Impedance Measurement of Inverter-Coupled Generation Using a Multimegawatt Grid Simulator

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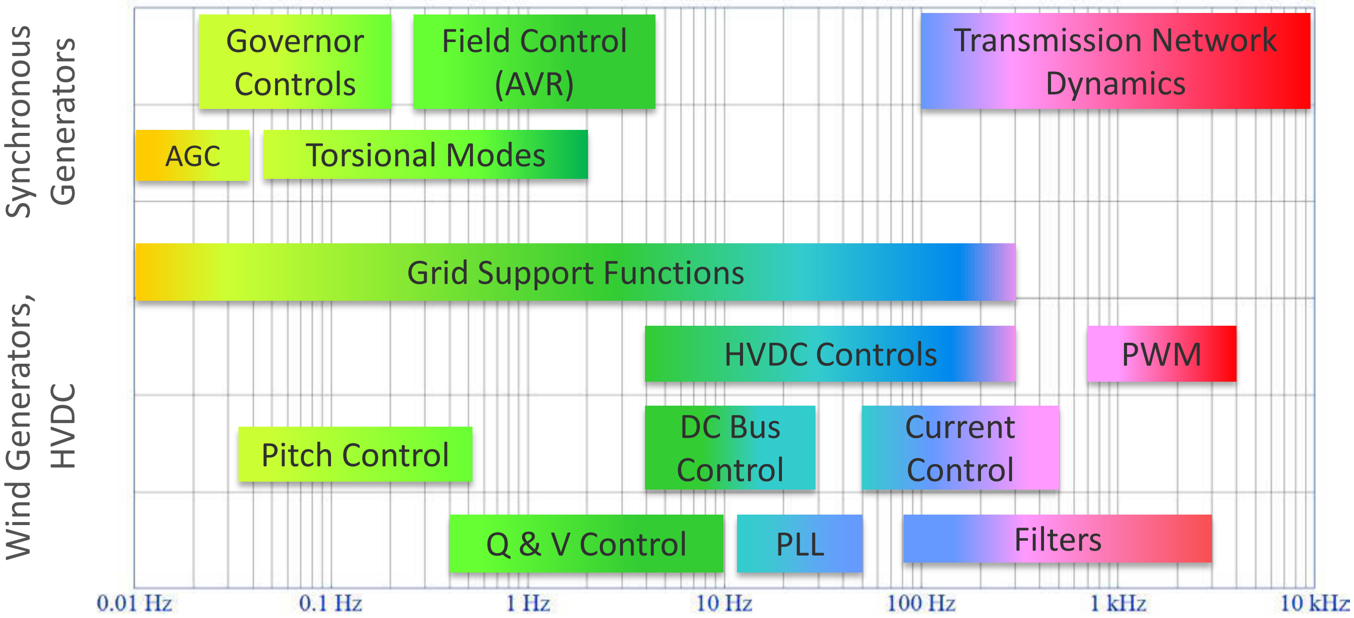
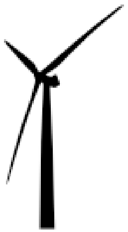
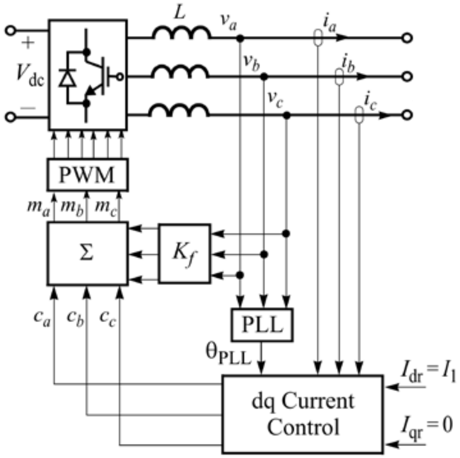
New Stability Problems: Control Interactions



- Impedance-based analysis has proven effective for the evaluation of resonance problems and control interactions in wind power plants.

Impedance-Based Stability Analysis





$Z_p(s)$

$Z_n(s)$

$Z_g(s)$

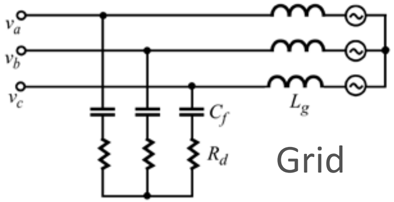


Photo by NREL

Loop gain:

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

- Transmission system operators have started demanding impedance response of wind turbines for the evaluation of resonance and control interaction problems.
- Impedance-based specifications are being developed for wind turbines to reduce the risks of resonance problems.

Controllable Grid Interface #1 (CGI)

Power rating

- 7 MVA continuous
- 39 MVA short-circuit capacity (for 2 s)
- 4-wire, 13.2 kV.

Possible test articles

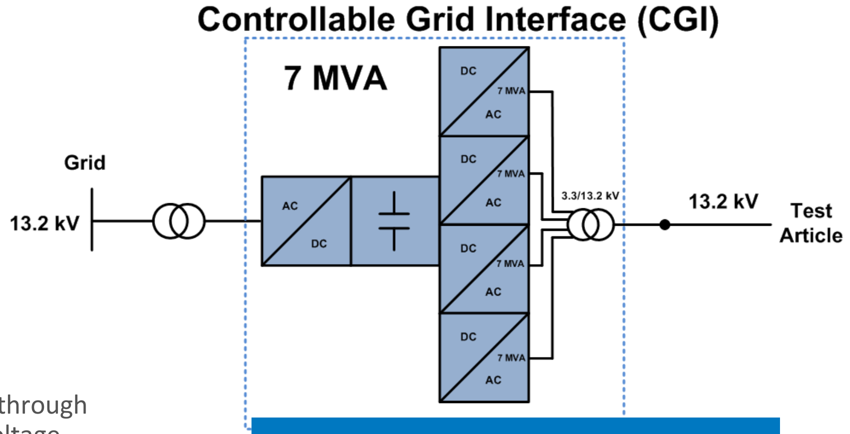
- Types 1, 2, 3, and 4 wind turbines
- Photovoltaic (PV) inverters, energy storage systems
- Conventional generators
- Combinations of technologies.

Voltage control (no load total harmonic distortion [THD] <1%)

- Balanced and unbalanced voltage fault conditions (zero-voltage ride-through [ZVRT] and 140% high-voltage ride through [HVRT])—independent voltage control for each phase on 13.2-kV terminals
- Response time—1 ms (from full voltage to zero, or from zero back to full voltage)
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0–10 Hz)—subsynchronous resonance (SSR) conditions
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)
- Impedance characterization of inverter-coupled generation.

Frequency control

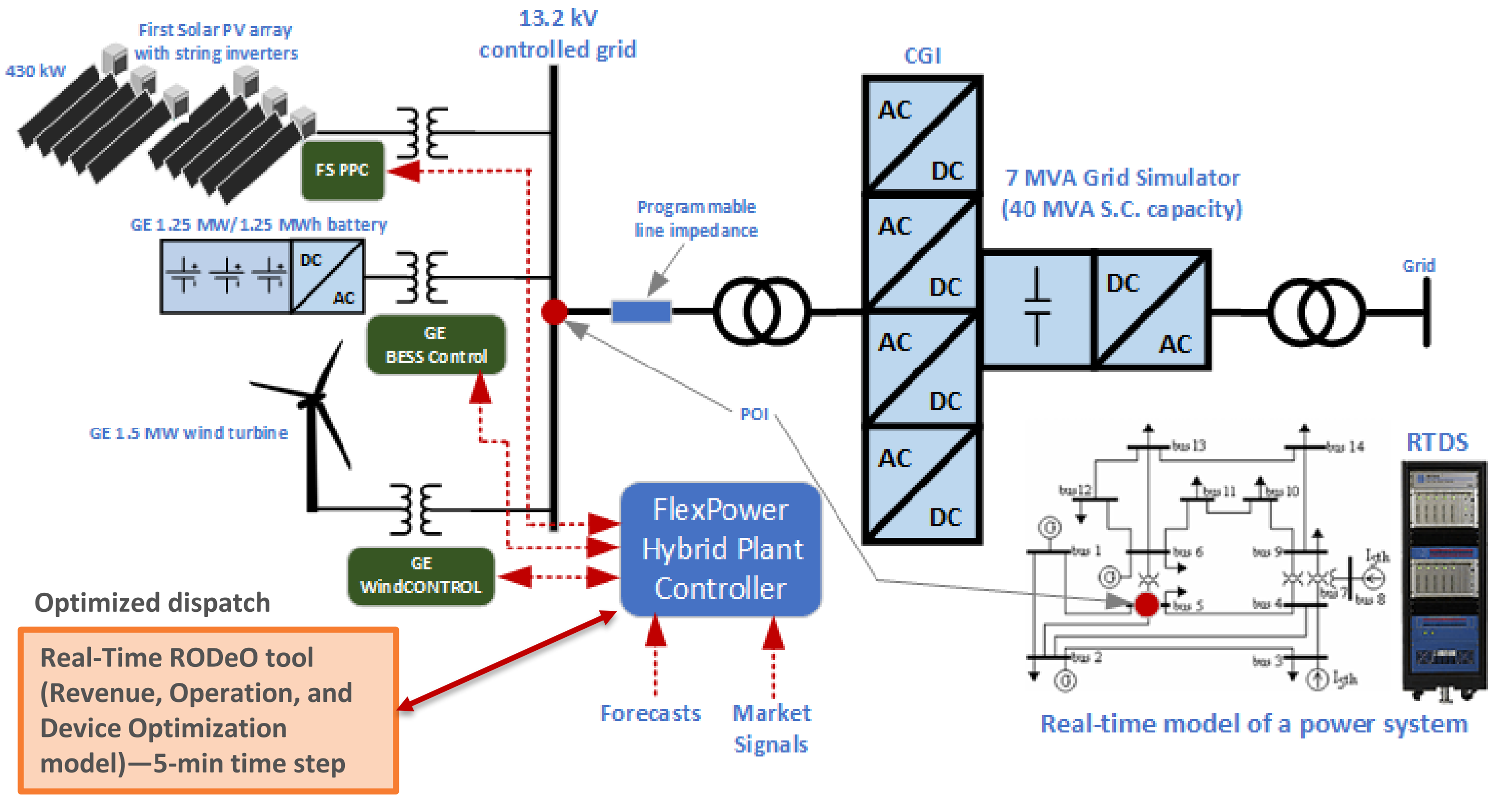
- Fast output frequency control (3 Hz/s) within 45–65-Hz range
- 50/60-Hz operation
- Can simulate frequency conditions for any type of power system
- Power-hardware-in-the-loop (PHIL) capable (coupled with RTDS, Opal-RT, etc.)
- Test bed for phasor measurement unit (PMU)-based wide-area stability controls.



Capabilities

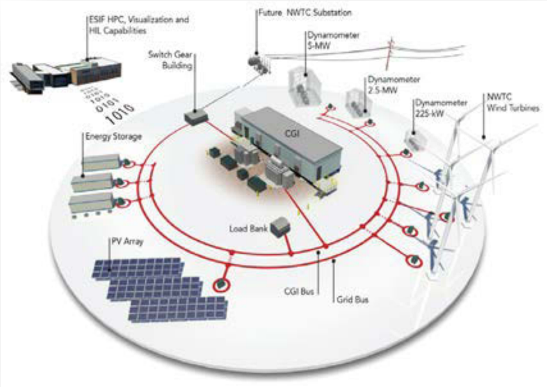
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing (over and under voltage and frequency limits)
- Islanding operation
- Sub-synchronous resonance conditions
- 50 Hz tests

Hybrid Systems Test and Control Validation Platform

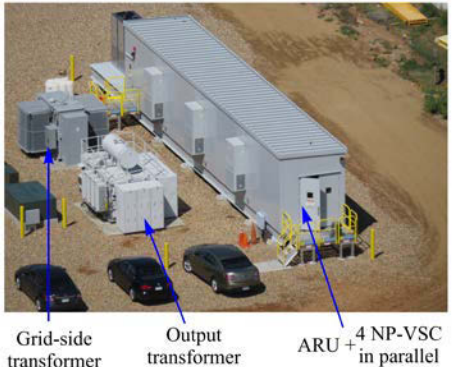


Impedance Measurement Test Bed at NREL

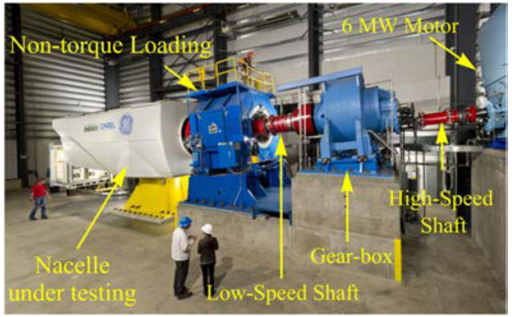
- 7-MVA grid simulator for injection of voltage perturbations
- Turbine nacelle coupled to a dynamometer
- GPS-synchronized medium-voltage measurements



7-MVA grid simulator



5-MW dynamometer



MV measurements

Photos by NREL

Injection of Positive- and Negative-Sequence Perturbations

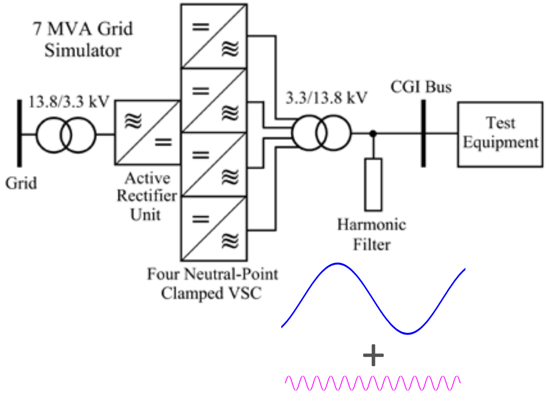
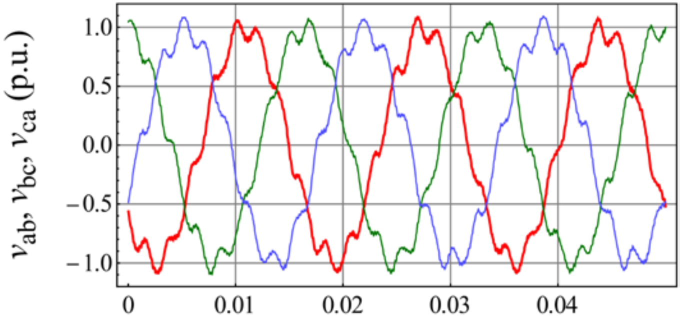
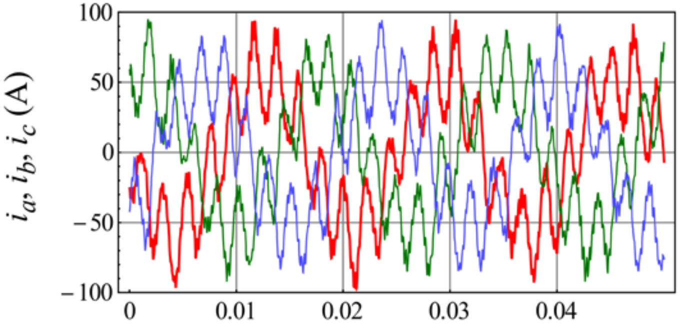


Photo by NREL

- Perturbed voltages

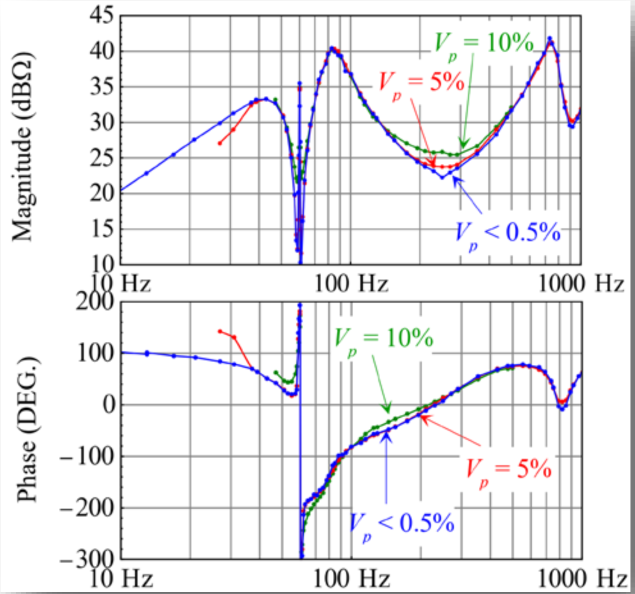


- Response currents



Positive-Sequence Impedance of a 4-MW Turbine

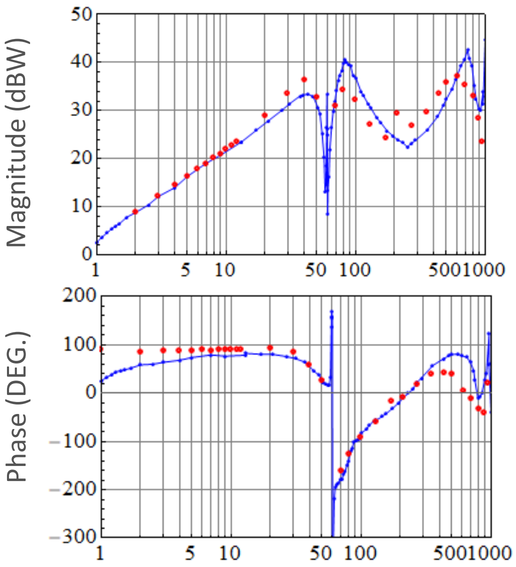
Photo by NREL



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

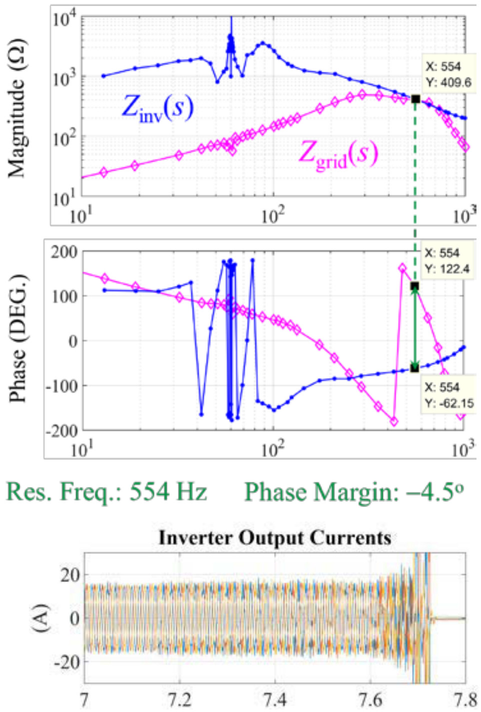
Applications of Impedance Measurement

- Model validation

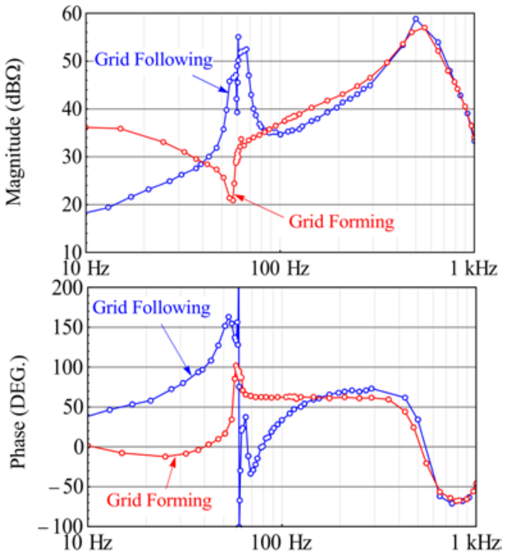


Blue: Measurements of 4-MW DFIG
Red: PSCAD model from OEM

- Resonance analysis

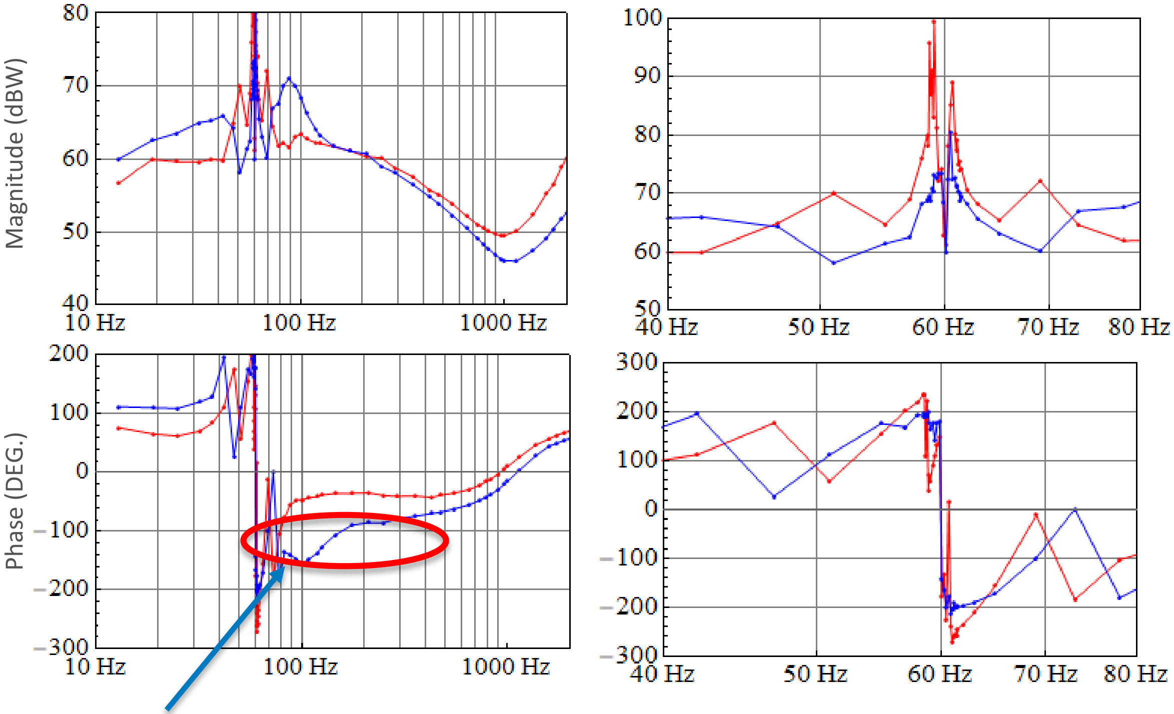


- Grid-forming inverters



Solve resonance problems, control design, grid codes

Impedance Characteristics of a Photovoltaic Plant



Instability region

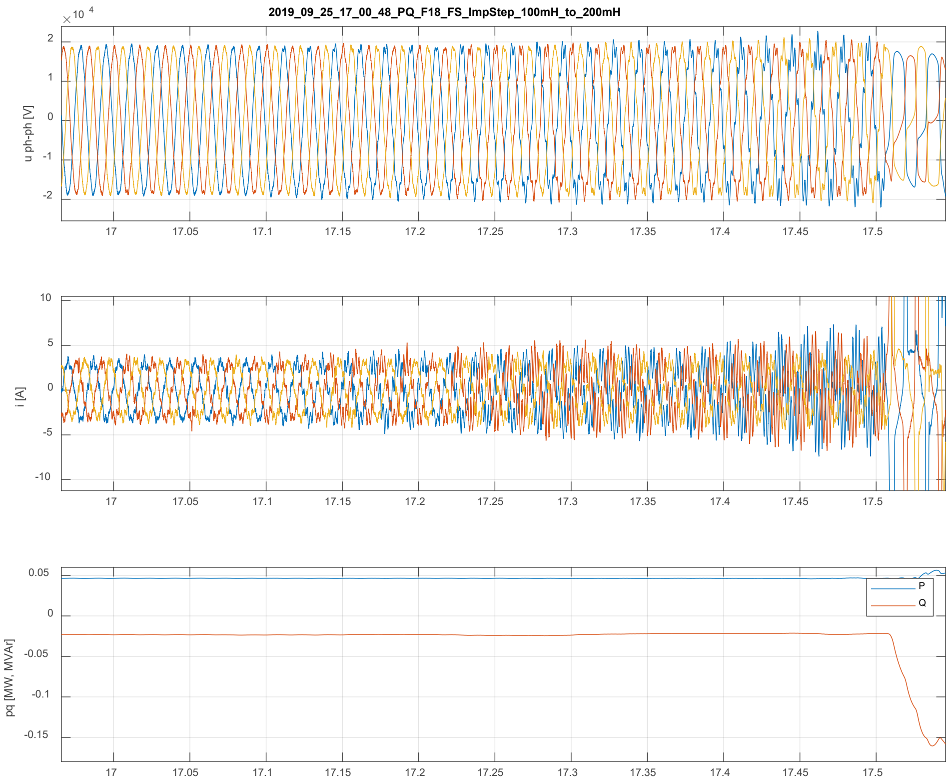
Inverter 1

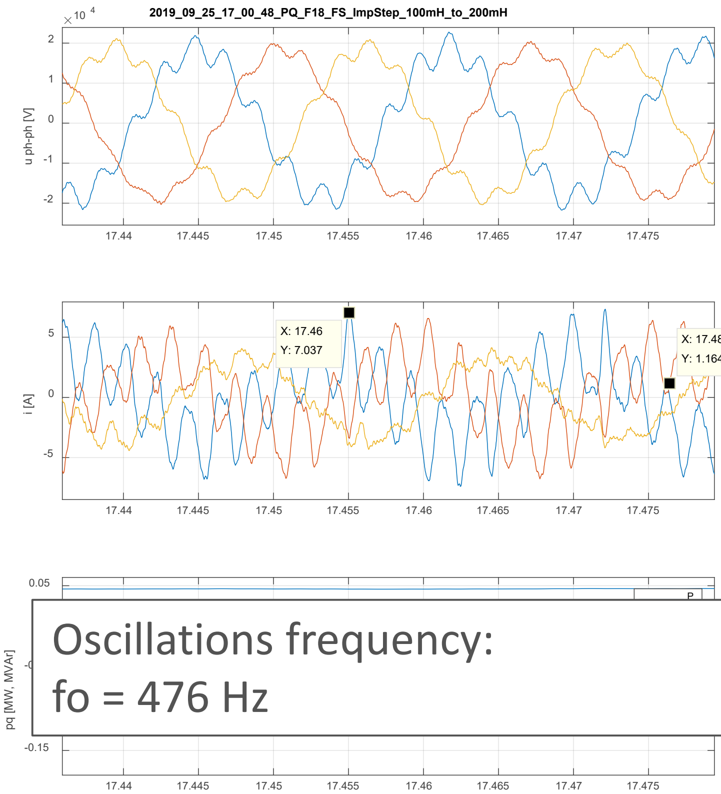
Inverter 2

- Phase response goes below -90 degrees between 60 Hz and 500 Hz
- Can potentially interact with grid and create undamped resonance.

Photo by NREL

Resonance Measured in a Photovoltaic Plant





Oscillations frequency:
fo = 476 Hz

Reference Frame of Sequence Impedance

Positive-sequence admittance

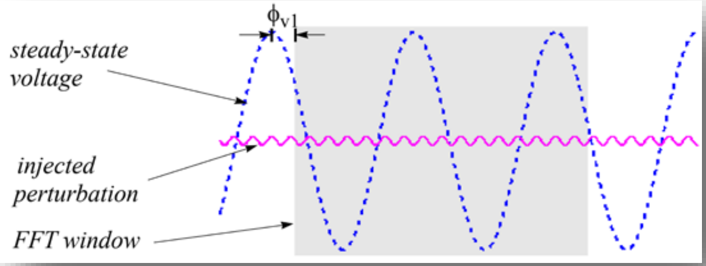
$$Y_p(s) = \frac{I_p(s)}{V_p(s)}$$

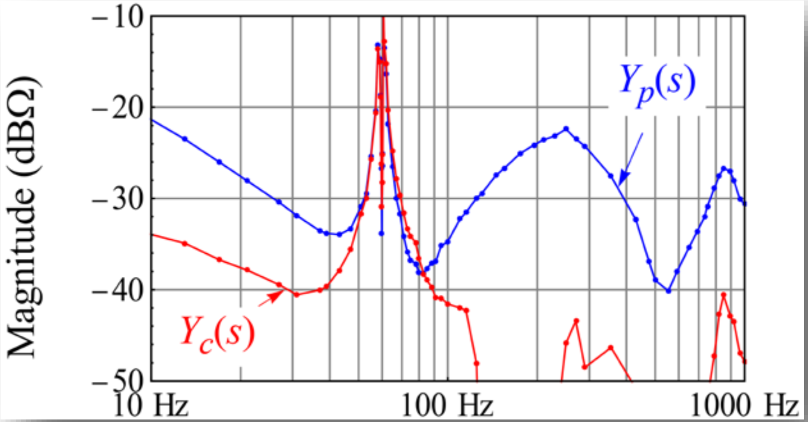
Coupling admittance

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

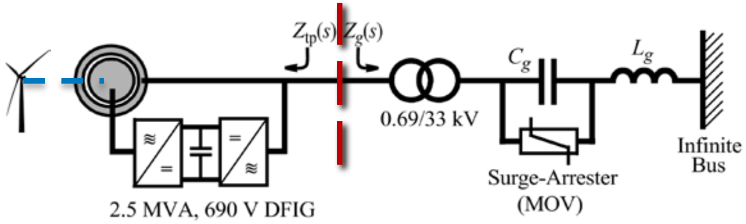
- Reference frame of sequence impedance is defined by the starting point of the data window used for FFT analysis with respect to the fundamental trajectory of voltages.

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

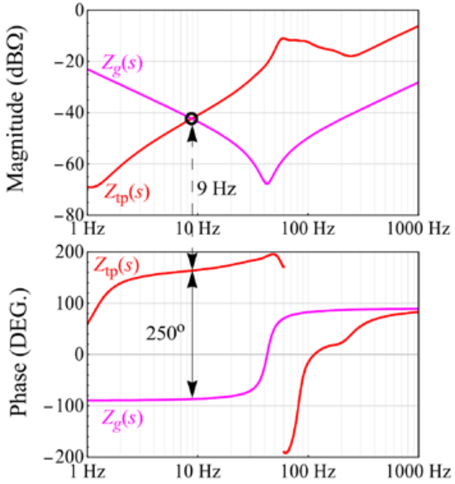




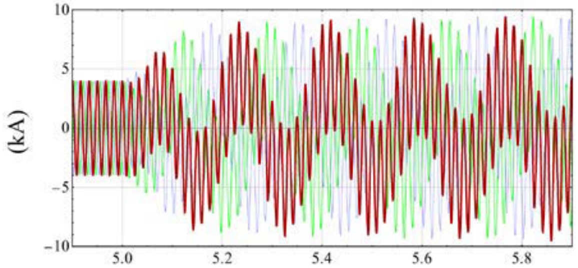
MOV in SSR of Type III Wind Power Plants

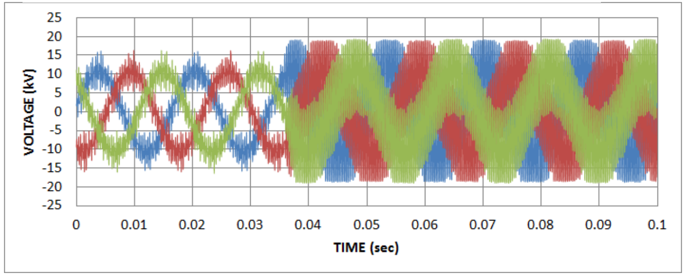


- Impedance analysis

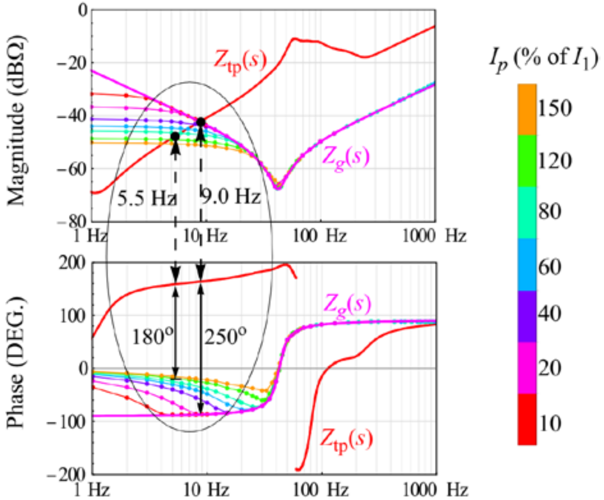


- DFIG output currents





Prediction of SSR-generated harmonics



Summary of CGI#2 Specifications

Power rating

- Continuous AC rating—19.9 MVA at 13.2 kV and 34.5 KV
- Overcurrent capability (x5.7 for 3 s, x7.3 for 0.5 s)
- 4-wire 13.2-kV or 35.4-kV taps
- Continuous operational AC voltage range: 0–40 kVAC
- Continuous DC rating—10 MW at 5 kVDC.

Possible test articles

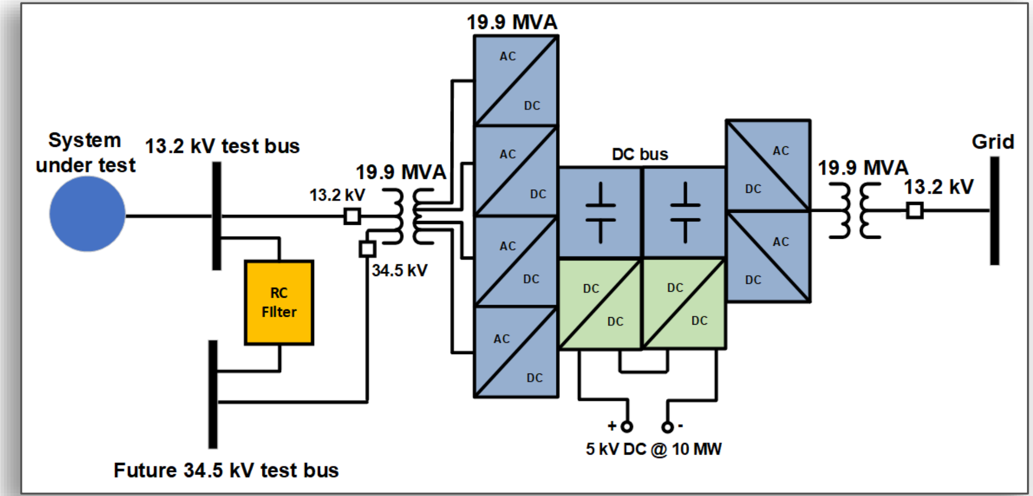
- Types 1, 2, 3, and 4 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies/hybrid systems
- Responsive loads.

Voltage control (no load THD <1%)

- Balanced and unbalanced voltage fault conditions (ZVRT, LVRT, and 140% HVRT)—independent voltage control for each phase on 13.2-kV and 34.5-kV terminals
- Response time—less than 1 ms (from full voltage to zero, or from zero back to full voltage)
- Programmable injection of positive-, negative-, and zero-sequence components
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0–10 Hz)—SSR conditions
- Programmable impedance (strong and weak grids, wide SCR range corresponding to a point of interconnection with up to 250 MVA of short-circuit apparent power)
- Injection of controlled voltage distortions
- Wide-spectrum (0–2-kHz) impedance characterization of inverter-coupled generation and loads
- All-quadrant reactive power capability characterization of any system.

Frequency control

- Fast output frequency control (3 Hz/s) within 45–65-Hz range
- 50/60-Hz operation
- Can simulate frequency conditions for any type of power system
- PHIL capable (can be coupled with RTDS, Opal-RT, Typhoon, etc.)
- Coupled with PMU-based wide-area stability controls validation platform.

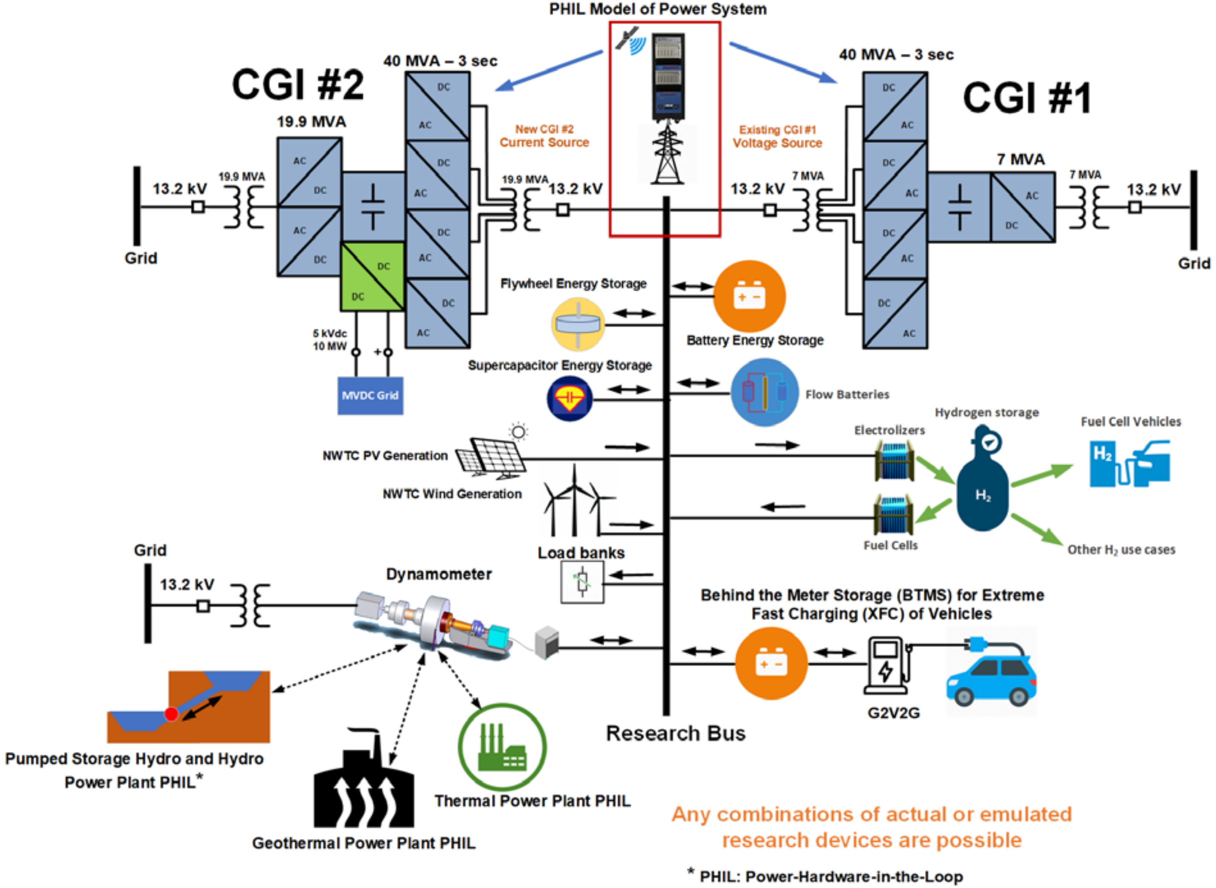


New features

- 5-kV MVDC grid simulator (PHIL capable)
- Voltage or current source operation
- Seamless transition between voltage and current source modes
- Emulation of full set of resilience services:
  - Black start
  - Power system restoration schemes
  - Microgrids.
- Flexible configurations are possible when combined with controllable grid interface (CGI) #1:
  - Two independent experiments
  - Parallel operation
  - Back-to-back operation
  - Emulation of isolated, partially, or fully grid-connected microgrids.

Optimized Hybrid Energy Storage Systems

- Validation of design optimization tools and operational strategies for hybrid energy storage systems for provision of grid services at various timescales (ms-s-min-hr-day)
- Development and validation of optimized control theory for hybrid energy storage to provide essential reliability and resilience services to the grid:
    - Optimal ratios between device-level, plant-level, and system-level controls
- Design and operation of hybrid renewable-storage plants for improved dispatchability, increased capacity factors, and enhanced grid services
- Optimized storage technology mixes for microgrids and islanded systems.



Summary

- Impedance measurement of wind turbines is becoming an important precommissioning test because of increasing stability events involving wind power plants
- Impedance measurements can be used for:
  - Evaluation and mitigation of resonance problems
  - Check compliance with impedance-based grid codes
  - Testing performance of new control solutions
  - High-fidelity model validation.
- Grid simulator can perform automated sequence impedance measurements including frequency cross-coupling effects.

Thank you!

Go raibh maith agat!

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