal{D}$, check if

$$V_\theta(x) \geq 0 \text{ and } \nabla_f V_\theta(x) < 0$$

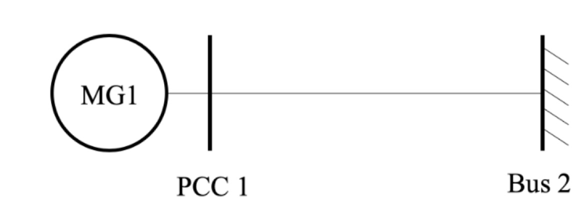
- How to check satisfiability: Satisfiability Modulo Theories (SMT) solver

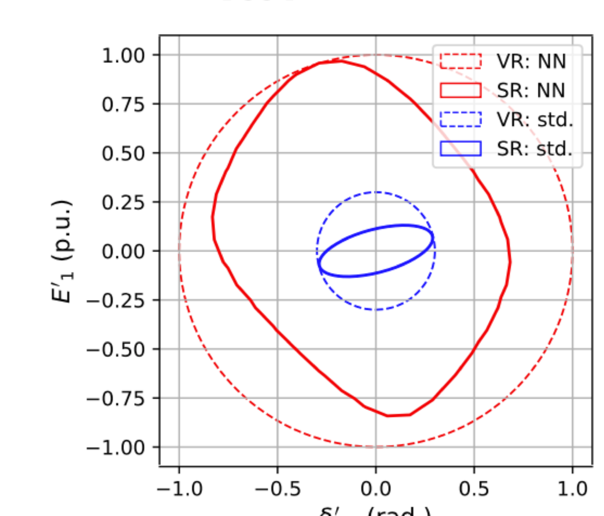
Implementation Scheme



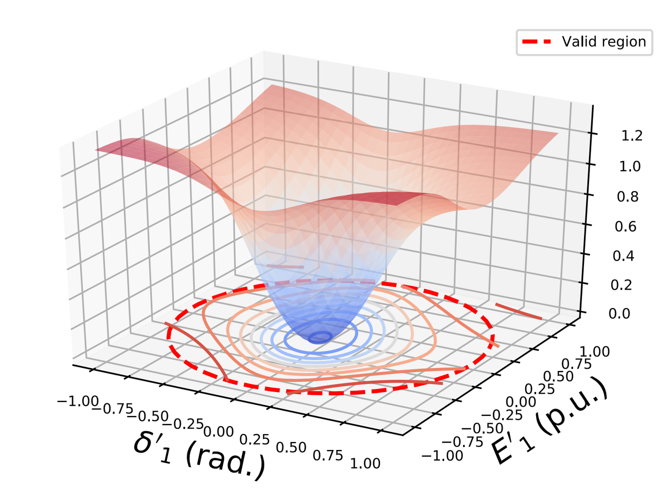
$R = \{x \in D \mid V(x) < c\}$

Case Studies



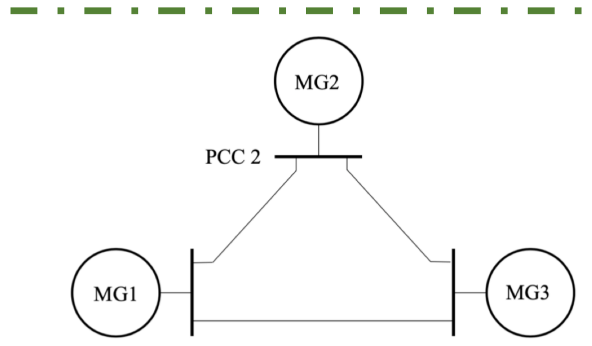


Comparison

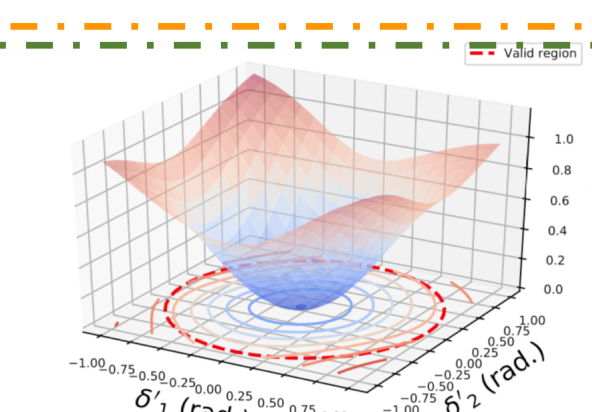


Lyapunov function learned

The proposed method is less conservative than a conventional method.



$\mathcal{R}_{0.7037} = \{\mathbf{x} \mid \|\mathbf{x}\|_2^2 \le 1, V_{\alpha^*}(\mathbf{x}) < 0.7037\}$



Lyapunov function learned

Conclusion

- A neural Lyapunov approach to transient stability assessment
- The proposed method is less conservative than a conventional approach
- Future work will test the algorithm in systems with various dynamics

Reference: T. Huang, S. Gao, X. Long, and L. Xie, "A neural Lyapunov approach to transient stability assessment in interconnected microgrids," in *HICSS-54*, 2021.