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Modeling and Control of Solar PVs for Large Grid Disturbances and Weak Grids

Using DQ-Domain Admittance Measurements to Tune Inverter Models

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Collaborators: Zhixin Miao, Shahil Shah, Przemyslaw Koralewicz, and Vahan Gevorgian

NASPI Work Group Virtual Meeting

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Motivation

- Historically, frequency-domain measurements have been used to find out synchronous generator's dq-axis reactances' transfer function (Krause' book, Chapter 7.8)

- Starting from the dq-frame model developed in [1, 2], **can we tune the model structure to match the DQ admittance frequency response**?

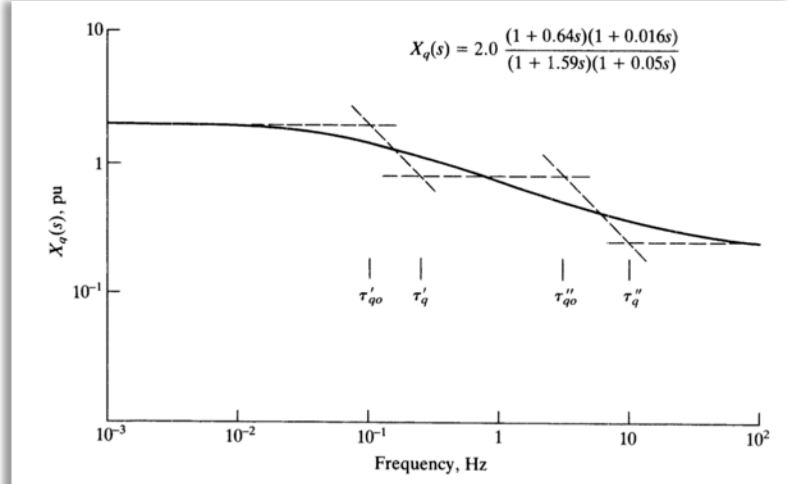
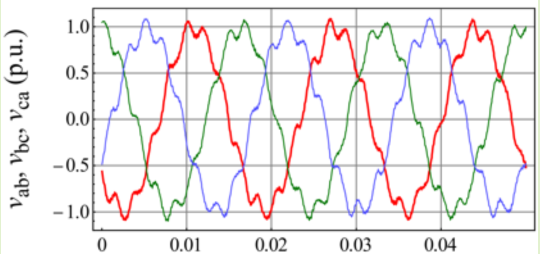
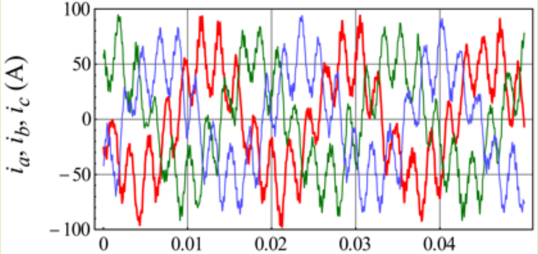
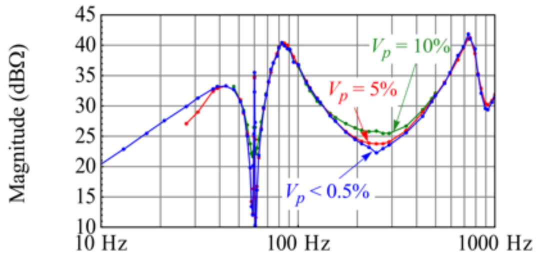


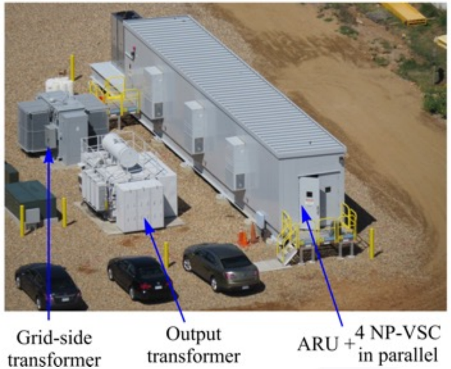
Figure 7.8-2 Two-rotor winding approximation of $X_q(s)$.

1. L. Fan, " **Modeling Type-4 Wind in Weak Grids**," TSTE 2018. DOI: 10.1109/TSTE.2018.2849849
2. M. Zhang, Z. Miao, L. Fan, "**Reduced-Order Analytical Model of Grid-Connected Solar Photovoltaic Systems for Low-Frequency Oscillation Analysis**," TSTE 2021. DOI: 10.1109/TSTE.2021.3061296

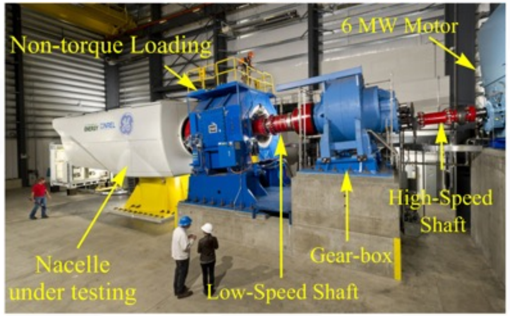
Impedance Measurement System at NREL

Injection of Perturbation in Turbine Voltages	Response in Turbine Output Currents	Measured Impedance of a 4 MW Wind Turbine
		

7-MVA grid simulator



5-MW dynamometer



Medium-voltage sensing

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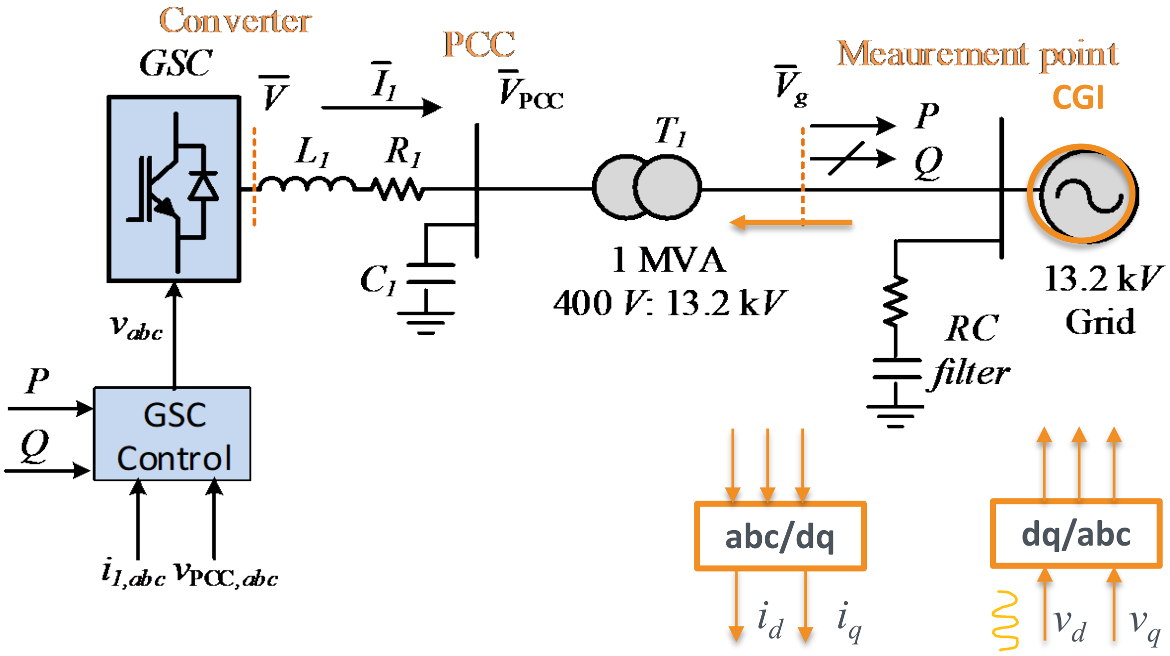
Measure a 2.3-MVA grid-following inverter



CGI: Controllable Grid Interface

DQ-domain: grid voltage at 1 pu 0.

Case 1: P=0 kW, Q=0kVAr

Case 2: P =500 kW, Q=0 kVAr

Case 3: P =0 kW, Q=500 kVAr

Case 4: P =1000 kW, Q=0 kVAr

$$\begin{bmatrix} \bar{I}_d \\ \bar{I}_q \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{dd}(j\omega) & Y_{dq}(j\omega) \\ Y_{qd}(j\omega) & Y_{qq}(j\omega) \end{bmatrix}}_{Y^m_{dq}(j\omega)} \begin{bmatrix} \bar{V}_d \\ \bar{V}_q \end{bmatrix}$$

Lingling Fan, Zhixin Miao, Przemyslaw Koralewicz, Shahil Shah, and Vahan Gevorgian, **"Identifying DQ-Domain Admittance Models of a 2.3-MVA Commercial Grid-Following Inverter Via Frequency-Domain and Time-Domain Data,"** *IEEE TEC 2020.* pdf

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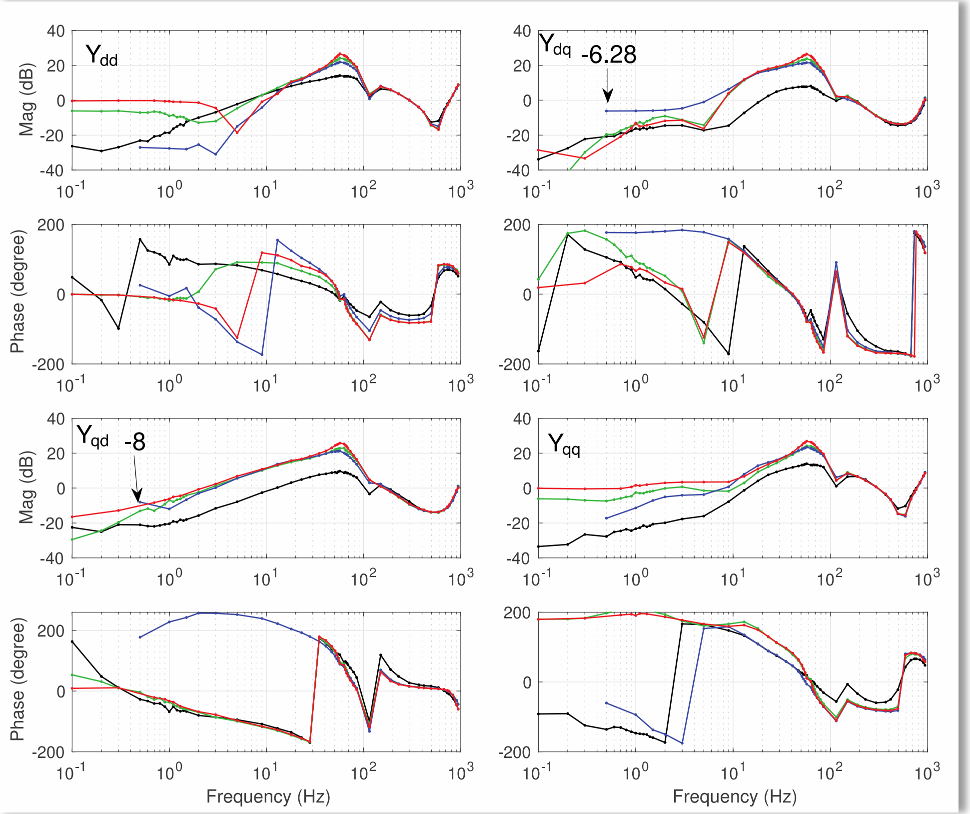
Insight 1: low-frequency range vs. PQ



$$\mathbf{Y}_{\mathrm{VSC}} = \frac{1}{V^2}\begin{bmatrix} P & -Q \\ -Q & -P \end{bmatrix}$$

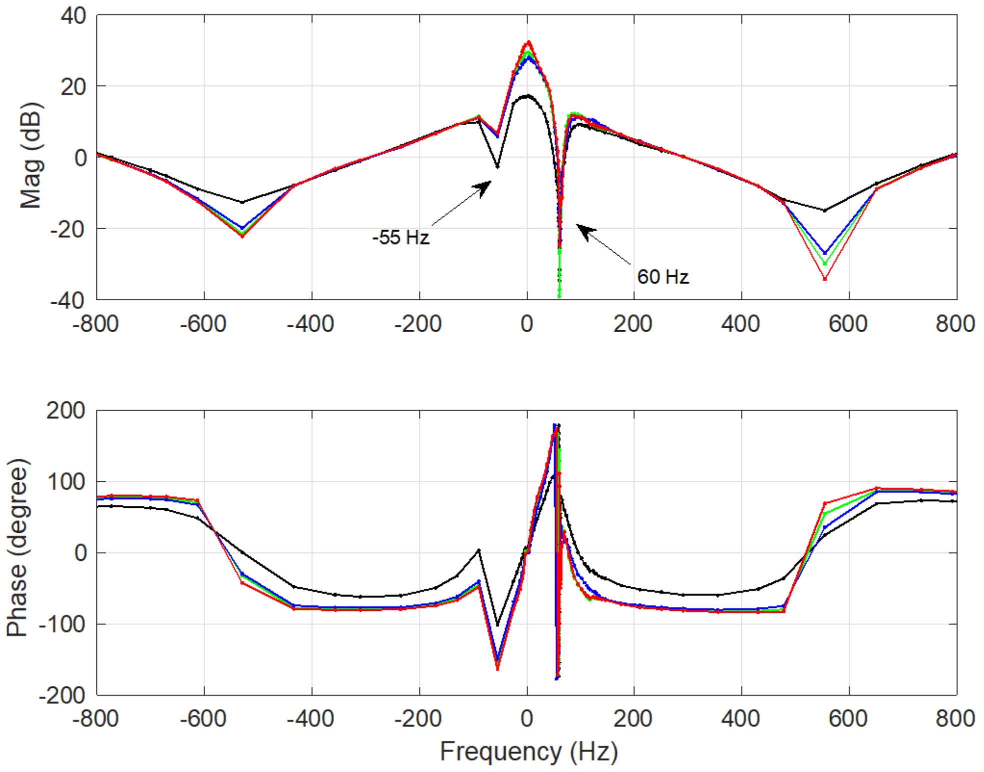
For PQ following control, the p.u. admittance in the low-frequency range (assuming the dq-frame aligned to the PCC voltage) is analytically derived.
Measurements match the analytical results.

Y gives information on operating conditions.

Case 1: P =0, Q=0
Case 2: P = 0.5 (-6 dB) , Q=0
Case 3: P =0, Q= 0.5 (-6 dB)
Case 4: P =1 (0 dB), Q=0

Insight 2: unbalanced control is included

Admittance viewed from the static abc frame.



At 60 Hz normal operating condition, the inverter acts as a current source. The shunt admittance is very small.

At -60 Hz (negative sequence), the inverter tries to suppress the -60 Hz current. Thus, it can be reasoned that unbalance control is included.

In dq-admittance, this is reflected **as dips at 120 Hz**.

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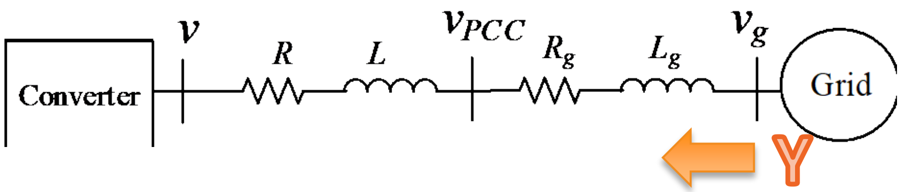
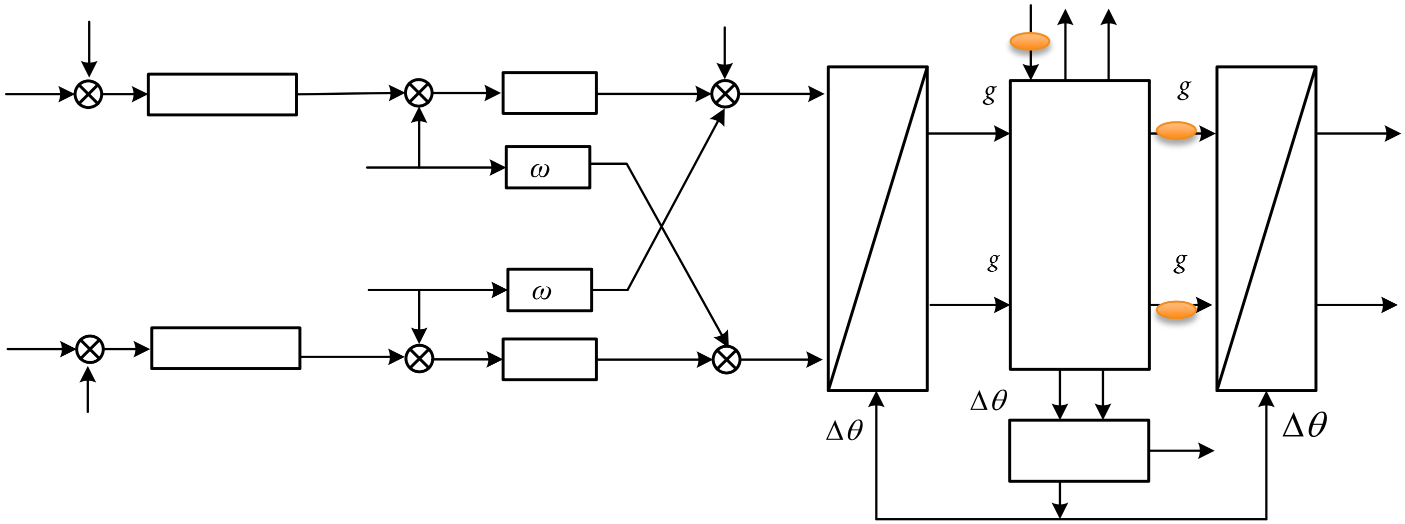
The analytical model to start from





1. L. Fan, " Modeling Type-4 Wind in Weak Grids," TSTE 2018. DOI: 10.1109/TSTE.2018.2849849

Initial comparison

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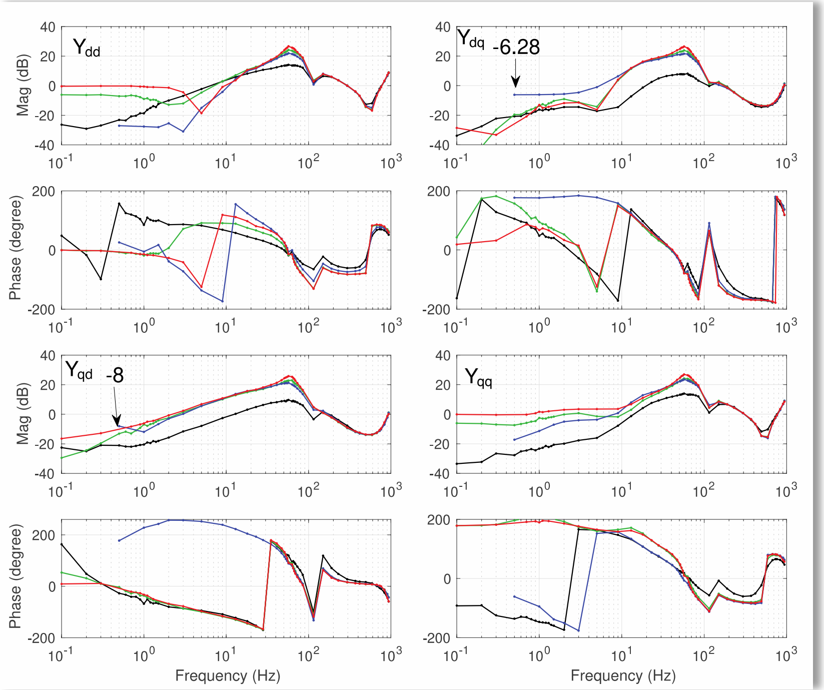

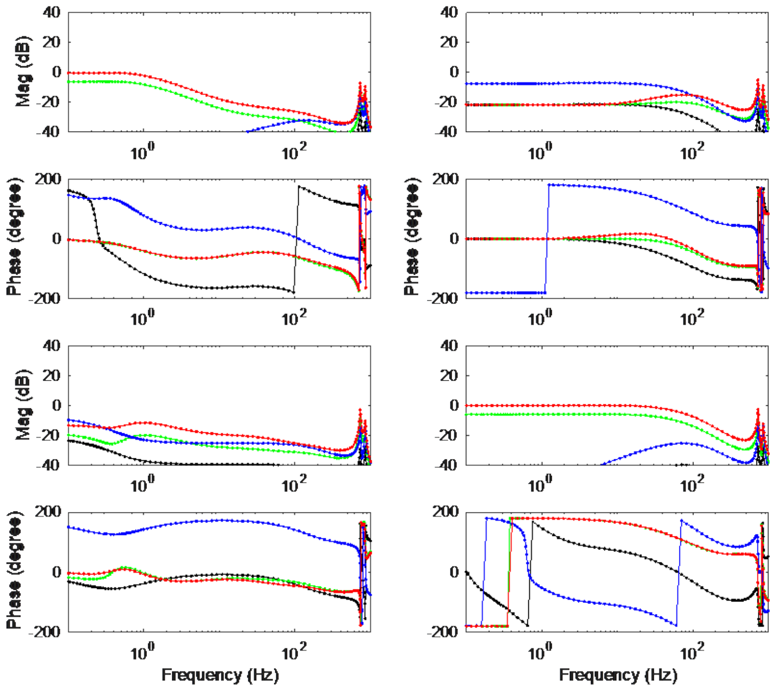

<1 Hz, match. The rest of the frequency responses (model versus CGI measurements) are not even remotely alike.

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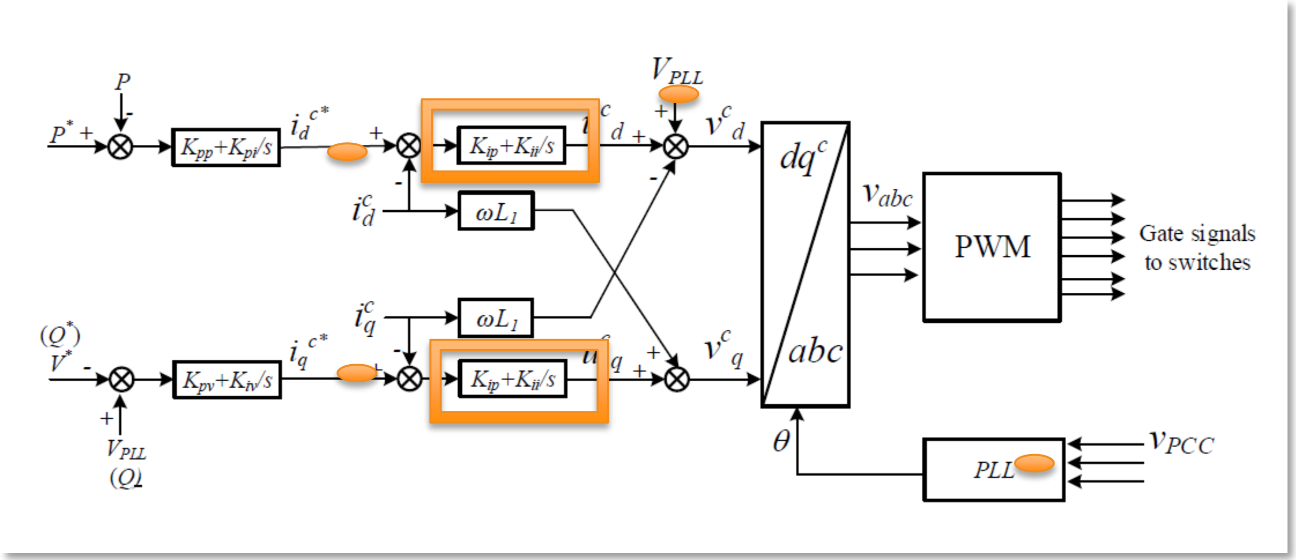
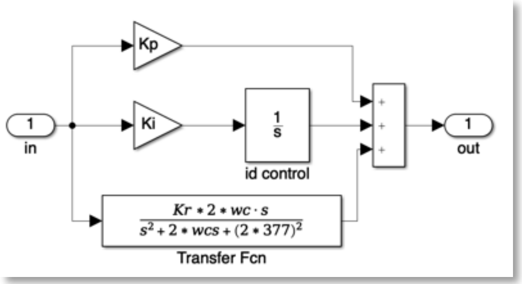
What should be the inverter model?



Unbalanced current control

- PI becomes PI+R



Starting from the dq-frame model, add low-pass filters in

- voltage feed forward (VFF)
- outer control
- phase-locked loop (PLL)

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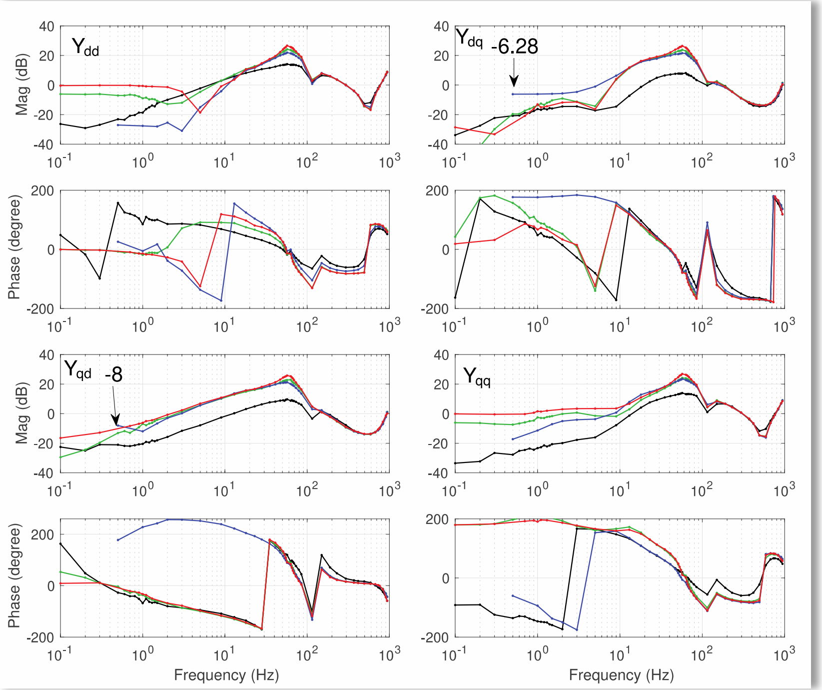
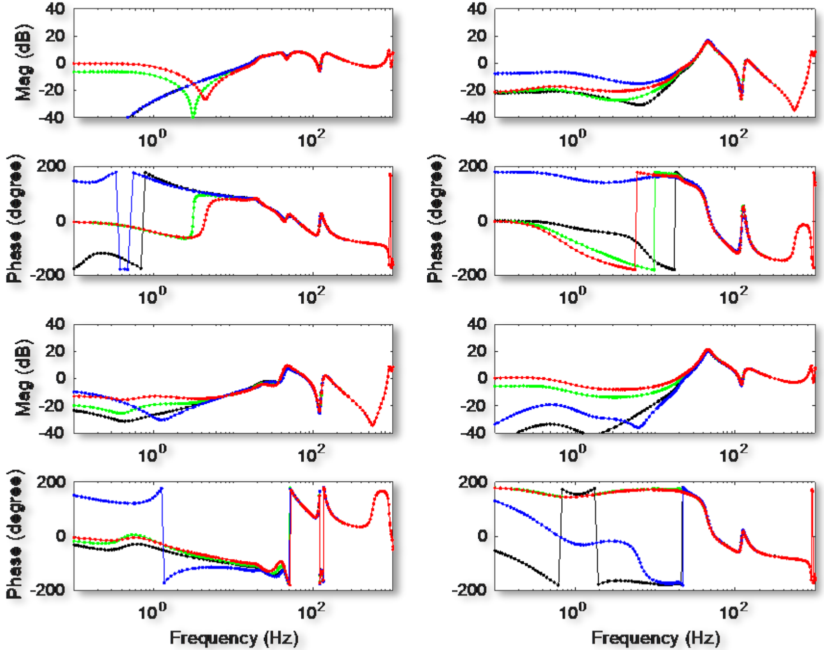
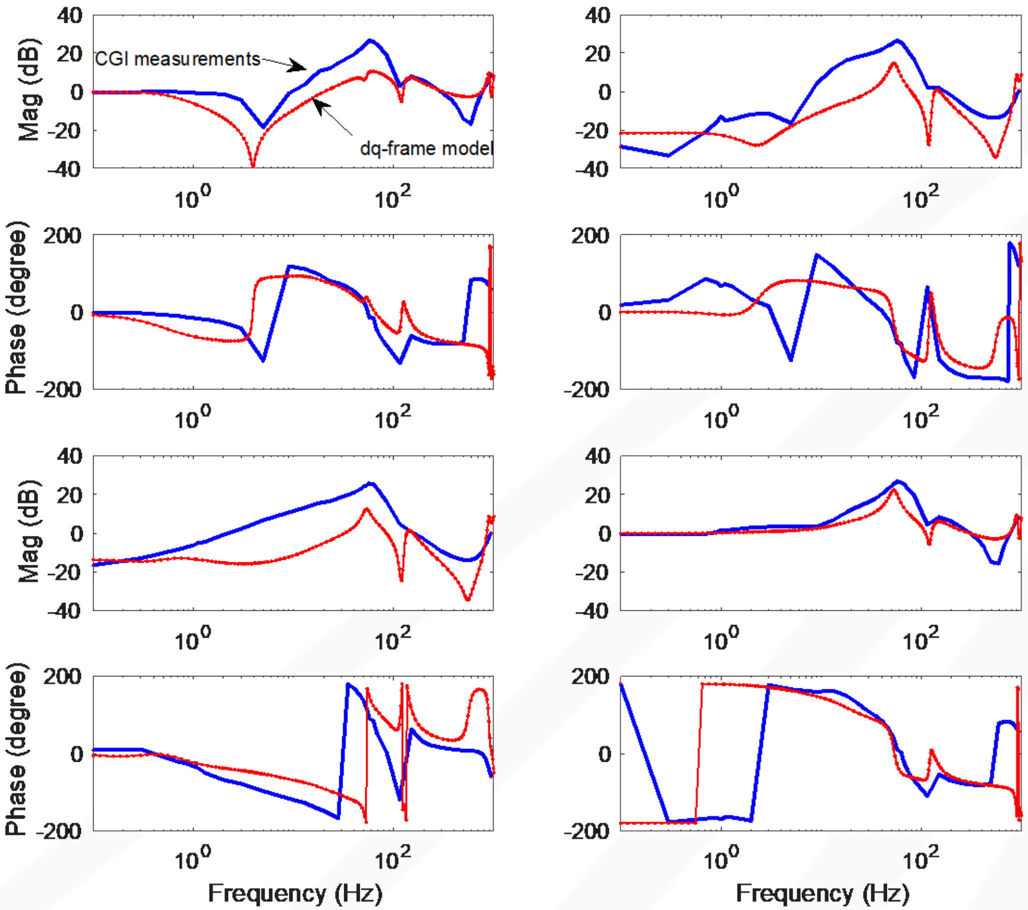
Left: CGI measurements; Right: model





Comparison

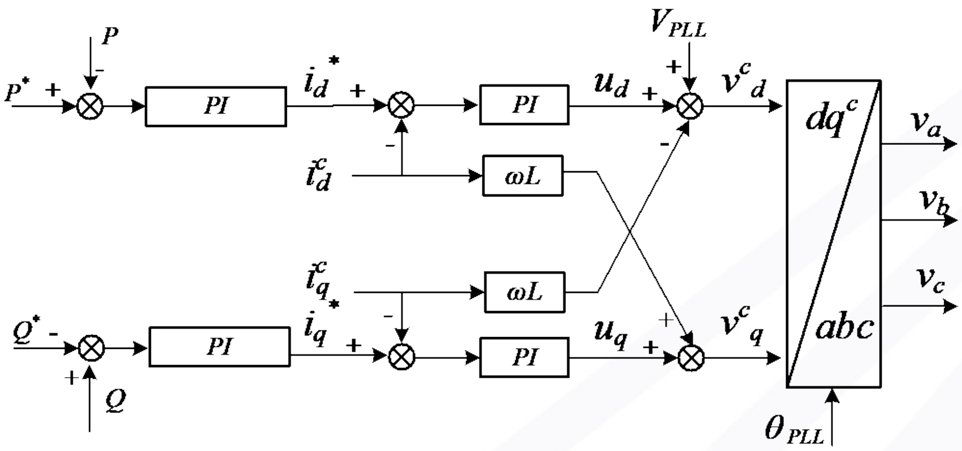


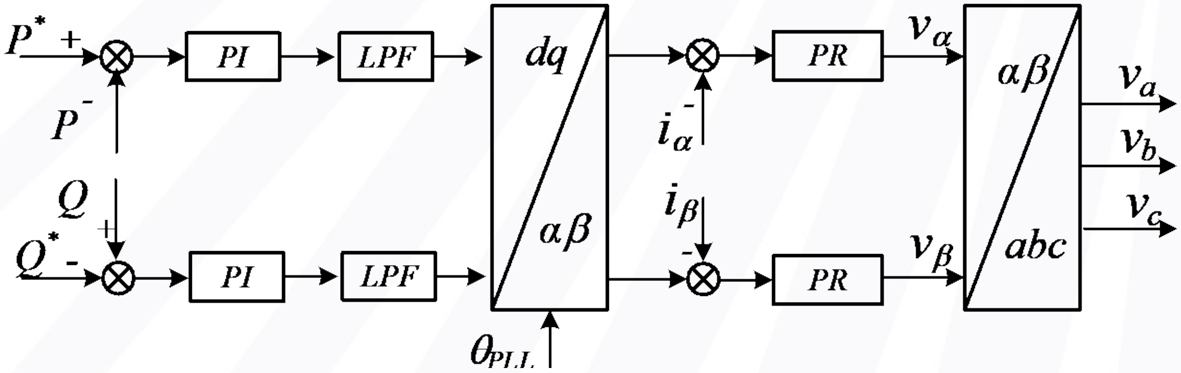
Y_{dd} can not reach over 25-30 dB (17-32).

This means that for a small voltage dip, the d-axis current will show large change (mode is about 60 Hz).

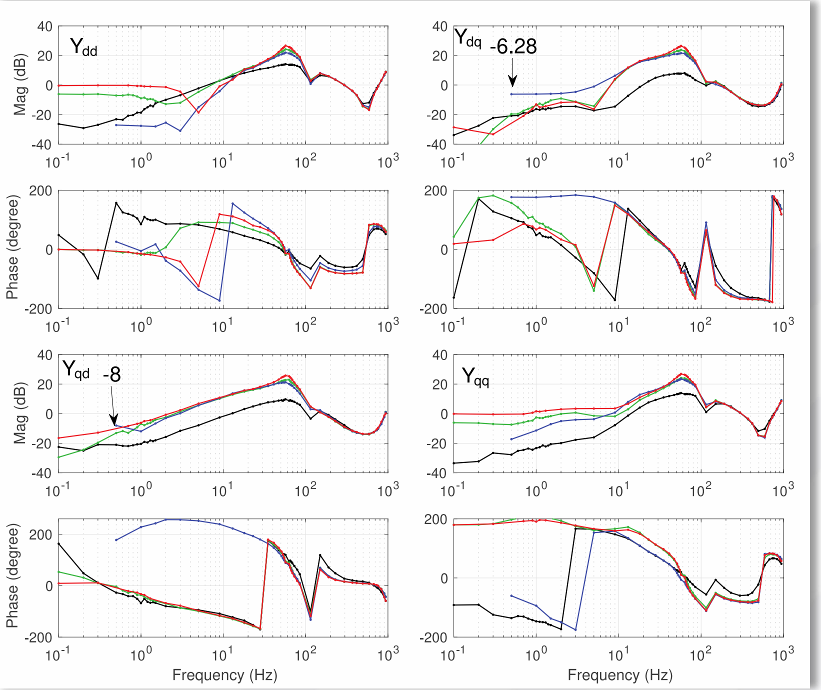
D-axis current reflects current magnitude if Q is 0.

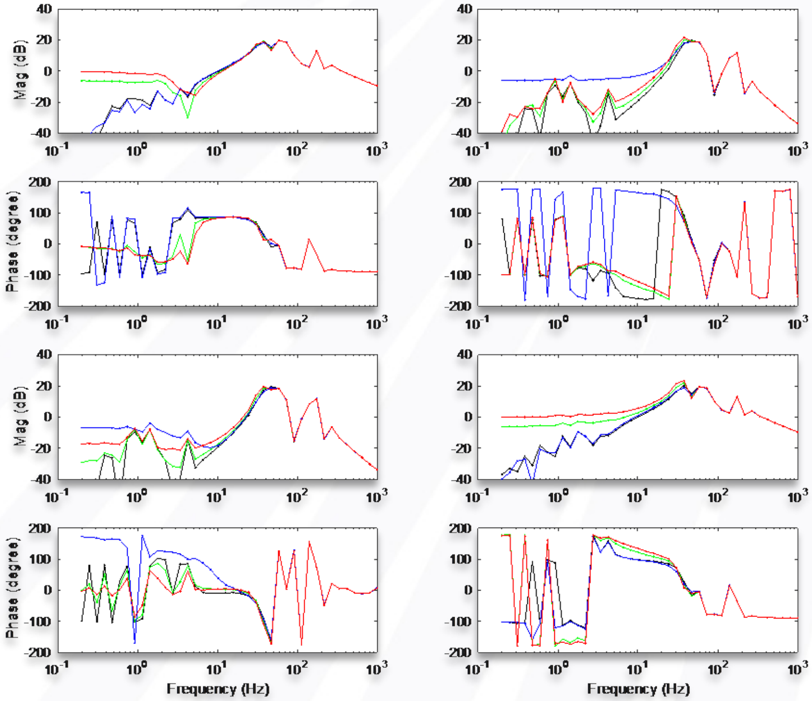
Change current control: dq-frame→αβ-frame





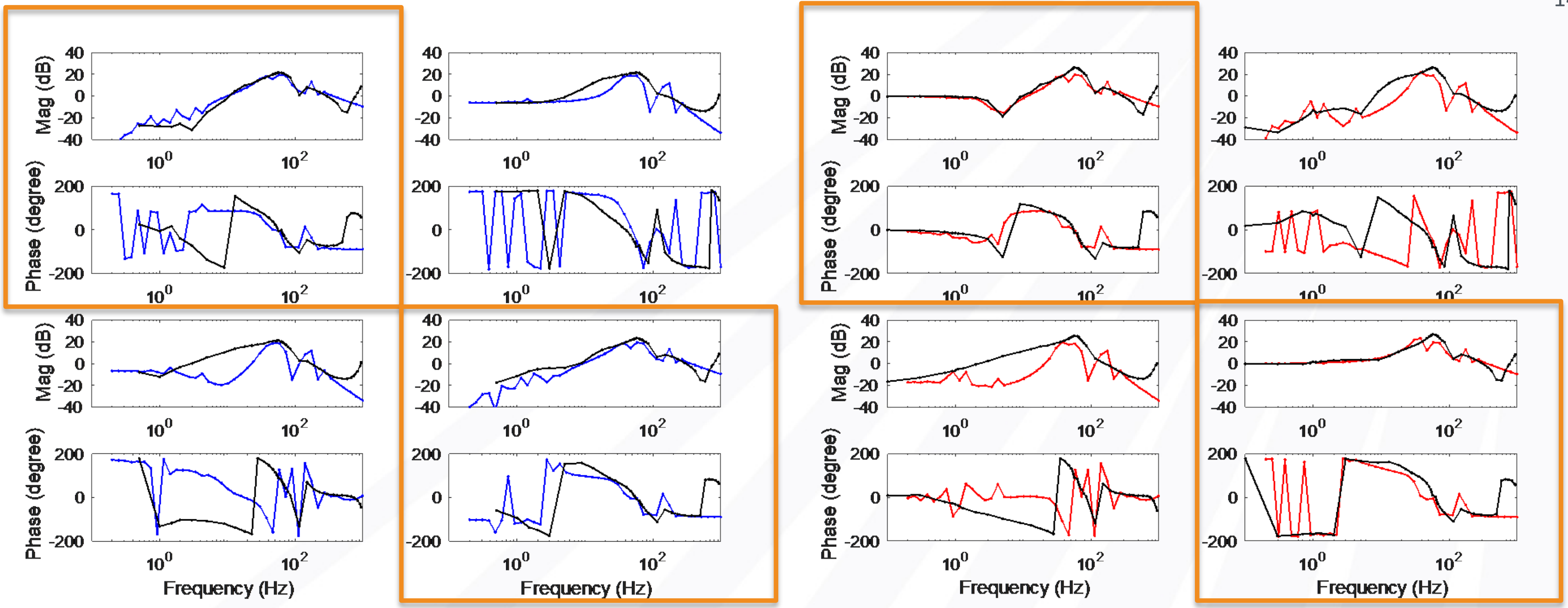
Change to static-frame resonant control





The model is built in the abc-framework. Linearization is no longer possible. We use sinusoidal injection for frequency-domain measurement of 40 points from 0.2 Hz to 1000 Hz. **Computing time: 1 ~ 2 hours**.

Ydd, Yqq match pretty well

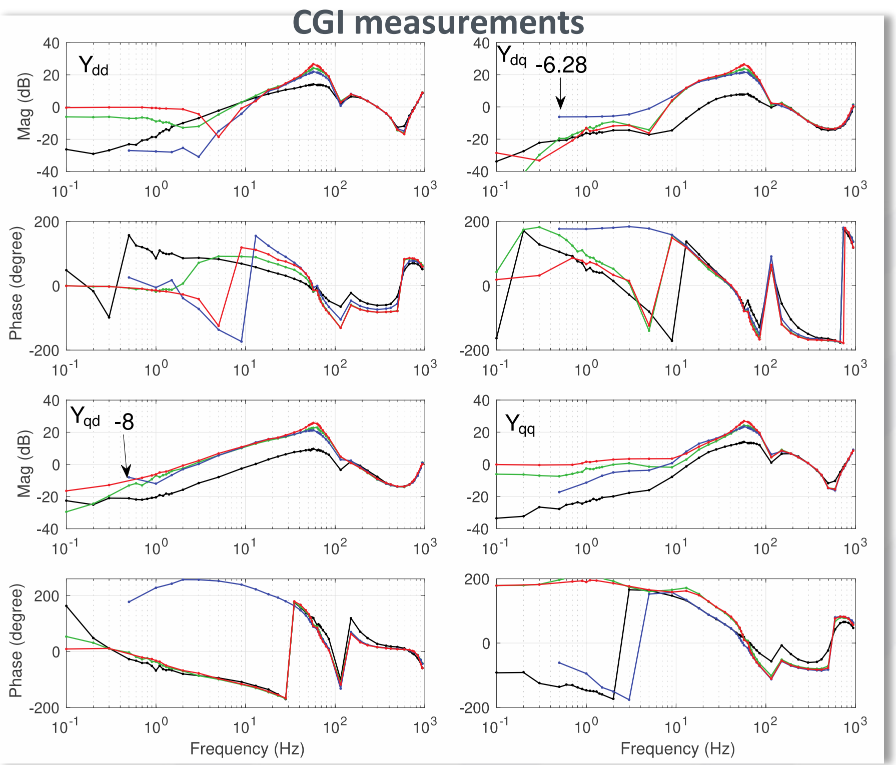


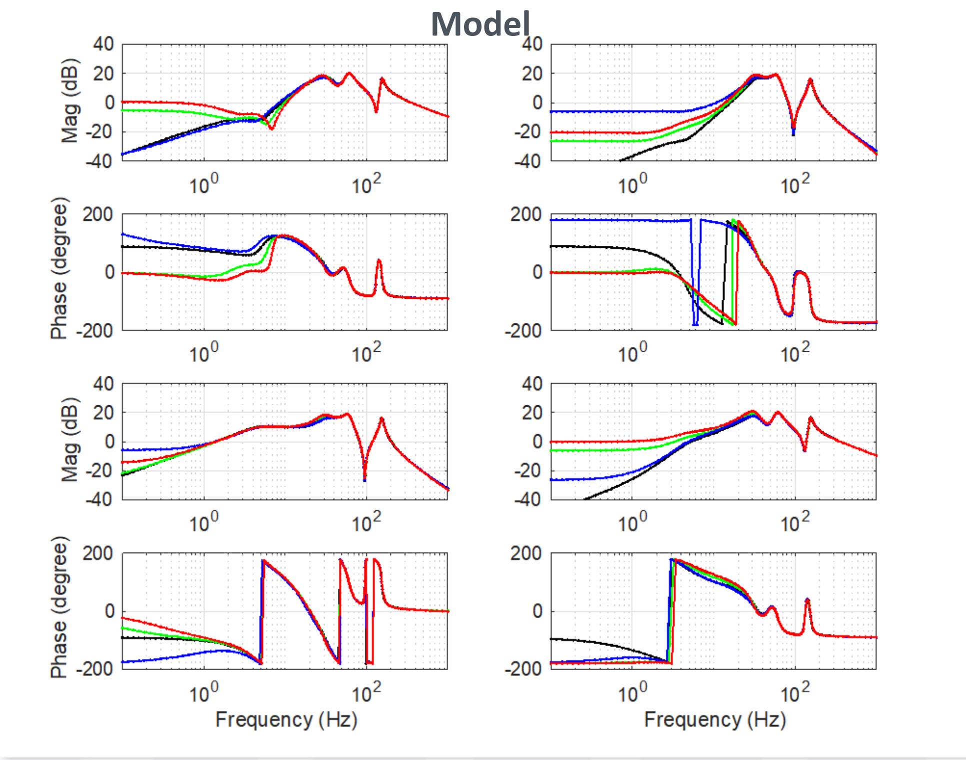
Black: CGI measurements.

Blue and red: Model

Y_{dq}, Y_{qd} need to be further matched after tuning V/Q control structure and parameters.

Tune the q-axis outer-control structure



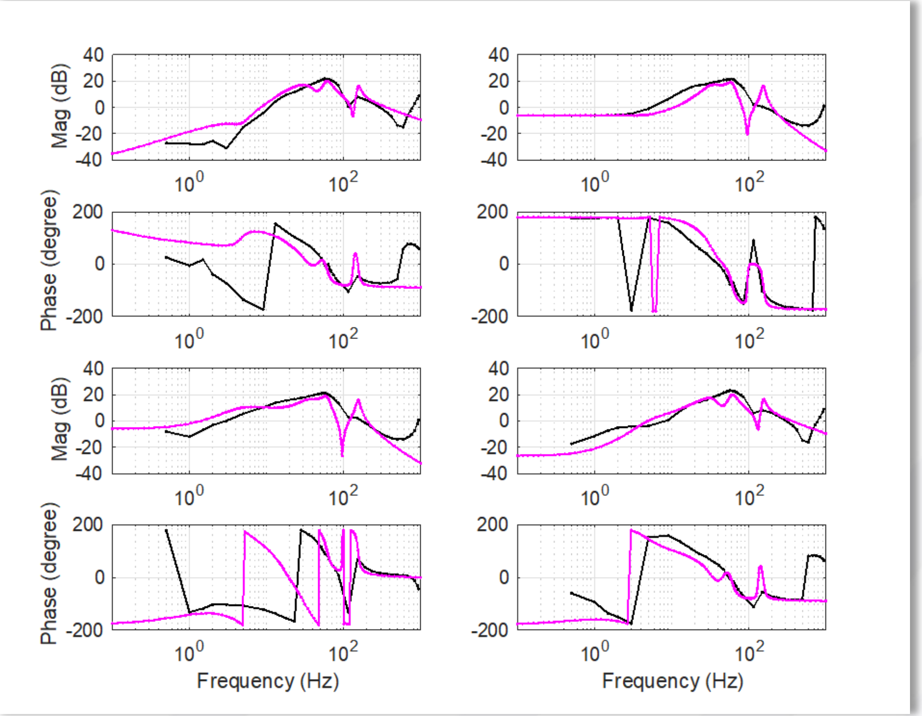


A faster approach: step response data (5 minutes)

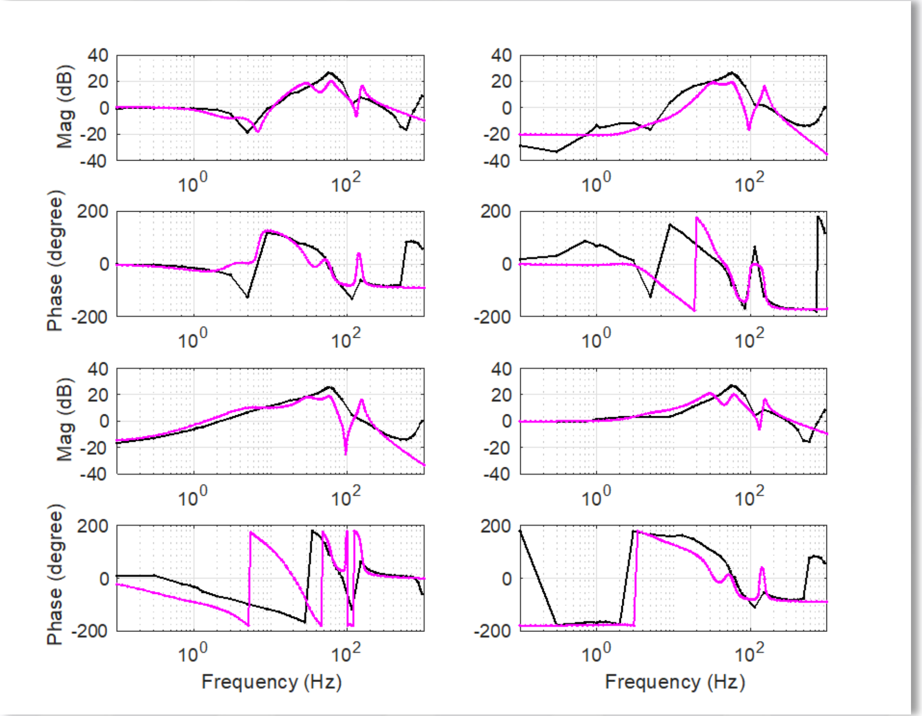
•L. Fan and Z. Miao, **"Time-Domain Measurements-Based DQ-Frame Admittance Model Identification of Inverter-Based Resources,"** *accepted, IEEE trans. Power Systems*. pdf

Comparison

Case 3: P =0 kW, Q=500 kVAr



Case 4: P =1000 kW, Q=0 kVAr



Black: CGI measurements.

Magenta: Model

Concluding remarks

- Frequency-domain measurements from 0.1 Hz to 1000 Hz provide a wide range of dynamic characteristics of an inverter.
- Insights from the measurements help tune the model structure as well as parameters.
- What are the lessons learnt?
  - Models can be built based on first principles and they need to be tuned using data.
  - Efficient DQ-domain admittance characterization tool is necessary for model tuning.
  - For a given model structure, it will be great to have a tool to optimize parameters, aka, IBR Gray-Box Model Identification Toolbox (NSF award 2103480).