Data-Driven Frameworks for Model Identification in IBR-dominated Power Systems

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1. Introduction

- **Small-signal stability** refers to the ability of a system to operate stably under **small perturbations**.
- General workflow: Select an operating point → linearise the system around this operating point → evaluate stability based on linear control theory [1].
- Entire system structure is available → time-domain methods based on **state-space models (SSMs)** and **eigenvalues** can be directly applied.
- Black-boxed components appear → frequency-domain based methods based on **input-output measurements** and **Nyquist criteria** are preferred [2].
- However, frequency-based methods suffer from **poor scalability** for large systems due to **limited representational capability** of symbolic transfer functions in the s-domain.
- This research proposes a **tangential matching** method [3] to achieve SSM of voltage-source converter (VSC) directly from **data**, which facilitates stability assessment in a **flexible** and **extensible** manner.

2. Dynamical Systems in Time and Complex Domain

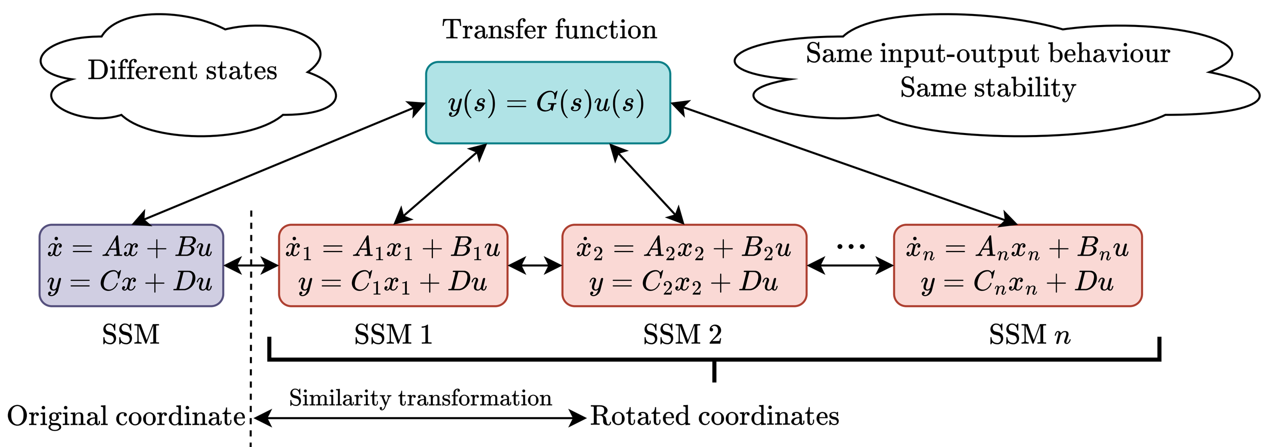

Figure 1: The relationship between state-space and transfer function presentations.

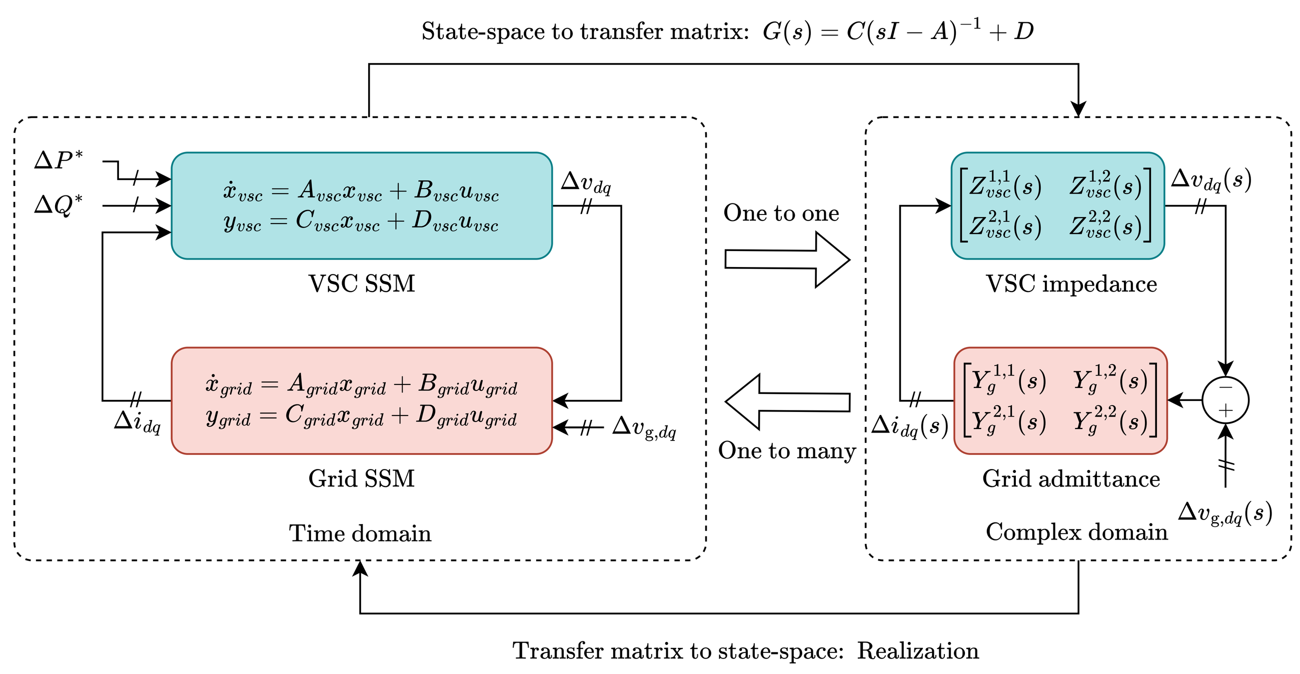

Figure 2: Closed-loop dynamical model for SMIB case: time-domain vs. complex-domain.

3. Mathematical Background of Tangential Matching

- The method seeks for a state-space realisation $[E, A, B, C, D]$ of $G(s)$ satisfying **left** and **right** matching conditions:

$$G(\lambda_i)r_i = [C(\lambda_i E - A)^{-1}B + D]r_i,$$
$$l_j G(\mu_j) = l_j[C(\mu_j E - A)^{-1}B + D] \quad (1)$$

  where λ_i and μ_j are **interpolation points**, r_i and l_j are right and left **tangential directions**.
- The Loewner matrix L and shifted Loewener matrix L_s satisfy **Sylvester equations** constructed from selected frequencies and directions:

$$-ML + L\Lambda = LW - VR,$$
$$-ML_s + L_s\Lambda = LW\Lambda - MVR. \quad (2)$$

- The existing of solution depends on **rank condition**.

4. Model Identification Framework for Black-boxed VSC

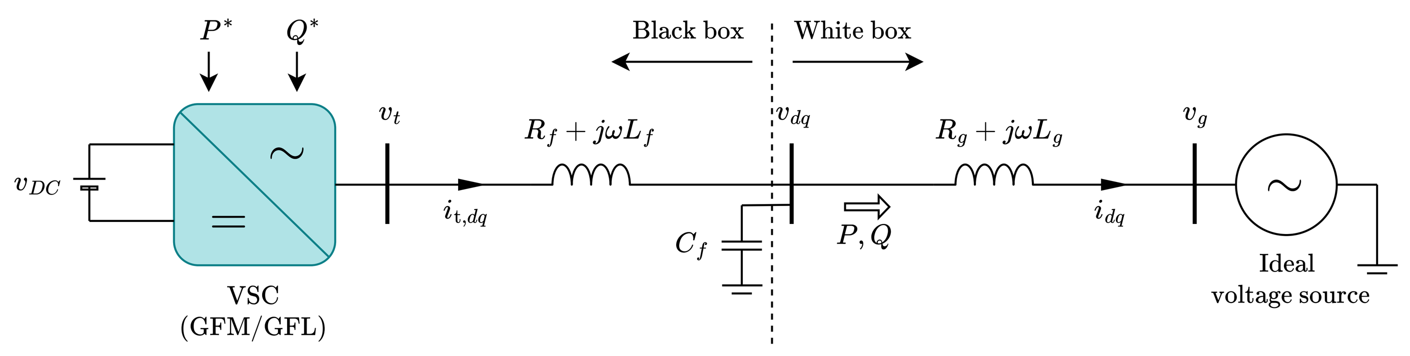

Figure 3: Physical interface of VSC-grid connected system.

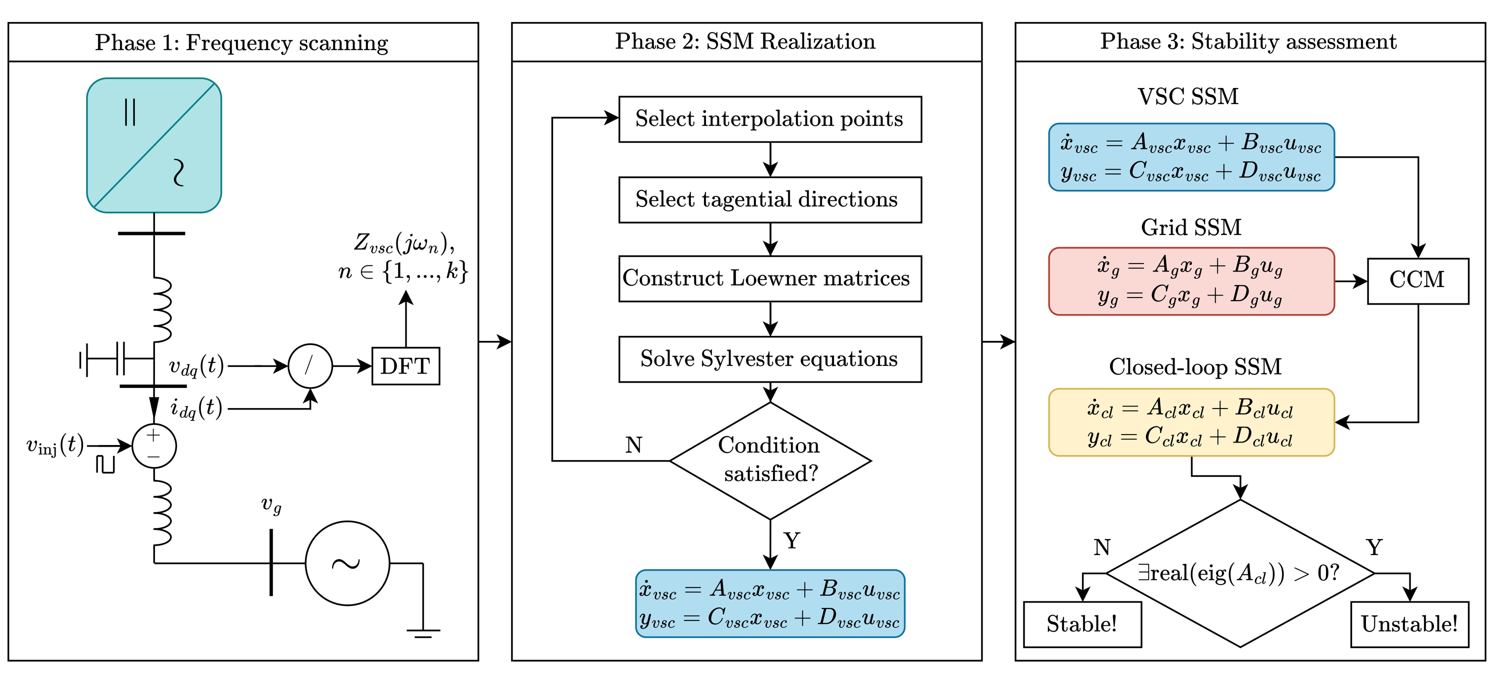

Figure 4: Identification framework.

5. Frequency Scanning Results

- Case study: Droop-controlled grid forming inverter connected to grid with adjustable SCR.
- A multisine voltage signal is injected in series with grid voltage.
- Frequencies of interest: 0.1 Hz to 1,000 Hz.

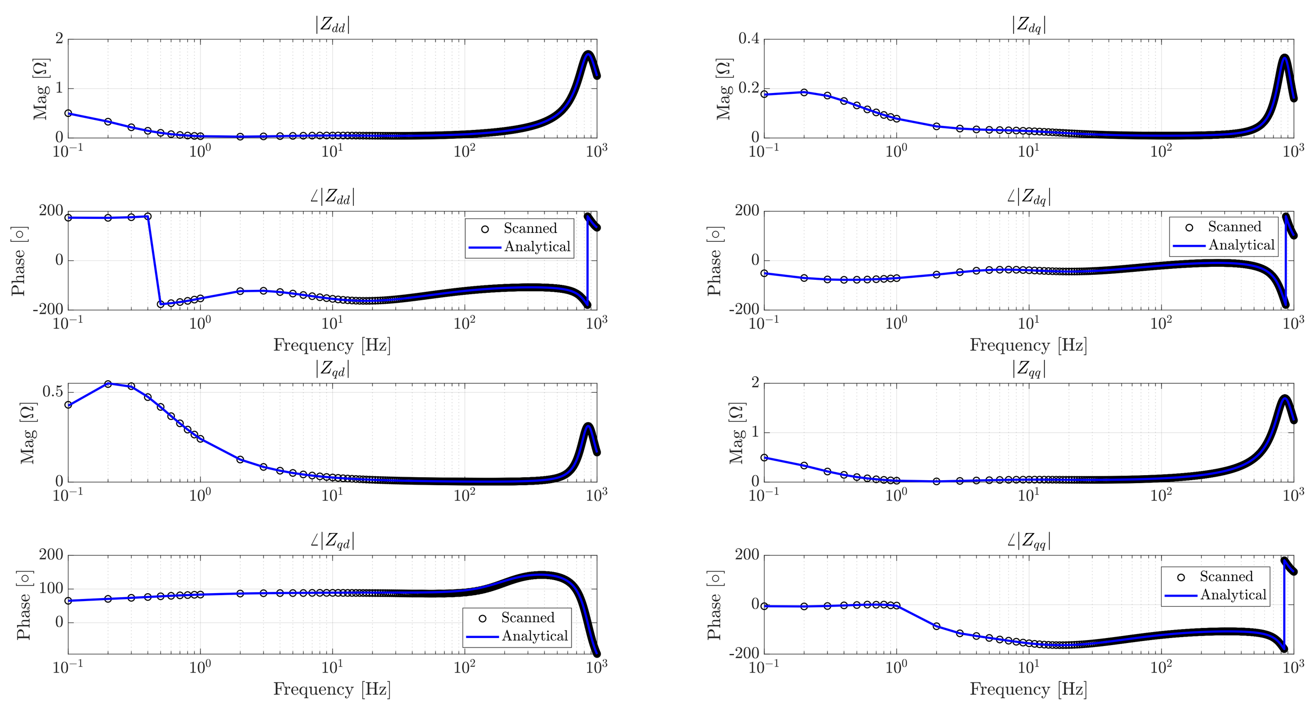

Figure 5: Frequency scanning of VSC.

→ The frequency scanning matches well with the analytical model.

6. Stability Analysis

Case 1: Strong grid (SCR = 20)

- The eigenvalues of the identified model match with the analytical model.
- There is a pair of weakly-damped mode at 5.89 Hz, indicating risk of instability.
- Strong oscillation at 5.61 Hz is also observed in time domain simulation when applying a small step change in active power reference, further validating the accuracy of the proposed method.

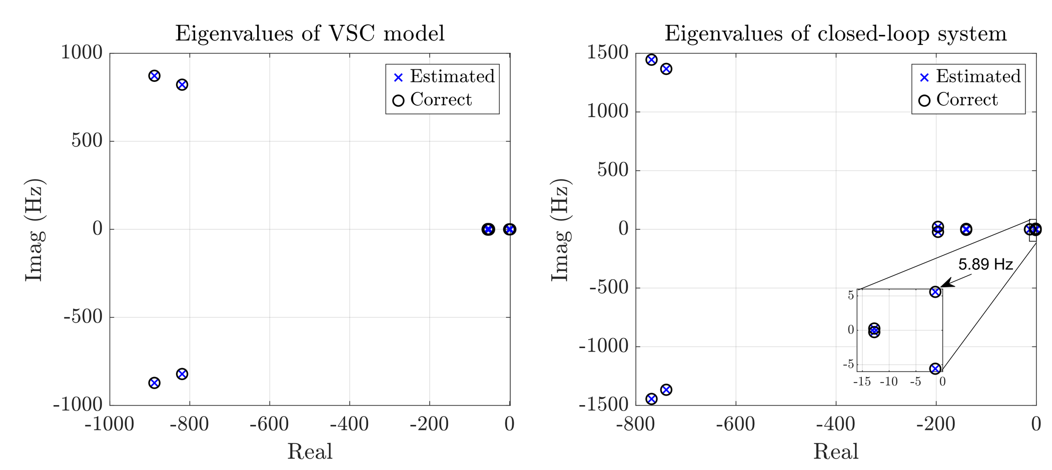

Figure 6: Eigenvalues spectrum (SCR=20)

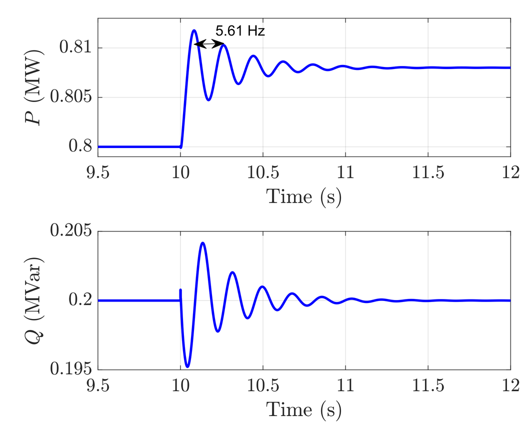

Figure 7: EMT simulation (SCR=20)

Case 2: Weak grid (SCR = 2)

- Low-frequency modes are well-damped, but a new real-valued weakly-damped mode appears.
- The time-domain responses experience much less oscillation but slow-decaying, which obeys the eigenvalue analysis.

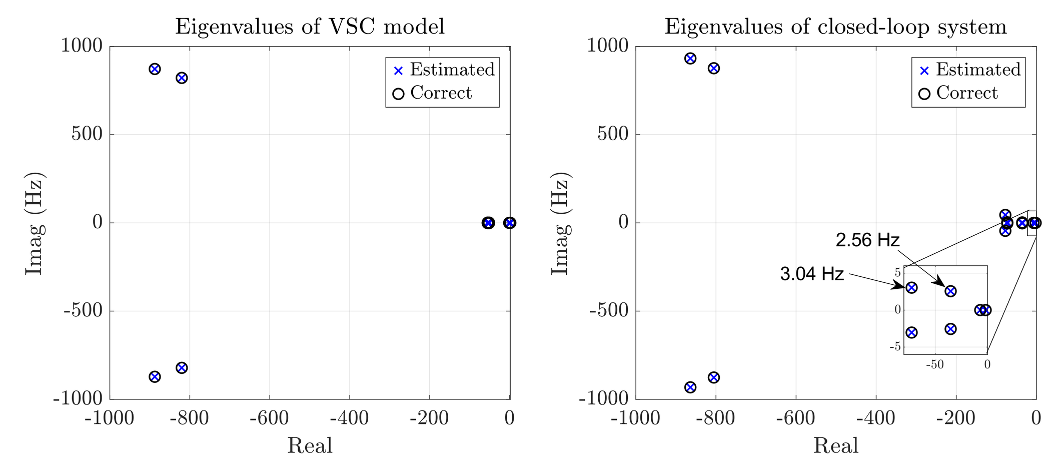

Figure 8: Eigenvalues spectrum (SCR=2)

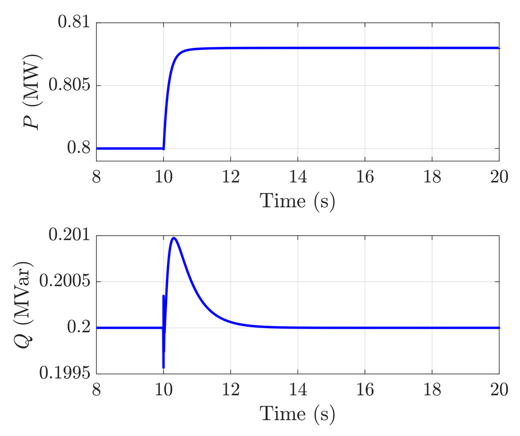

Figure 9: EMT simulation (SCR=2)

7. Conclusions

1. Tangential matching method is proposed to identify small-signal model of VSC, which can accurately evaluate stability under different grid conditions.
2. The robustness of the method under diverse VSC's configurations should be further investigated.
3. Future research includes developing operating-point dependent model for VSC from data, which offers plug-and-play solution for large-scale stability assessment.

References

1. W. Zhou, N. Mohammed and B. Bahrani, "Comprehensive Modeling, Analysis, and Comparison of State-Space and Admittance Models of PLL-Based GFLI's Considering Different Outer Control Modes," in IEEE Access, 2022.
2. N. Mohammed, W. Zhou, B. Bahrani, D. Hill and F. Blaabjerg, "PRBS-Based Impedance Measurement Tool for Stability Analysis of Black-Box EMT Models in PSCAD," in eSmarTA, 2024.
3. Mayo, A. and Antoulas, A., "A framework for the solution of the generalized realization problem," in Linear Algebra and Its Applications, 2007.