NREL
Transforming ENERGY

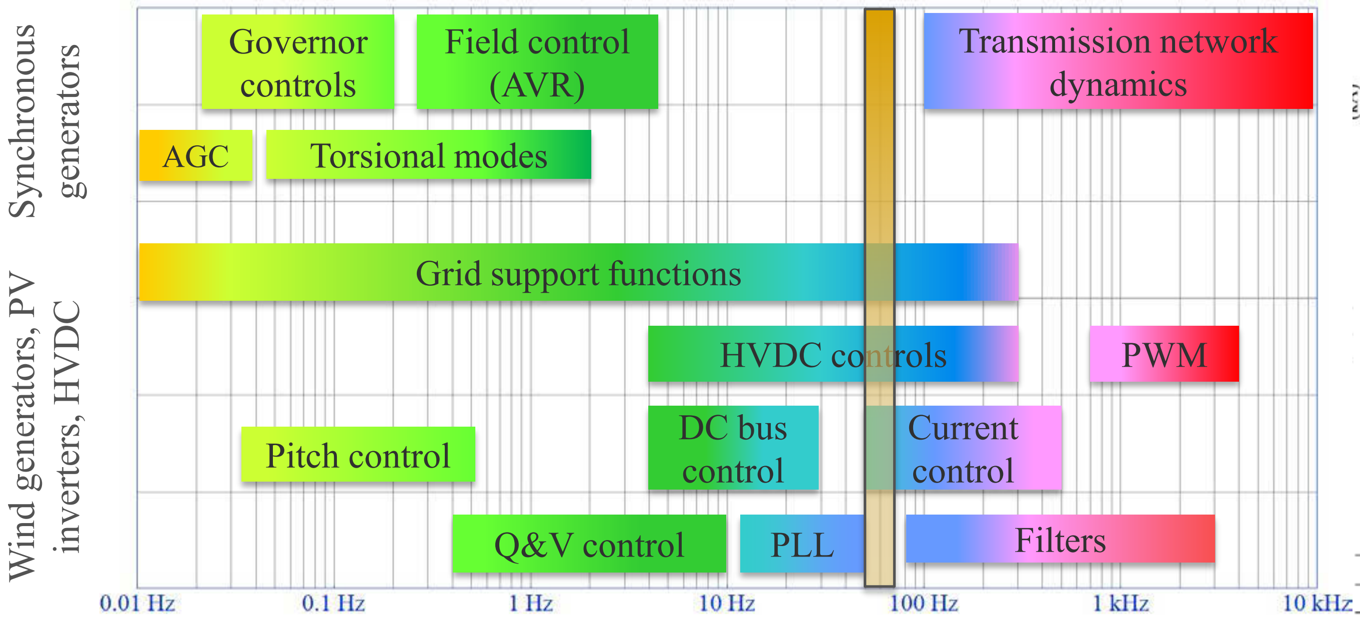
Impedance Methods for Analyzing Stability Impacts of Inverter-Based Resources

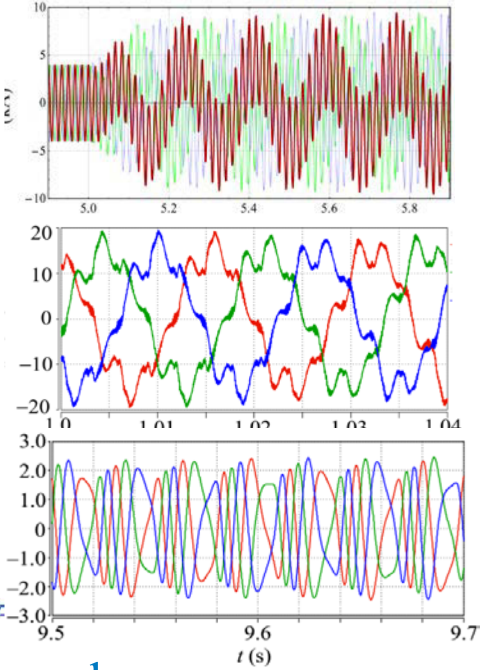
Shahil Shah
Team: V. Gevorgian, P. Koralewicz, R. Wallen, W. Yan
NSF Workshop on Power Electronics-Enabled Operation of Power Systems
Chicago, Illinois
October 31 – November 1, 2019

Outline

- Control interactions and resonance in power electronics systems
- Impedance-based stability analysis:
  - Impedance modeling
  - Measurement
  - Applications.
- Extension to other stability problems in modern power systems
- Future development.

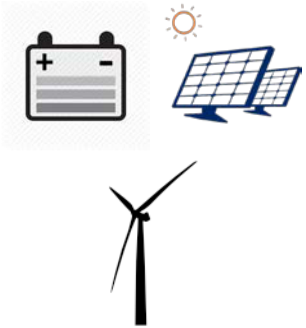
Control Interactions

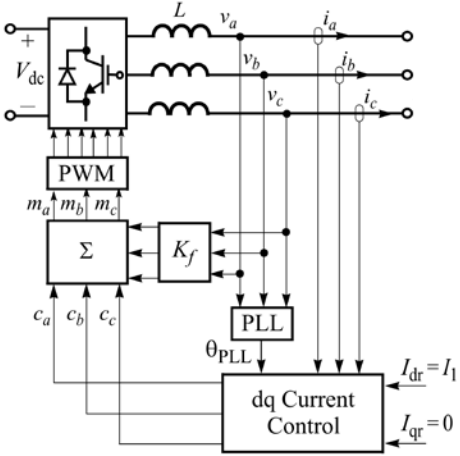




- Two major challenges: (1) diversity of controls in inverter-based resources; (2) unavailability of high-fidelity dynamic models

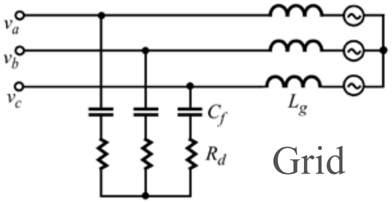
Impedance-Based Stability Analysis





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

$Z_g(s)$

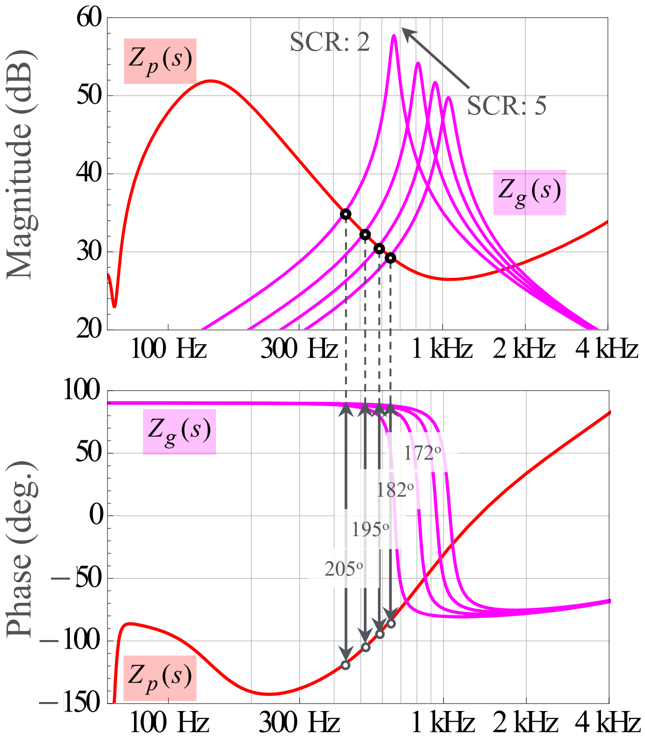


Loop gain:

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

- Impedance responses of two subsystems are compared:
  - Magnitude response intersection points give frequencies of resonance modes.
  - Phase difference at intersection points gives damping.

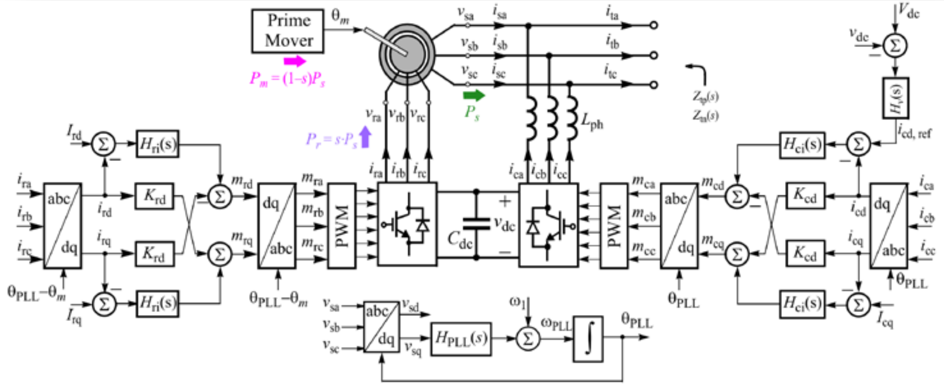
Resonance: Frequency and Damping

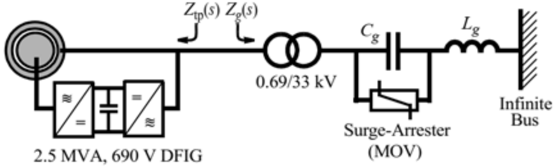


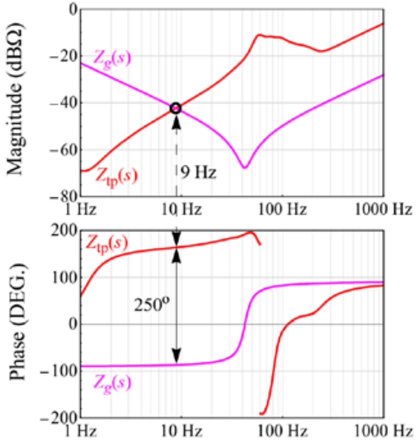
SCR	Grid Inductance, L_g	Resonance Frequency	Phase Margin
5	4.6 mH	641 Hz	+8°
4	5.7 mH	584 Hz	−2°
3	7.6 mH	512 Hz	−15°
2	11.5 mH	441 Hz	−25°

- Unstable resonance for weak grids:
  - Unstable for SCR<5.0
  - Resonance frequency decreases with SCR and its "severity" increases.

Impedance Modeling (e.g., Type III Wind Turbine)







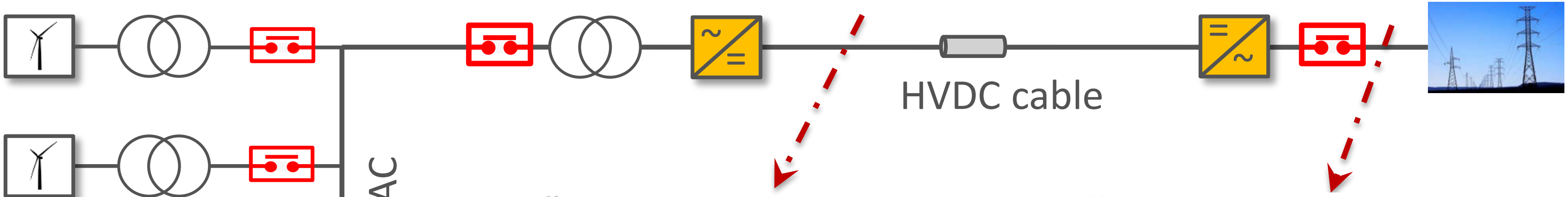
$$Z_{sp}(s) \equiv -\frac{V_{sp}(s)}{I_{sp}(s)} = \frac{R_s + \frac{R_r'}{\sigma_p(s)} + s(L_{ls} + L_{lr}') + k_m V_{dc}\left(\frac{N_s}{N_r}\right)^2\left[\frac{H_{ri}(s-j\omega_1) - jK_{rd}}{\sigma_p(s)}\right]}{1 - \frac{T_{PLL}(s-j\omega_1)}{2}\frac{k_m V_{dc} N_s}{\sigma_p(s) N_r}\left\{\frac{\mathbf{M}_{r1}}{V_1} + [H_{ri}(s-j\omega_1) - jK_{rd}]\frac{\mathbf{I}_{r1}}{V_1}\right\}}$$

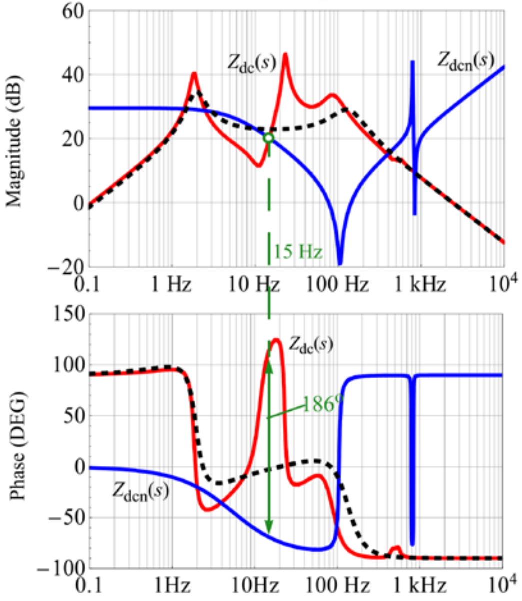
$$Z_{tp}(s) = \frac{Z_{sp}(s) \cdot Z_{cp}(s)}{Z_{sp}(s) + Z_{cp}(s)}$$

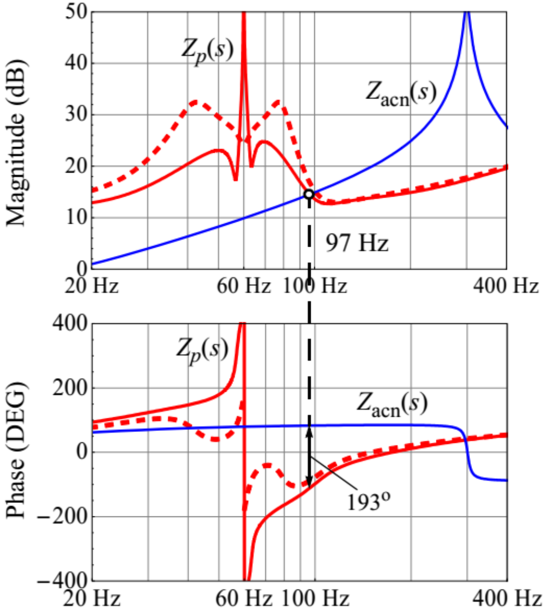
$$Z_{cp}(s) \equiv -\frac{V_{sp}(s)}{I_{cp}(s)} = \frac{sL_{ph} + k_m V_{dc}[H_{ci}(s-j\omega_1) - jK_{cd}]}{1 - \frac{T_{PLL}(s-j\omega_1)}{2}\left[1 + \frac{\mathbf{I}_{c1}}{V_1} k_m V_{dc} H_{ci}(s-j\omega_1)\right]}$$

Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

Offshore Wind with HVDC Transmission





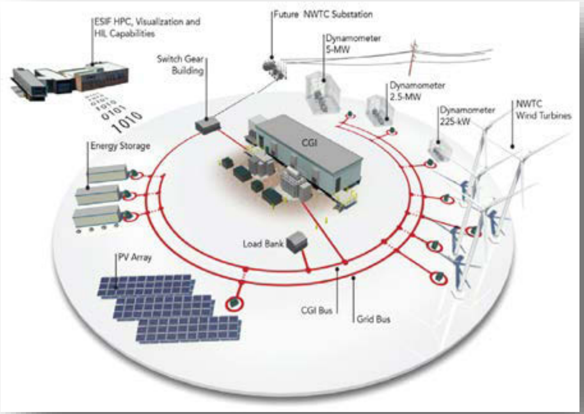


- Impedance analysis is performed at different interface points.

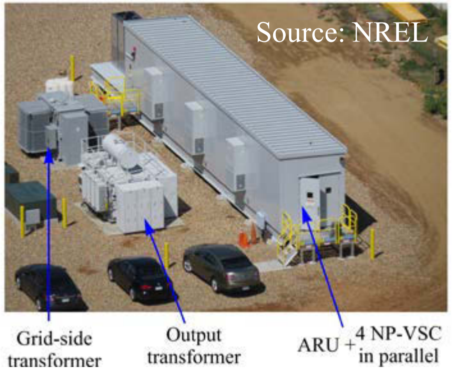
Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

Impedance Measurement at NREL

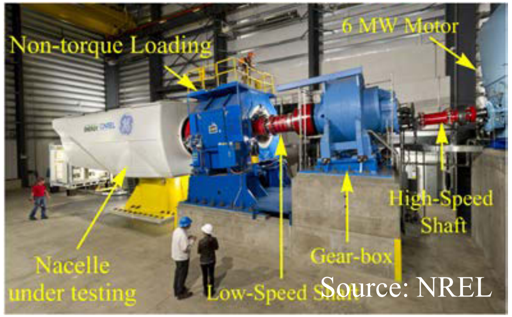
- 7-MVA grid simulator for perturbation injection
- Turbine nacelle coupled to a dynamometer
- GPS-synchronized medium-voltage measurements.



7-MVA grid simulator



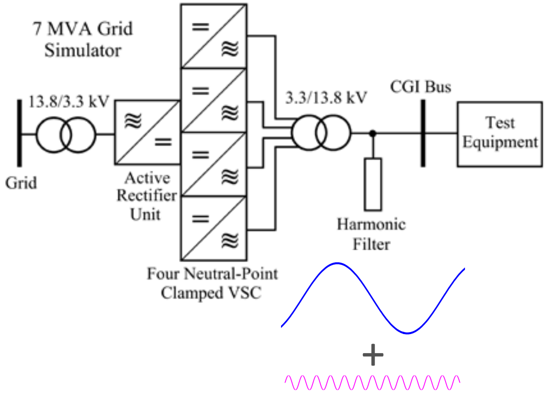
5-MW dynamometer



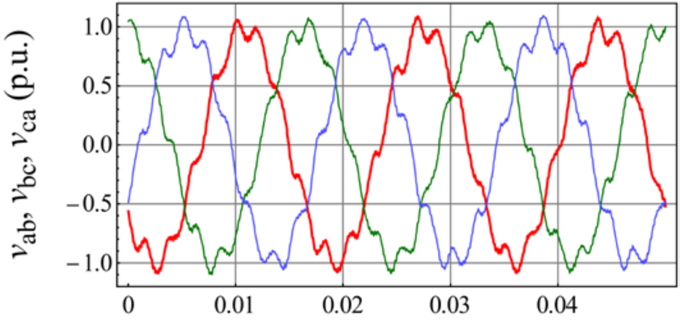
Medium-voltage measurements

Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

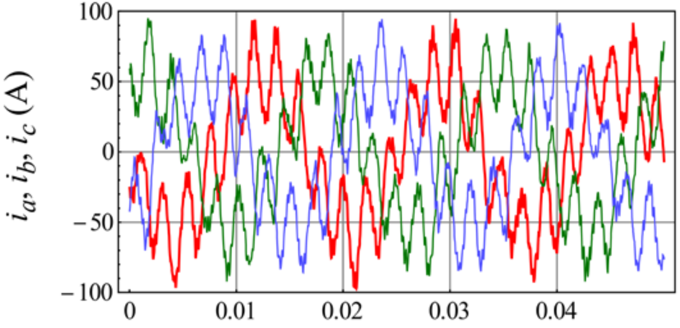
Injection of +ve and –ve Sequence Perturbations



- Perturbed voltages

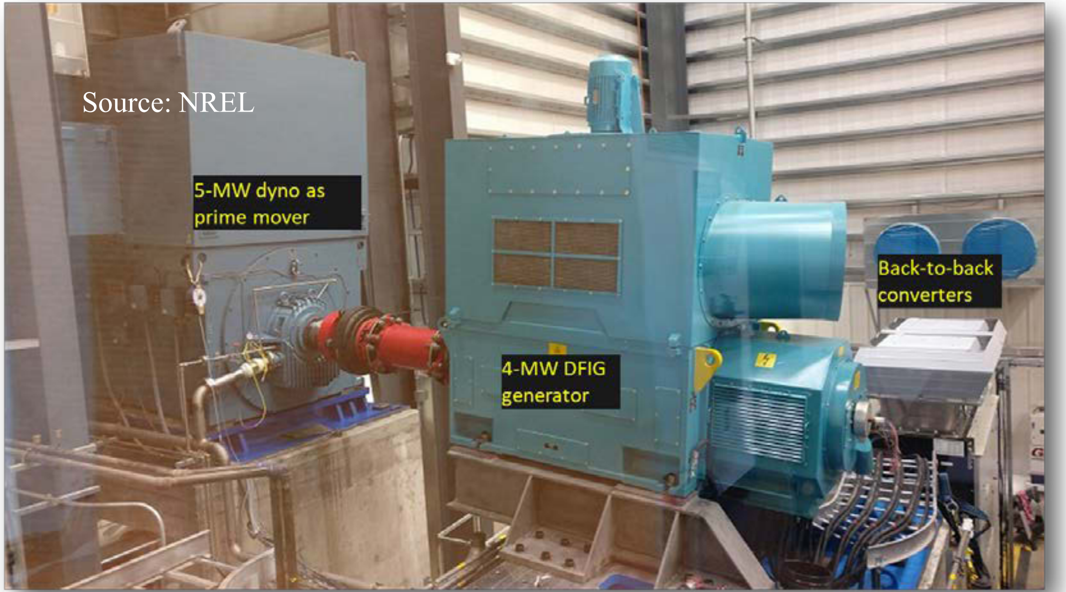


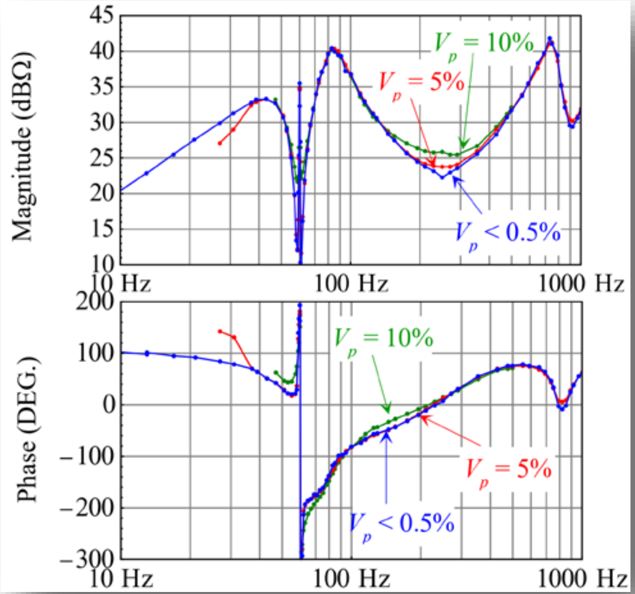
- Response currents



Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

Positive-Sequence Impedance of a 4-MW Turbine

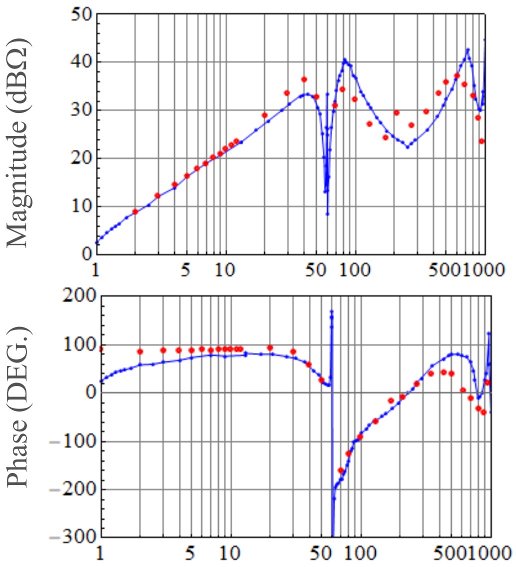




- Automated sequence impedance measurement by grid simulator for different operation conditions

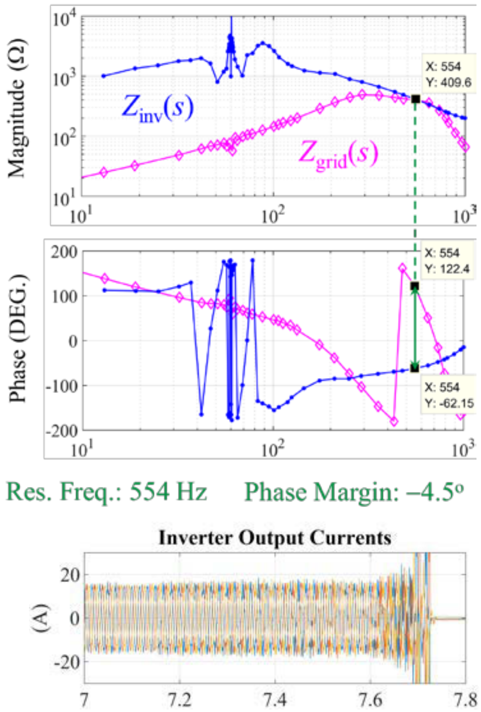
Applications

- Model validation

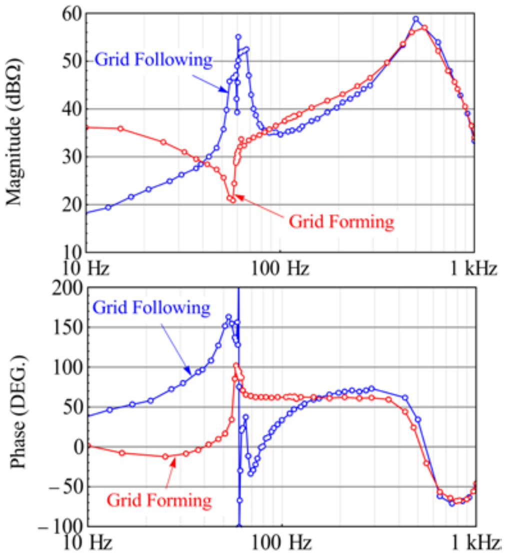


Blue: Measurements of 4-MW DFIG
Red: PSCAD model from OEM

- Resonance analysis



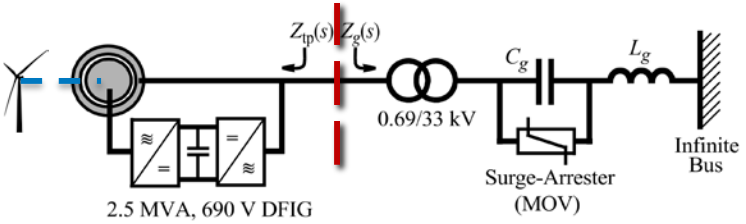
- Grid-forming inverters



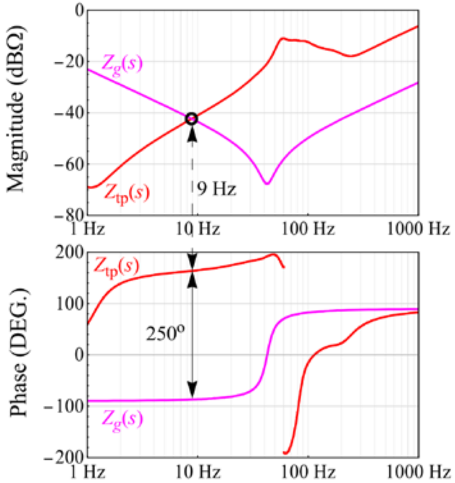
Solve resonance problems, control design, grid codes

Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

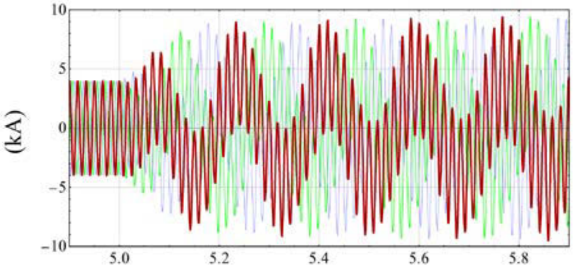
Role of Protection in Resonance



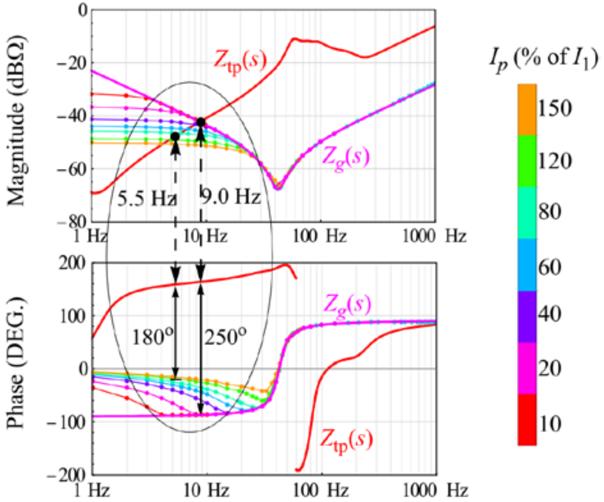
- Impedance analysis



- DFIG output currents

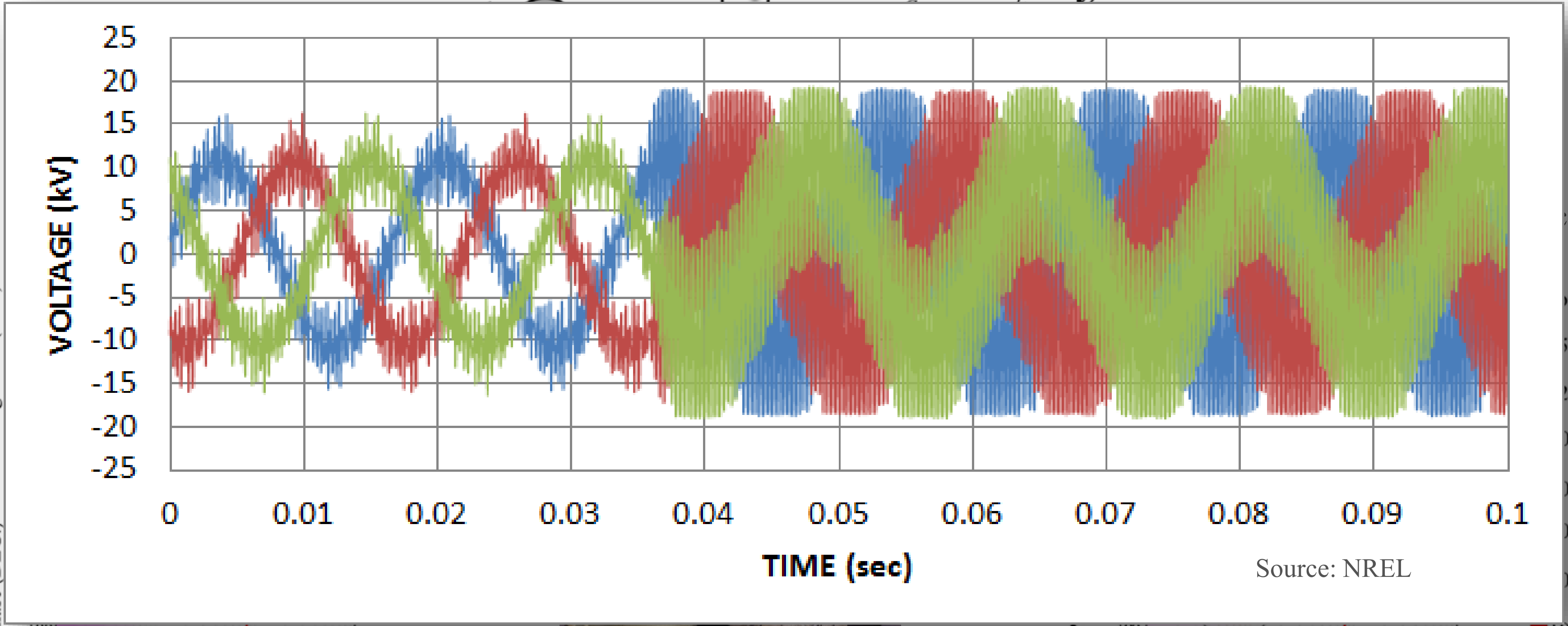


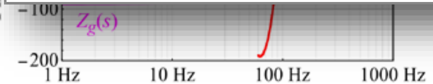
Prediction of SSR-generated harmonics

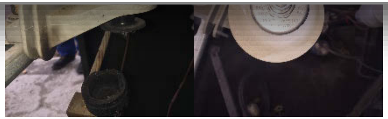


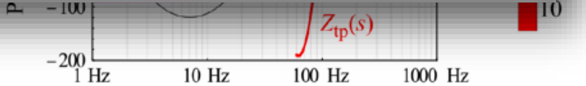
Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

Role of Protection in Resonance



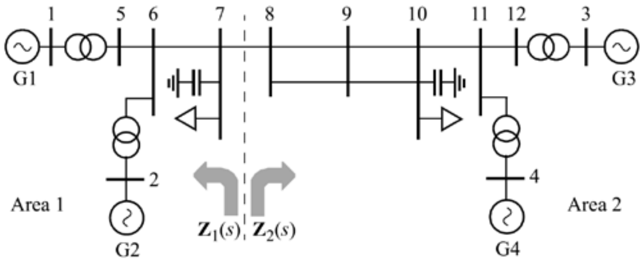




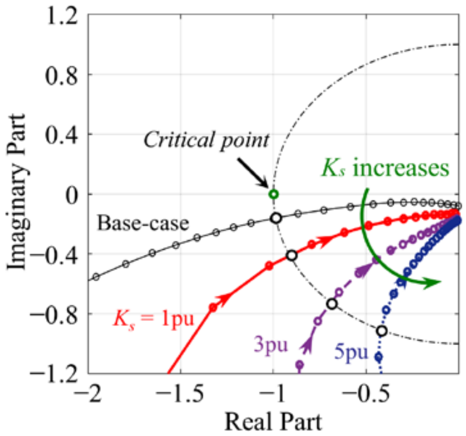


Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

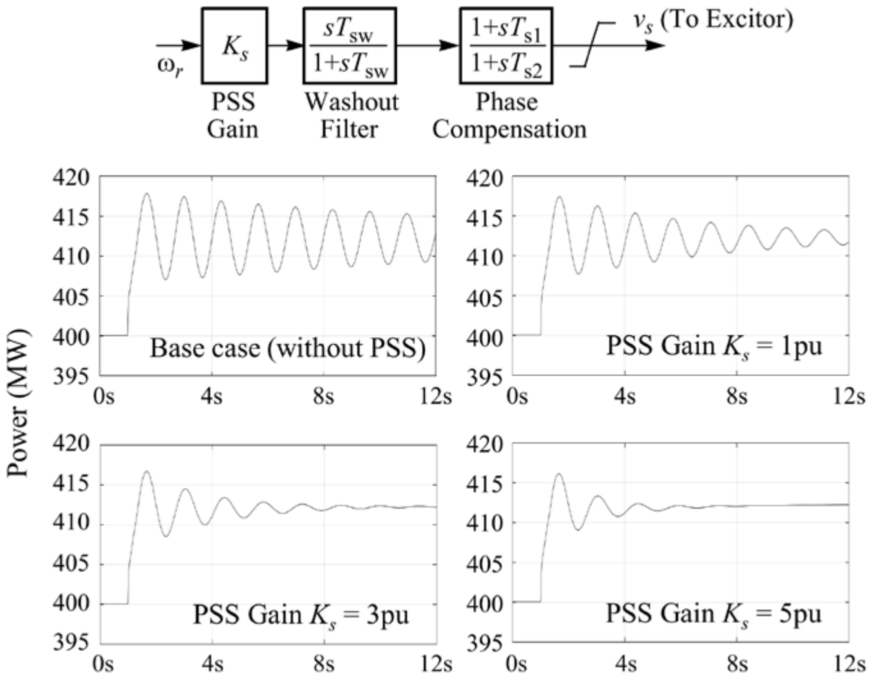
Impedance Analysis of Power System Oscillations



- Impedance analysis

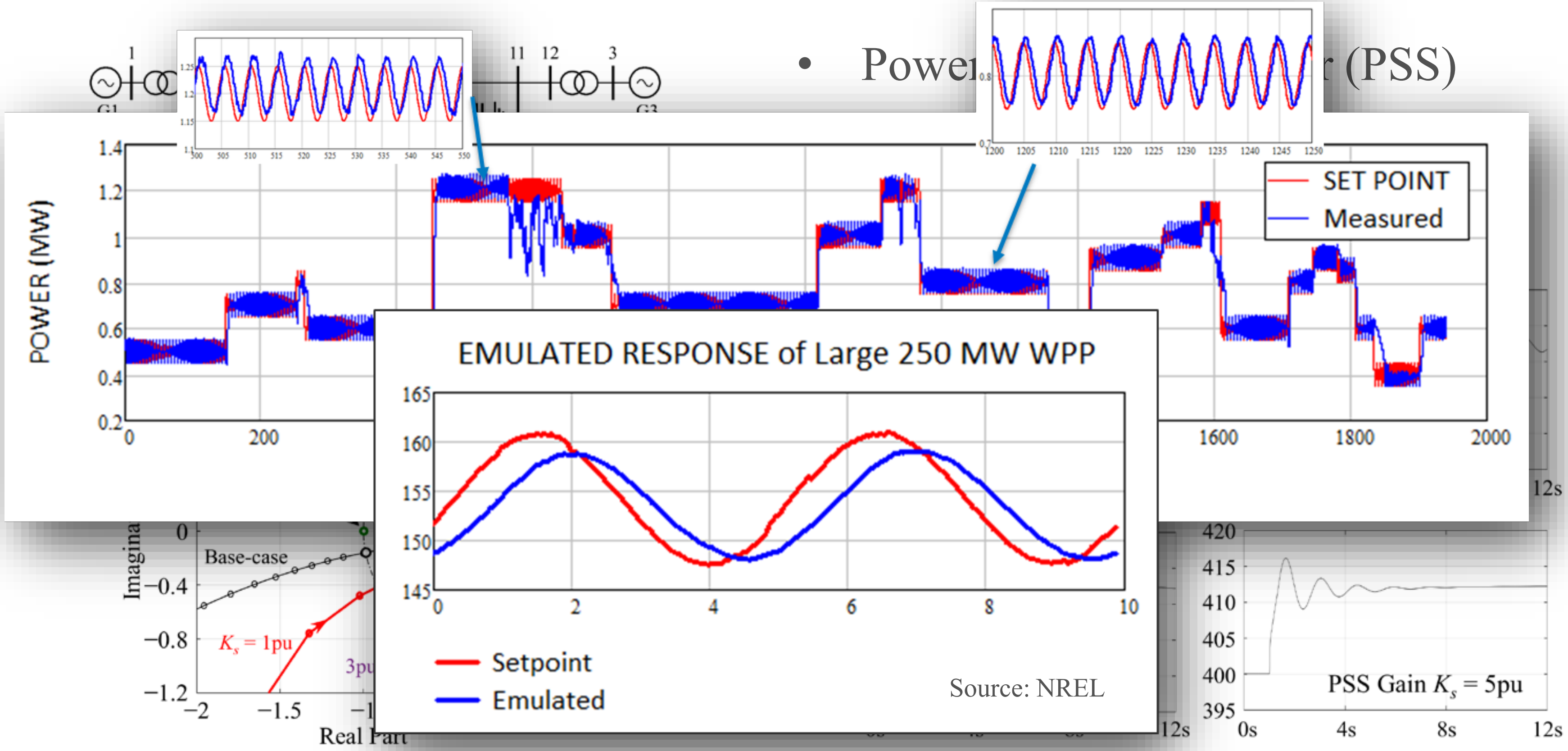


- Power system stabilizer (PSS)



Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

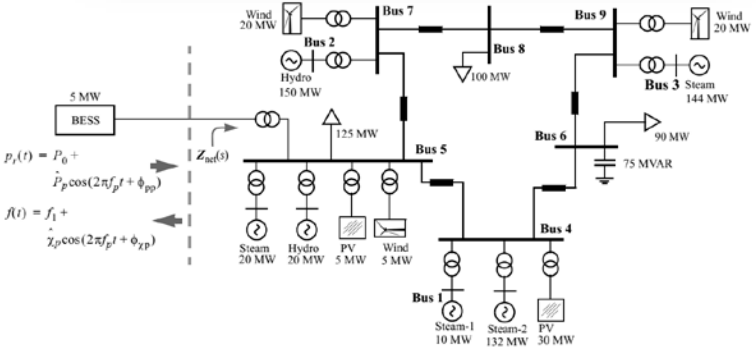
Power Modulation from a GE 1.5-MW Turbine



Shahil Shah, NSF Workshop on Power Electronics-Enabled Operation of Power Systems

Online Monitoring of Frequency Response

- Transfer function from active power to frequency



- Prediction of primary frequency response and inertia

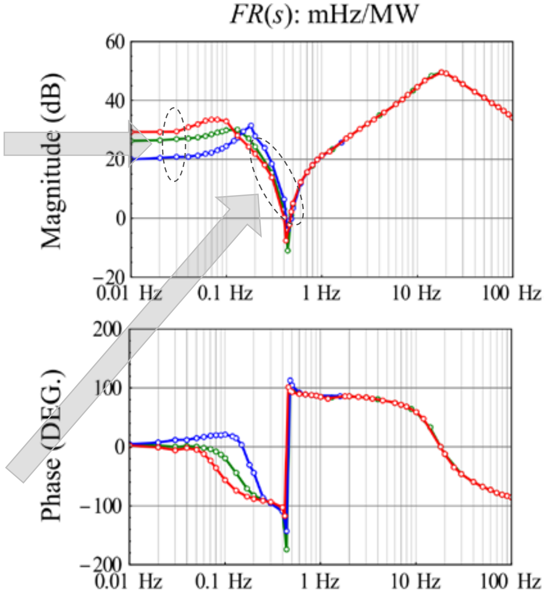
MW/0.1 Hz

3.1 MW/0.1Hz
4.6 MW/0.1Hz
10 MW/0.1Hz

Inertia

$$\frac{f(s)}{P(s)} = \frac{1}{sC_H} \qquad 2H\frac{d\overline{f}}{dt} = \Delta\overline{P}$$

1974 MW·*s*



Future Development

- New impedance-based tools for stability analysis of modern power systems
  - State-space modal analysis: mainstream tool for stability analysis of traditional power systems
  - Impedance-based analysis: established as the main tool for stability analysis of power electronics systems.
- Impedance as platform for comparing advanced control methods, e.g., grid-forming inverters
- Impedance-based grid codes:
  - Agnostic to internal controls
  - Easy to characterize and understand
  - Supports system stability analysis.
- Standardized controls and models for inverter-based resources.

References

1. S. Shah, P. Koralewicz, V. Gevorgian, R. Wallen, K. Jha, D. Mashtare, R. Burra, and L. Parsa, "Large-Signal Impedance-Based Modeling and Mitigation of Resonance of Converter-Grid Systems," *IEEE Transactions on Sustain. Energy*, p. 12, Mar. 2019.
2. S. Shah and L. Parsa, "Impedance-Based Prediction of Distortions Generated by Resonance in Grid-Connected Converters," *IEEE Trans. on Energy Conv.*, vol. 34, no. 3, pp. 1264–1275, Sep. 2019.
3. S. Shah, V. Gevorgian, and H. Liu, "Impedance-Based Prediction of SSR-Generated Harmonics in Doubly-Fed Induction Generators," in *Proc. 2019 Power and Energy Soc. Gen. Meeting (PESGM)*, Atlanta, GA.
4. S. Shah and V. Gevorgian, "Impedance-Based Characterization of Power System Frequency Response," in *Proc. 2019 Power and Energy Soc. Gen. Meeting (PESGM)*, Atlanta, GA.
5. S. Shah, P. Koralewicz, R. Wallen, and V. Gevorgian, "Impedance Characterization of Utility-Scale Renewable Energy and Storage Systems," in *Proc. 2019 Energy Conv. Cong. Expo. (ECCE)*, Baltimore, MD.
6. S. Shah, P. Koralewicz, V. Gevorgian, and R. Wallen, "Impedance Measurement of Wind Turbines Using a Multimegawatt Grid Simulator," in *Proc. 18th Wind Integr. Workshop*, Dublin, Ireland.
7. S. Shah, P. Koralewicz, V. Gevorgian, and R. Wallen, "Large-Signal Impedance Modeling of Three-Phase Voltage Source Converters," in *Proc. 44th Annual Conf. IEEE Ind. Electron. Soc. IECON 2018*, Washington, D.C., Nov. 2018.
8. S. Shah and L. Parsa, "Small-Signal Modeling and Design of Phase-Locked Loops Using Harmonic Signal-Low Graphs," accepted for publication in *IEEE Trans. Energy Conv.*, 2019.
9. S. Shah, P. Koralewicz, V. Gevorgian, "CGI for Impedance Characterization of Inverter-Coupled Generation" in *Proc. 5th Annual Int. Workshop on Grid Simulator Testing of Wind Turbine Powertrains*, 2018, Tallahassee, FL. [Online]. Available: https://www.nrel.gov/docs/fy19osti/72899.pdf
10. S. Shah and L. Parsa, "Impedance Modeling of Three-Phase Voltage Source Converters in dq, Sequence, and Phasor Domains" *IEEE Transactions on Energy Conversion*, vol. 32, no. 3, pp. 1139–1150, Sep. 2017.

Thank you!

www.nrel.gov

Shahil.Shah@nrel.gov

NREL/PR-5D00-75345

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.

NREL Transforming ENERGY