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

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Dang Duong Nguyen

Department of Electrical & Computer Systems Engineering
Monash University
Melbourne, Australia

Problem statements

- Future power system involves **mixture of energy sources** with **highly complex dynamics**
- Oscillatory instability may happen in **wider range of frequency**
- Hidden components **further challenges** stability assessment.

→ **Urgent need for system identification!**

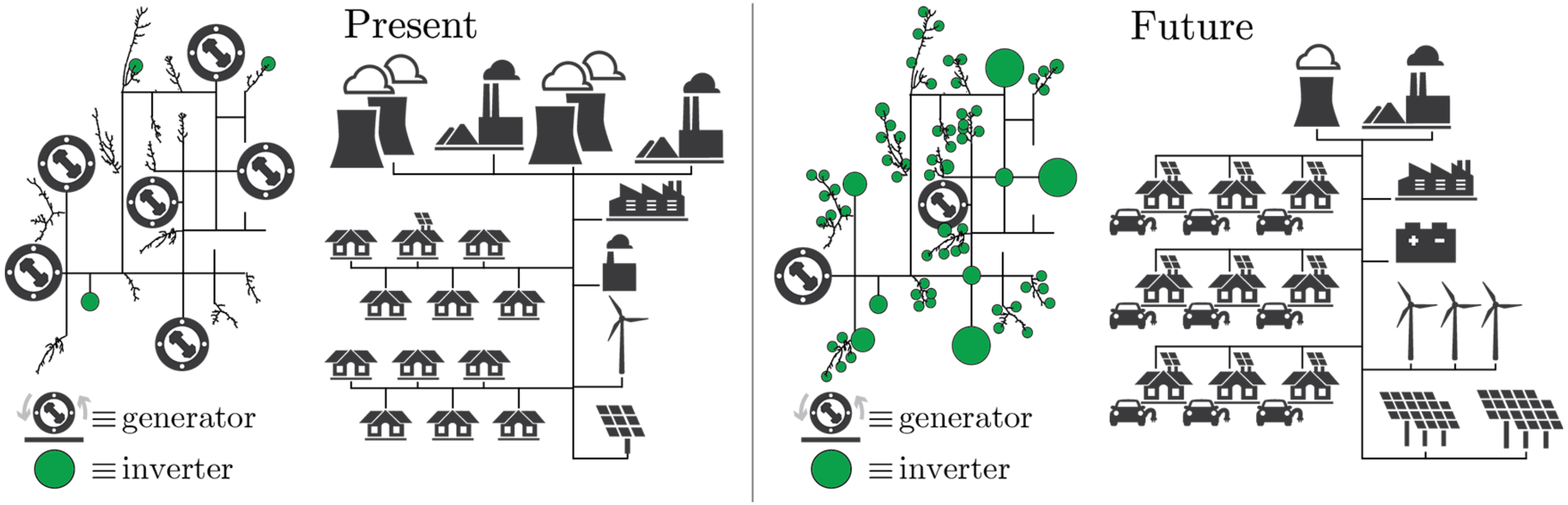

Image source: Grid-Forming Inverter Controls - NREL

Techniques for small-signal stability analysis

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- Eigenvalue-based methods: Consider **detailed** models of all **components** of the system

→ Tell us about stability of **general linear systems,** modes of oscillation and contribution of each components

→ Not always sufficient due to **unknown parts**

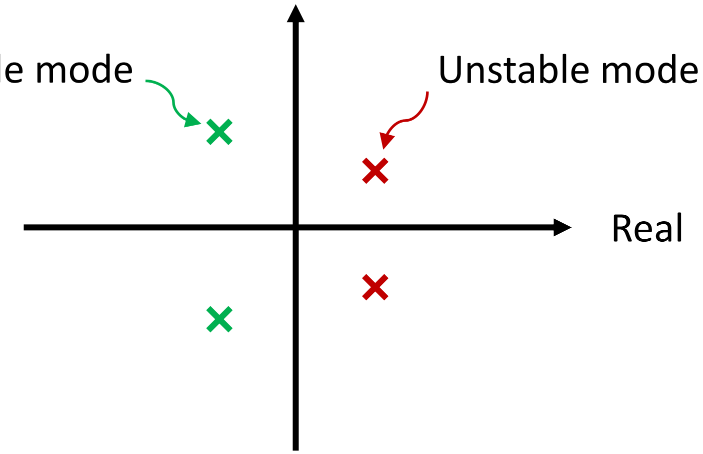


Figure: Eigenvalues spectrum

- Impedance-based methods: Convert the system into 2 **Thevenin/Norton equivalent** connected systems

→ Tell us about stability of **feedback systems**

→ Applicable to **black-boxed** systems

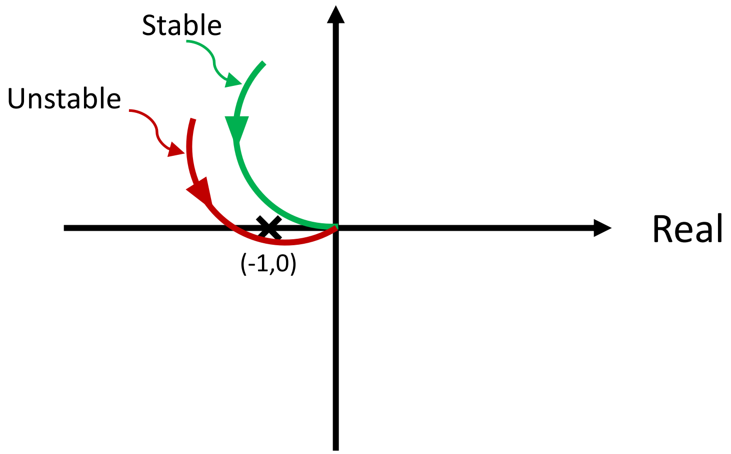
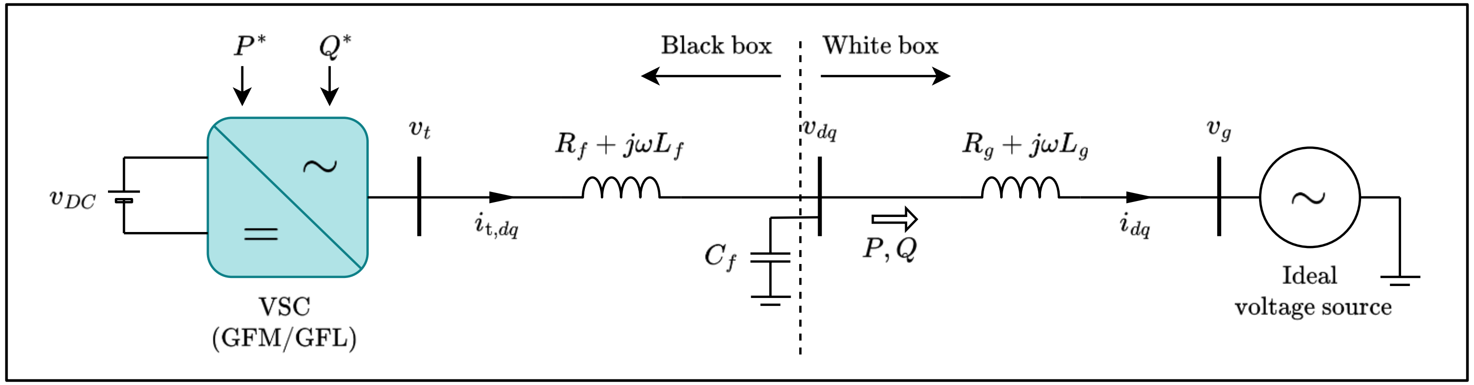
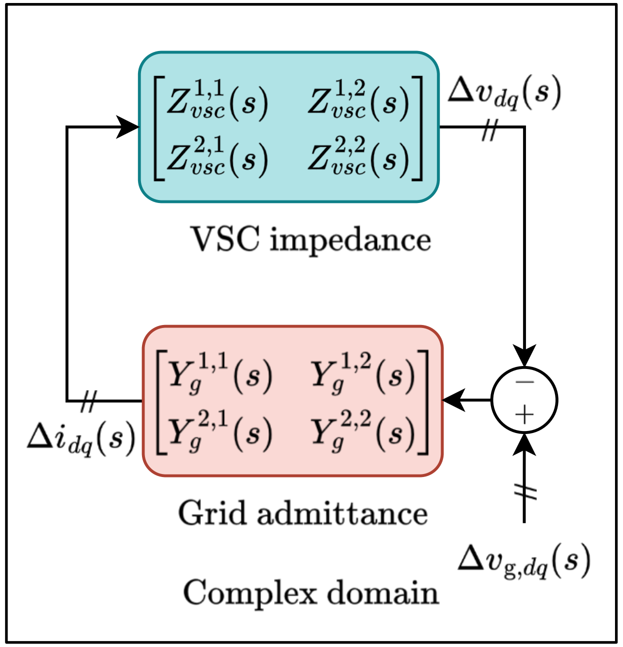


Figure: Nyquist plot of frequency responses

- Impedance-based stability is a natural choice for black-boxed system, because:
  - Detailed state-space models are **not required**
  - Frequency responses are **utilized** for stability conclusion





VSC and grid connected together is simply a feedback system!

Dynamical Systems in Time and Complex Domain

- However, impedance-based analysis is relied on **transfer functions**, which suffer from **poor scalability**

→ How to achieve state-space models from transfer functions?

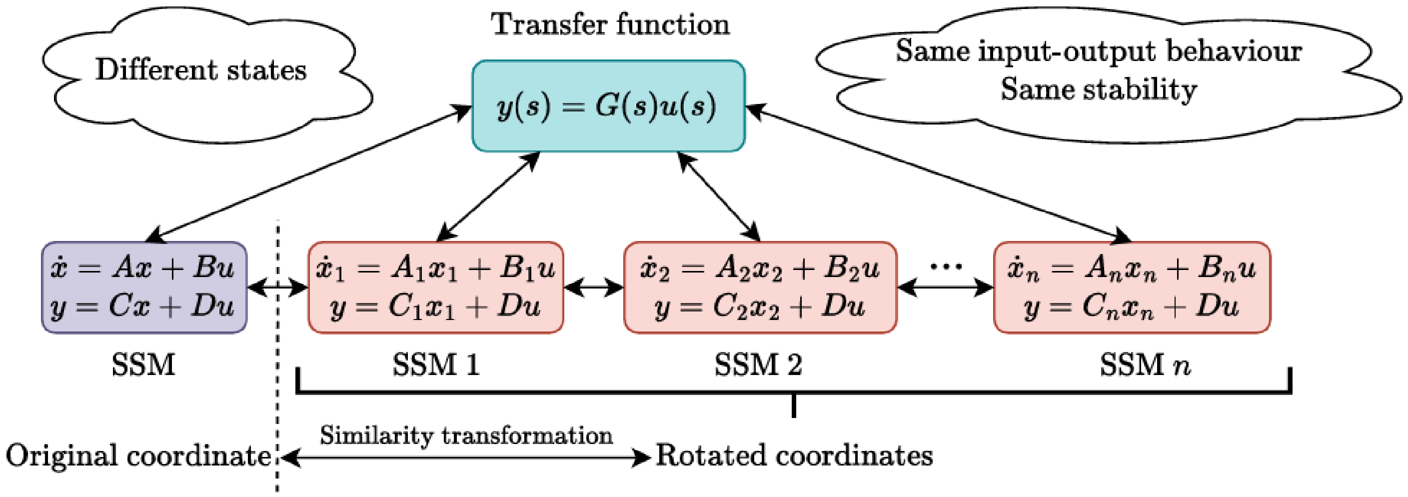


Figure: The relationship between state-space and transfer function presentations

→ Can we have state-space models from data?

Frequency response measurement

- General approach: Input an **excitation signal** to the object → Measure the responses → Convert to frequency domain by **DFT**

→ Most common signals (multisine or PRBS) are **periodic**

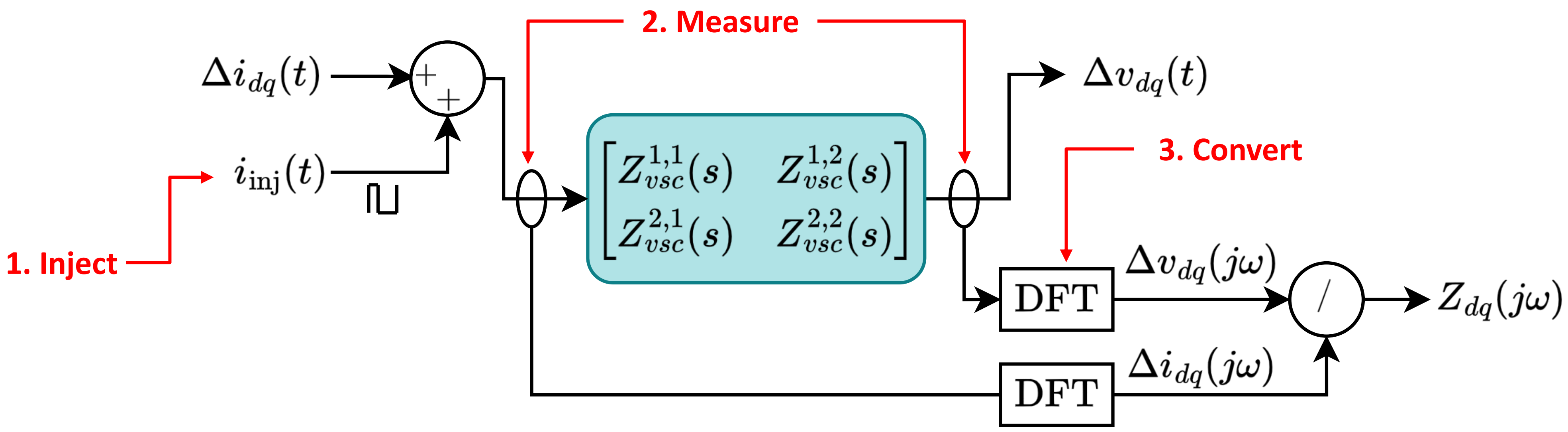
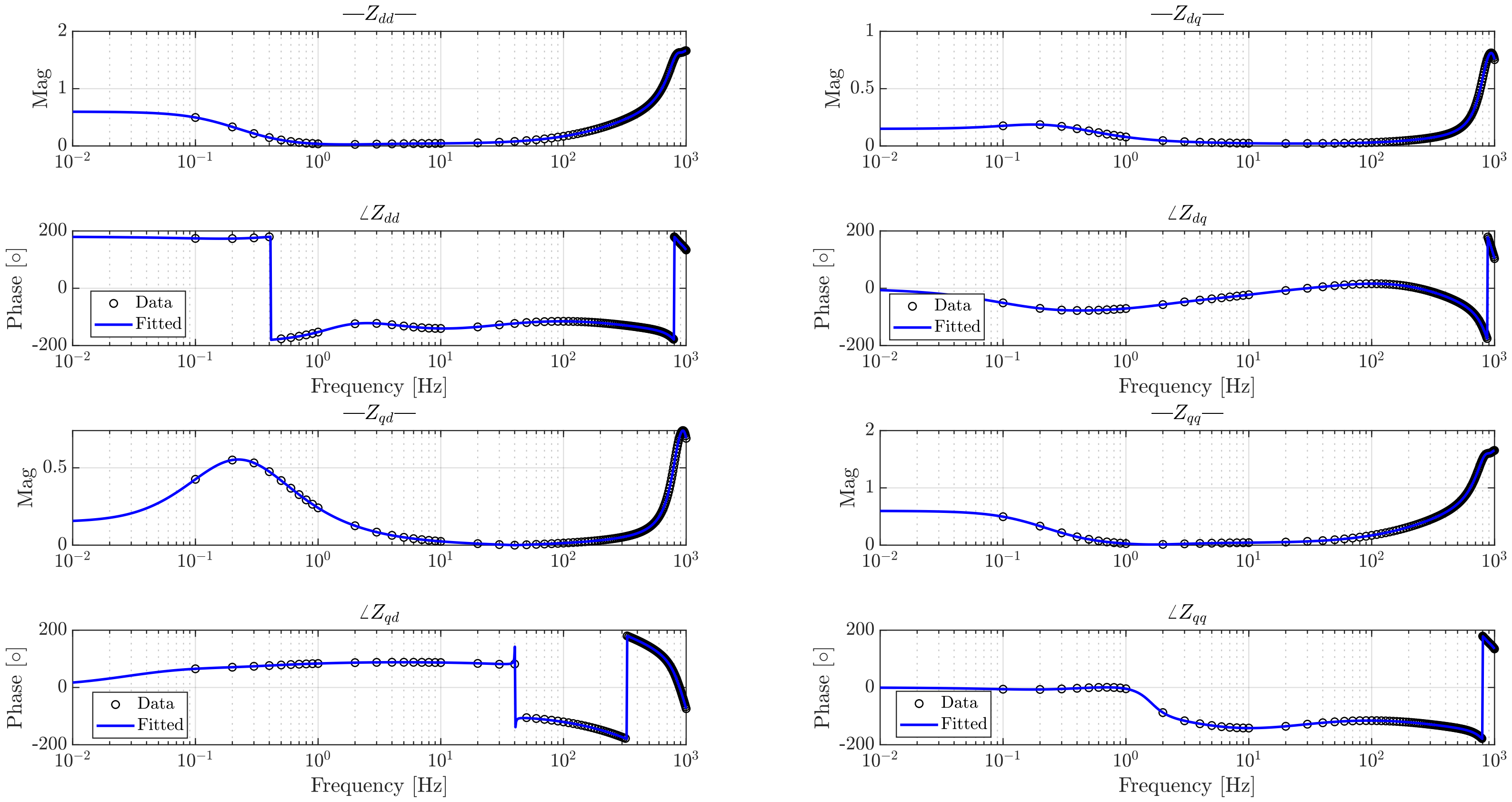


Figure: Frequency response estimation using Discrete Fourier Transform

Estimate tranfer function from data

- Given frequency response **at a set of points**, we seek for transfer function **which fits those points**



Black dots – frequency response data ***Blue line – fitted model***

Convert and connect systems

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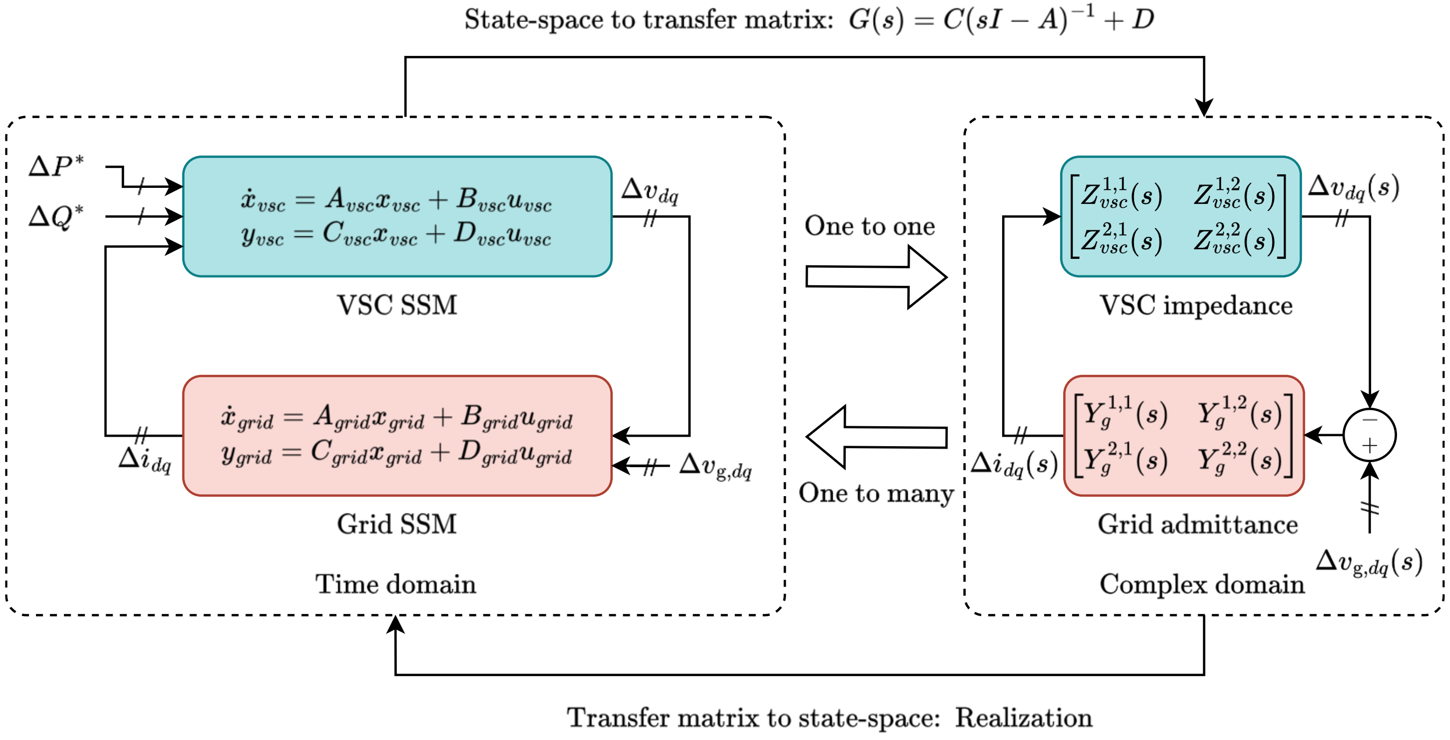
- The transfer function is converted to state-space using **realization techniques**
- Large system is achieved by **connecting** smaller subsystems (i.e. using Component Connection Methods)



General framework for data-driven stability analysis

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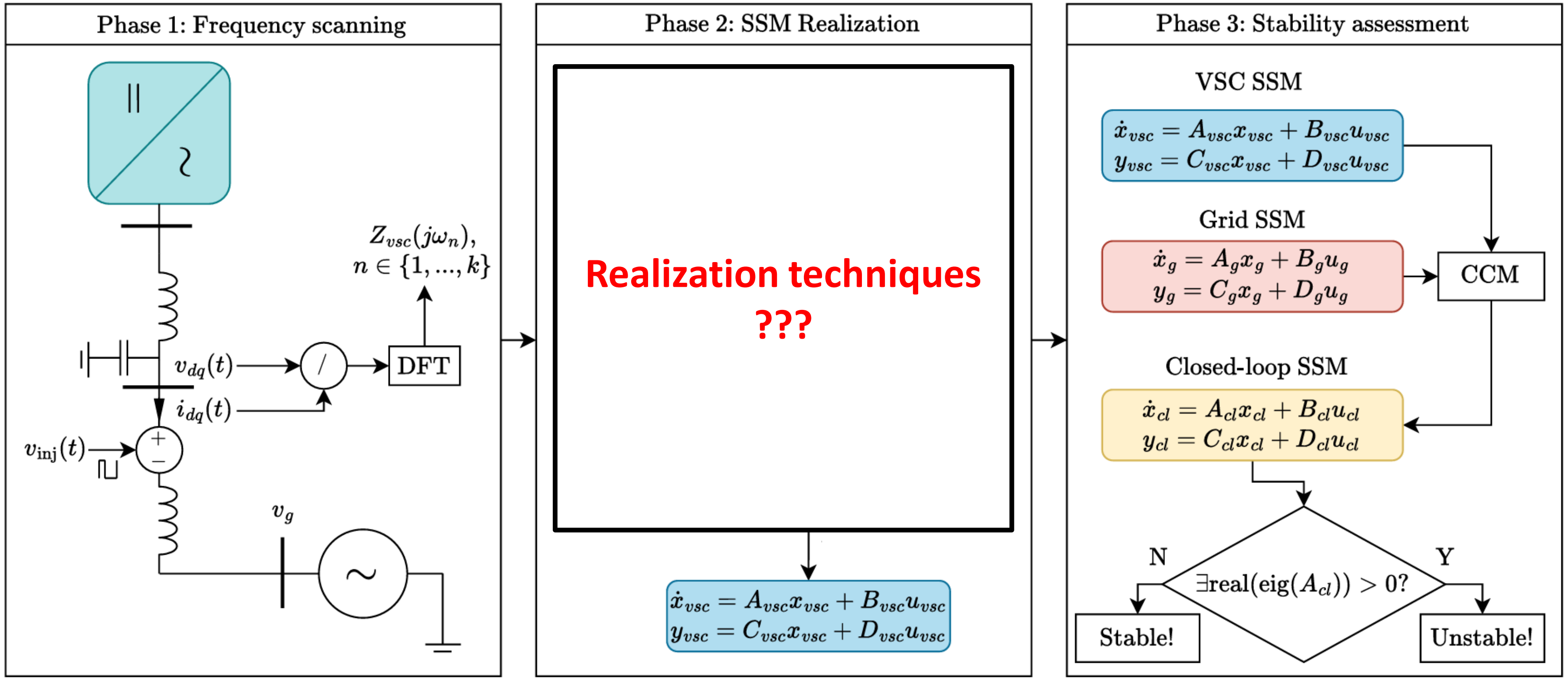
- **Phase 1:** Measure the frequency responses
- **Phase 2: Construct state-space model based on response data**
- **Phase 3:** Stability assessment using eigenvalues



Realization technique: Tangential matching?

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- Seeks for a state-space realization [E,A,B,C,D] or G(s) satisfying left and right matching condition.
- In a nutshell, this method try to **match exactly** the frequency responses at some **predefined frequency and direction**.

✔ Strong and rigorous mathematical conditions

✘ Sensitive to noises

→ Need **robust and adaptive** approaches.

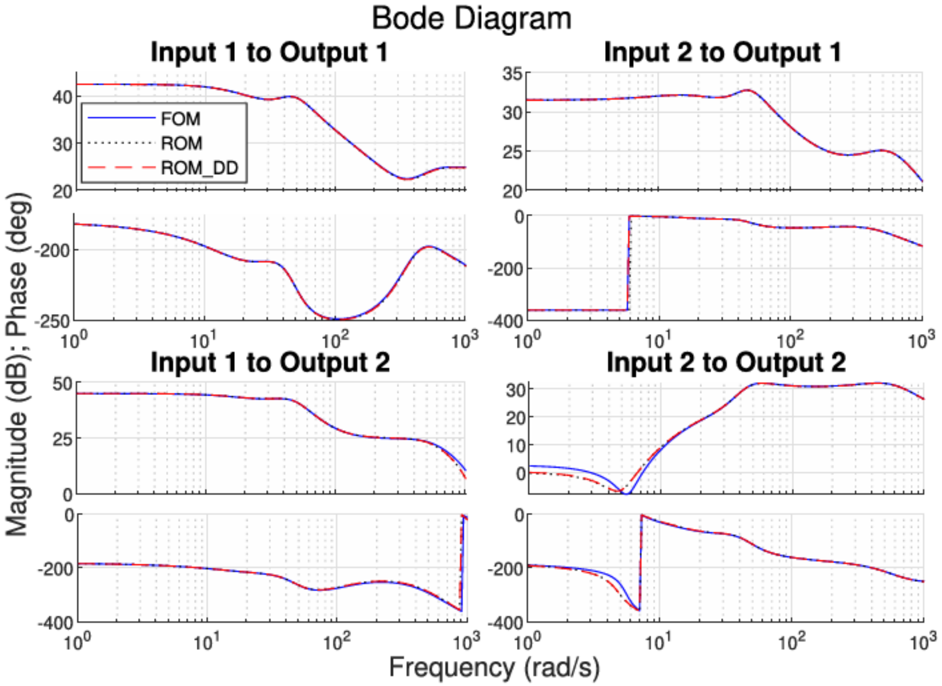

*Figure: Moment matching for model reduction for large wind farm**

** Z. Gong, J. Mao, A. Junyent-Ferré and G. Scarciotti, "Model Order Reduction of Large-Scale Wind Farms: A Data-Driven Approach," in IEEE Transactions on Power Systems, 2025*

- **Problem 1: Operating-point dependent models?**

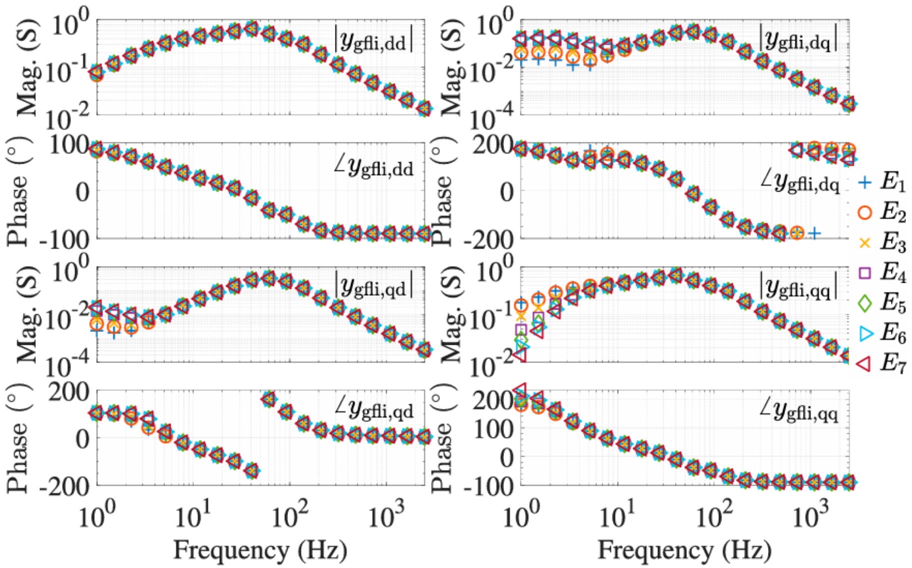

*Figure 1: Varying frequency response by operating points**

- **Problem 2: Multi-port connection?**

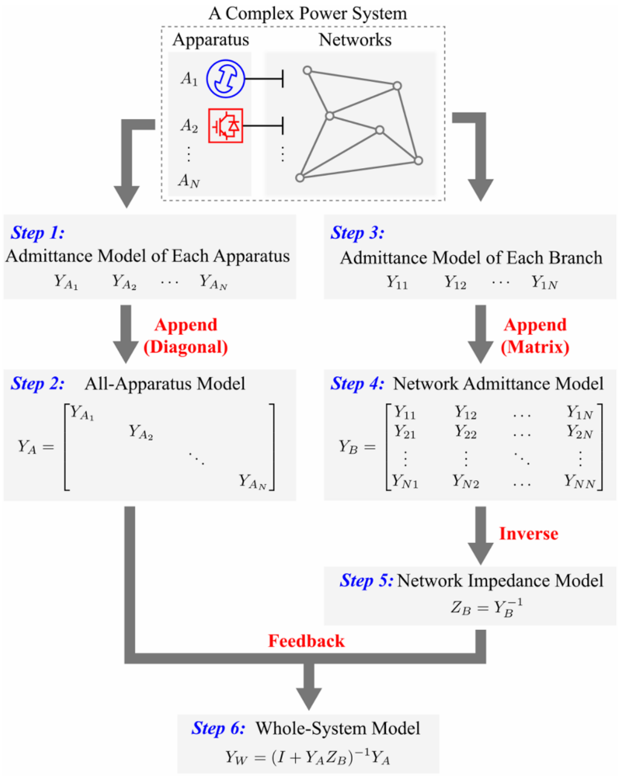

*Figure 2: Connect machines and grid using desciptor models***

** 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, 2024*

*** Y. Li, T. C. Green and Y. Gu, "Descriptor State Space Modeling of Power Systems," in IEEE Transactions on Power Systems, 2024*

Thank you for listening!

Let seek for reliable and scalable model from data!