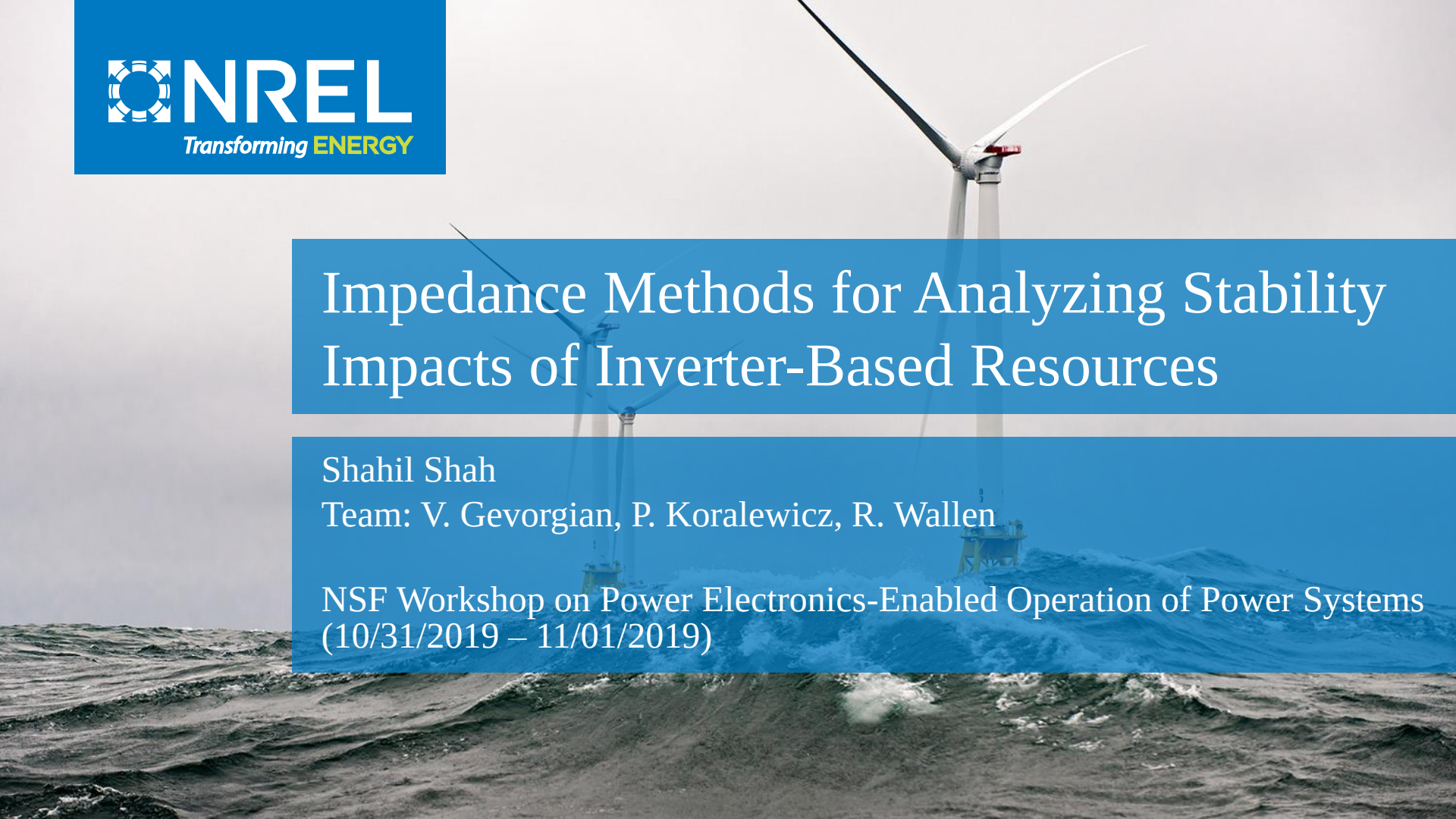


Impedance Methods for Analyzing Stability Impacts of Inverter-Based Resources

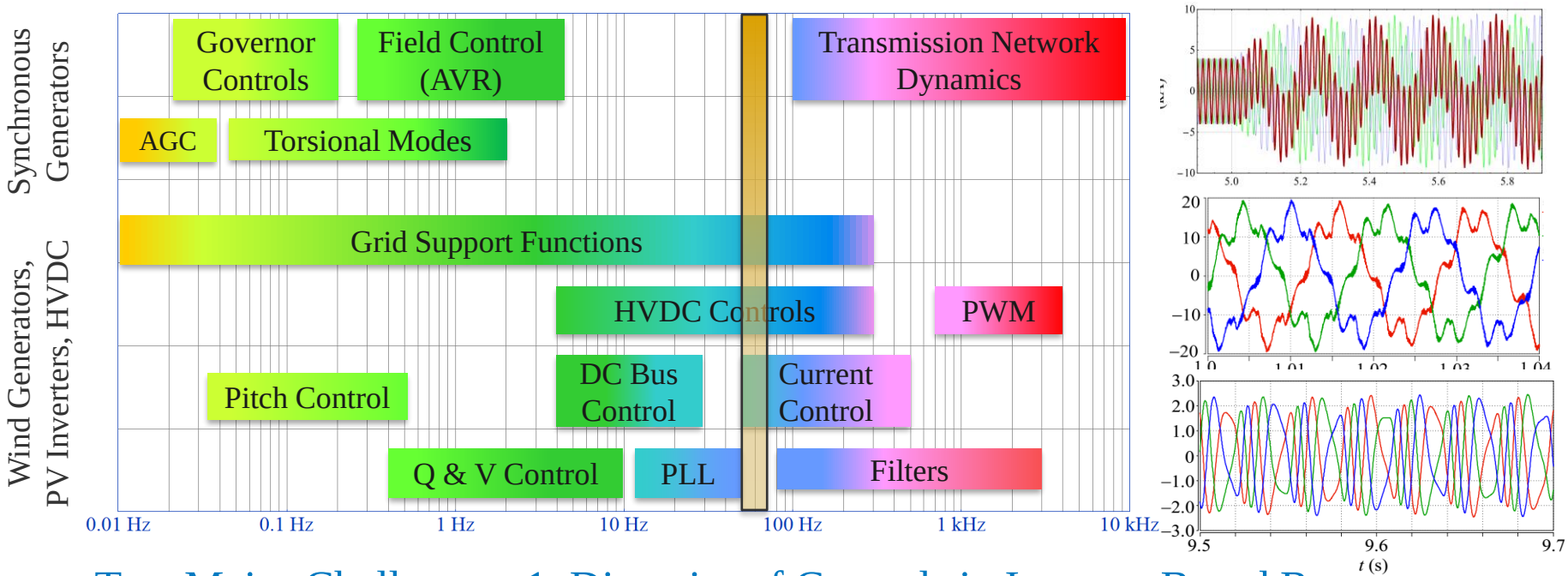
Shahil Shah
Team: V. Gevorgian, P. Koralewicz, R. Wallen

NSF Workshop on Power Electronics-Enabled Operation of Power Systems
(10/31/2019 – 11/01/2019)

Outline

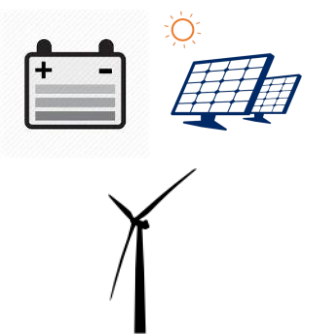
- Control Interactions and Resonance in Power Electronics Systems
- Impedance-Based Stability Analysis
  - Impedance Modeling
  - Measurement
  - Applications
- Extension to Other Stability Problems in Modern Power System
- Future Development

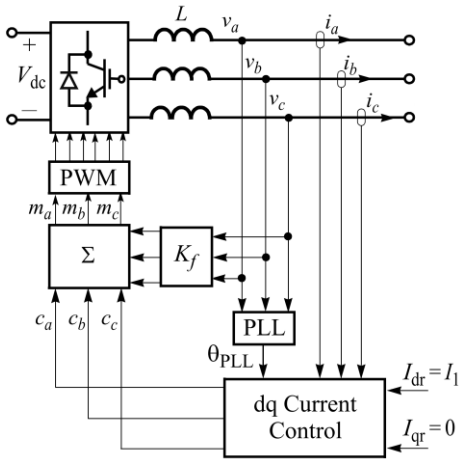
Control Interactions



- Two Major Challenges: 1. Diversity of Controls in Inverter-Based Resources; 2. Unavailability of High-Fidelity Dynamic Models

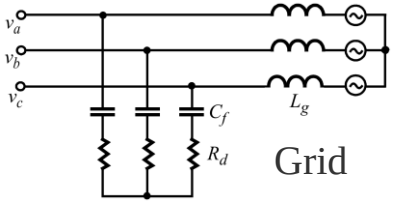
Impedance-based Stability Analysis





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

$Z_g(s)$

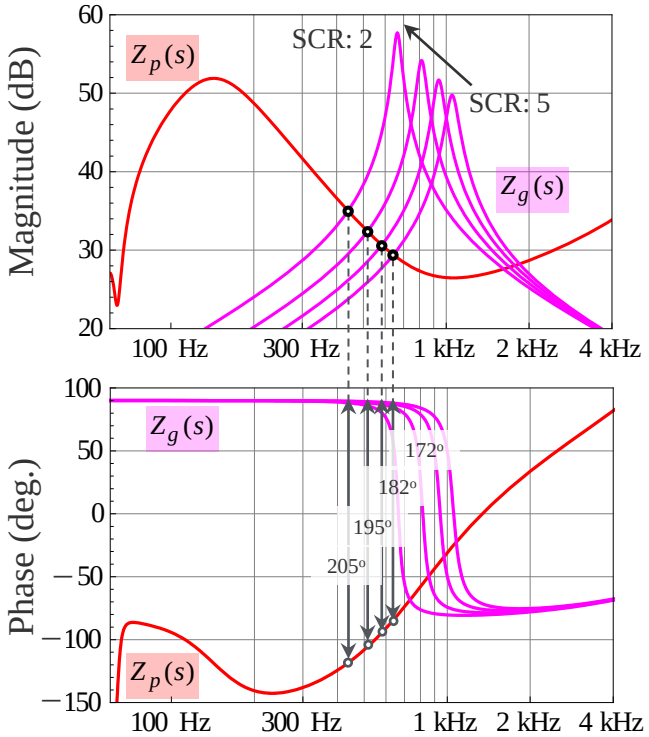


Loop gain:

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

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

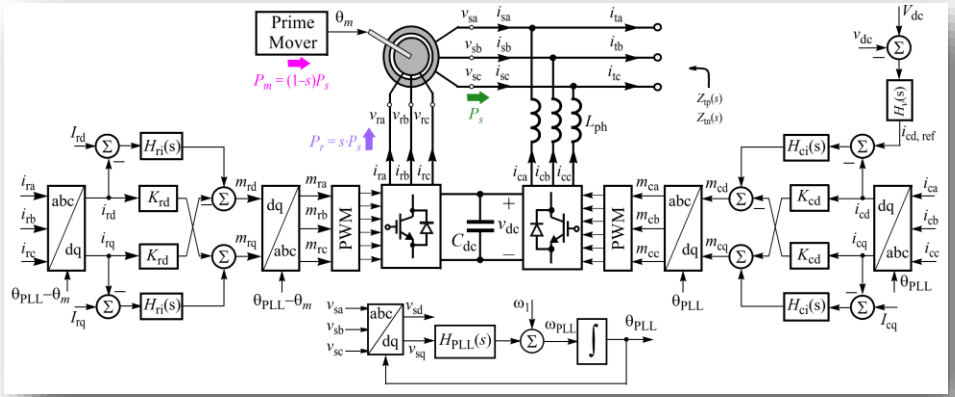
Resonance: Frequency and Damping

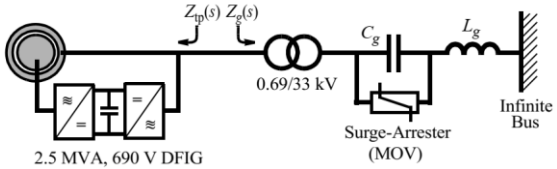


SCR	Grid Inductance, L_g	Resonance Frequency	Phase Margin
5	4.6 mH	641 Hz	+8°
4	5.7 mH	584 Hz	–2°
3	7.6 mH	512 Hz	–15°
2	11.5 mH	441 Hz	–25°

- 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)

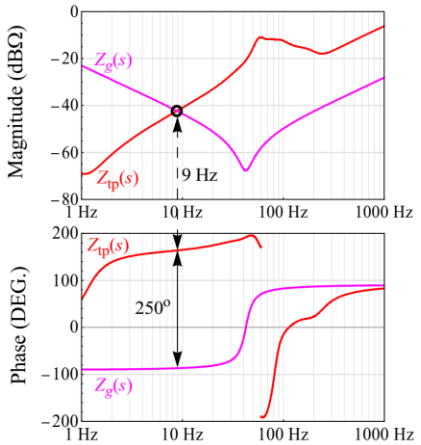




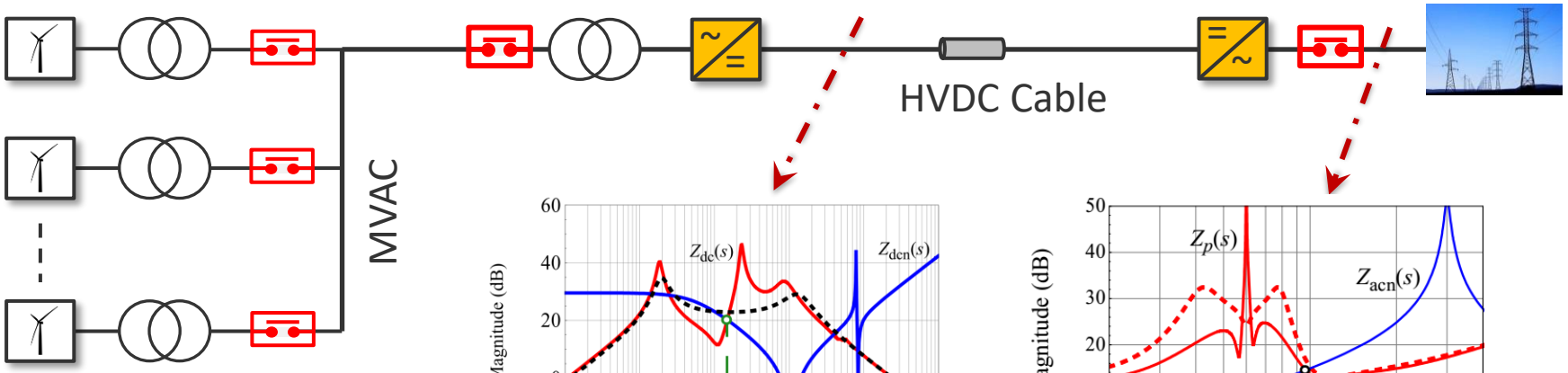
$$Z_{tp}(s) = \frac{Z_{sp}(s) \cdot Z_{cp}(s)}{Z_{sp}(s) + Z_{cp}(s)}$$

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

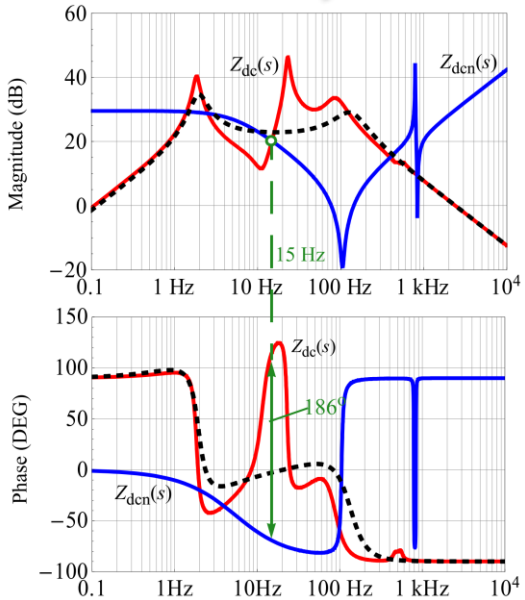
$$Z_{cp}(s) \equiv -\frac{V_{sp}(s)}{I_{cp}(s)} = \frac{sL_{ph} + k_m V_{dc}[H_{ci}(s-j\omega_1) - jK_{cd}]}{1 - \dfrac{T_{PLL}(s-j\omega_1)}{2} \left[1 + \dfrac{\mathbf{I}_{c1}}{V_1} k_m V_{dc} H_{ci}(s-j\omega_1)\right]}$$

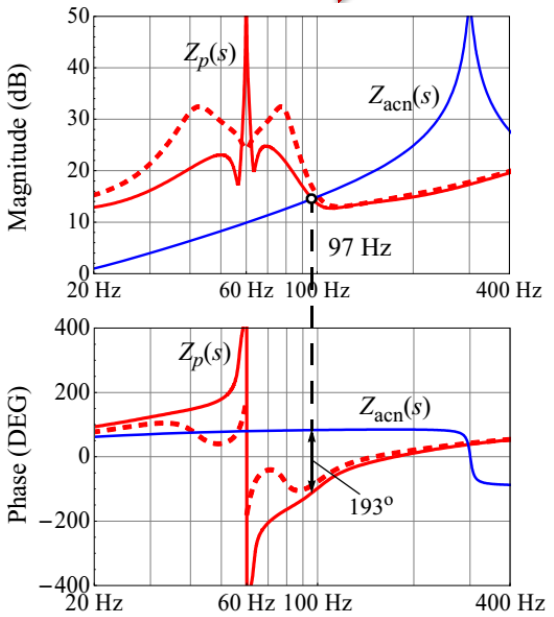


Offshore Wind with HVDC Transmission



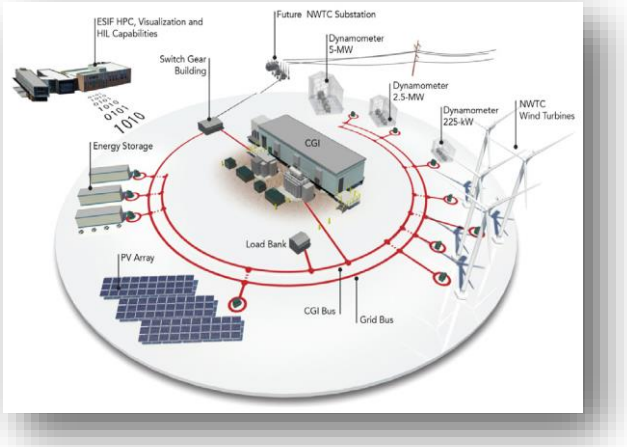
- Impedance Analysis is Performed at Different Interface Points



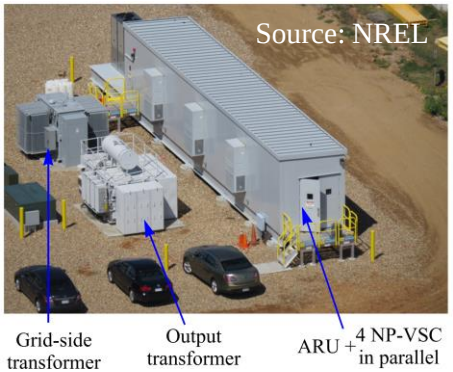


Impedance Measurement at NREL

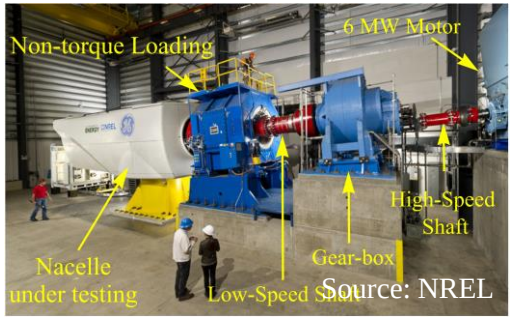
- 7-MVA Grid Simulator for Perturbation Injection
- Turbine Nacelle Coupled to a Dynamometer
- GPS-Synchronized MV Measurements



7-MVA Grid Simulator



5-MW Dynamometer



MV Measurements

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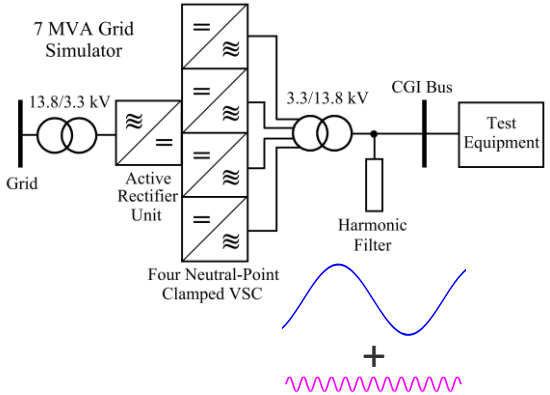
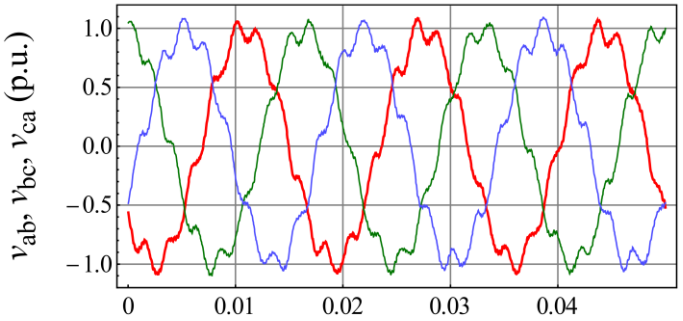
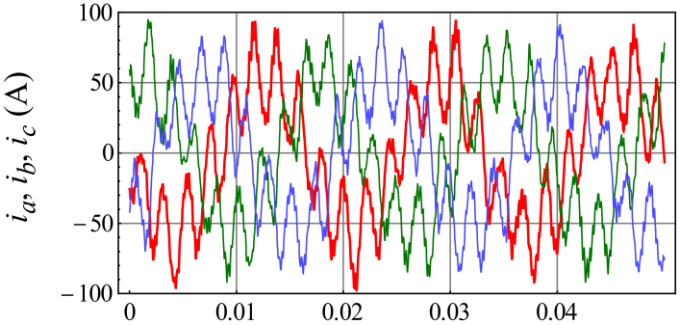
Injection of +ve and –ve Sequence Perturbations



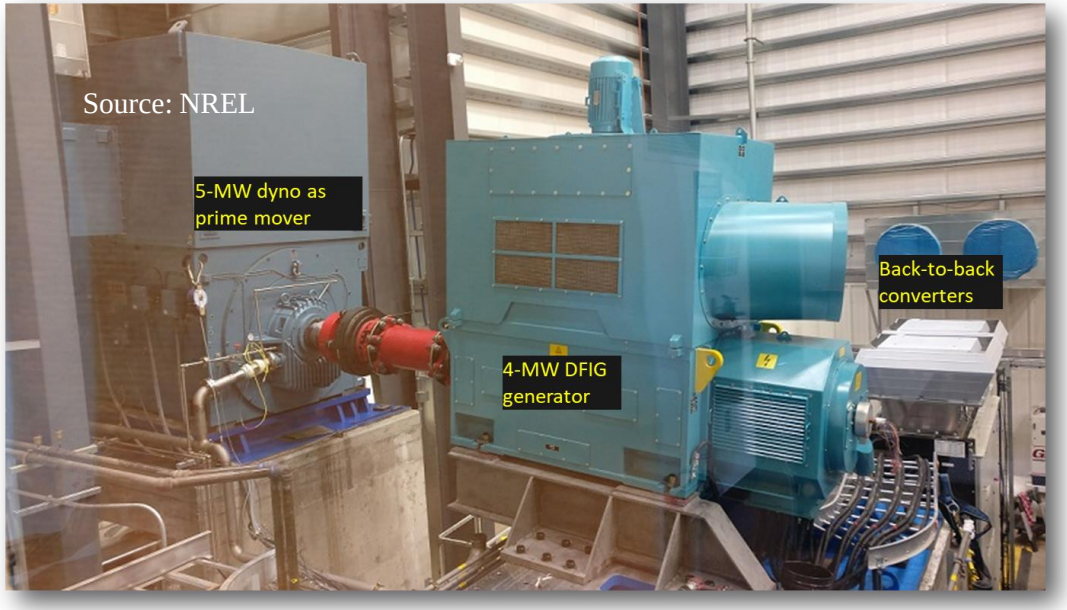
- Perturbed voltages

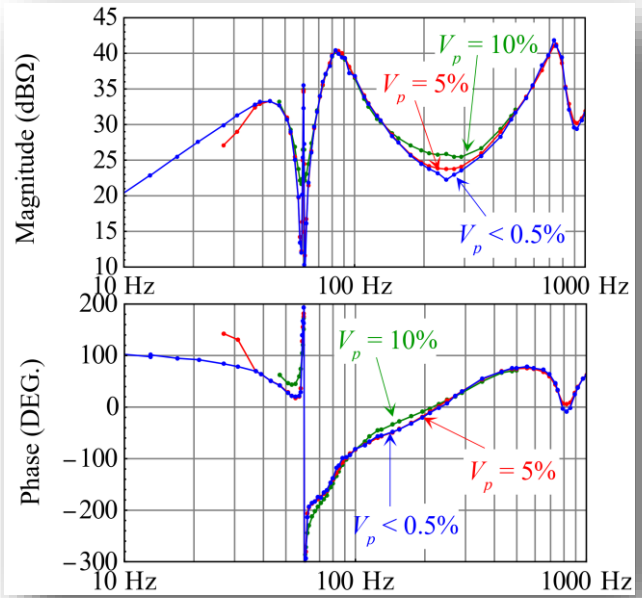


- Response currents



Positive Sequence Impedance of a 4-MW Turbine

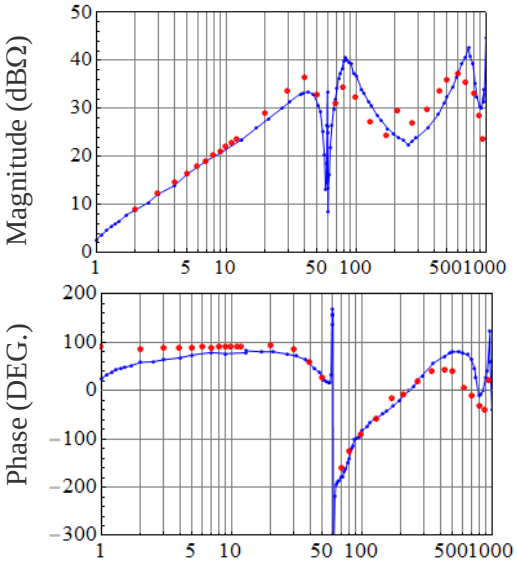




- Automated Sequence Impedance Measurement by Grid Simulator for Different Operation Conditions

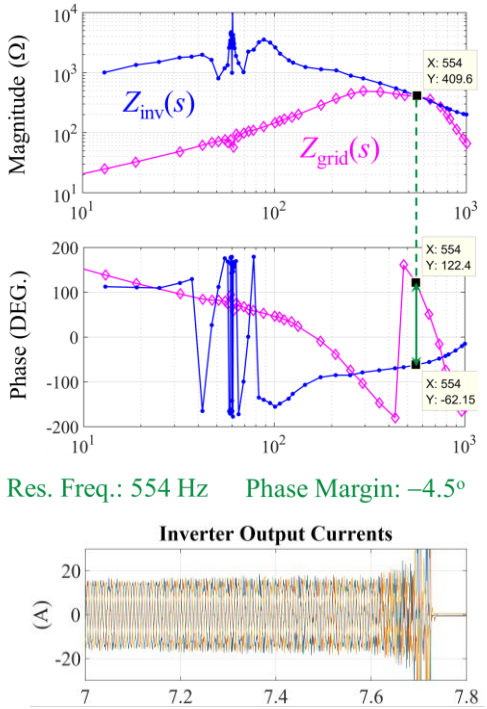
Applications

- Model Validation

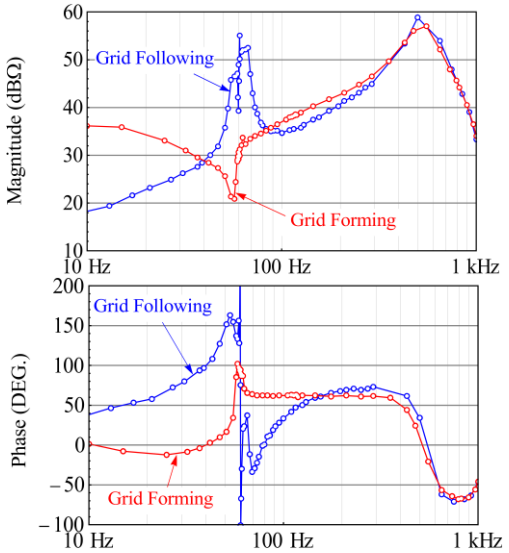


Blue: Measurements of 4-MW DFIG
Red: PSCAD model from OEM

- Resonance Analysis

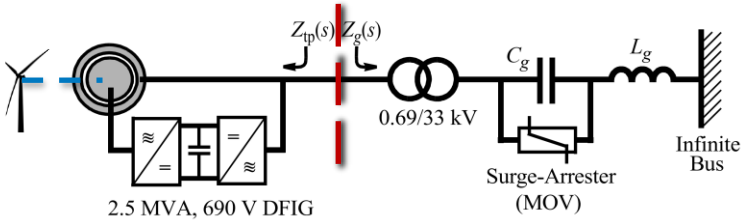


- Grid-forming Inverters

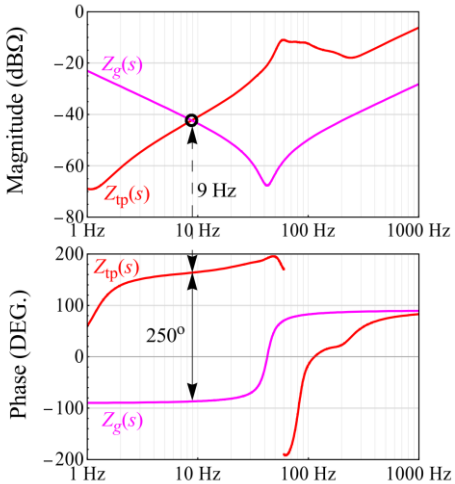


Solve Resonance Problems, Control Design, Grid-codes

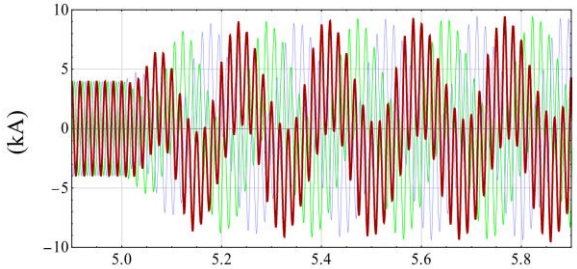
Role of Protection in Resonance



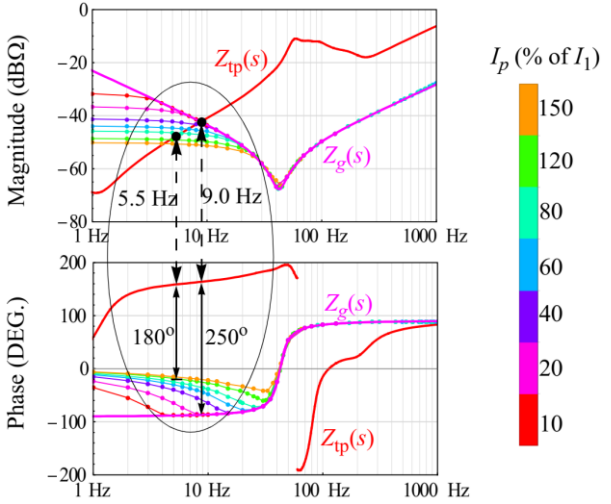
- Impedance analysis



- DFIG output currents



Prediction of SSR-generated harmonics



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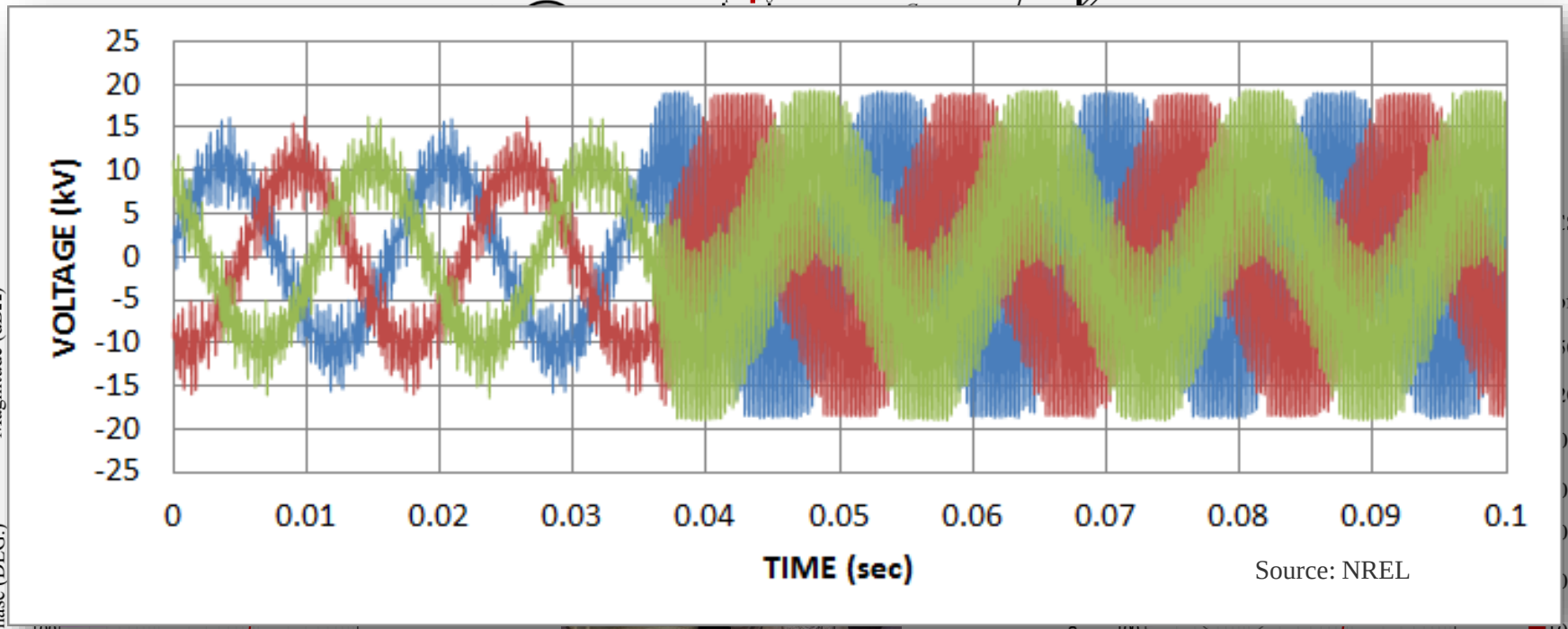
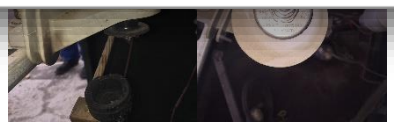
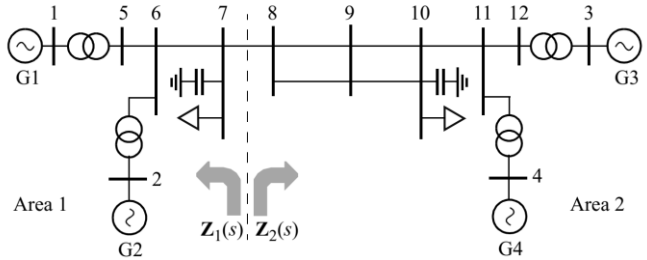
Role of Protection in Resonance



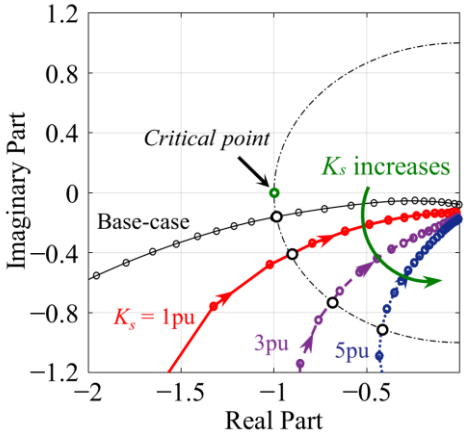
Source: NREL



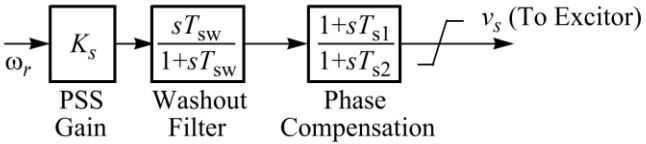
Impedance Analysis of Power System Oscillations

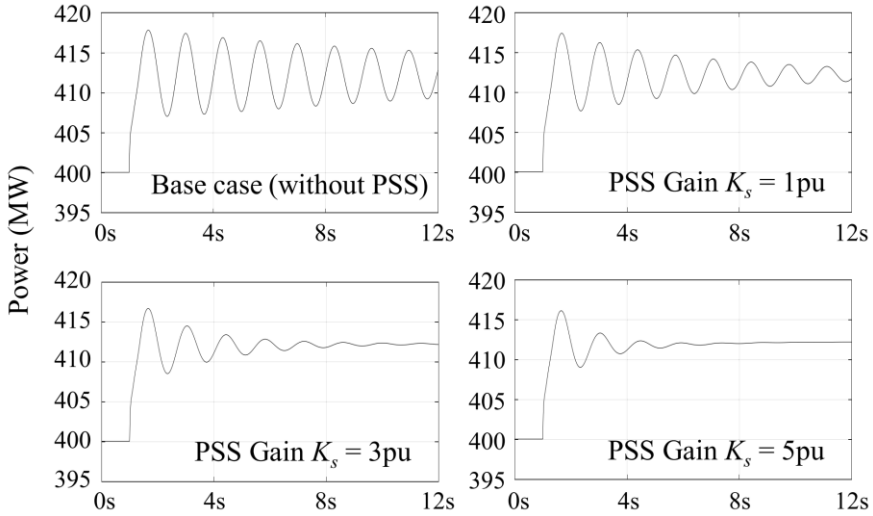


- Impedance Analysis



- Power System Stabilizer (PSS)





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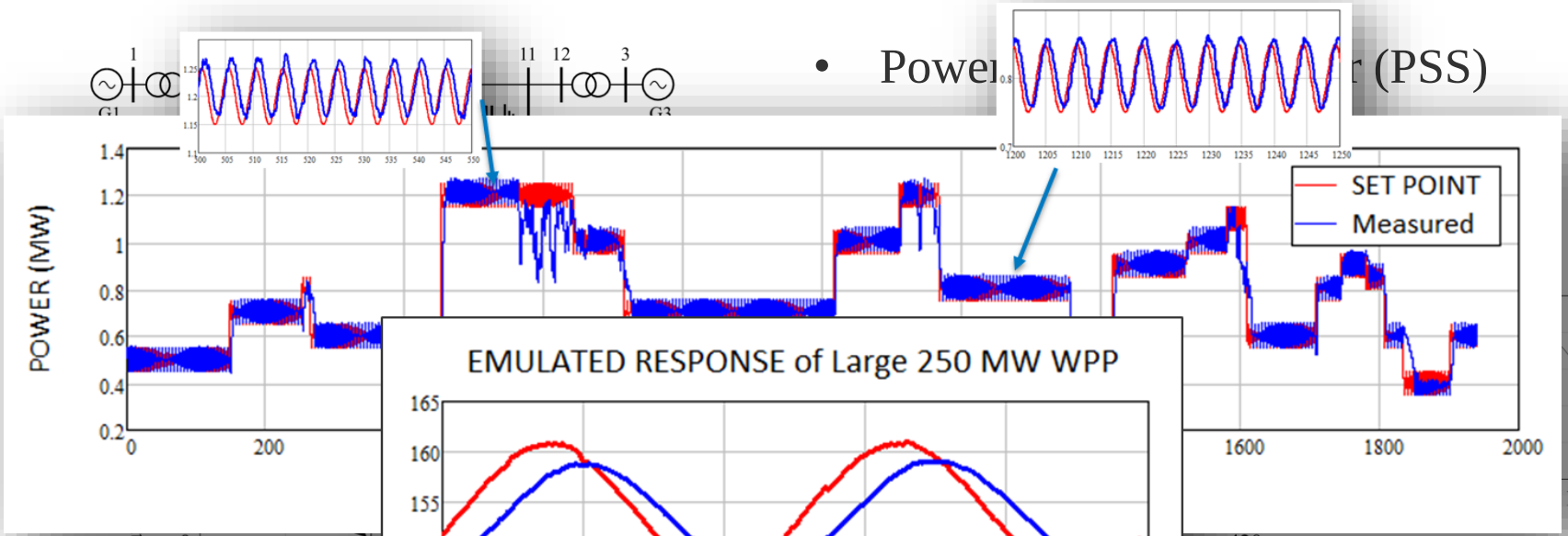
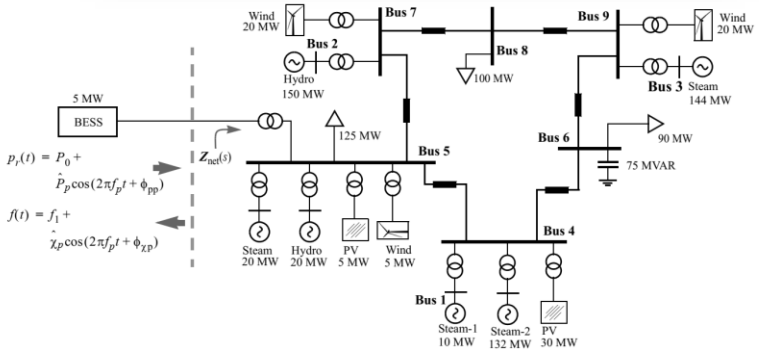
Power Modulation from a GE 1.5-MW Turbine

- Power (PSS)



Online Monitoring of Frequency Response

- Transfer Function from Active Power to Frequency



- Prediction of Primary Frequency Response and Inertia

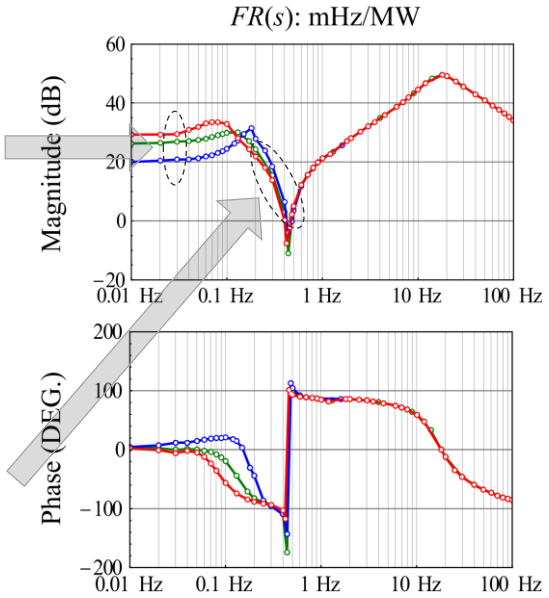
MW/0.1Hz

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

Inertia

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

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

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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.
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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-flow 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.