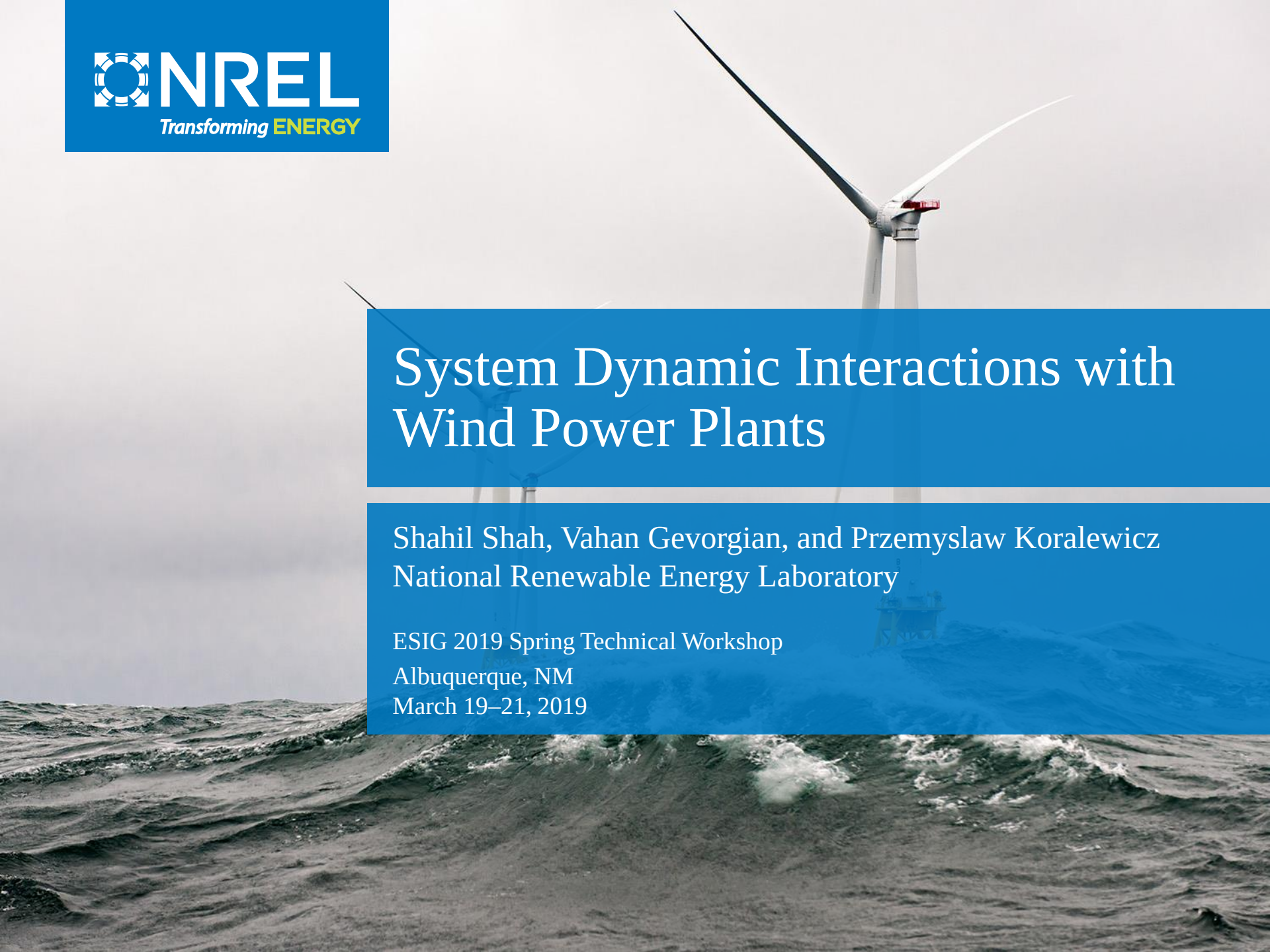
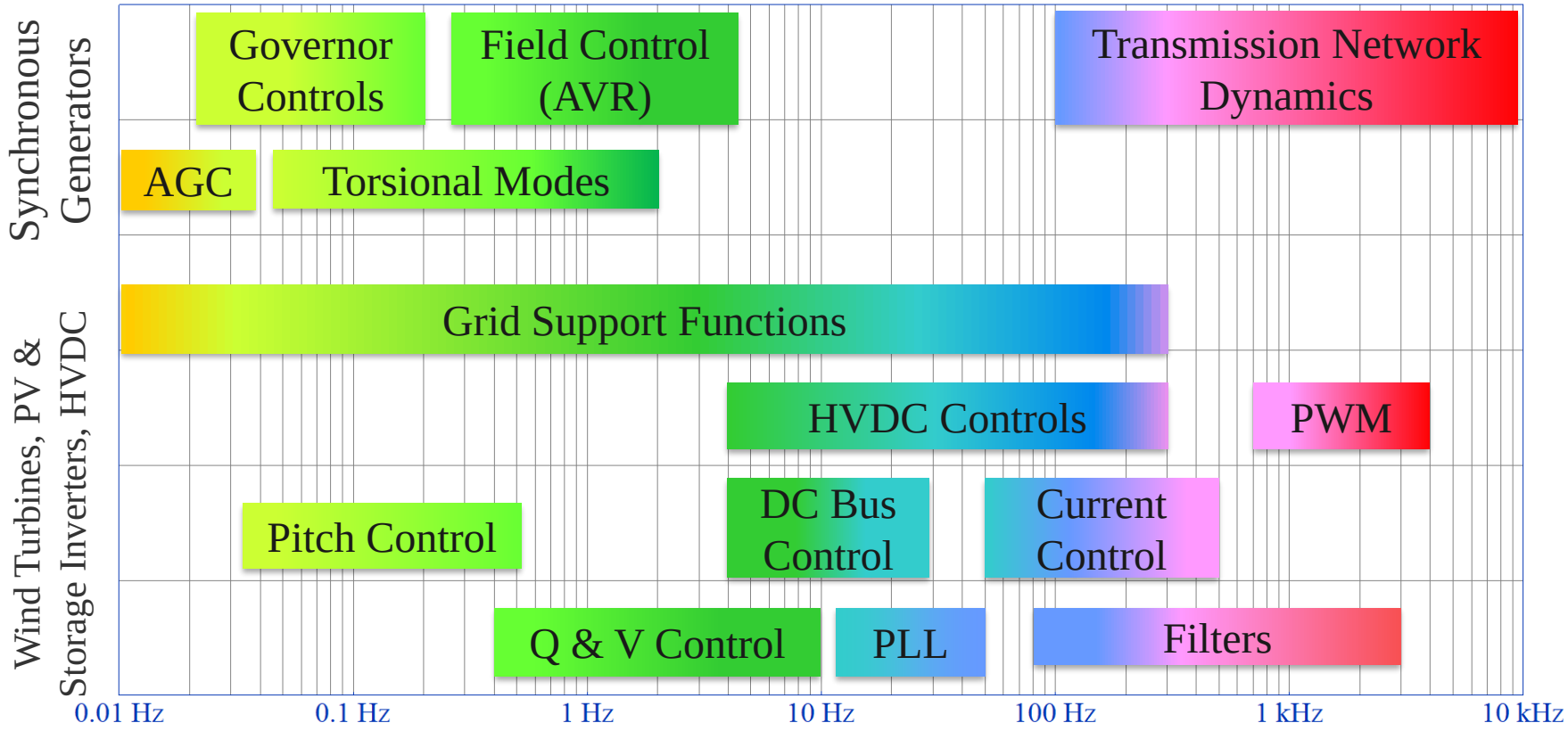


System Dynamic Interactions with Wind Power Plants

Shahil Shah, Vahan Gevorgian, and Przemyslaw Koralewicz
National Renewable Energy Laboratory

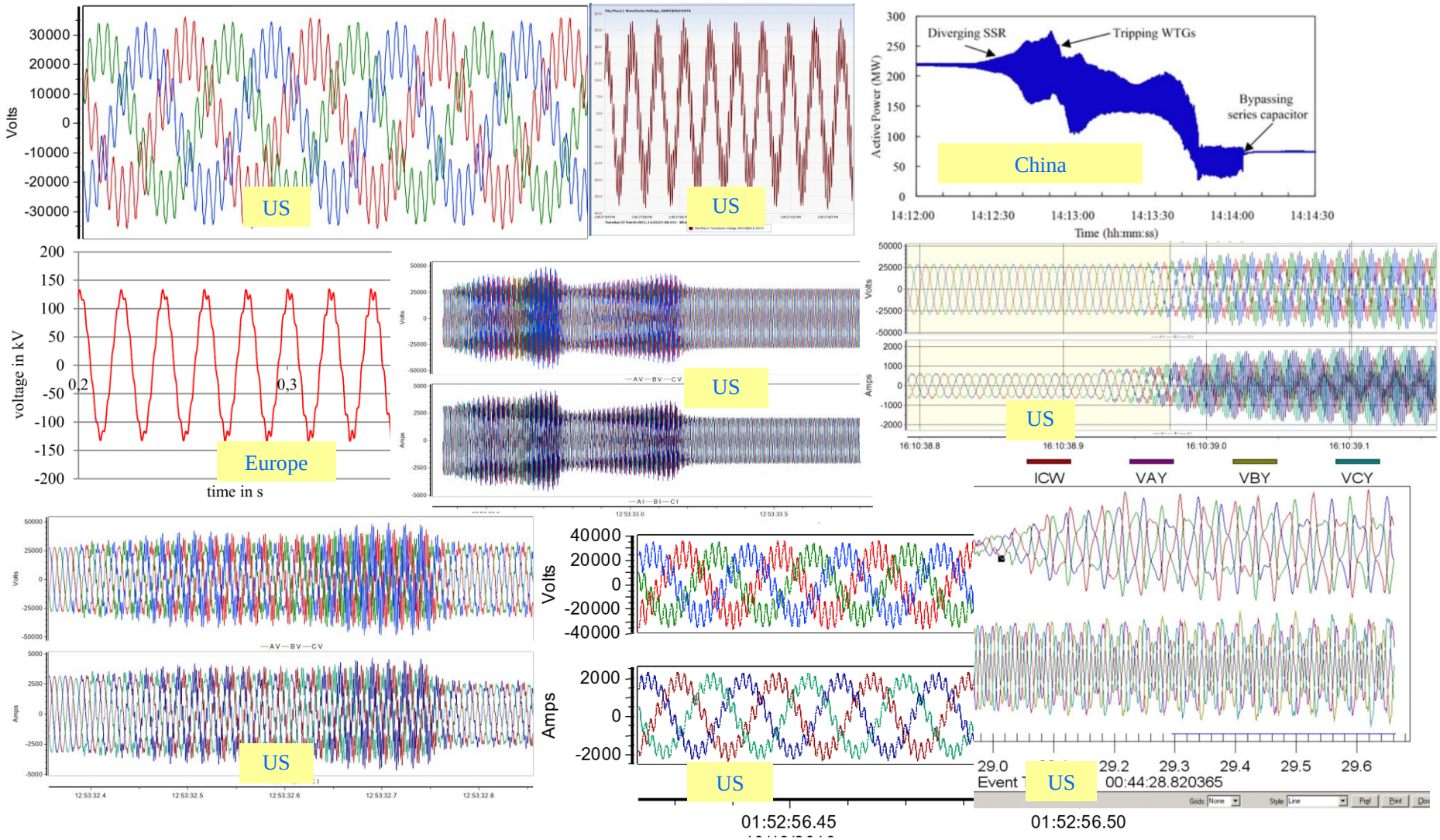
ESIG 2019 Spring Technical Workshop
Albuquerque, NM
March 19–21, 2019

Control Interactions

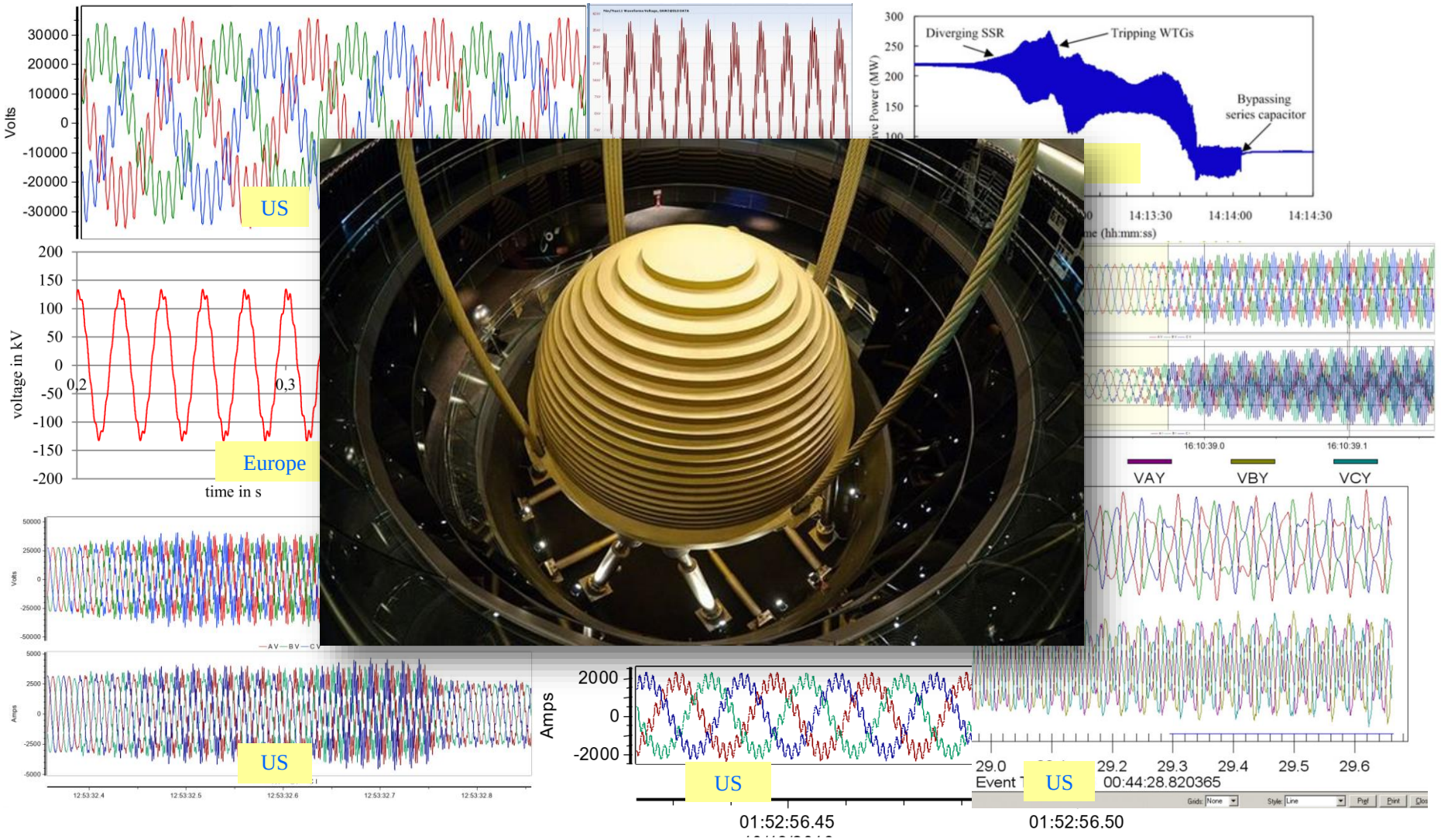


- Power electronics-based generation and transmission technologies have increased control interaction problems

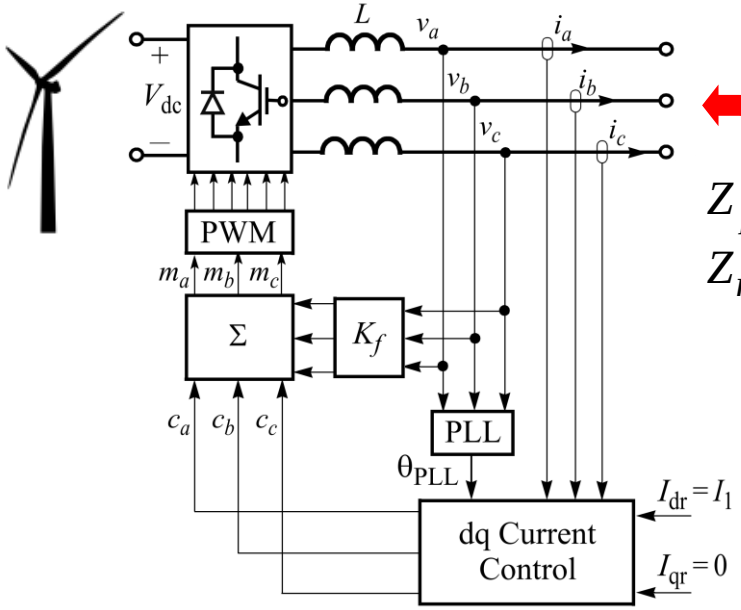
Resonance in Wind Power Plants



Resonance in Wind Power Plants

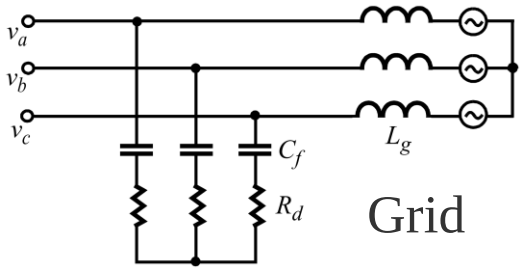


Impedance-Based Analysis



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

$Z_g(s)$

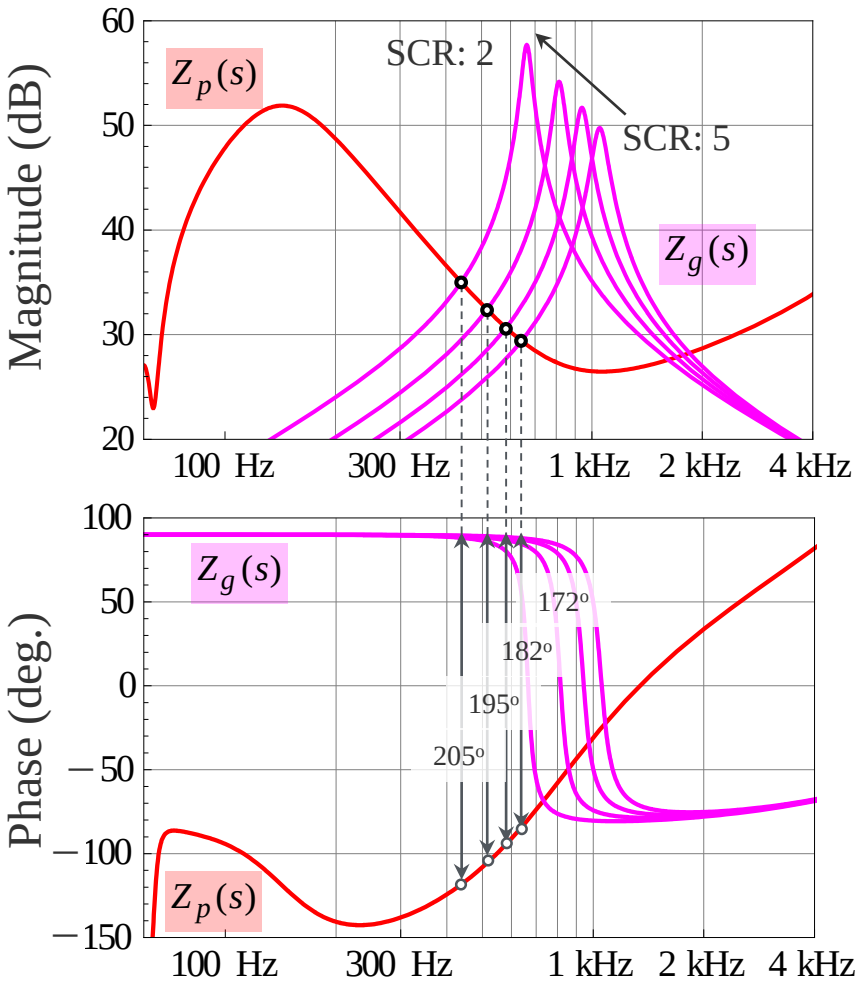


Loop gain:

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

- Impedance responses of turbine/plant and grid are compared
  - Impedance intersection points give frequencies of resonance modes
  - Phase difference at intersection points gives damping

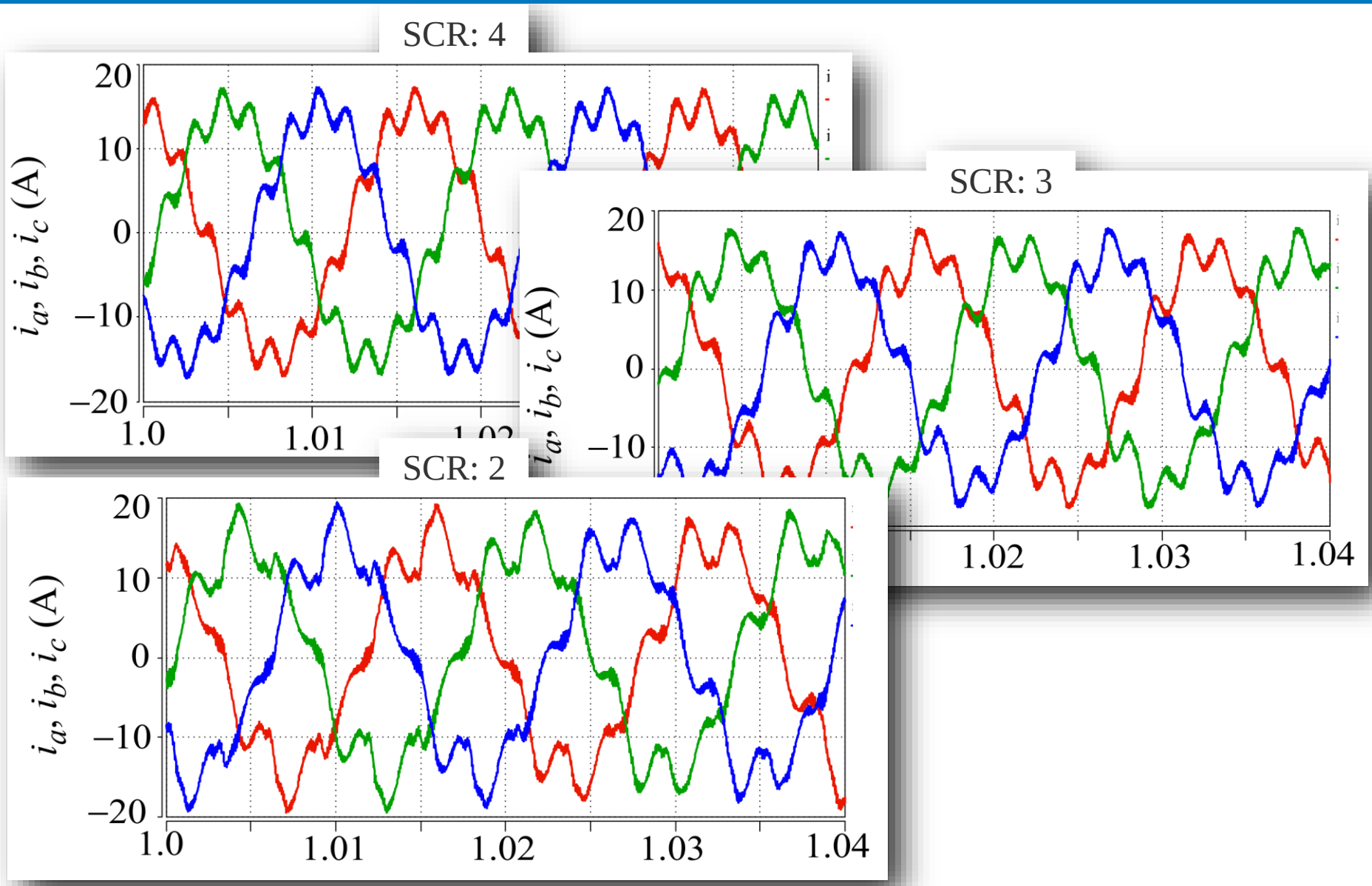
Resonance: Frequency and Damping



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°

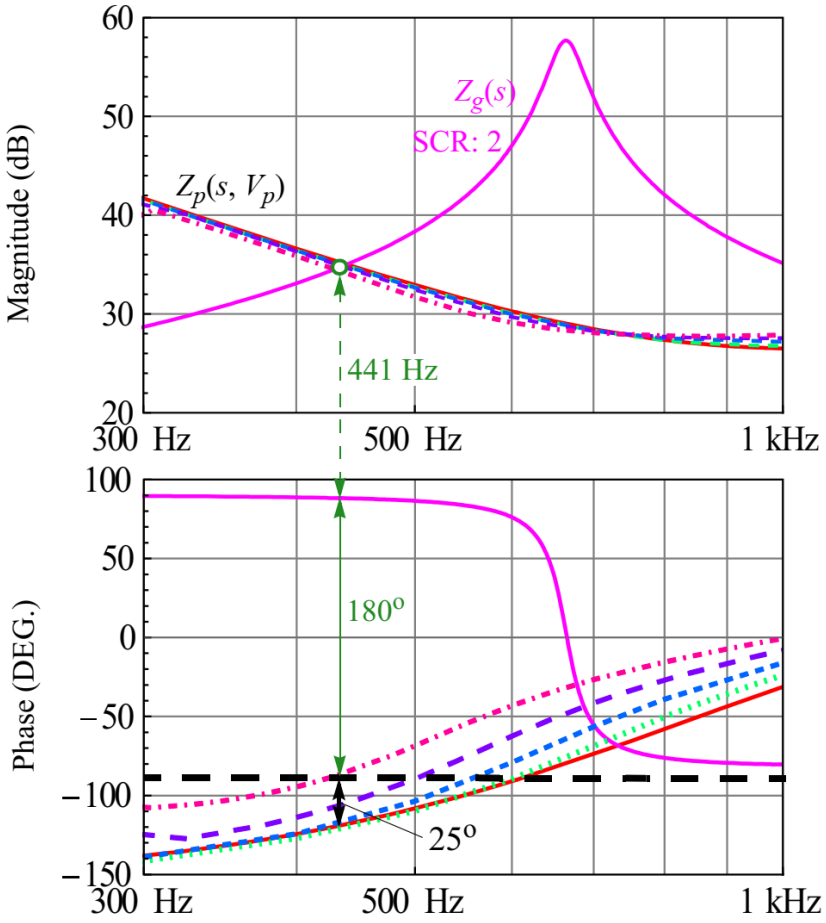
- Unstable Resonance for Weak Grids
  - Unstable for SCR<5.0
  - Resonance Frequency Decreases with SCR and its “Severity” Increases

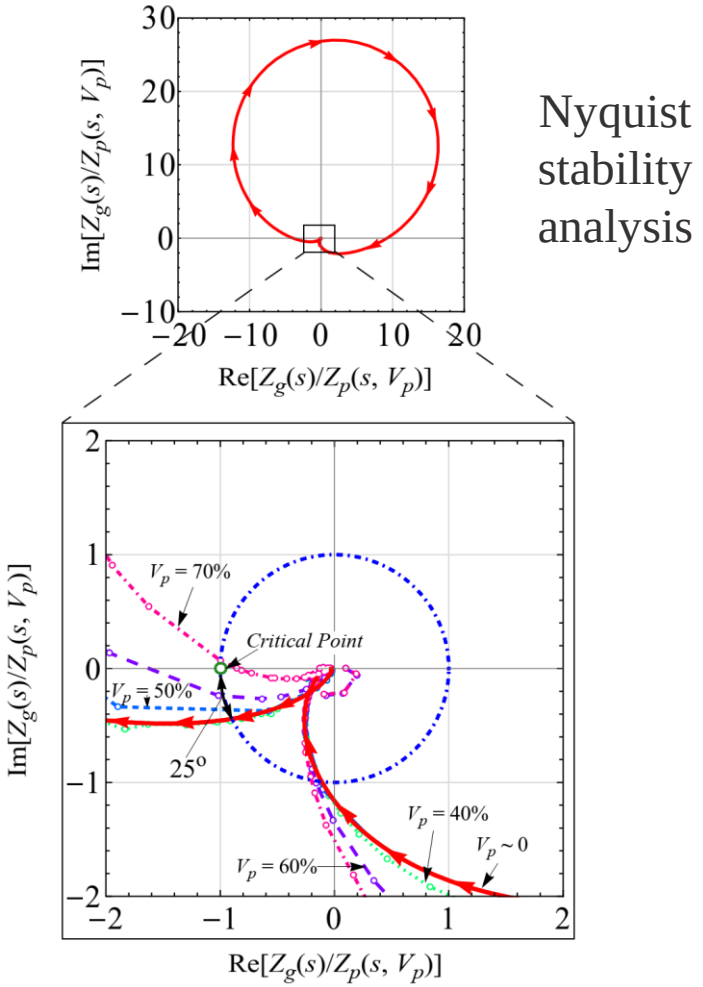
Resonance-Generated Distortions



Large-Signal Impedance Theory

- Impedance changes with resonance magnitude

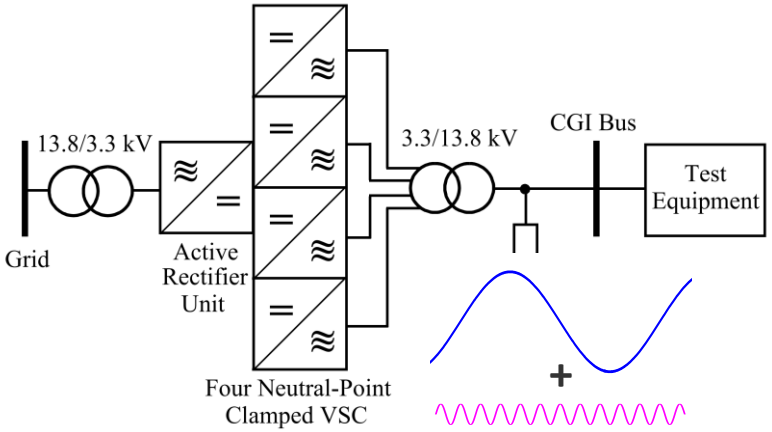




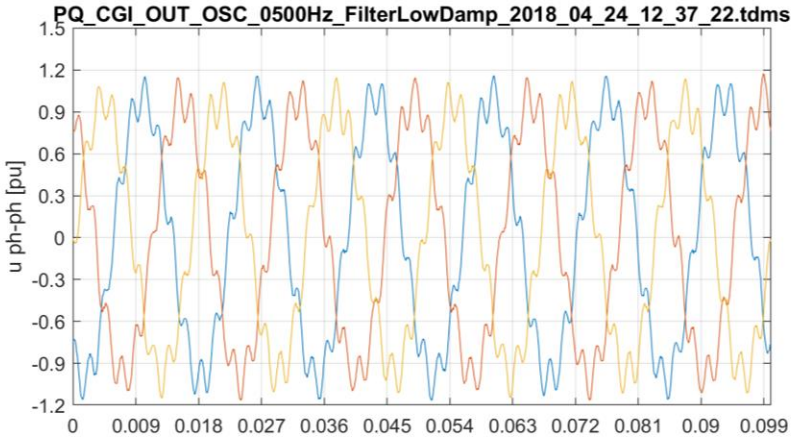
Nyquist stability analysis

Impedance Measurement Using CGI

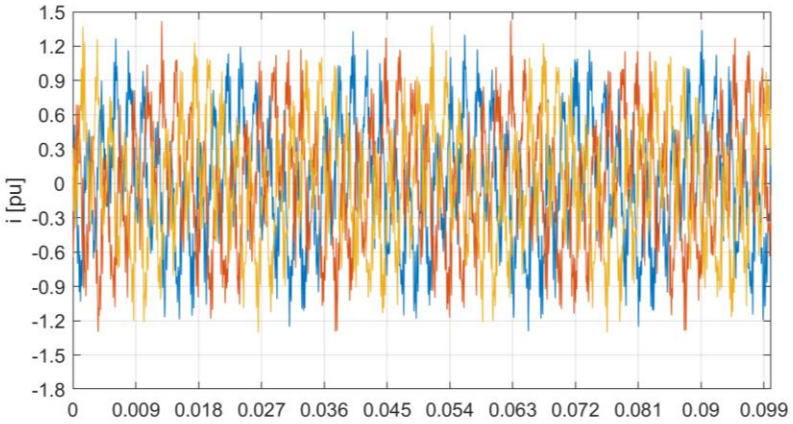
- 7-MVA, 13.2-kV grid simulator (CGI)



- Perturbed voltages



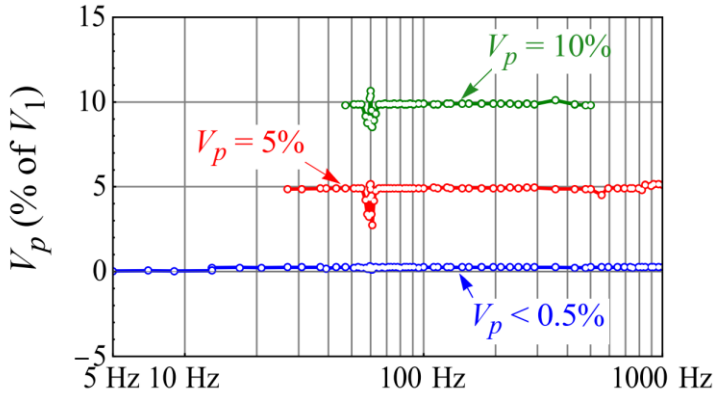
- Response currents



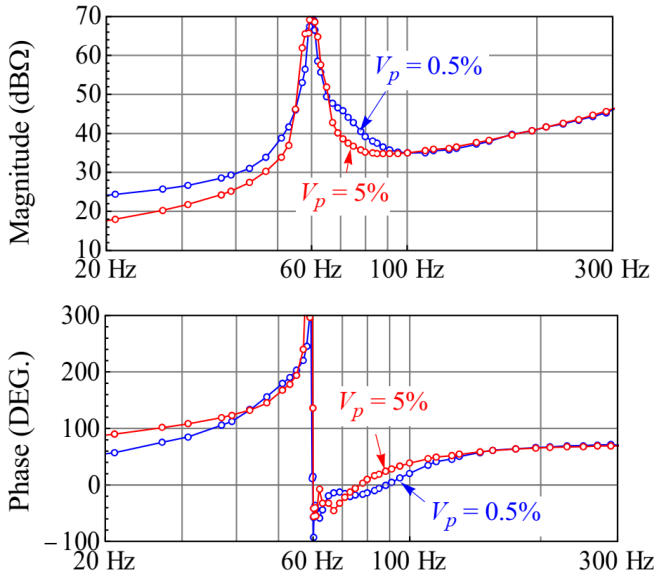
Impedance of 1-MW/13.8-kV Inverter

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

  - Voltage perturbation magnitude

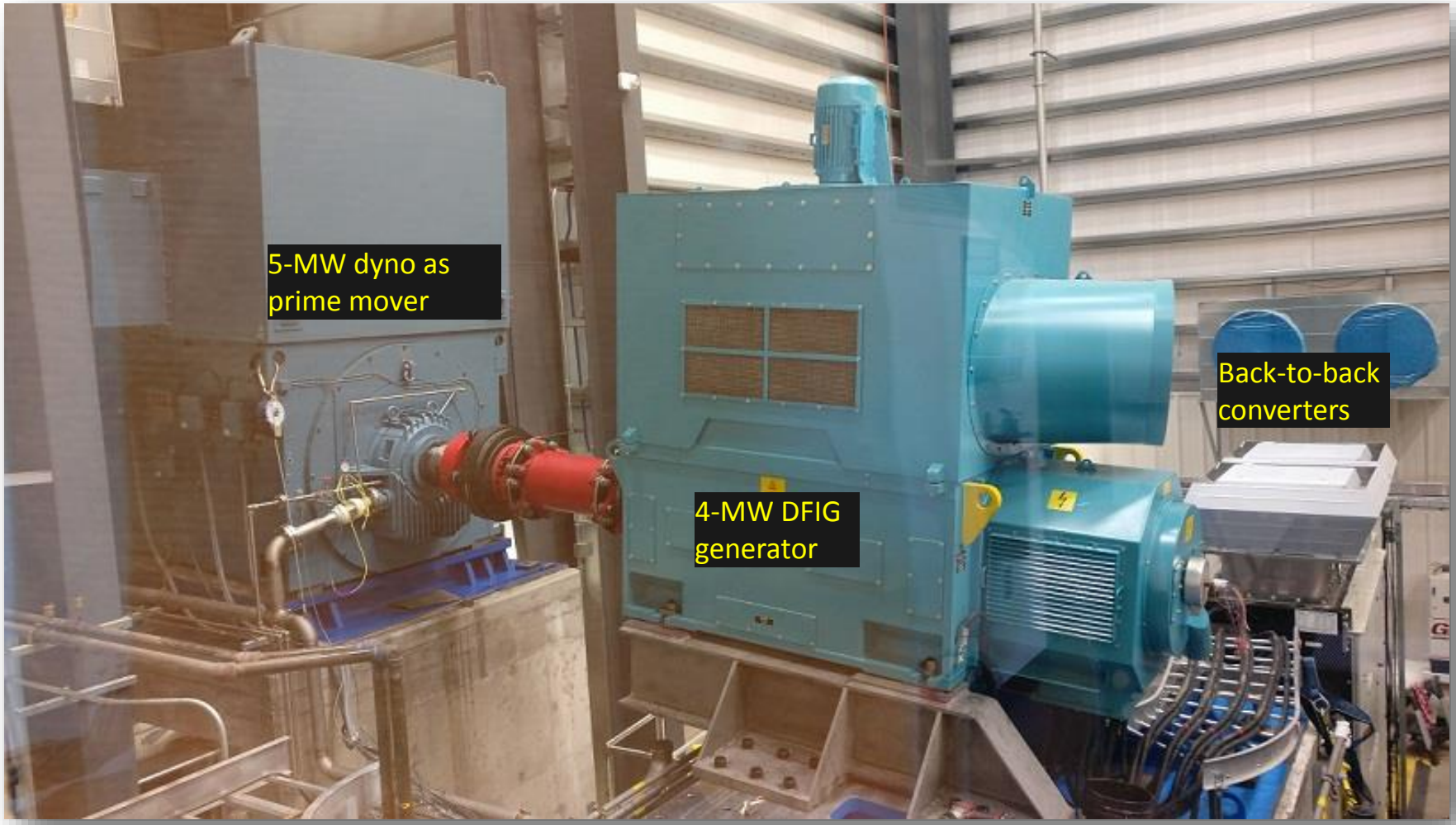


- Impedance response



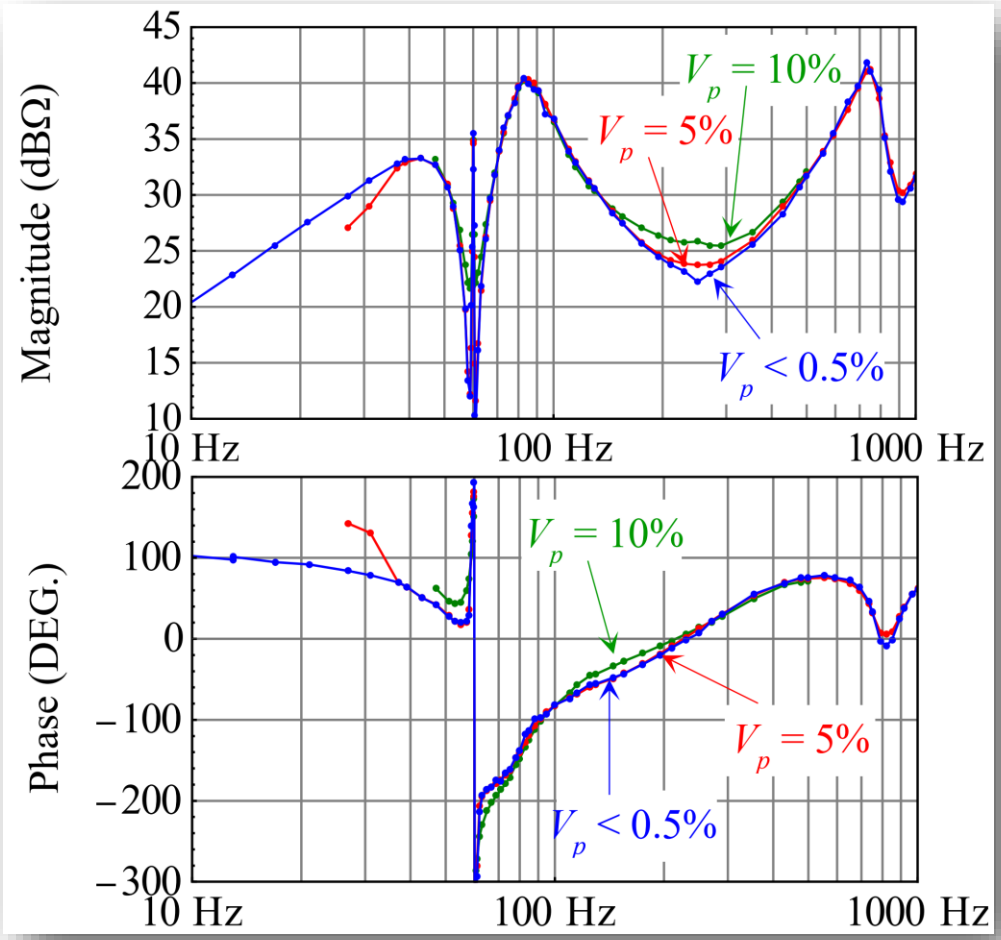
- Different control elements dominate at different frequencies.

4-MW Type III Wind Turbine Drivetrain



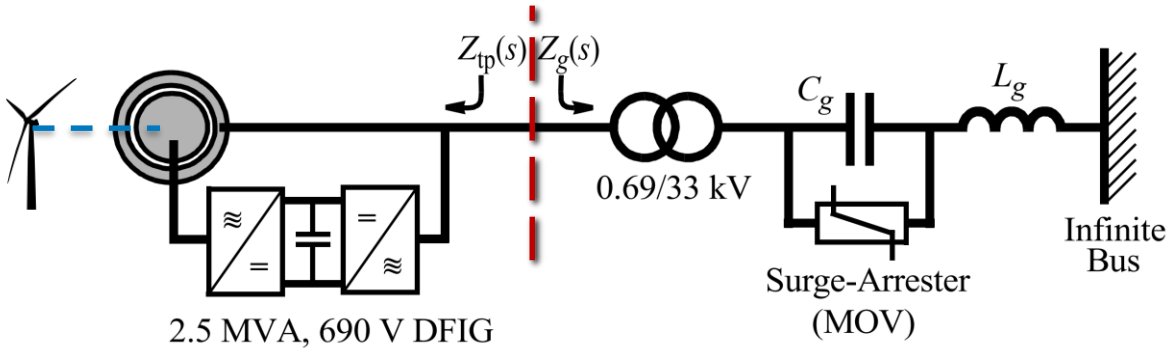
Positive-Sequence Impedance of DFIG

Measurements of 4-MW DFIG

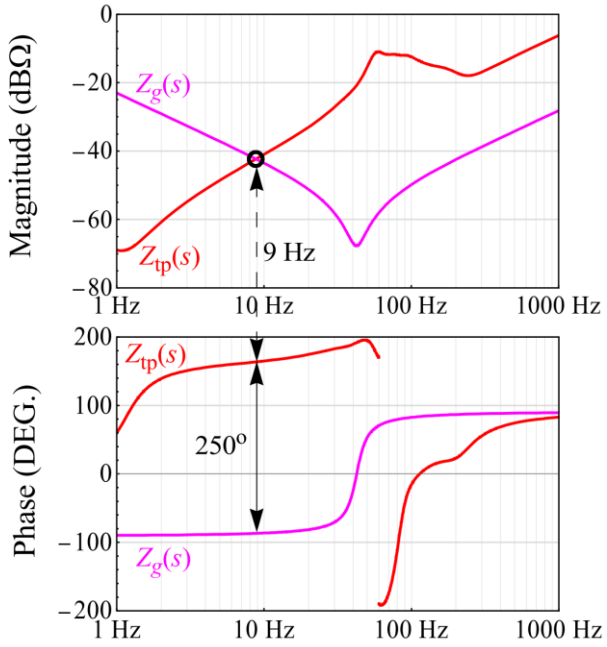


- Low-frequency inductive behavior because of induction machine
  - Phase higher than 90°: Negative resistance
  - Subsynchronous resonance (SSR)
- Capacitive behavior between 80–250 Hz because of current control
- EMI filters dominate high-frequency response

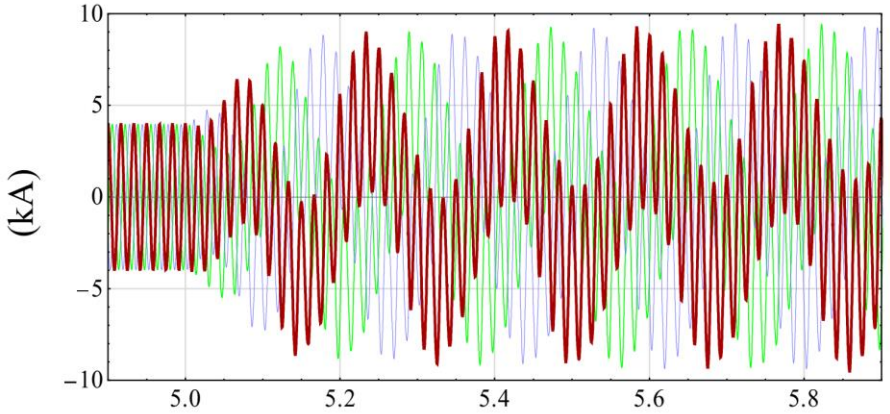
SSR in Type III Wind Turbines



- Impedance analysis

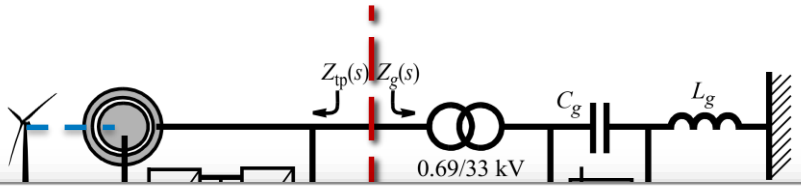


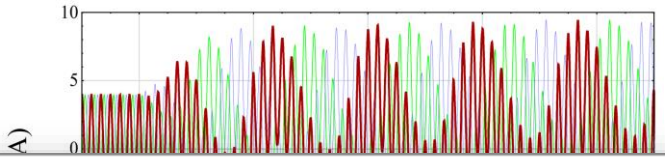
- DFIG output currents

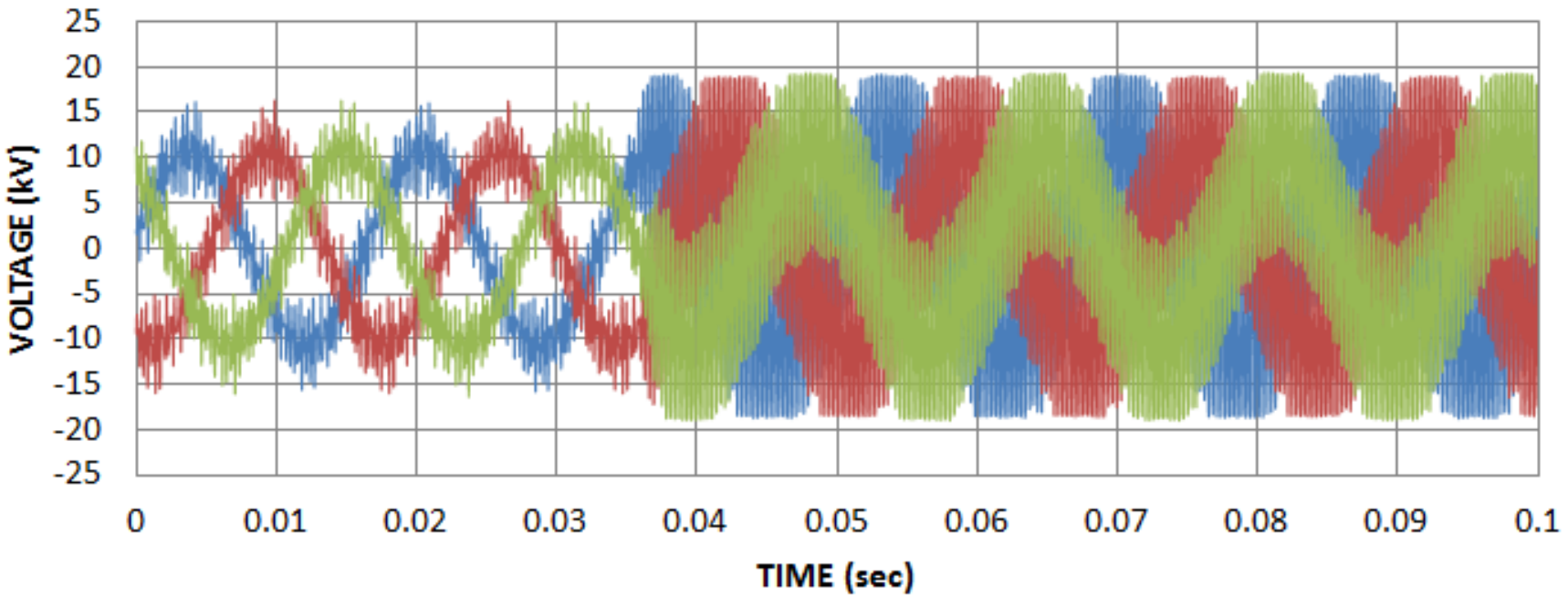


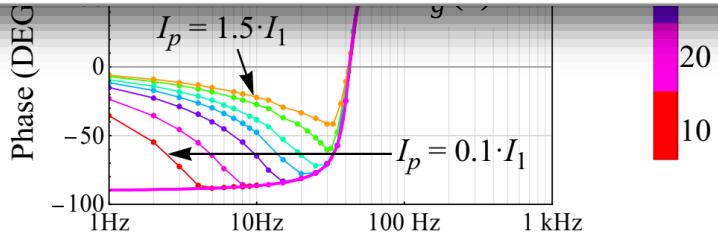
- Control design to mitigate turbine-turbine and farm-grid dynamic interactions.

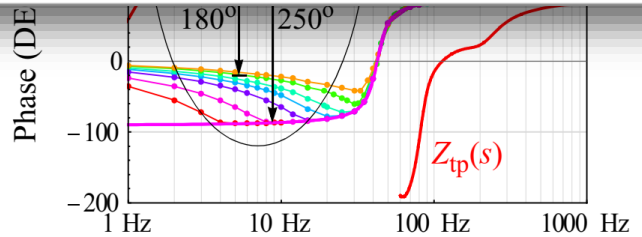
SSR-Generated Harmonics



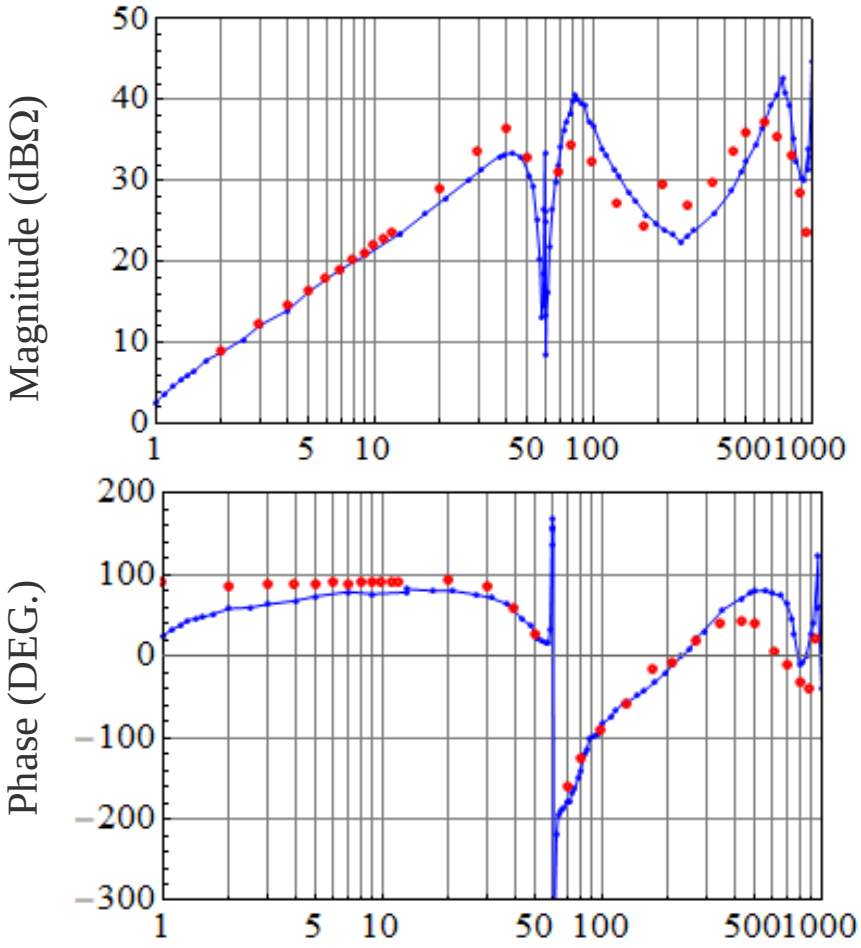








Model Validation



Blue: Measurements of 4-MW DFIG

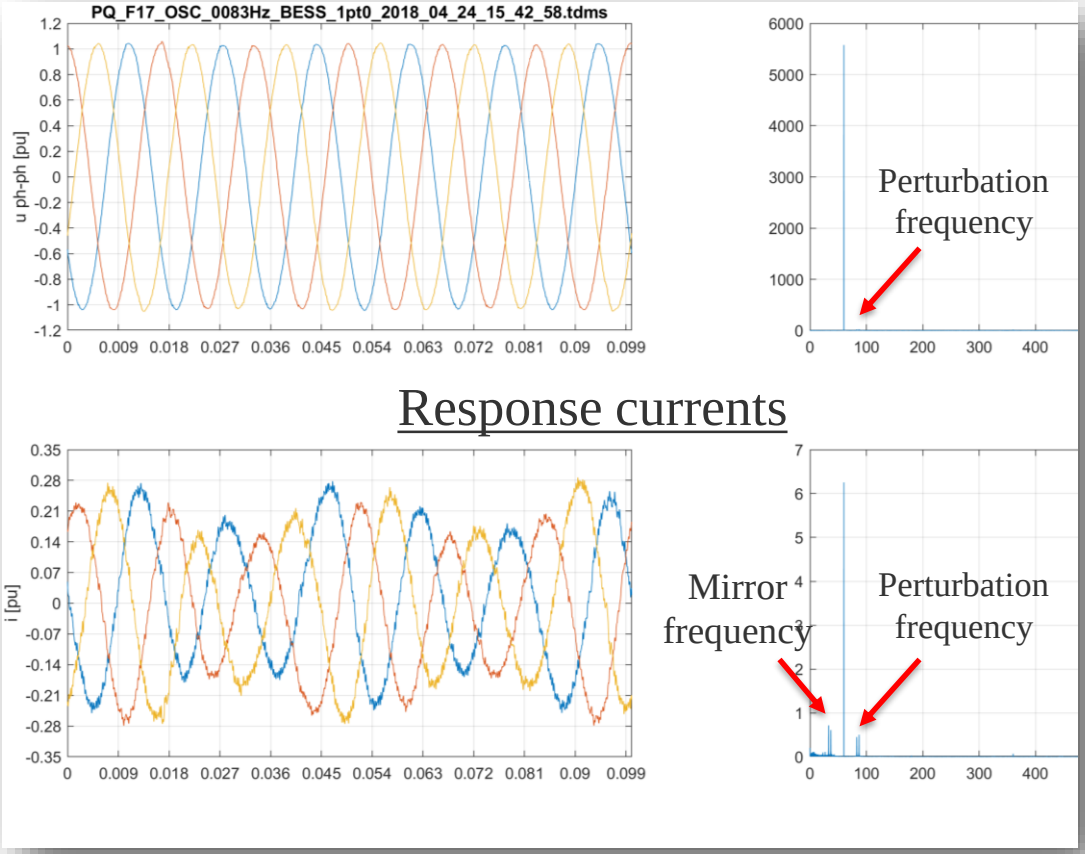
Red: OEM PSCAD model

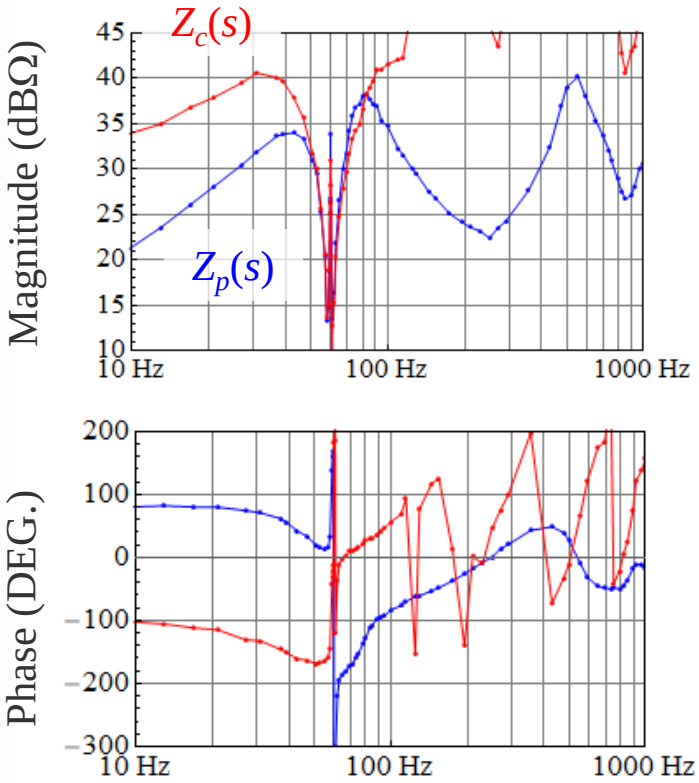
- High-fidelity model validation
- Validated models can be used to evaluate:
  - Farm-grid and turbine-turbine interactions
  - Grid-support functions
  - Transient performance
  - Control design
  - System integration studies – *Black-box model for utilities*

Frequency Cross-Coupling

- Voltage perturbation at a frequency produces current response also at the *mirror frequency*

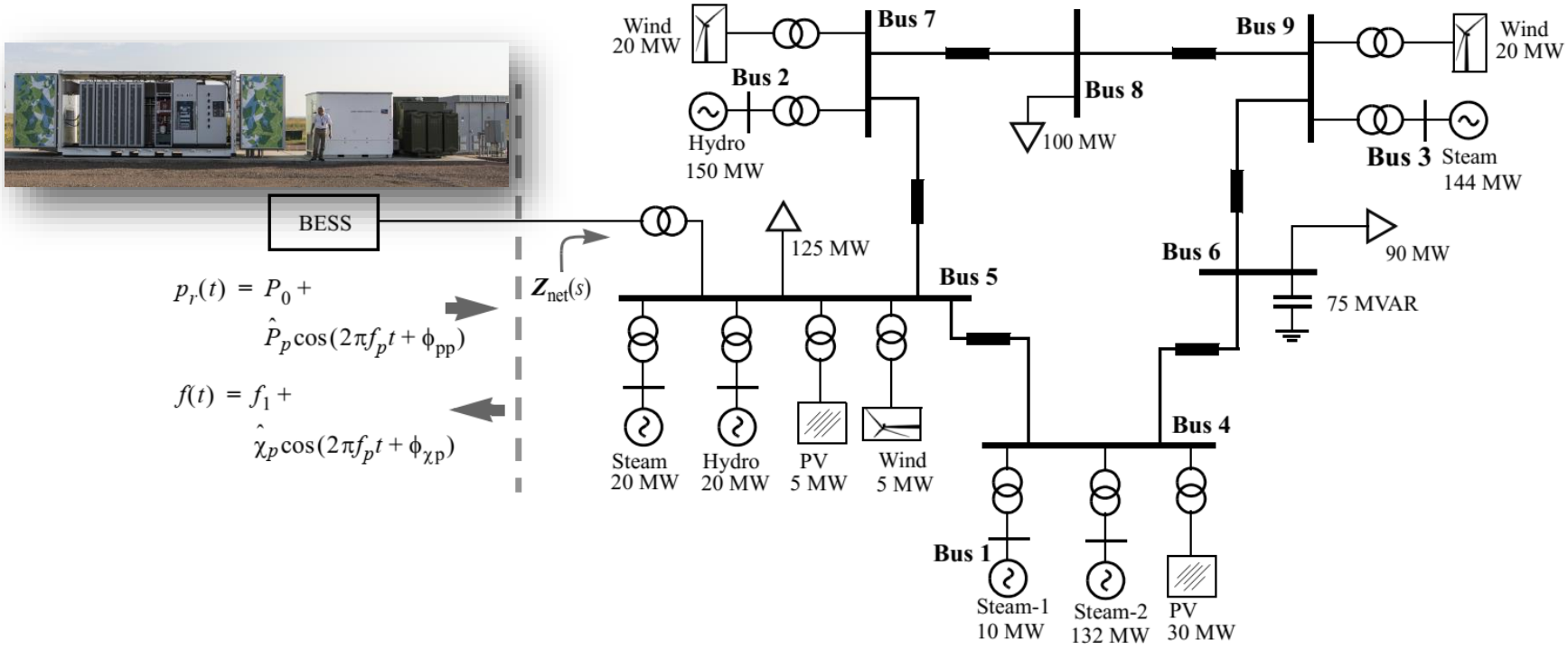
Perturbed voltages



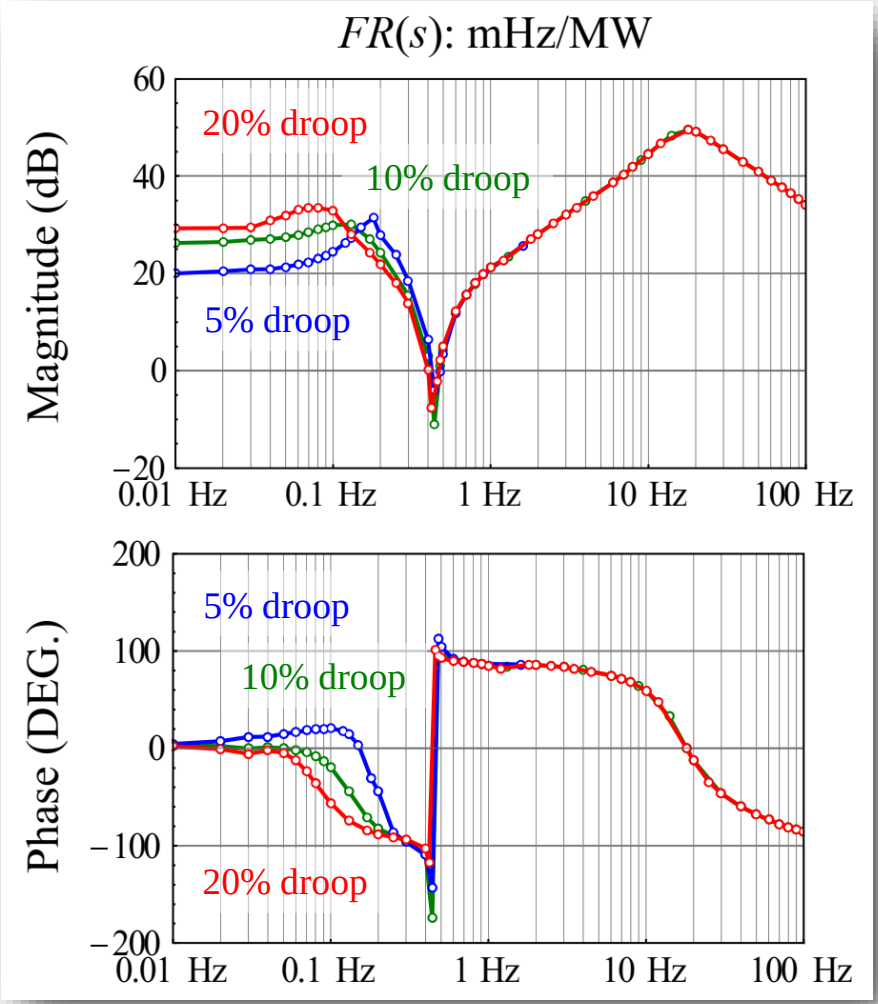


Power-Domain Impedance

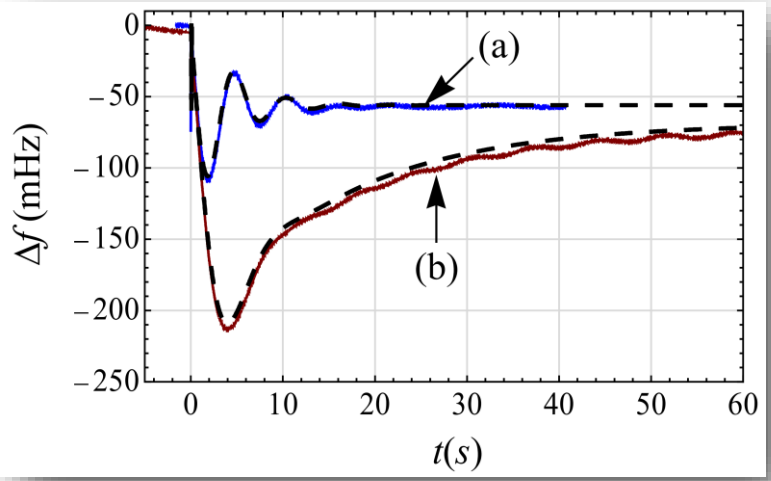
- Transfer function from Active Power to Frequency at Point of Interconnection



Frequency Response Characterization



Loss of generation



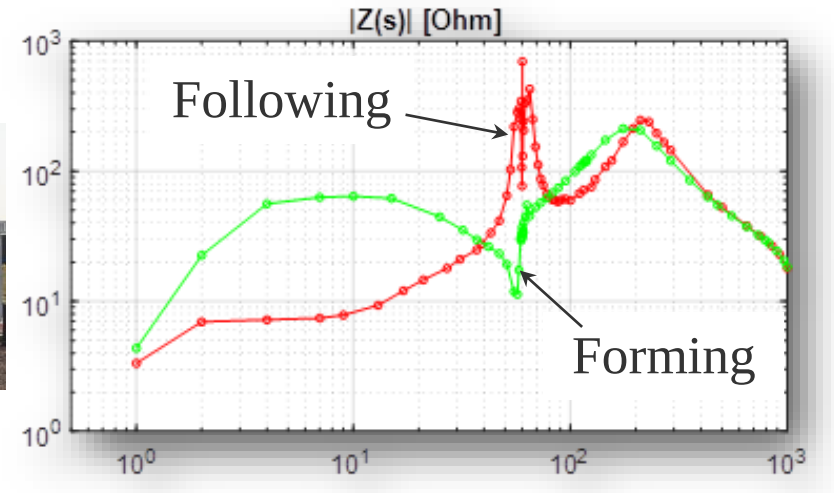
Applications:

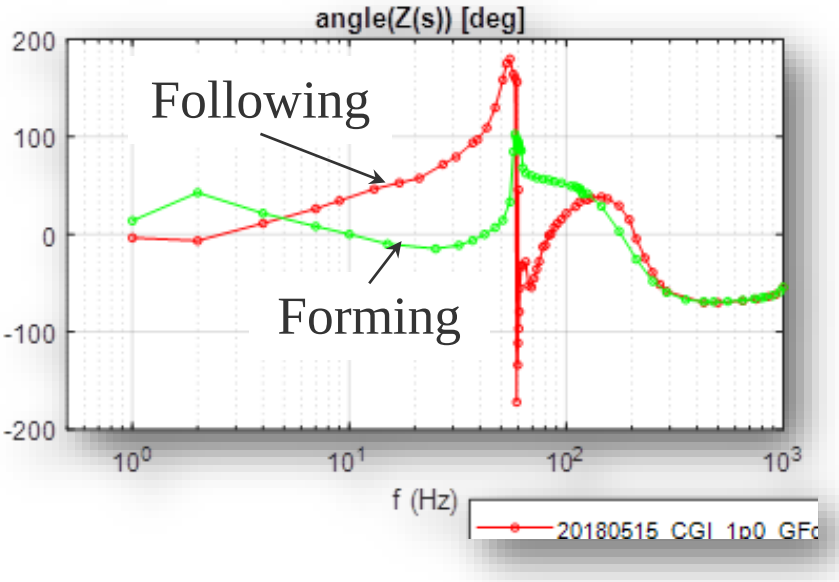
- Real-time Estimation of Inertia, Primary Frequency Response (PFR), Nadir, etc.
- Frequency Support Design by Renewable Generation

Grid-Forming Inverter from *Outside*

- BESS Inverter

- Impedance measurements can **quantify** different aspects of grid-forming ability





Future Development

- Adoption of impedance characterization by industry
  - Root-cause finding, grid codes, control design, impedance specs
- Impedance measurement using grid simulators
  - High-fidelity model validation
  - Control design; Testing for grid codes
- New impedance-based tools
  - Design of grid-support functions
  - Testing of grid-forming ability of inverters

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3. 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
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6. S. Shah and V. Gevorgian, "Impedance-based characterization of power system frequency response," in *Proc. IEEE Power and Energy Soc. General Meeting*, Atlanta, GA, July, 2019.
7. S. Shah and L. Parsa, "Impedance-based prediction of distortions generated by resonance in grid-connected converters," *IEEE Transactions on Energy Conversion*, Mar. 2019.
8. S. Shah and L. Parsa, "Impedance modeling of three-phase voltage source converters in dq, sequence, and phasor domains" *IEEE Transactions on Energy Conversion*, Sep. 2017.

Thank You

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