Black-Box Impedance Identification and Stability Analysis of Grid-Connected Inverter Under Multiple Operating Points

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1. Introduction

- Inverter-based resources (IBRs) support high renewable energy penetration, but also introduce new challenges to power system, such as **low-frequency oscillations**.
- **Small-signal analysis** enables stability assessment of grid-connected inverter system around steady state operating points.
- Small-signal models can be derived using component connection methods (CCM), but the reliance on internal IBR details motivates black-box approaches.
- To enable black-box modeling, frequency domain impedance is identified via **frequency scan**, with **polynomial representations** parameterized by multiple operating points.
- The identified impedance is synthesized into a **state-space model (SSM)** via **vector fitting** and combined with a single machine infinite bus (SMIB) grid model to form the overall system SSM.
- **Eigenvalue-based analysis** is conducted under varying **short-circuit ratios (SCRs)**, and validated through time-domain simulations.

2. Overall Framework for Black-Box Impedance Modeling

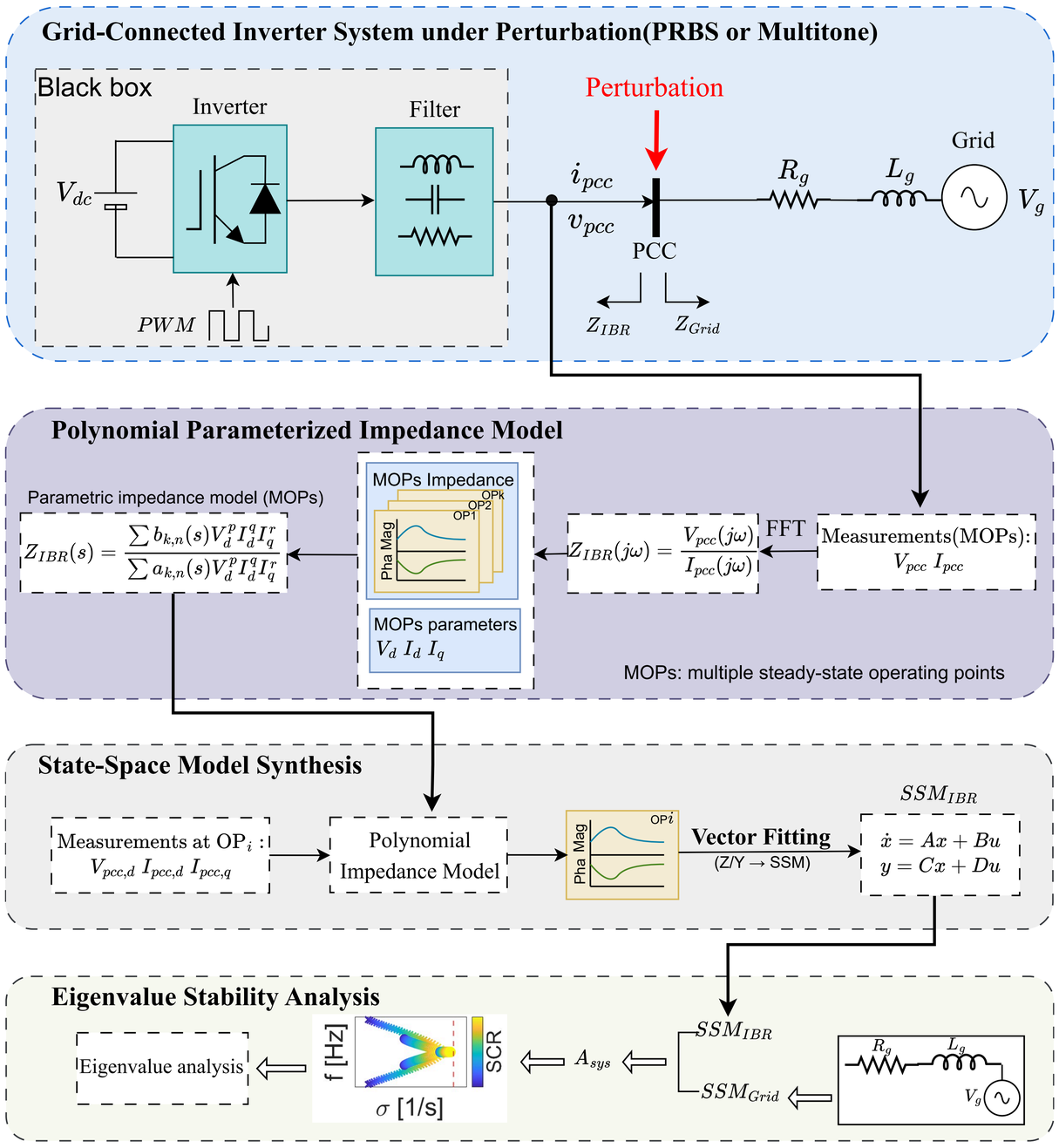

Figure 1: Overview of the proposed black-box impedance modeling and stability analysis framework.

3. Multi-Operating-Point Impedance Identification Results

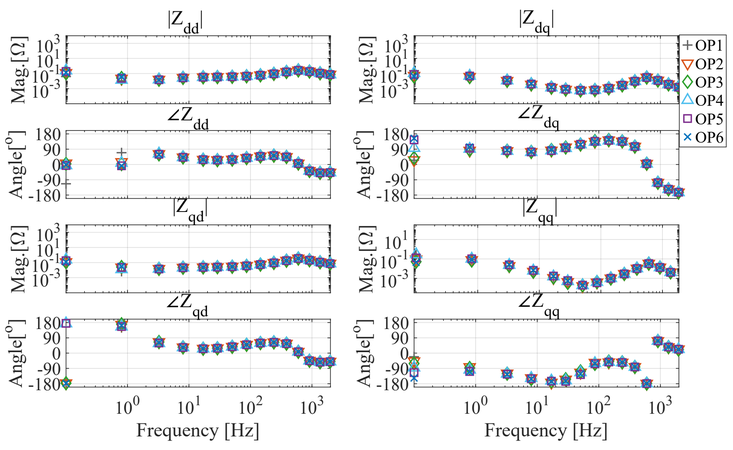

Figure 2: Measured impedance at six operating points (VSG-GFMI).

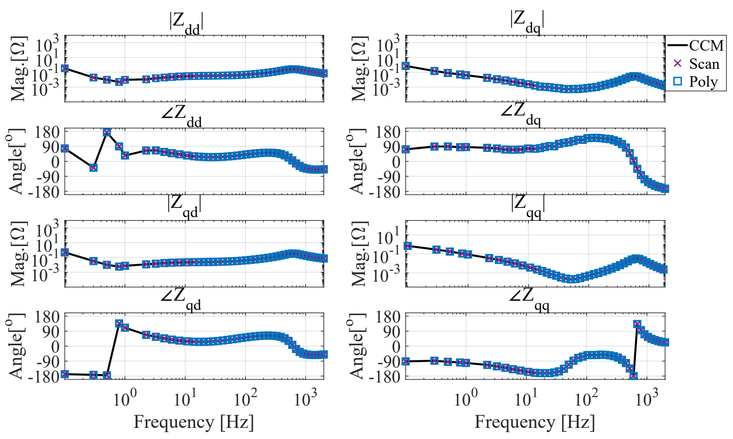

Figure 3: Polynomial-identified impedance at an unseen operating point (VSG-GFMI).

4. Eigenvalue-Based Stability Analysis and Validation

- Vector fitting converts the identified impedance into a SSM, which is interconnected with the grid to form the grid-connected inverter system SSM.
- Eigenvalue analysis under varying SCRs shows stable modes in the left-half plane and unstable modes emerging in the right-half plane.

Grid-Following Inverter (GFLI)

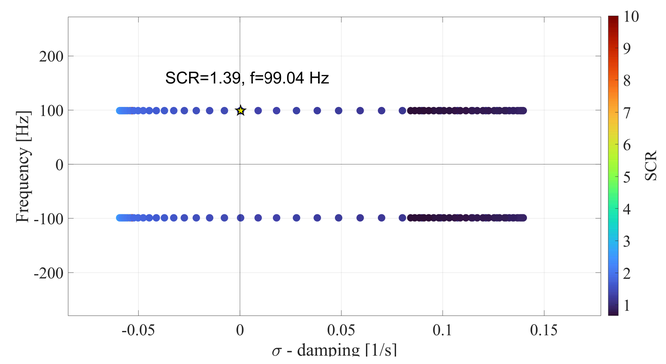

Figure 4: Eigenvalue Trajectory of the grid-connected CC-GFLI system under varying SCR.

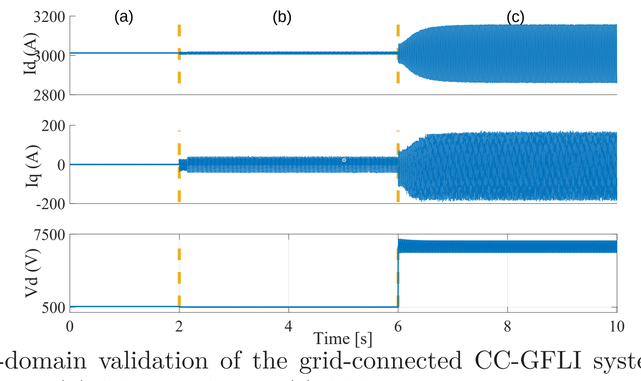

Figure 5: Time-domain validation of the grid-connected CC-GFLI system under varying SCR: (a) SCR = 10, (b) SCR = 1.5, and (c) SCR = 1.

Grid-Forming Inverter (GFMI)

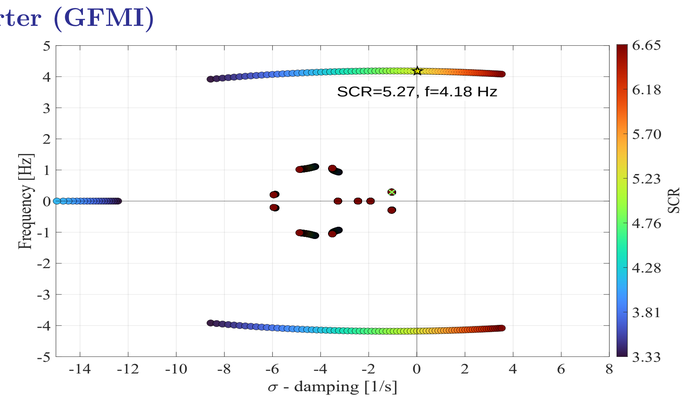

Figure 6: Eigenvalue Trajectory of the grid-connected VSG-GFMI system under varying SCR.

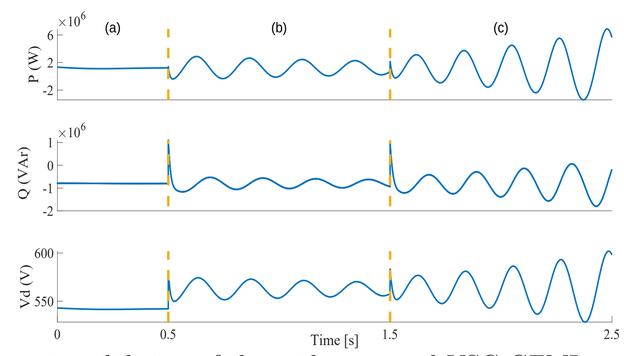

Figure 7: Time-domain validation of the grid-connected VSG-GFMI system under varying SCR: (a) SCR = 3, (b) SCR = 5.2, and (c) SCR = 6.

5. Conclusions

1. A black-box impedance identification and eigenvalue-based stability analysis framework is developed for a grid-connected IBR.
2. Frequency-domain impedance is identified via frequency scanning and represented using parameterized polynomial models.
3. Vector fitting is applied to synthesize the identified impedance into a state-space model, allowing eigenvalue-based stability assessment across different grid conditions.
4. Future work will explore deep learning-based impedance identification to learn nonlinear mappings from operating parameters to frequency domain impedance, along with alternative perturbation excitation methods for accurate and fast impedance identification.

6. References

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2. W. Zhou, N. Mohammed and B. Bahrani, "Operating-Point-Parameterized State-Space Models of Black-Boxed Grid-Following Inverters for Maximum Transferable Active Power Prediction," in IEEE Transactions on Industrial Electronics, vol. 71, no. 12, pp. 16882-16887, Dec. 2024.
3. N. Cifuentes, M. Sun, R. Gupta and B. C. Pal, "Black-Box Impedance-Based Stability Assessment of Dynamic Interactions Between Converters and Grid," in IEEE Transactions on Power Systems, vol. 37, no. 4, pp. 2976-2987, July 2022.