IMPERIAL
Department of Electrical
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Data-Driven Geometric Identification of Operating-Point-Induced Changes in Modal Structure of Black-Box IBRs

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Introduction and Motivation

Detailed IBR models are often unavailable, and only black-box representations are accessible at **specific operating points**.

Data-driven methods are promising, but operating condition variations can induce **changes in system structure**, altering system dynamics.

This work identifies structural changes using a **geometric parametrisation** of the **singular value decomposition** (SVD), enabling the detection of **structurally coherent** operating regions.

Geometric parametrisation

Using the SVD, the continuity of a transfer function due to a parameter change α can be expressed as

$$\Delta \mathbf{G}_\alpha(j\omega) = \mathbf{U}_\alpha \Big[\mathbf{\Sigma}_\alpha - \underbrace{(\mathbf{U}_\alpha^H \mathbf{U}_0)}_{U\text{-alignment}} \mathbf{\Sigma}_0 \underbrace{(\mathbf{V}_\alpha \mathbf{V}_0^H)^H}_{V\text{-alignment}} \Big] \mathbf{V}_\alpha^H$$

Then, the **continuity** and **smoothness** of a transfer function depends on:

- **Variations** in the singular values
- **Alignment** of the left- and right-singular vectors

Similar structural conditions lead to similar vector alignments

Bloch sphere of a projection matrix $\mathbf{P}_k$

$$\mathbf{r}_k(\omega) = \begin{bmatrix} x_k(\omega) \\ y_k(\omega) \\ z_k(\omega) \end{bmatrix} = \begin{bmatrix} \mathbf{P}_{k,12} + \mathbf{P}_{k,21} \\ \mathbf{P}_{k,12} - \mathbf{P}_{k,21} \\ \mathbf{P}_{k,11} - \mathbf{P}_{k,22} \end{bmatrix}$$

For a set of operating points, the singular vectors of the IBR admittance $Y(j\omega)$ define a set of projection matrices $\mathbf{P}_1$ and $\mathbf{P}_2$

↓

Each projection can be mapped onto the surface of a unit **Bloch sphere**, yielding trajectories $\mathbf{r}_1$ and $\mathbf{r}_2$

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A combined geometric trajectory can then be defined as a weighted superposition of the two singular trajectories

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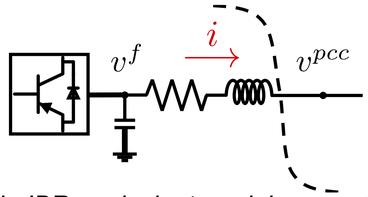
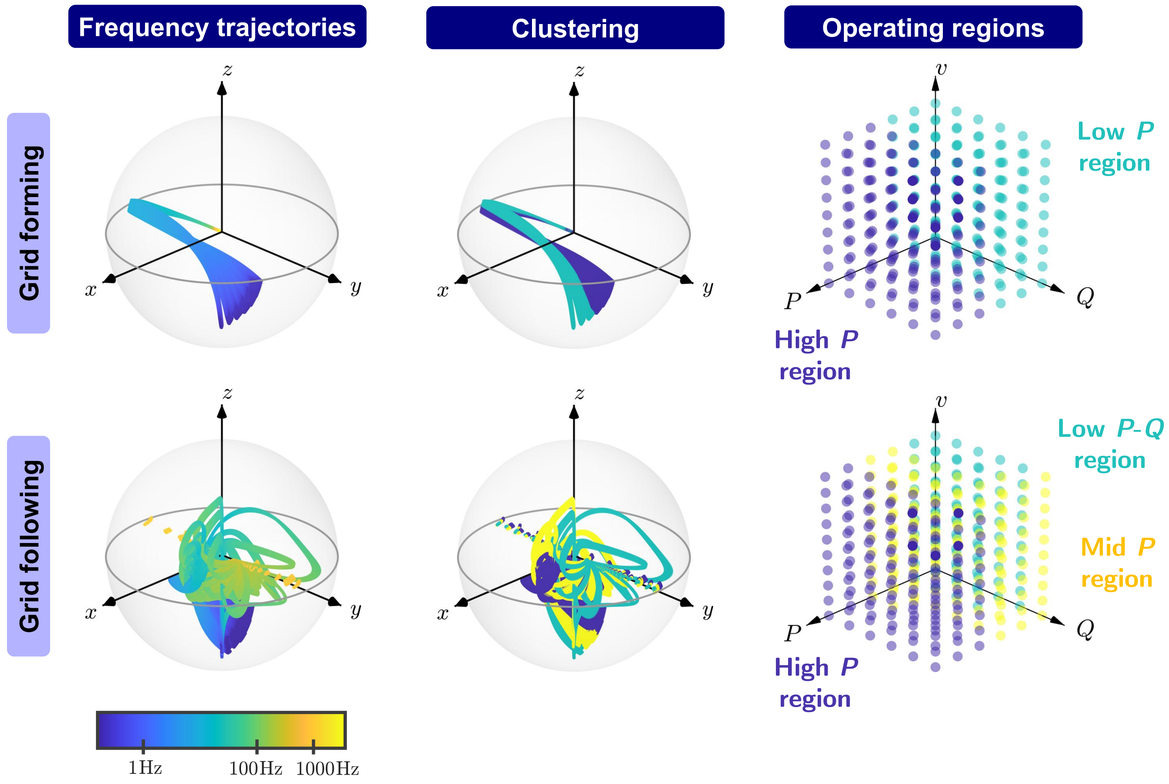
Clustering of modal trajectories based on the geometric trajectories and singular values

Study case and results



Single IBR equivalent model connected to the grid through a coupling impedance

- **Control modes:** Grid following and grid forming
- **Frequency scan range:** 0.15 - 3500 Hz
- **Operating conditions:** 324 combinations of (P, Q, V)



Applications

- **Identification** of coherent dynamic operating regions and system sensitivities
- **Enhanced data-driven** estimation of IBR models via dataset partition