Measuring Commercial Wind Turbine Impedances for Stability Analysis

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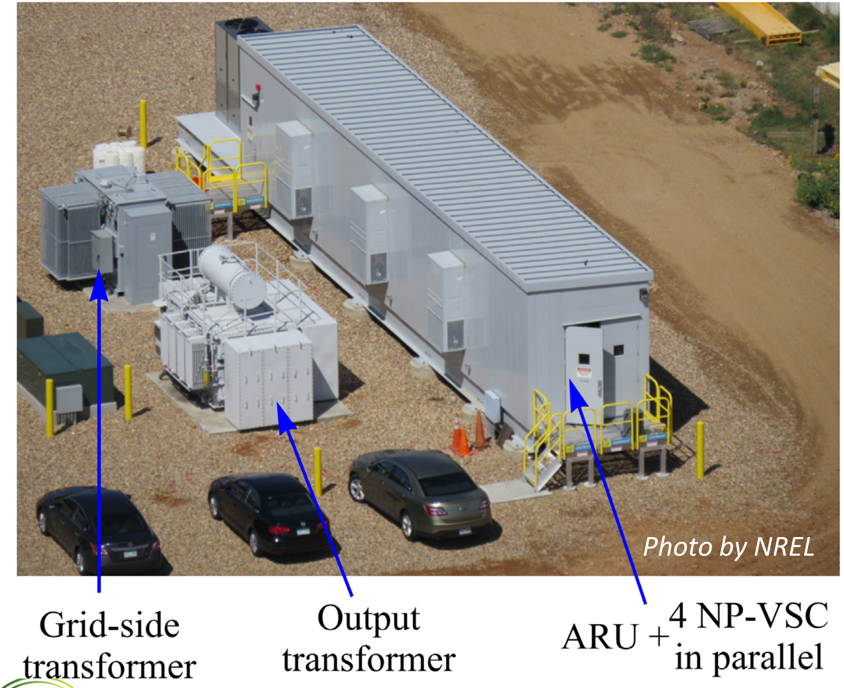
Outline

- Impedance measurement system at NREL:
  - Grid simulator, dynamometer, medium-voltage data acquisition
- Sequence impedance measurement:
  - Reference frame, relation with DQ impedance measurement
- Power impedance measurement:
  - Analysis of reactive power oscillations
  - Weak inductive grid provides damping.

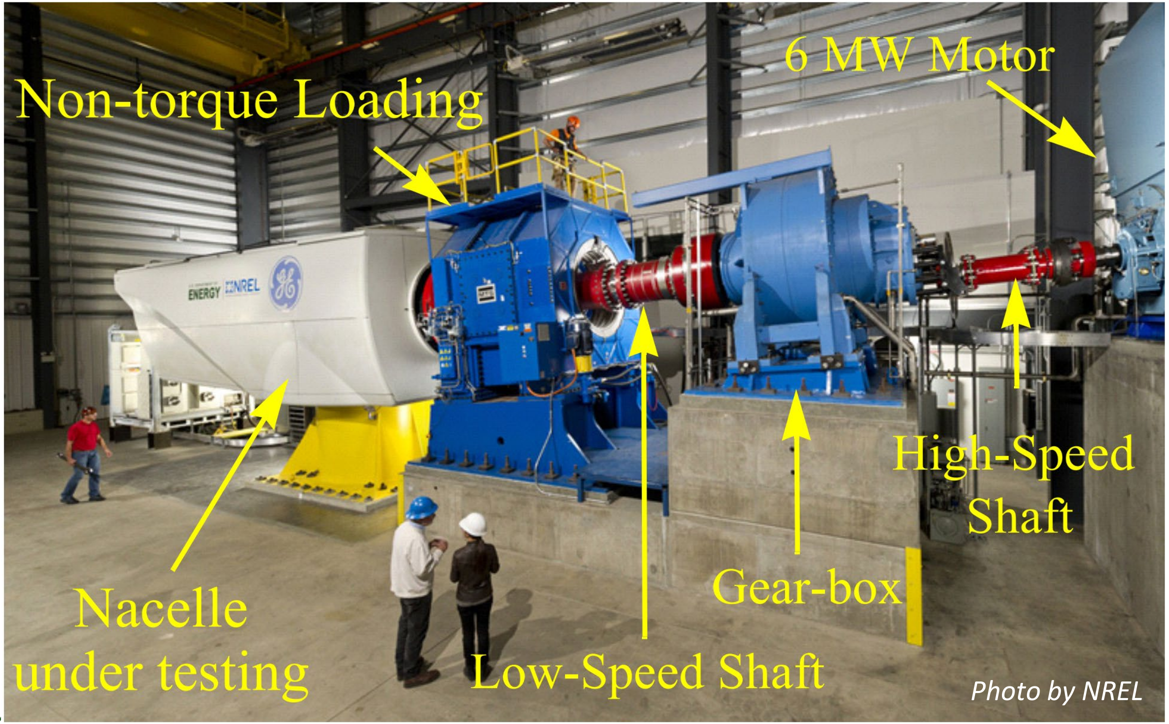
Flatirons Campus (NREL)

Grid Simulator



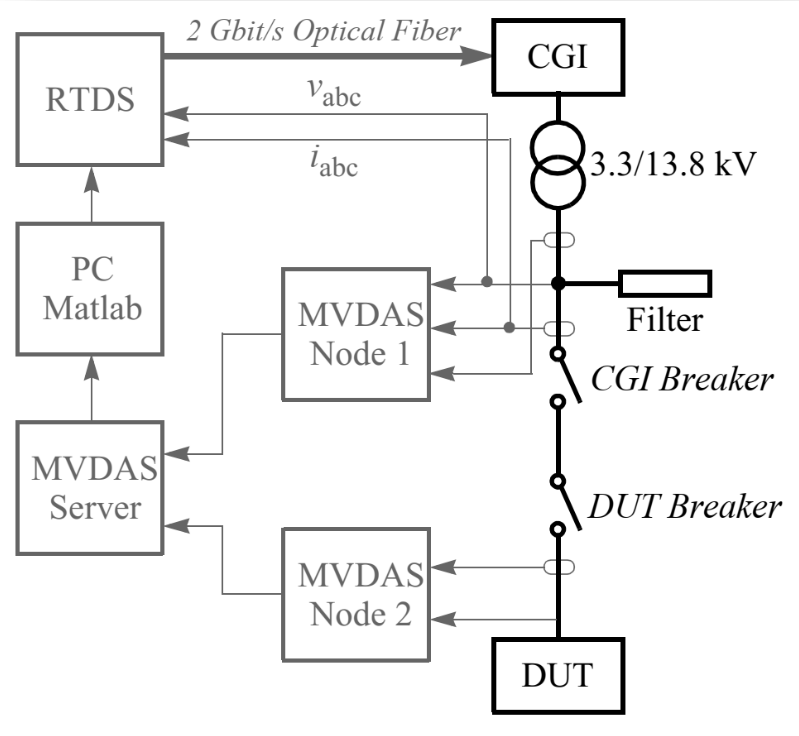
- Rating: 7 MVA continuous and 39 MVA short-term (2 s)
- 4-wire, 13.2 kV
- Response time: 1 ms
- Independent control of all three phases
- Programmable impedance
- Interfaced with real-time digital simulator by 2-Gbit/s optical fiber.

Dynamometer



- Can host nacelle of up to 5-MW rating
- Can emulate different wind conditions.

Automation and Data Acquisition

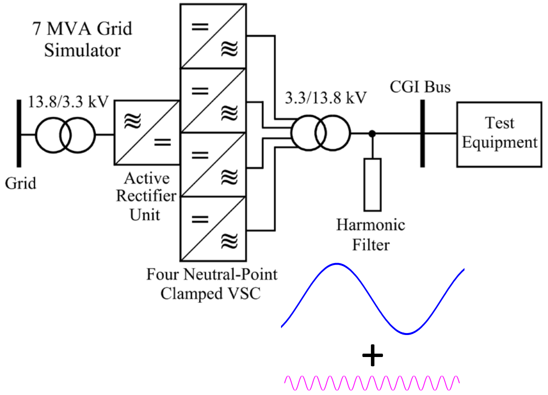


Control room

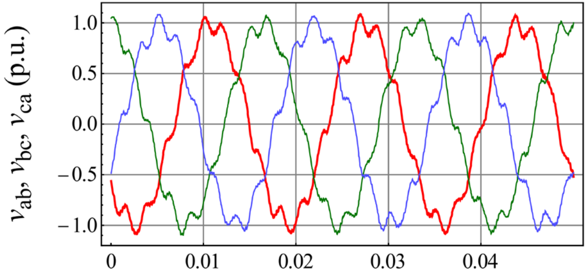
MVDAS node

All photos by NREL

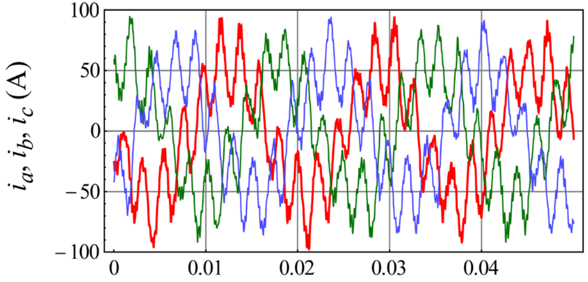
Different Types of Perturbations



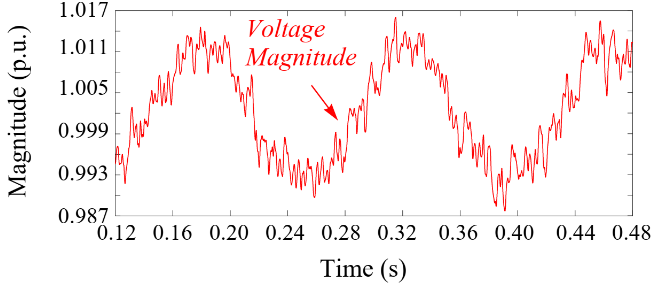
- Seq. pert. at 477 Hz:

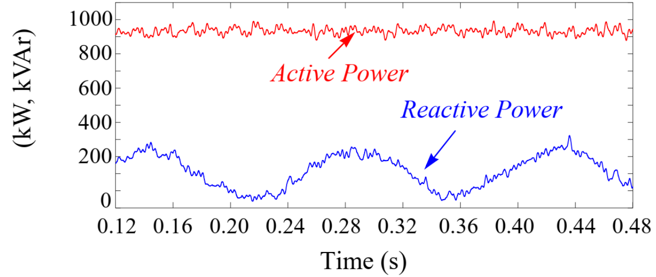


- Response currents:



- Voltage magnitude pert. at 7 Hz:





Representations of Seq. Admittance

1. Transfer matrix:

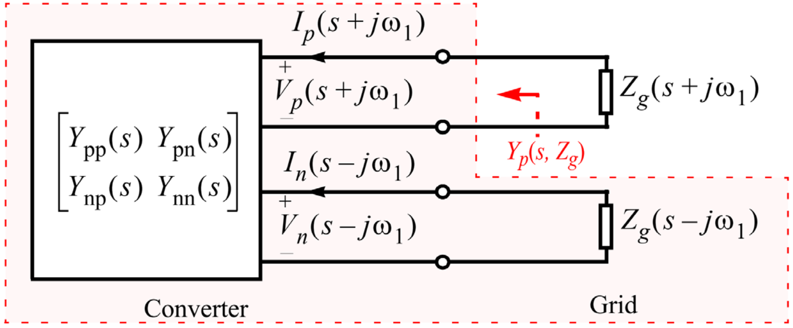
$$\begin{bmatrix} I_p(s+j\omega_1) \\ I_n(s-j\omega_1) \end{bmatrix} = \begin{bmatrix} Y_{pp}(s) & Y_{pn}(s) \\ Y_{np}(s) & Y_{nn}(s) \end{bmatrix} \begin{bmatrix} V_p(s+j\omega_1) \\ V_n(s-j\omega_1) \end{bmatrix}$$

2. SISO transfer functions:

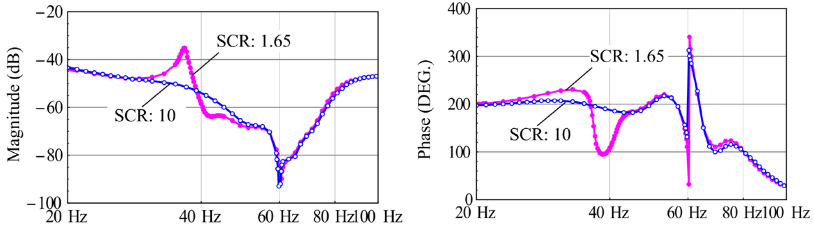
$$Y_p(s) = \frac{I_p(s)}{V_p(s)}, \quad Y_{cp}(s) = \frac{I_n(s-j2\omega_1)}{V_p(s)} \quad \text{while } V_n(s-j2\omega_1) = 0$$

$$Y_n(s) = \frac{I_n(s)}{V_n(s)}, \quad Y_{cn}(s) = \frac{I_p(s+j2\omega_1)}{V_n(s)} \quad \text{while } V_p(s+j2\omega_1) = 0$$

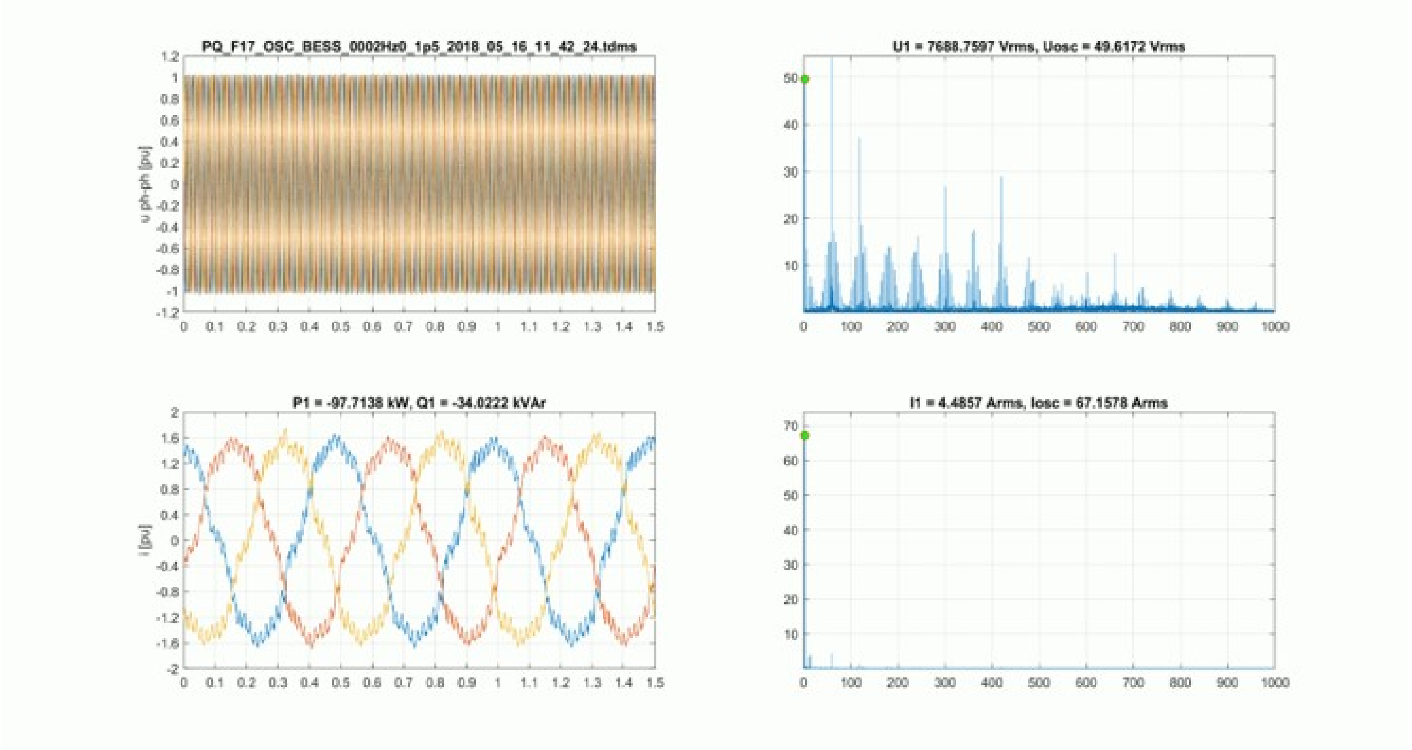
3. Grid-dependent impedance:



Ex: Positive-seq. admittance of wind turbine:



Impedance Sweep



Credit:
P. Koralewicz

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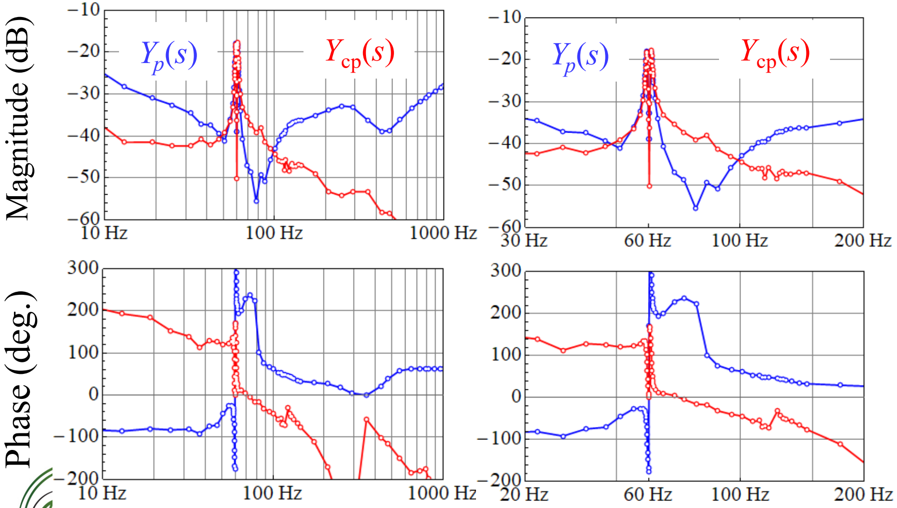
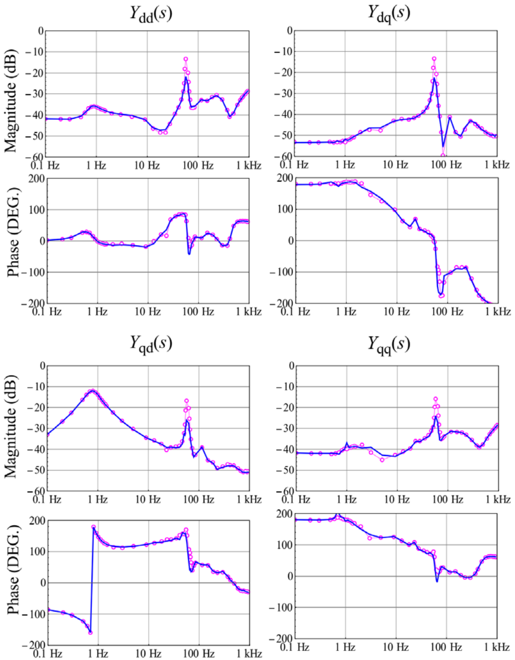
Admittance of a 1.9-MW Wind Turbine

- Seq. admittance measurement:

$$Y_p(s) = \frac{I_p(s)}{V_p(s)}, \qquad Y_{cp}(s) = \frac{I_n(s-j2\omega_1)}{V_p(s)} \qquad \text{while } V_n(s-j2\omega_1) = 0$$



- DQ admittance measurement:



Blue lines: derived from sequence measurements

Pink lines: direct DQ measurements

Reference Frame of Seq. Admittance

Positive-sequence admittance:

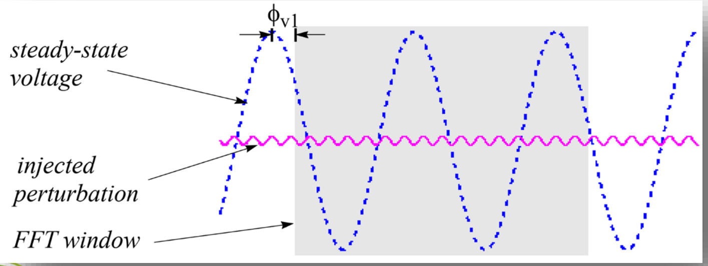
$$Y_p(s) = \frac{I_p(s)}{V_p(s)}$$

Coupling admittance:

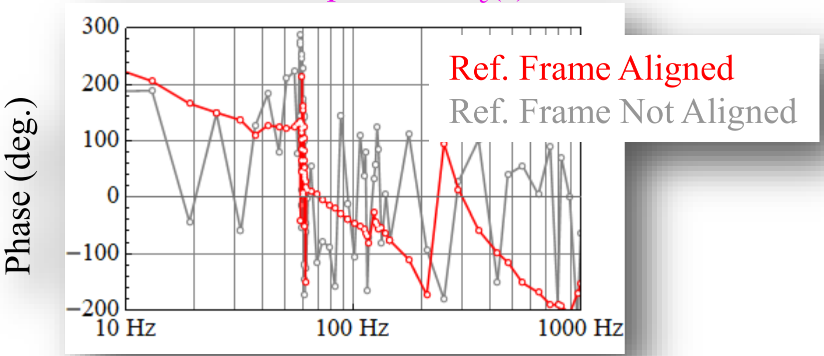
$$Y_c(s) = \frac{I_n(s - j2\omega_1)}{V_p(s)}$$

The reference frame of the sequence impedance is defined by the starting point of the data window used for FFT analysis with respect to the fundamental trajectory of voltages.

$$\angle Y_c(s)\big|_{\phi_{v1} = 0} = \angle Y_c(s)\big|_{\phi_{v1} = \alpha} + 2\alpha$$

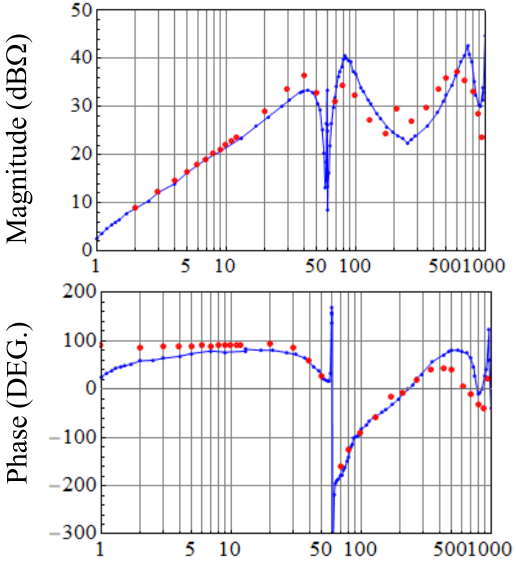


Phase Response of $Y_c(s)$



Applications

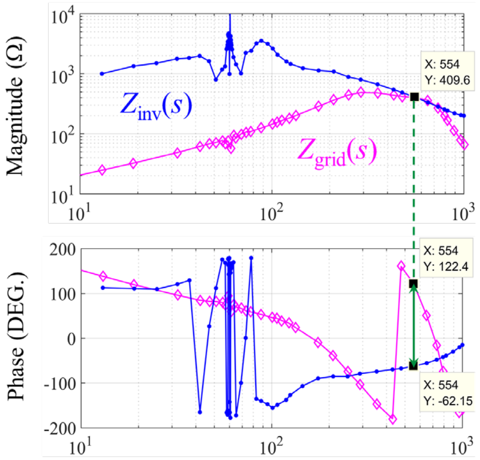
- Model validation:



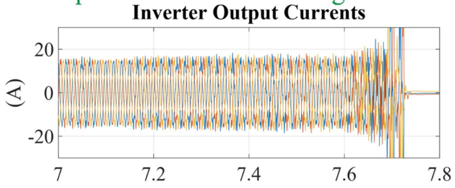
Blue: measurements of 4-MW DFIG

Red: PSCAD model from OEM

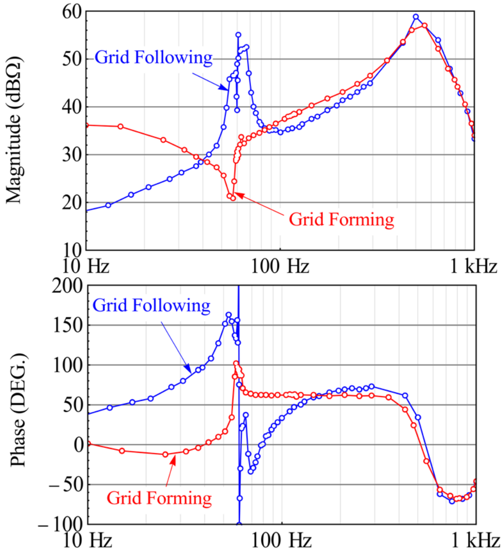
- Resonance analysis:



Res. Freq.: 554 Hz Phase Margin: –4.5°



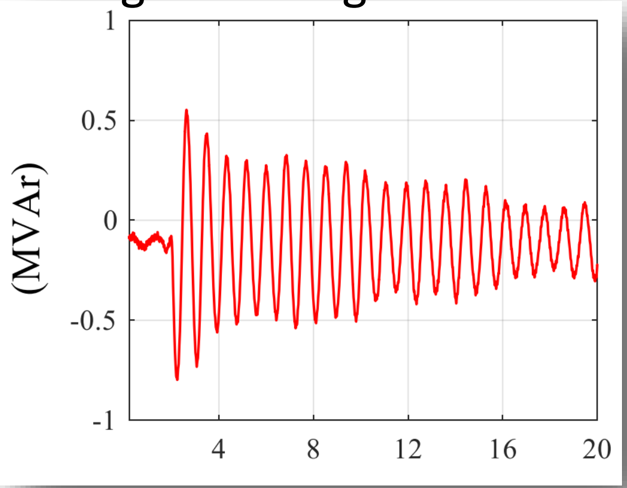
- Grid-forming inverters:



Positive-seq. impedance of a 2.2-MVA inverter for GFL and GFM operation modes

Reactive Power Oscillations

- 4-MW wind turbine at NREL:
  - 1.2-Hz reactive power oscillations following a 1% step change in voltage.

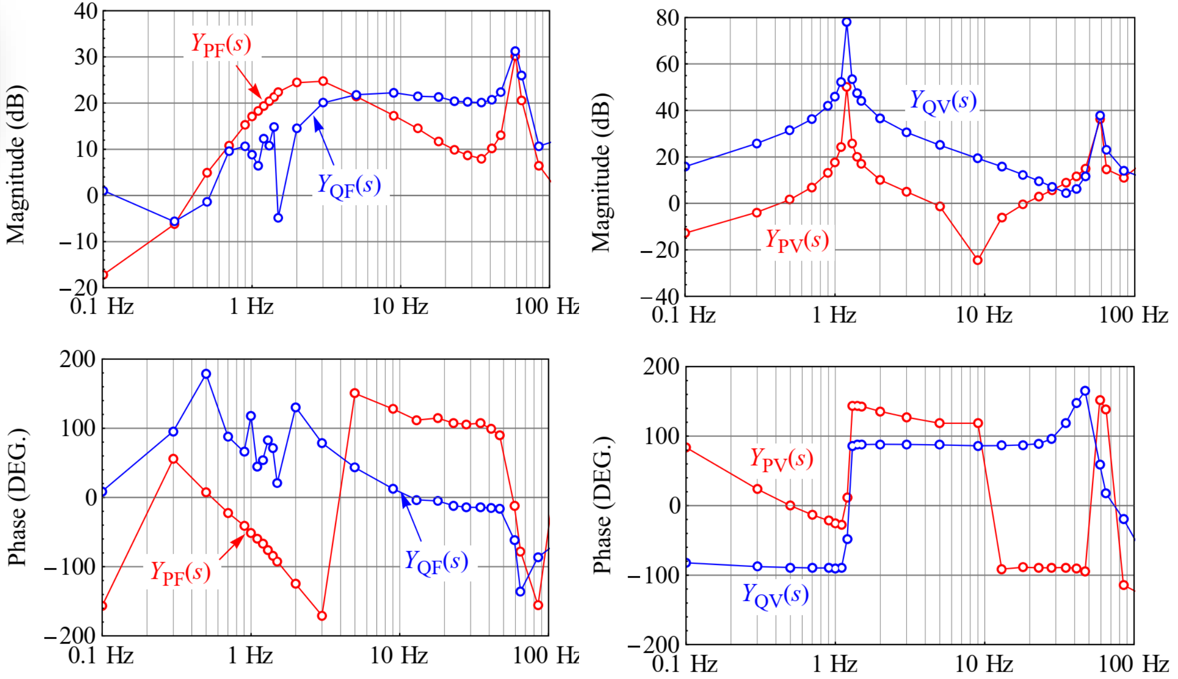


- Hornsea Wind Plant in U.K.:
  - Hornsea plant output experienced reactive power oscillations before the major blackout event in August 2019.
  - The frequency of reactive power oscillations was 8.5 Hz, and it was excited by a small (2%) step change in the voltage magnitude.

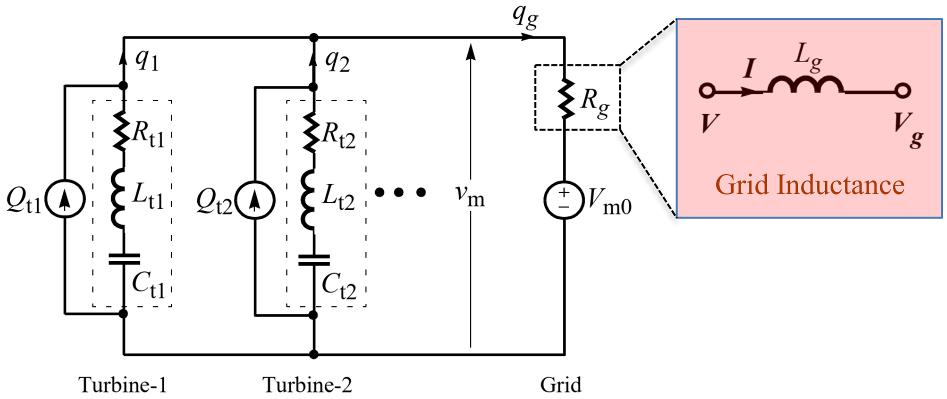
Power Admittance of the Turbine

$$\begin{bmatrix} P(s) \\ Q(s) \end{bmatrix} = \begin{bmatrix} Y_{PF}(s) & Y_{PV}(s) \\ Y_{QF}(s) & Y_{QV}(s) \end{bmatrix} \begin{bmatrix} F(s) \\ V_m(s) \end{bmatrix}$$

- Analysis of low-frequency active and reactive power oscillations
- Directly shows effect of slow active and reactive power control loops.



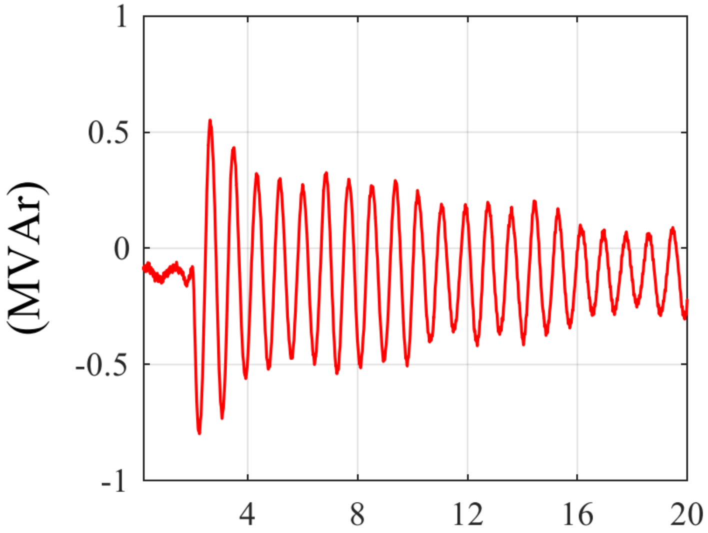
Equivalent Circuit Analysis



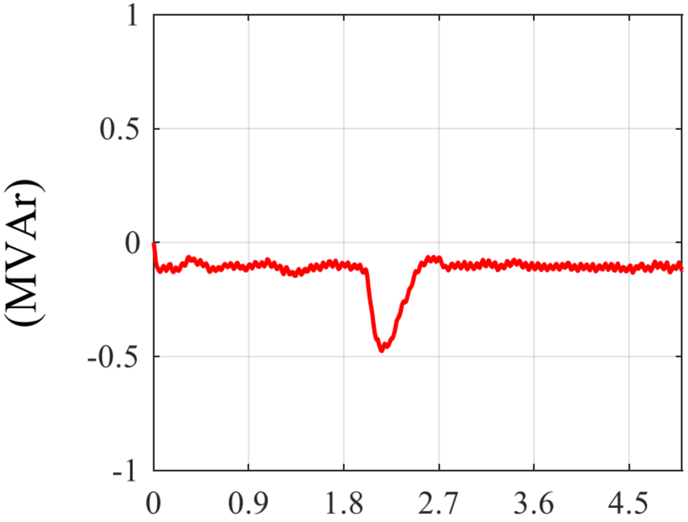
- Reactive power flow as instantaneous current
- Voltage magnitude as instantaneous voltage
- *Inductive grid acts as a resistor for reactive power dynamics.*

Effect of Grid Strength

- Strong grid (L_g = 0):



- Not-so-strong grid (L_g = 8 mH):



- Weak grid damps reactive power oscillations from wind power plants.

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Summary

- Multimegawatt grid simulator for impedance testing
- Sequence impedance measurement should consider frequency coupling effects and reference frame.
  - DQ impedance can be obtained from sequence measurements.
- Voltage magnitude and frequency perturbations for power-domain impedance measurement
  - Evaluation of active and reactive power oscillations.

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Thank you!

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