CGI for Impedance Characterization of Inverter-Coupled Generation

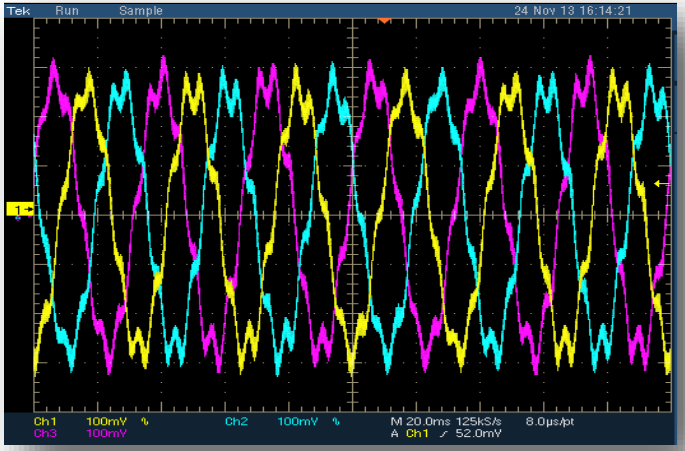
Shahil Shah, Przemyslaw Koralewicz, and Vahan Gevorgian

Fifth International Workshop on Grid Simulator Testing
Tallahassee, Florida
November 15–16, 2018

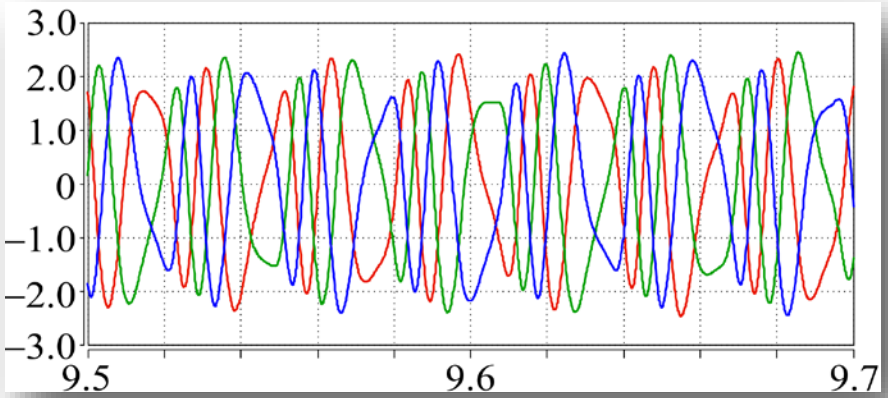
NREL/PR-5D00-72899

Problem: Control Interactions – Resonance

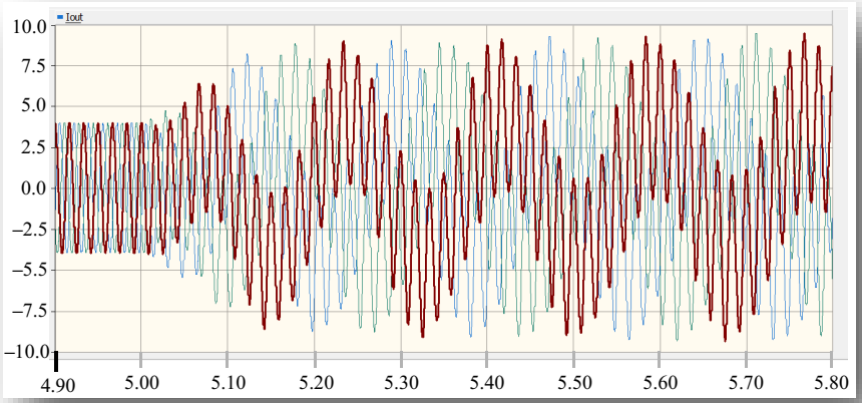
Super-synchronous resonance



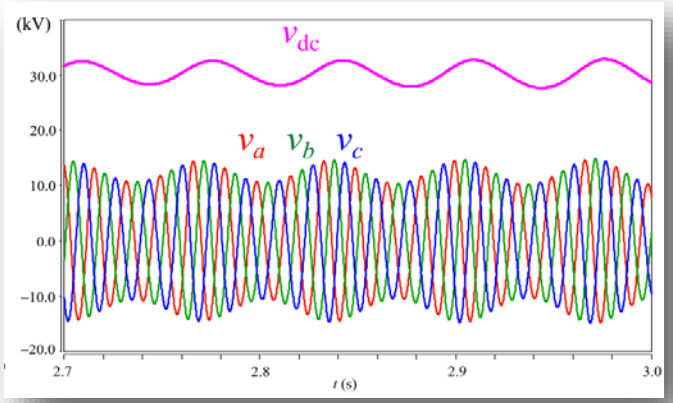
Multifrequency resonance



Sub-synchronous resonance



AC/DC hybrid resonance



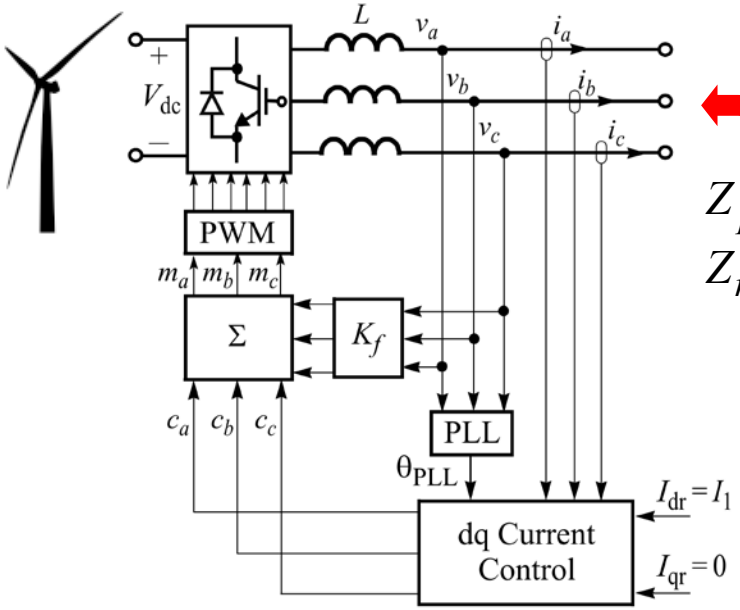
Outline

- Challenges of time-domain power-hardware-in-the-loop (PHIL) characterization
- Frequency-domain impedance-based characterization
- Impedance measurement using 7 MW grid simulator (controllable grid interface: CGI)
  - Evaluation of dynamic interactions
  - Validation of original equipment manufacturer (OEM) dynamic models.
- Large-signal impedance theory of resonance
  - Prediction of resonance-generated harmonics in Type-III wind turbines
  - Effect of MOV surge arresters on grid impedance
- Impedance-based characterization of frequency response

Challenges of Time-Domain Characterization

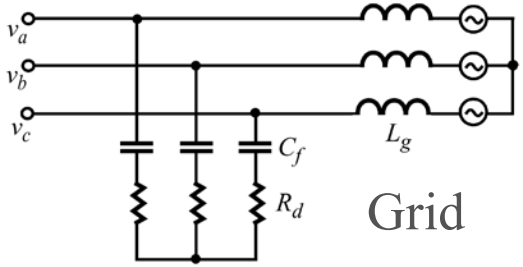
- PHIL
  - Difficult to gain insights for control design
  - Shows device behavior only for a specific condition
  - Does not support high-fidelity model validation
  - Does not excite entire dynamic space of device under test
- Simulation
  - All of the above, plus:
  - Outcome highly dependent on model accuracy
  - Not all dynamics can be captured in simulations
    - Parasitic elements, switching artifacts, complex nonlinearities—transformer saturation, control saturation, protection functions, thermal/mechanical losses

Impedance-Based Analysis



$Z_p(s)$
$Z_n(s)$

$Z_g(s)$

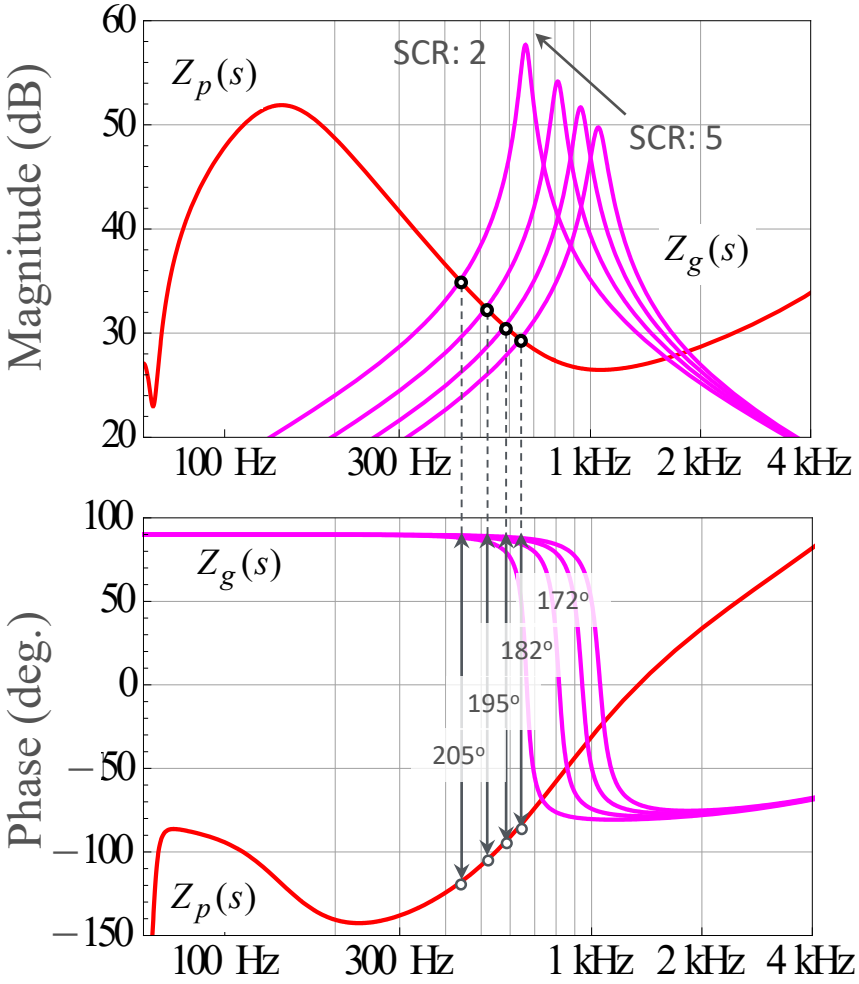


Loop gain:

$Z_g(s)/Z_p(s), \quad Z_g(s)/Z_n(s)$

- Impedance response of converter and grid are compared
  - Impedance intersection point gives resonance frequency
  - Phase difference at intersection point gives stability margin

Resonance Frequency and Phase-Margin

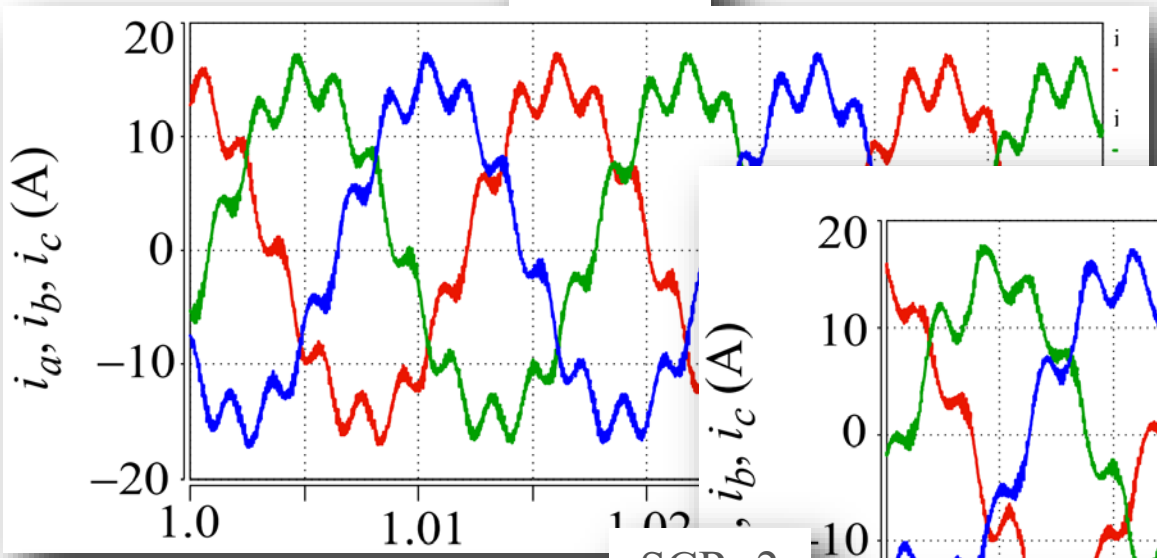


SCR	Grid Inductance, L_g	Resonance Frequency	Phase Margin
5	4.6 mH	641 Hz	+8°
4	5.7 mH	584 Hz	–2°
3	7.6 mH	512 Hz	–15°
2	11.5 mH	441 Hz	–25°

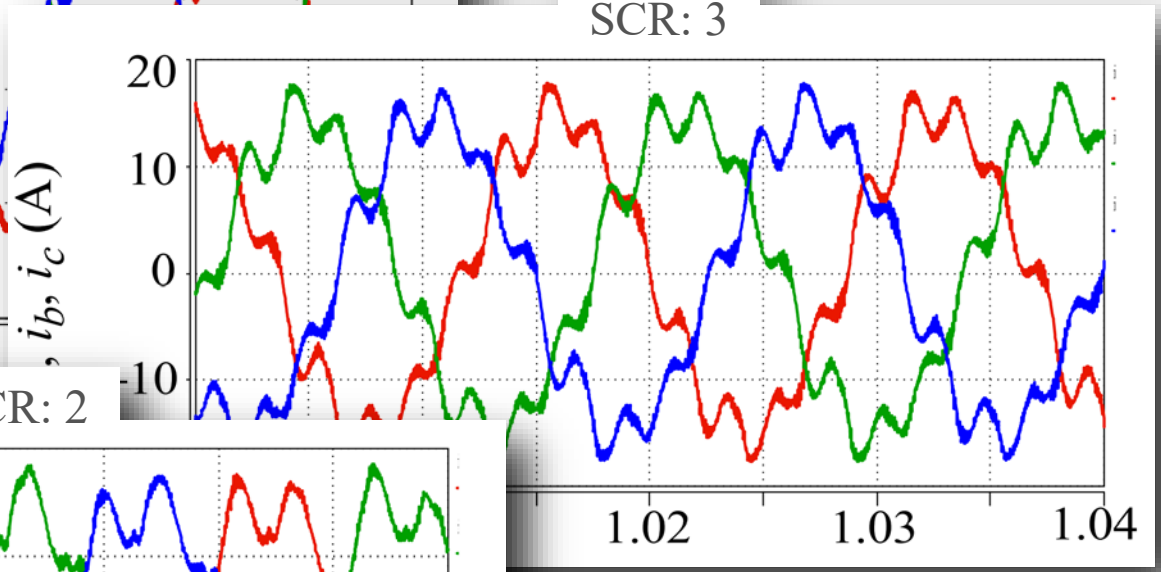
- VSC becomes Unstable during Weak Grid Operation
  - Unstable for SCR<5.0
  - Resonance Frequency Decreases with SCR and its “Severity” Increases

Resonance-Generated Distortions

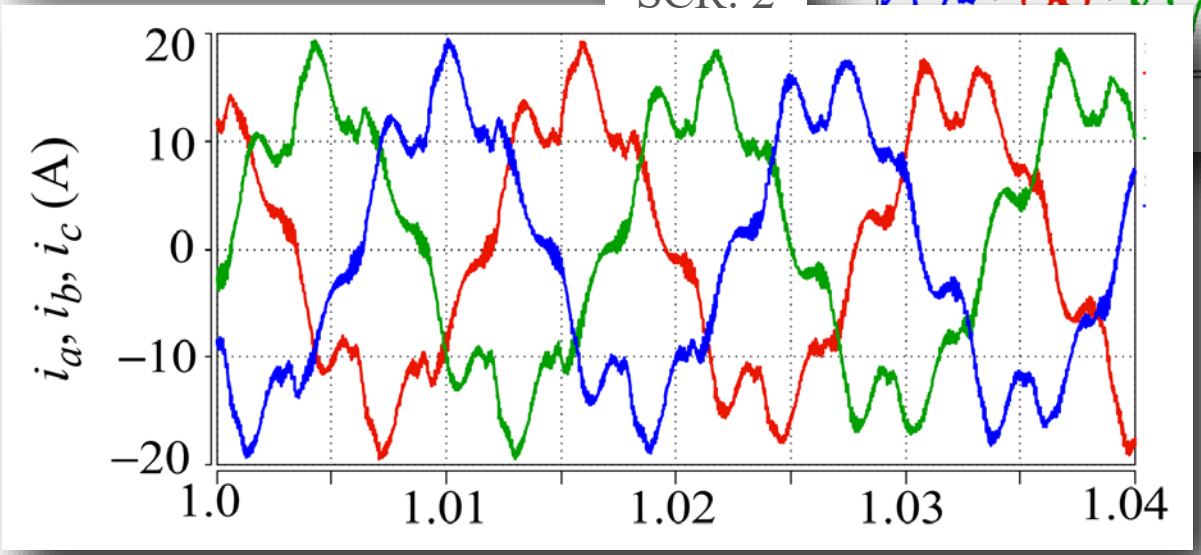
SCR: 4



SCR: 3



SCR: 2



Impedance Measurement Using CGI

- 7-MVA, 13.2-kV grid simulator (CGI)

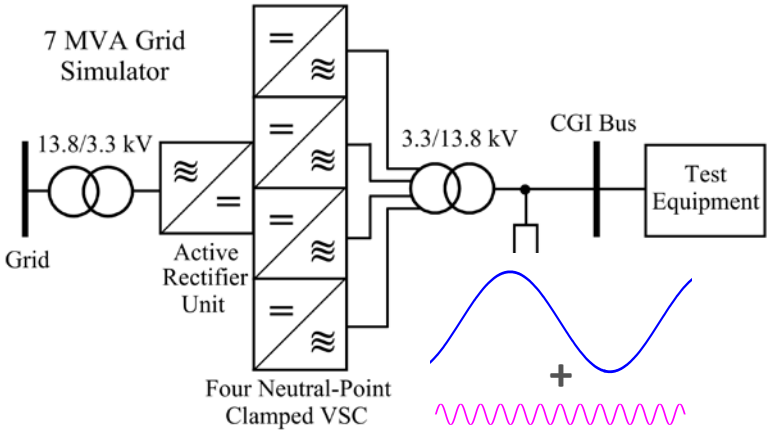
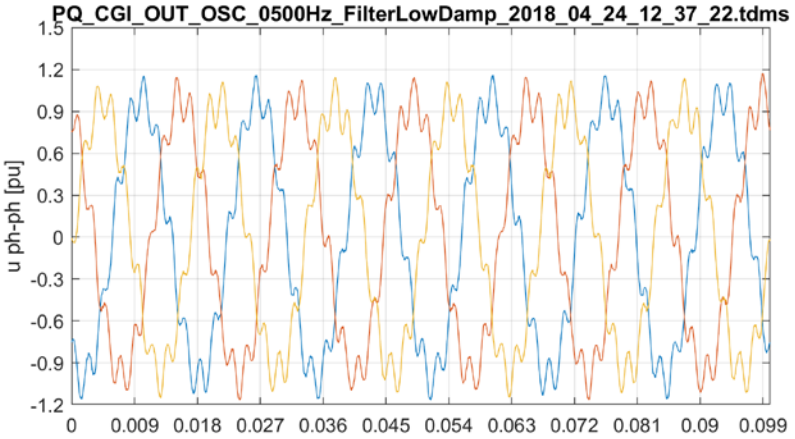
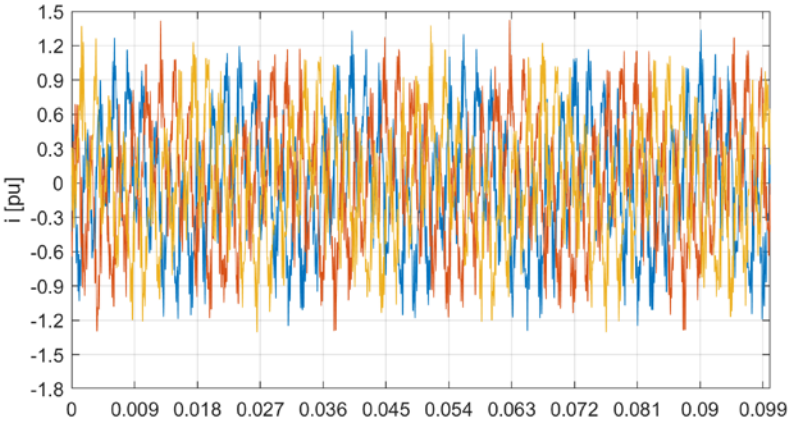


Photo by Mark McDade, NREL

- Perturbed voltages



- Response currents

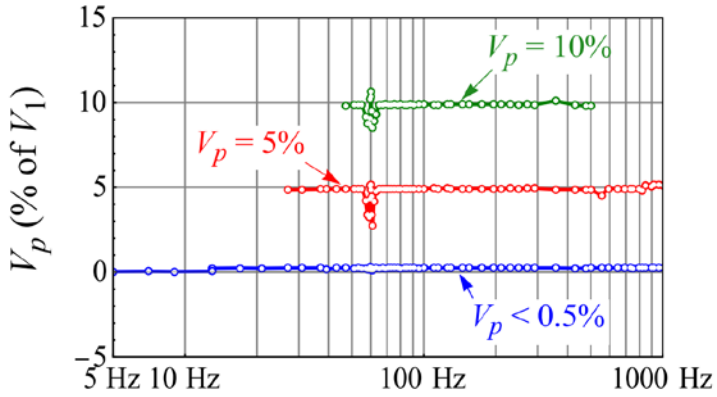


Impedance of 1-MW/13.8-kV Inverter

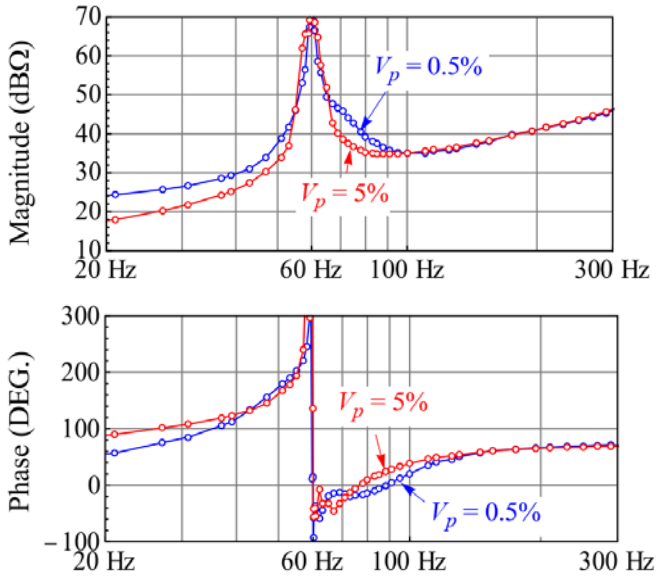
- Inverter-interfacing 1-MW/ 1-MWh battery energy storage system

Photo by Dennis Schroeder, NREL

  - Voltage perturbation (% of 13.8 kV)



- Impedance response

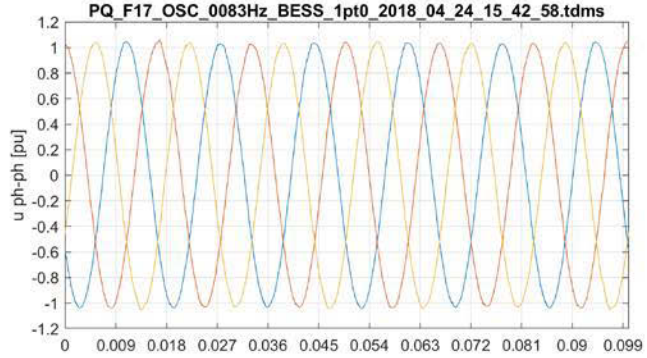


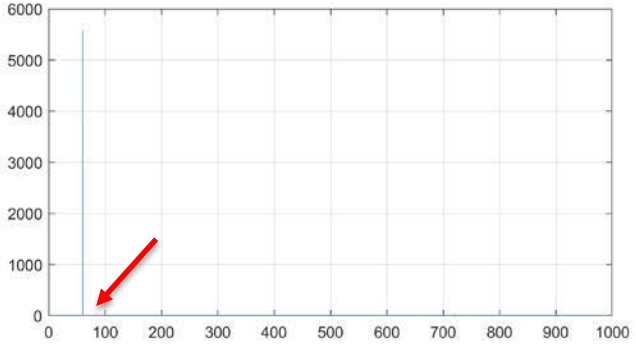
- Different control elements dominate at different frequencies.

Frequency Cross-Coupling

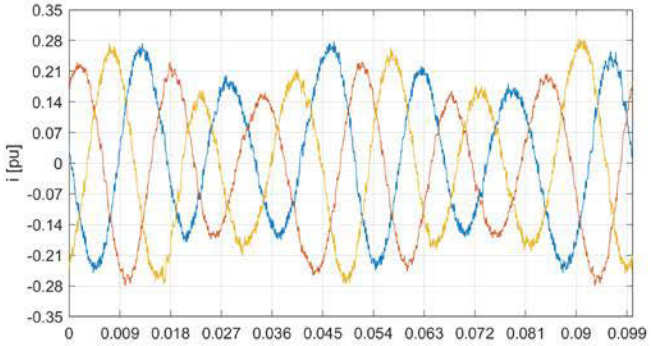
- Voltage perturbation at a frequency produces current response *also* at other frequencies

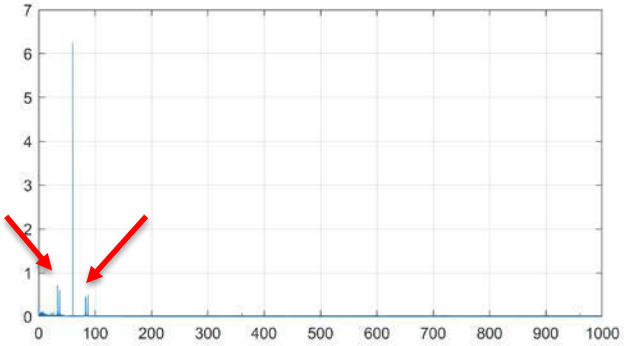
Perturbed voltages





Response currents





4-MW Type III Wind Turbine Drivetrain

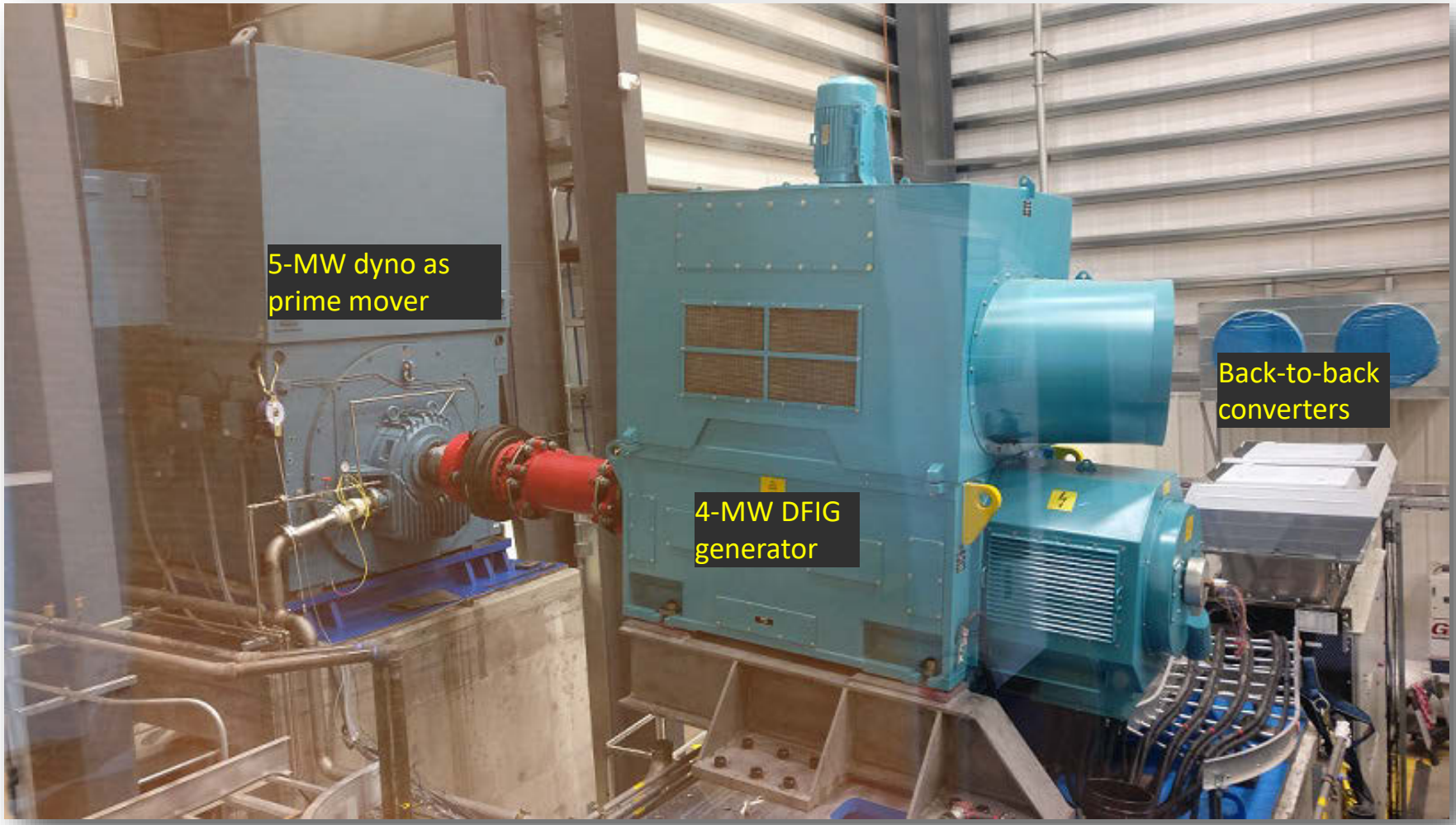
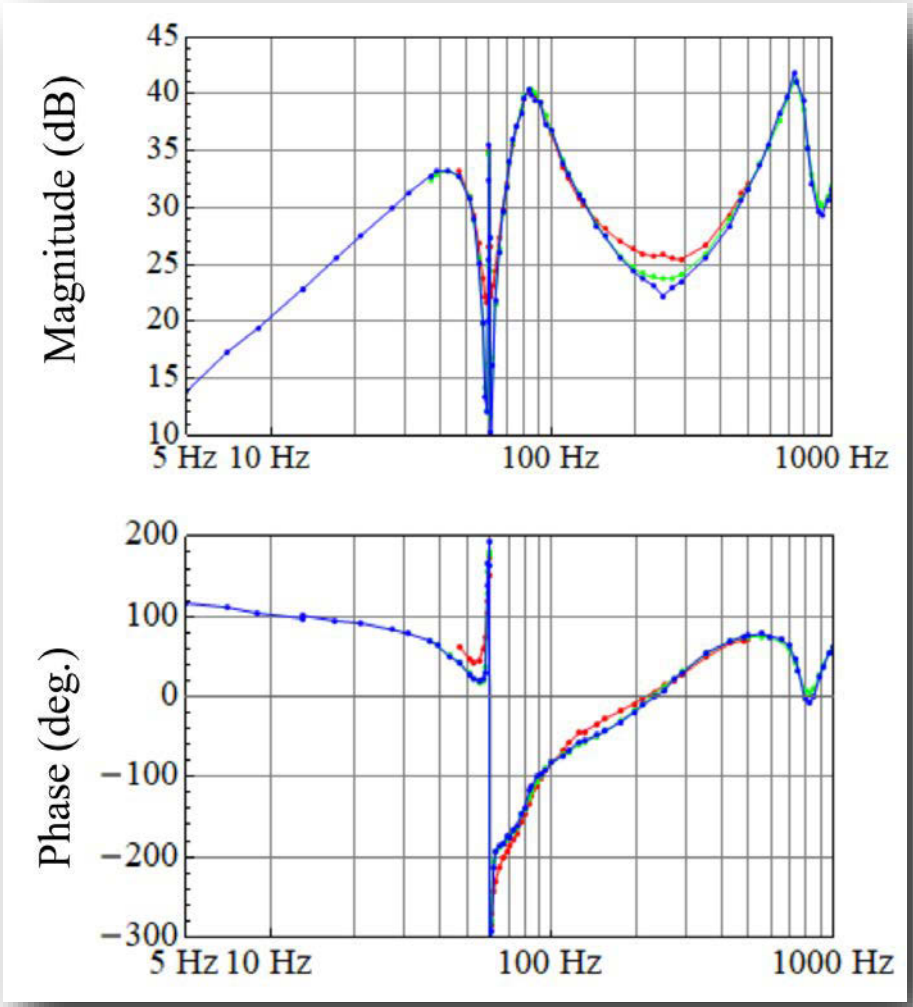


Photo from NREL

Positive-Sequence Impedance of DFIG

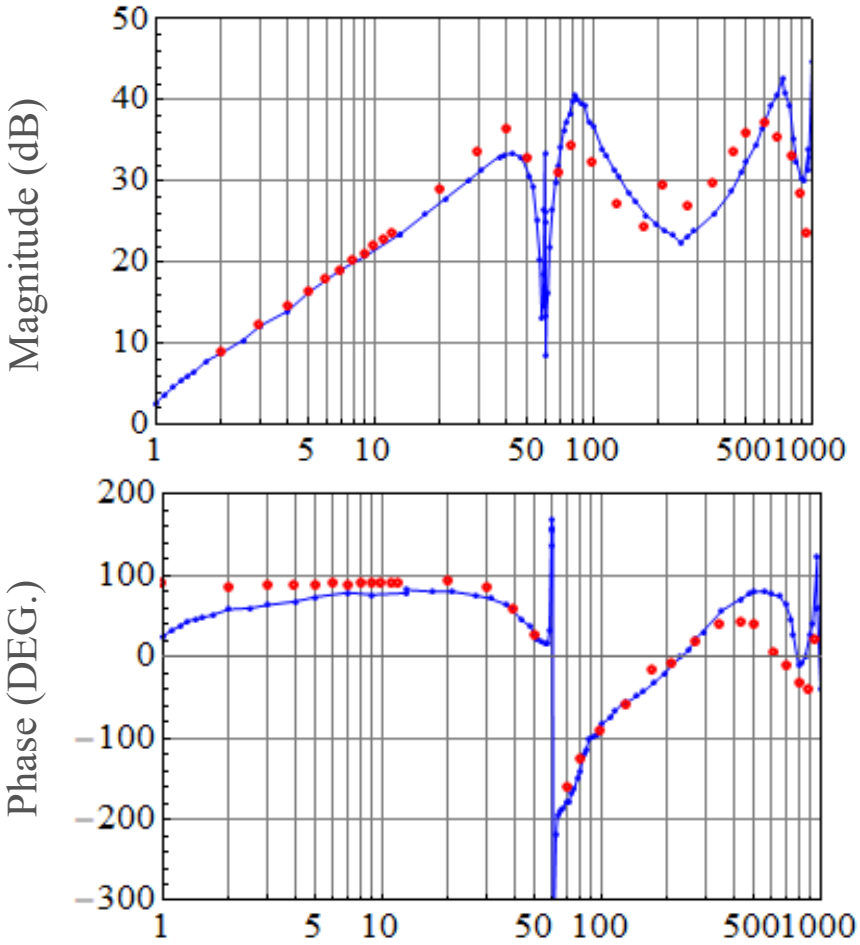
Measurements of 4-MW DFIG



- Low-frequency inductive behavior because of induction machine
  - Phase higher than 90°: Negative resistance
  - Subsynchronous resonance (SSR)
- Capacitive behavior between 80–250 Hz because of current control
- EMI filters dominate high-frequency response

Impedance for Dynamic Model Validation

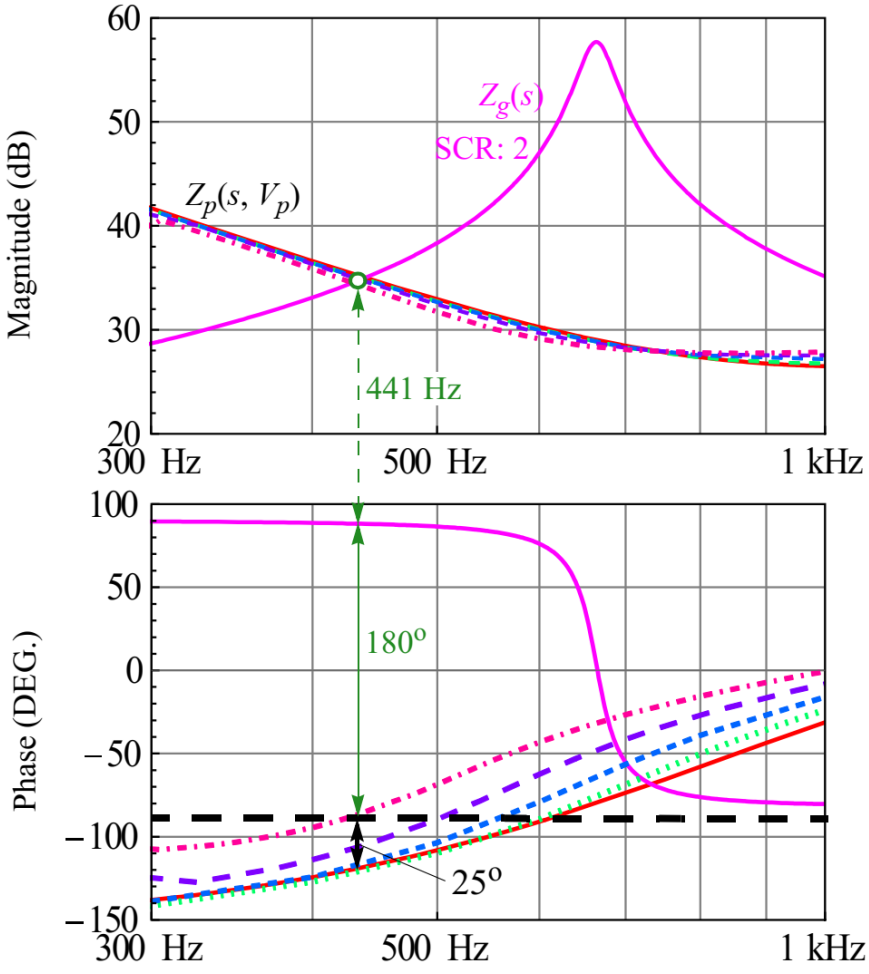
Blue: Measurements of 4-MW DFIG
Red: PSCAD model from OEM

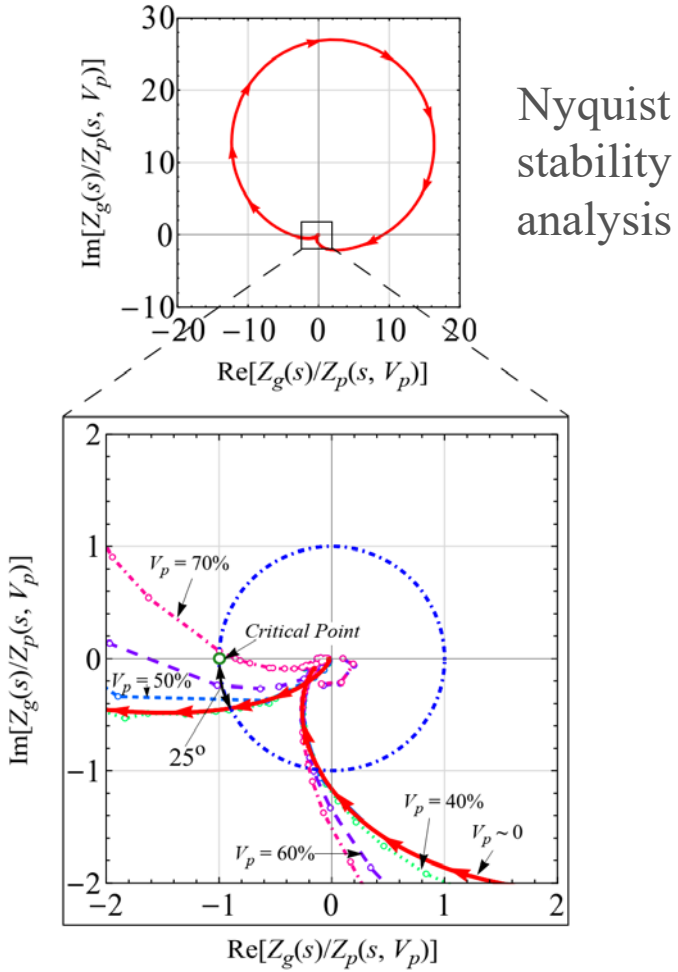


- High-fidelity model validation
- Validated model can be used to evaluate:
  - Farm-grid and turbine-turbine interactions
  - Grid-support functions
  - Transient performance
  - Control redesign

Large-Signal Impedance Theory

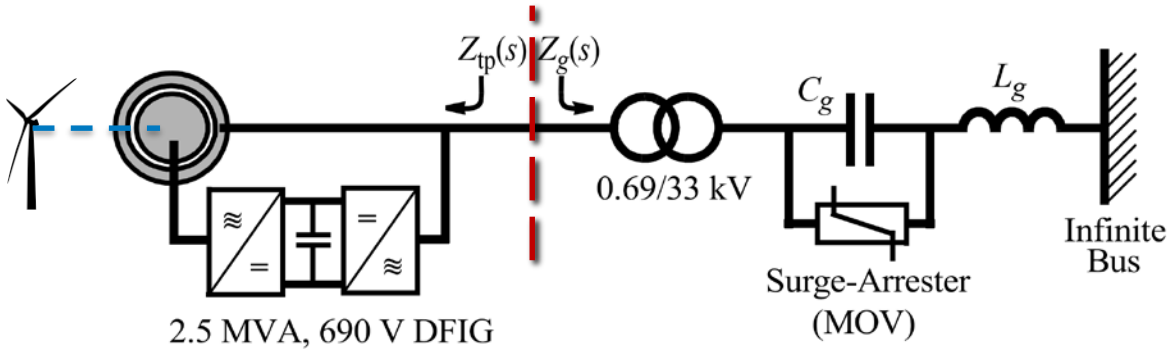
- IDEA: Impedance changes with resonance magnitude



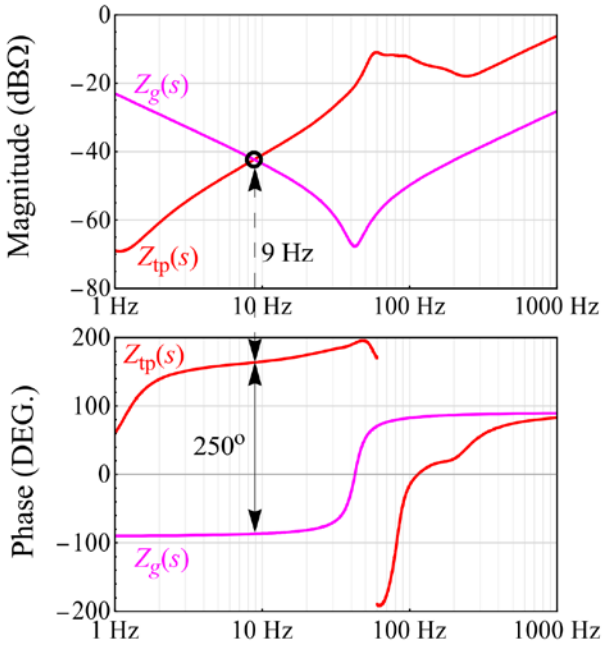


Nyquist stability analysis

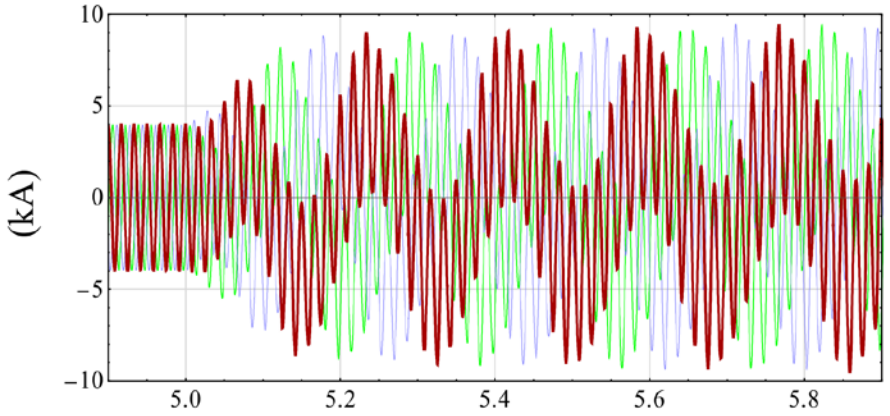
SSR in Type III Wind Turbines



- Impedance analysis

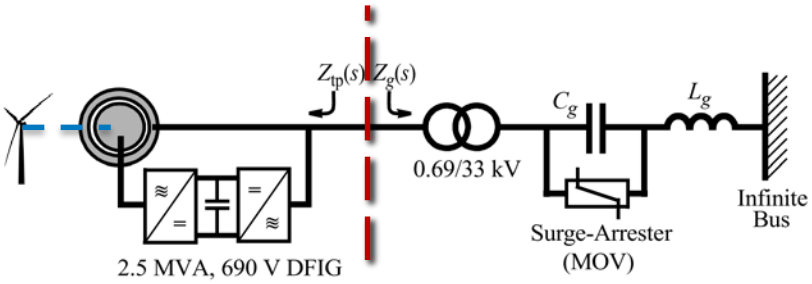


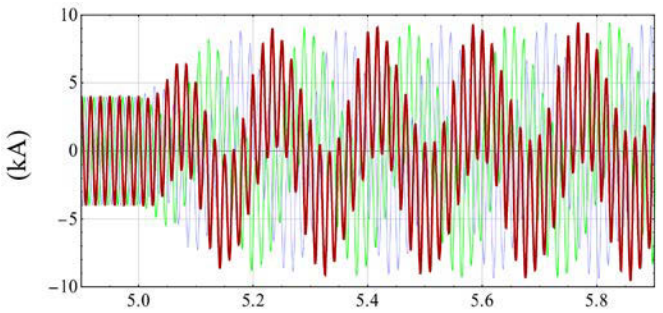
- DFIG output currents



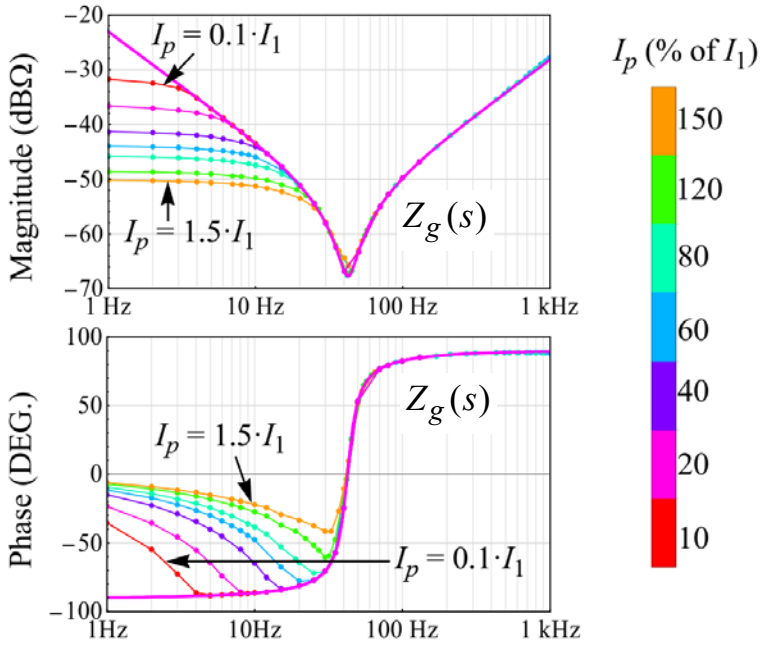
- Control design to mitigate turbine-turbine and farm-grid dynamic interactions.

Prediction of SSR-Generated Harmonics

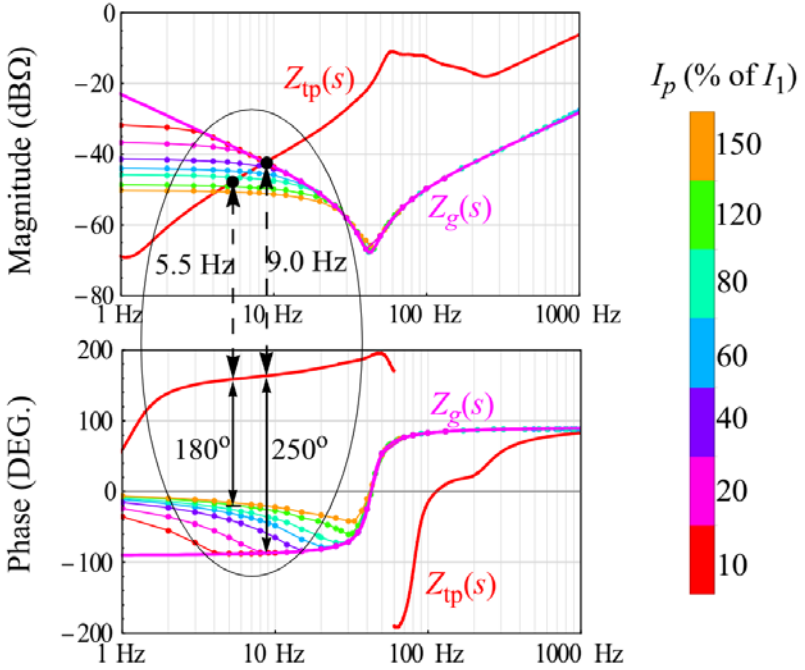




Grid impedance changes with resonance (and perturbation) magnitude because of MOVs

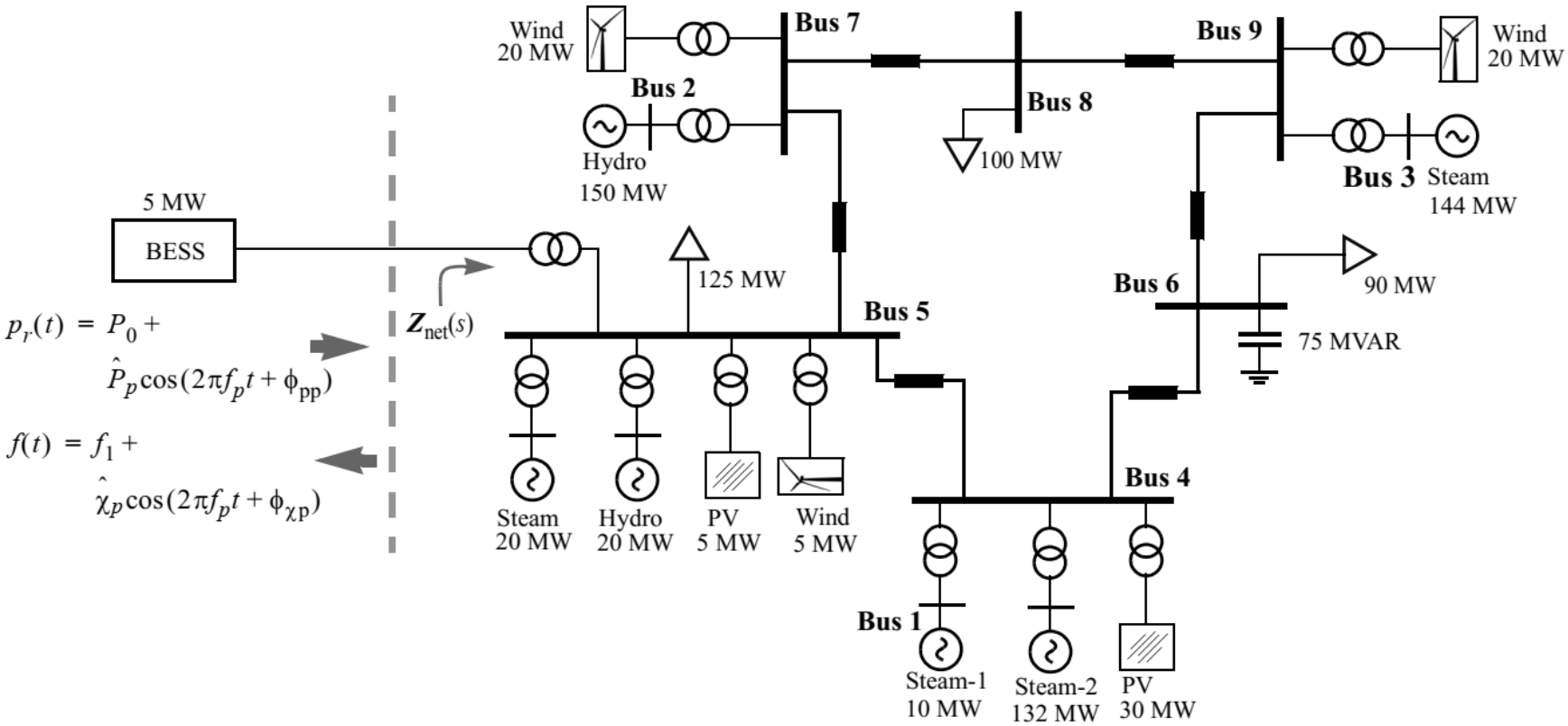


Prediction of SSR-generated harmonics



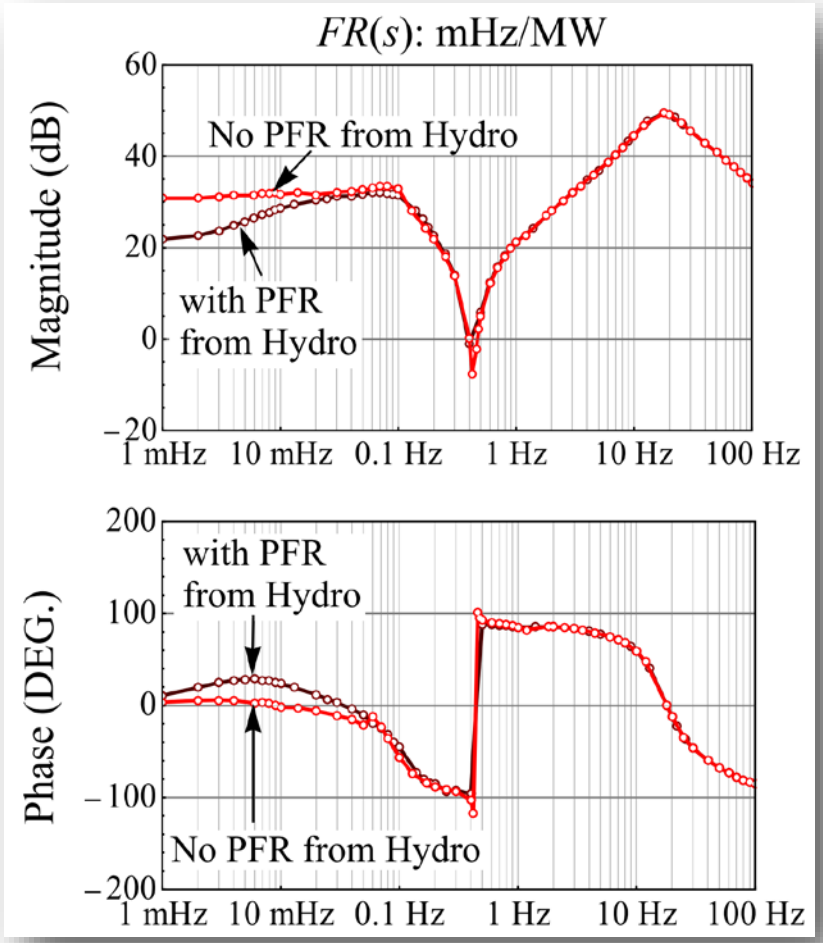
Frequency Response Characterization

- Transfer function from active power to frequency at the point of common coupling

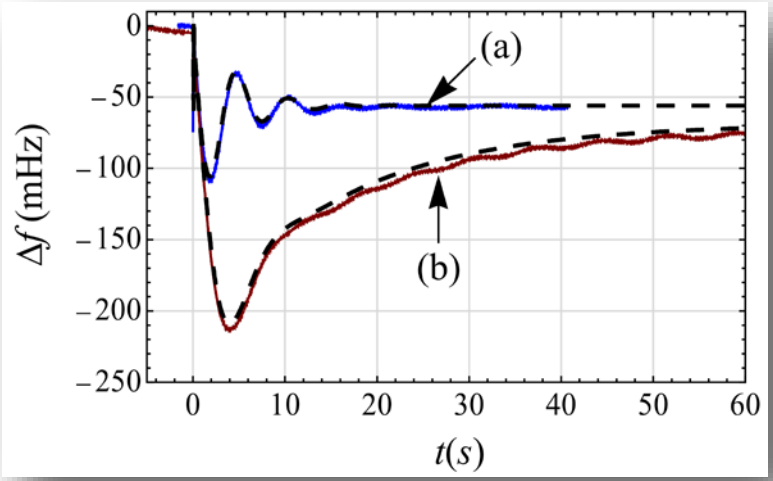


Characterization of Frequency Response

- *P* (power) to *f* (frequency) transfer function



- Loss of generation



- Applications:
  - Real-time estimation of system inertia and primary frequency response (PFR)
  - Design of frequency support by inverters

Summary

- Adoption of impedance characterization by wind industry for dynamic interactions
  - Root-cause finding, new grid codes, control design, impedance specs
- Impedance measurement using grid simulator can play critical role
  - Covers entire dynamic space of device under test
  - High-fidelity model validation
  - Control design
  - Optimization of dynamic and transient performance.
- New frequency-domain characterization tools for grid-support functions such as frequency and voltage support

Thank You

www.nrel.gov

Shahil.Shah@nrel.gov

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. **Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office**. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.