NREL

Power-Hardware-In-the-Loop Demonstration of Synchronous Wind

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ATC
RTDS APPLICATIONS & TECHNOLOGY CONFERENCE

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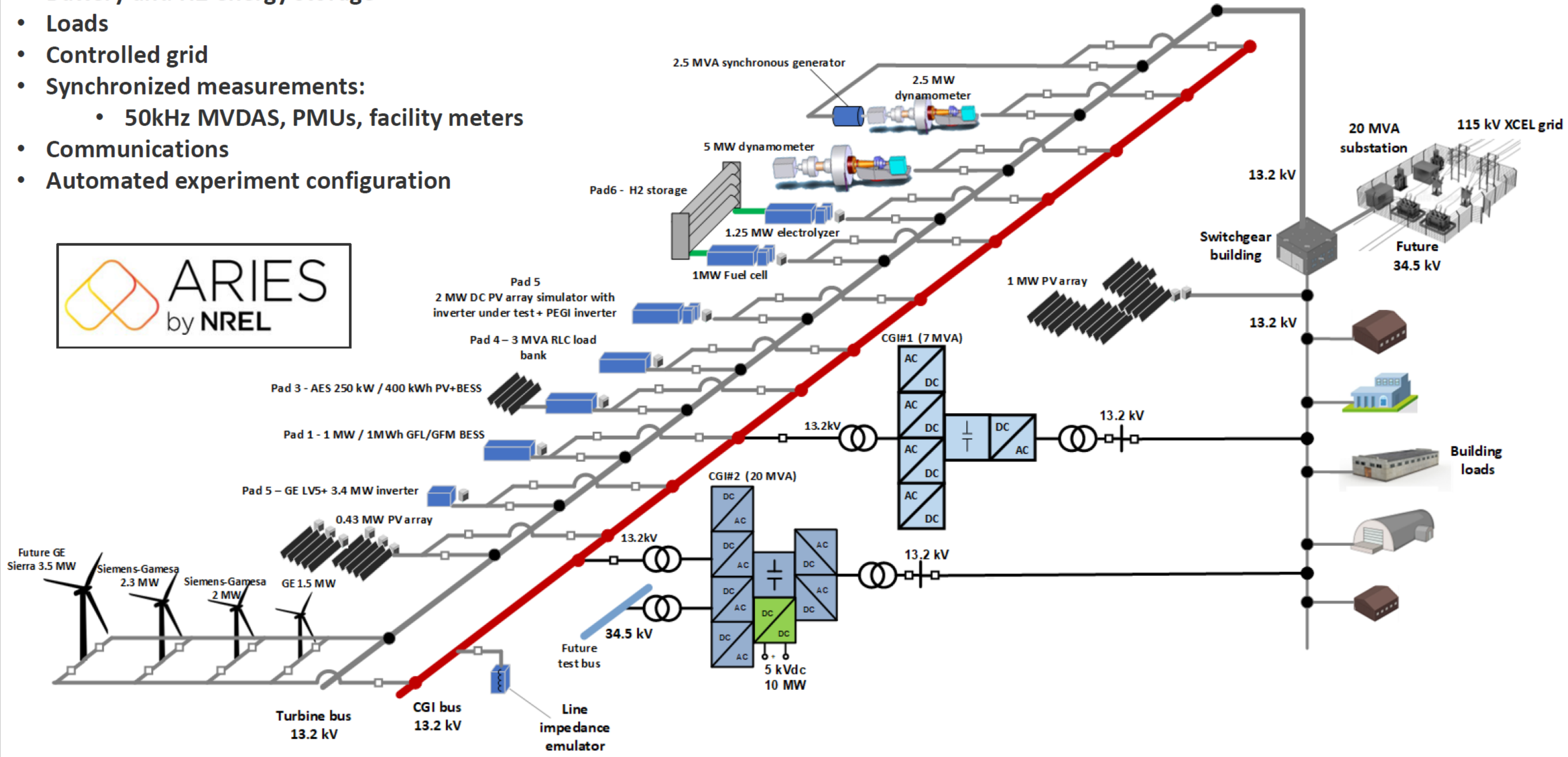
CHICAGO, ILLINOIS, U.S.A.

RTDS Technologies
AMETEK

Outline

NREL Flatirons Campus Test and Validation Platform

- Utility-scale wind
- Utility-scale PV
- Battery and H2 energy storage
- Loads
- Controlled grid
- Synchronized measurements:
  - 50kHz MVDAS, PMUs, facility meters
- Communications
- Automated experiment configuration



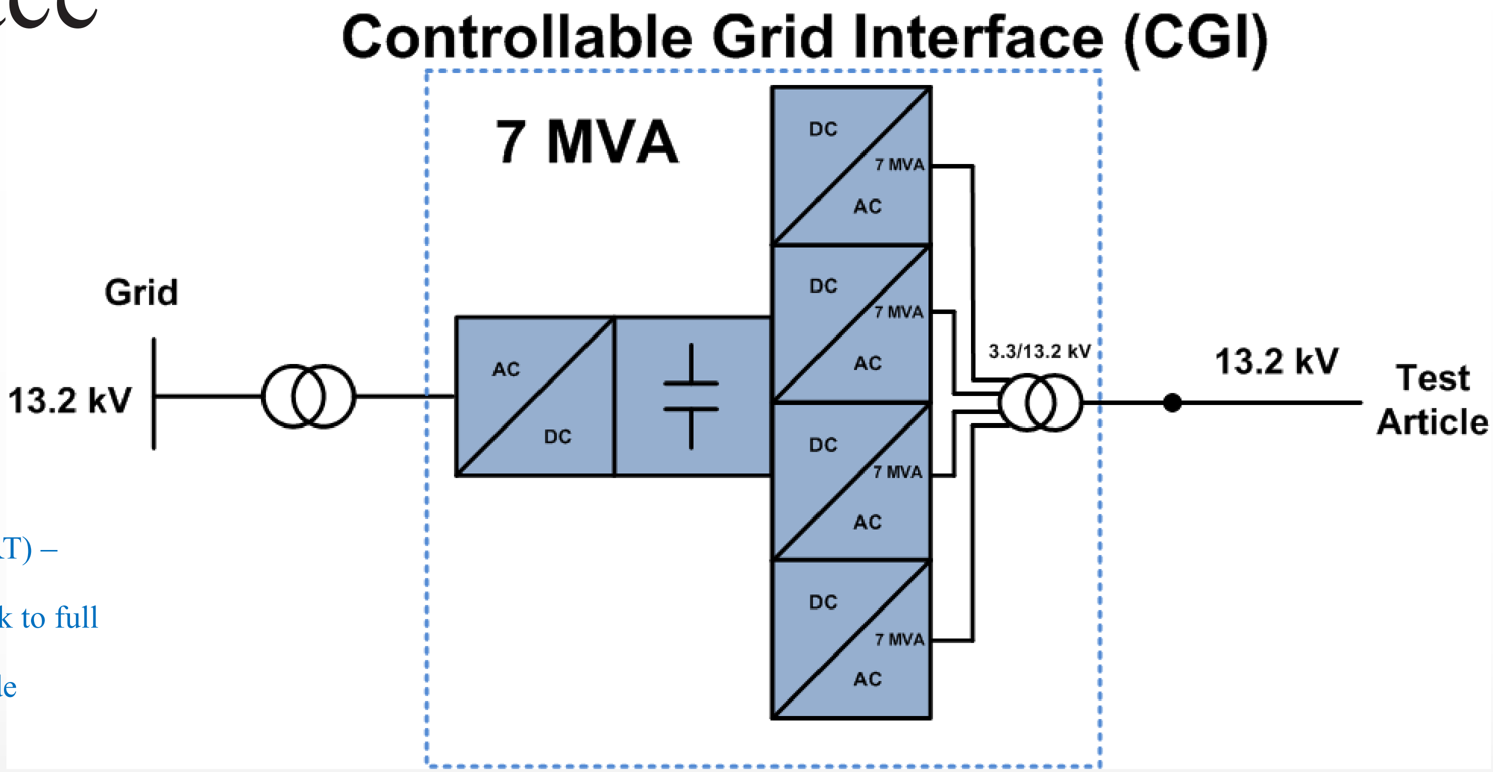
Controllable grid Interface

Power rating
- 7 MVA continuous
- 39 MVA short circuit capacity (for 2 sec)
- 4-wire, 13.2 kV

Possible test articles
- Types 1, 2, 3 and 4 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies

Voltage control (no load THD <1%)
- Balanced and un-balanced voltage fault conditions (ZVRT and 140% HVRT) – independent voltage control for each phase on 13.2 kV terminals
- Response time – 1 millisecond (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) – SSR conditions
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)
- Impedance characterization of inverter-coupled generation
- Full STATCOM functionality

Frequency control
- Fast output frequency control (5 Hz/sec) within 45-65 Hz range
- 50/60 Hz operation
- Can simulate frequency conditions for any type of power system
- PHIL capable (coupled with RTDS)
- Test-bed for PMU-based wide-area stability controls
- **Test article impedance scan**



Less than 1 ms response time

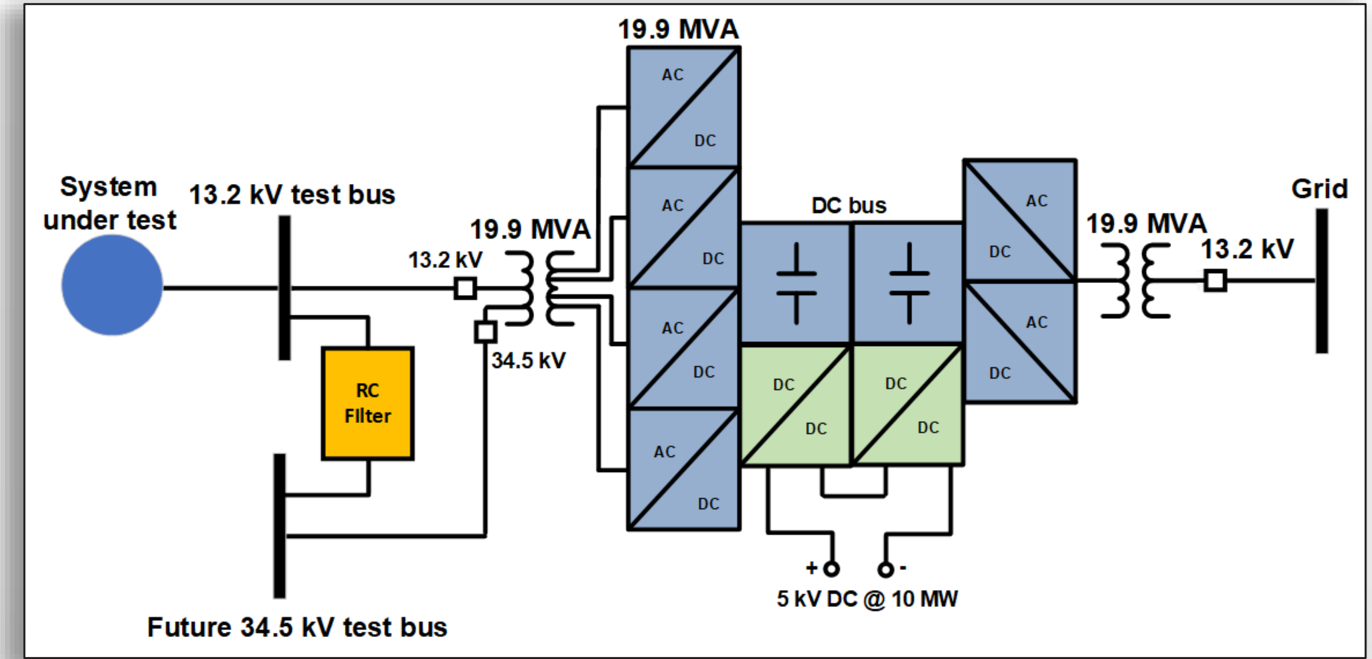
Summary of CGI#2 Specifications

Power rating
- Continuous AC rating - 19.9 MVA at 13.2kV and 34.5 KV
- Overcurrent capability (x5.7 for 3 sec, x7.3 for 0.5 sec)
- 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

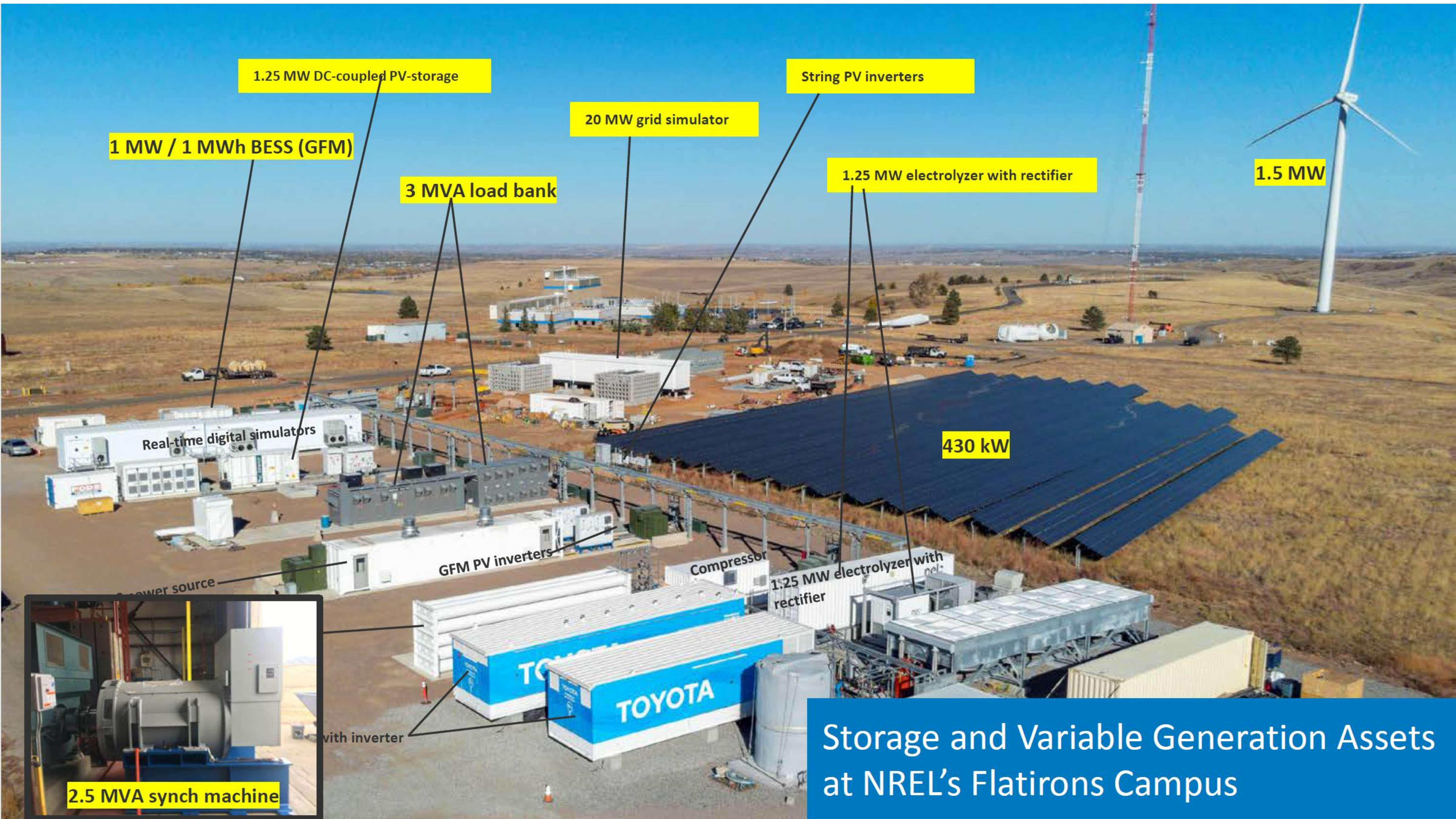
Voltage control (no load THD <1%)
- Balanced and unbalanced voltage fault conditions (ZVRT, LVRT and 140% HVRT) – independent voltage control for each phase on 13.2 kV and 34.5 kV terminals
- Response time – less than 1 millisecond (from full voltage to zero, or from zero back to full voltage)
- Programmable 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 POI with up to 250 MVA of short circuit apparent power)
- Injection of controlled voltage distortions
- Wide-spectrum (0-2kHz) 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/sec) 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)
- Coupled with PMU-based wide-area stability controls validation platform



100 µS response time

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 resiliency services:
  - Black start
  - Power system restoration schemes
  - Microgrids
- Flexible configurations are possible when combined with CGI#1:
  - Two independent experiments
  - Parallel operation
  - Back-to-back operation
  - Emulation of isolated, partially or fully grid-connected microgrids



Storage and Variable Generation Assets at NREL's Flatirons Campus

Type-5 Synchronous Wind

Wind Energy Grid Integration

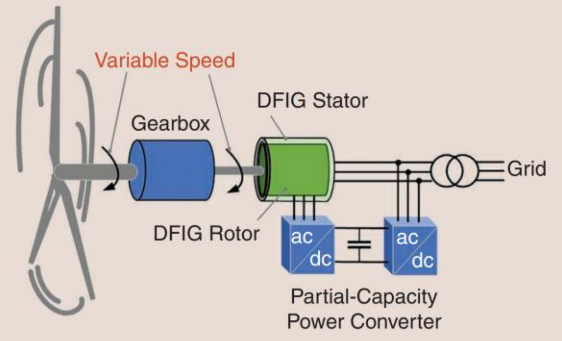
Type-3 and Type-4 Wind Turbine Generators play predominant roles in the modern wind industry :

- Variable-speed operation for high efficiency power conversion
- Power electronics-based energy conversion, **low short-circuit current contribution**
- Weak grid oscillation appears more often due to replacement of SGs and the integration of IBRs

Synchronous WTGs has been around since the 1990s:

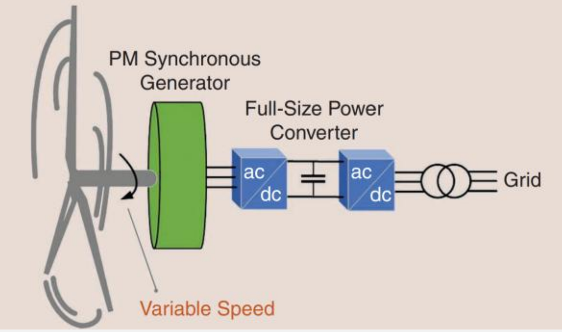
- Interface to the grid via a synchronous machine and maintaining the grid strength
- Always synchronize to the grid
- Inherently behaves as GFM resources with physical inertia
- Variable-speed operation through a hydraulic torque converter.
- Better overloading capability.
- It was not a popular choice in the 2000s for wind integration

Grid-forming Wind Turbines



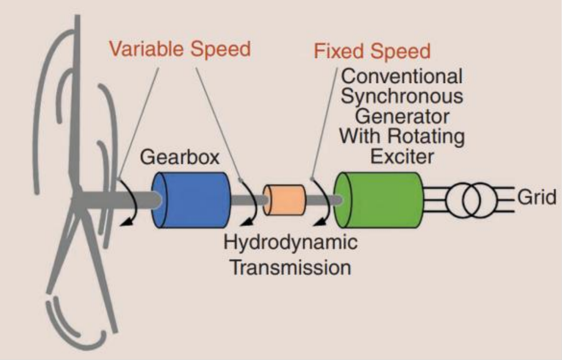
Type-3 DFIG WTGs

- DFIG and inverter coupled with grid.
- GFM control available through modify RSC's control.



Type-4 PMSG WTGs

- Inverter coupled with grid.
- Gearbox-less WTG.
- GFM control similar to PV and BESS.



Type-5 hydraulic torque converter

- Synchronous machine maintain synchronism to the grid.
- Turbine variable speed operation via torque converter.
- Inherently as a GFM WTG

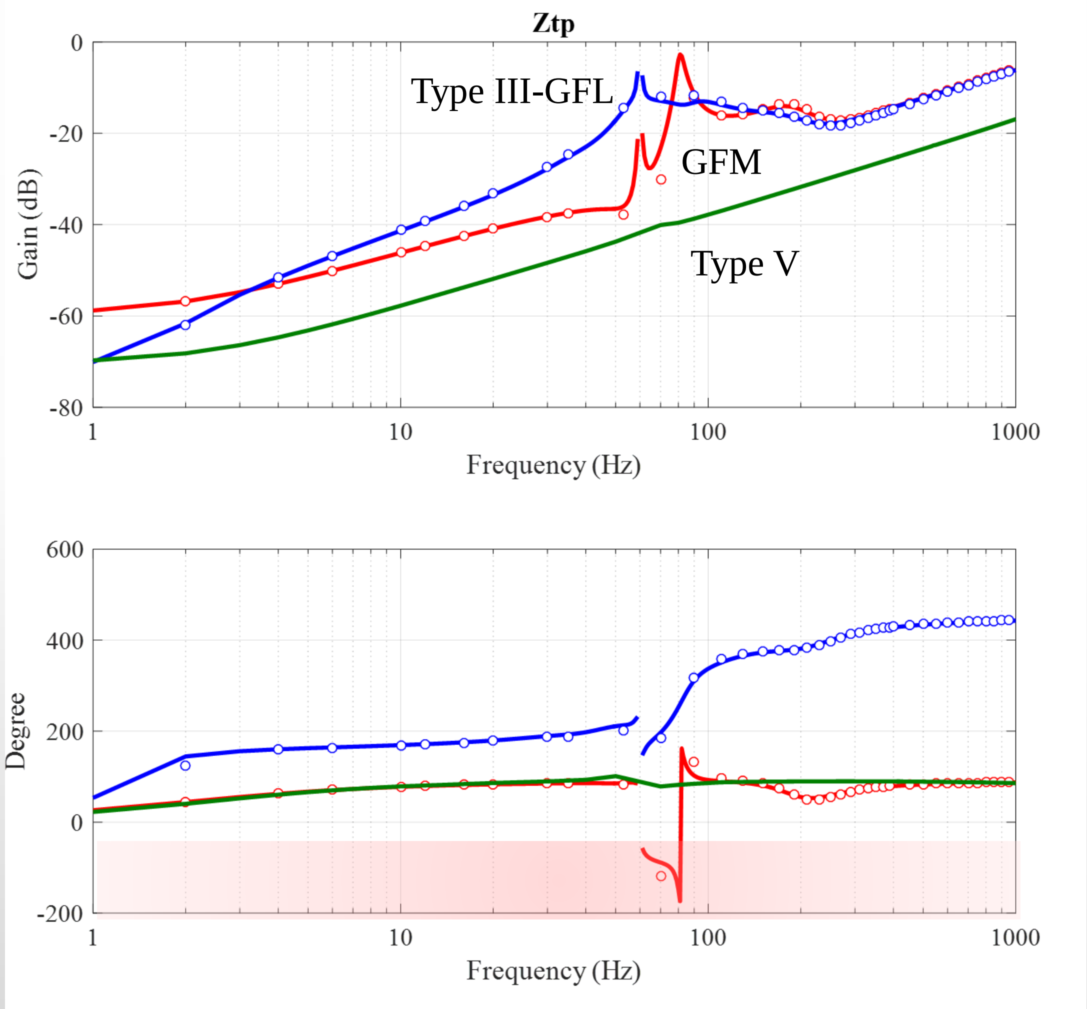
A comparison of advantages for specific turbine types

Grid Integration Challenge	Type 3	Type 4	Type 5
Weak grid operation	Yes, with controls		Yes, no controls needed, tends to make grid stronger Operation at sites with low short-circuit ratio (SCR) yet to be demonstrated
Short circuit current contribution	Limited	No, unless significantly oversized	High, no controls needed
Contribution to system inertia	Inertia-like response using controls, no curtailment	Inertia-like response using controls, with curtailment	Yes, no controls or curtailment needed (for example, a two-pole generator would give four-times real inertia compared to a four-pole generator)
Fast frequency response	Yes, fast response with special controls, curtailment, and/or transient uprating		
Primary frequency response	Yes, fast response with special controls and curtailment		
Participation in frequency regulation	Yes, curtailment needed		Yes, curtailment needed
Independent control of active and reactive power	Yes, with controls		Yes, with controllable automatic voltage regulator (AVR)
Transient performance and ride-through	Yes, with special controls		Yes, same as conventional synchronous generator with AVR
Voltage control	Yes, with special controls		Yes, same as conventional synchronous generator with AVR
GFM operation	Yes, with controls		Yes, no controls (default operation mode)
Black start and islanded operation	Yes, with controls and energy storage		Yes, no controls
Medium-voltage operation	Yes, with step-up transformer; transformerless might be possible in the future		Yes, up to 20 kV with no transformer
Protection impacts	May require adjustment to protection to accommodate lower short-circuit current than synchronous generation (Type 3 has more SCC capability than Type 4)		No change in the existing protection framework
Wind-free voltage support	Yes, with special controls (voltage control only, no inertia)		Yes, with clutch to disconnect generator from gearbox (synchronous condenser mode, provides voltage control and inertia, enhances grid strength)
Brushless operation	Brushes needed	Yes	Yes
Generator	Special design	Special design, dependence on rare-earth minerals for perma-nent magnet generators	Mass produced, global maintenance network and workforce exists, no depen-dence on rare-earth minerals
Cybersecurity	Yes	Yes	Fewer controls means fewer targets for external attacks

"Grid-Forming Wind: Getting ready for prime time, with or without inverters,"
V. Gevorgian, S. Shah, W. Yan, and G. Henderson, *IEEE Electrification Magazine*, 2022.

Stability Characteristics of Sync Wind

- Comparison of frequency scan between Type III and Type



DFIG with GFM control:

$$Z_{\mathrm{sp}}(s)=\frac{R_s+\frac{R_r'}{\sigma_p(s)}+s\left(L_{\mathrm{ls}}+L_{\mathrm{lr}}'\right)+\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\left(\frac{N_s}{N_r}\right)^2\left[\left(1-\frac{L_s}{L_m}\right)H_{\mathrm{ri}}(s-j\omega_1)-jK_{\mathrm{rd}}\right]+j\frac{3}{4}\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\frac{N_s}{N_r}V_1\left[\left(\mathbf{I}_{r0}-\frac{N_s}{N_r}\frac{L_s}{L_m}\mathbf{I}_{s0}\right)H_{\mathrm{ri}}(s-j\omega_1)-j\mathbf{I}_{r0}K_{\mathrm{rd}}+\mathbf{M}_{r0}\right]T_p(s-j\omega_1)+\frac{3}{4}\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\left(\frac{N_s}{N_r}\right)^2 V_1 T_q(s-j\omega_1)}{1-j\frac{1}{2}\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\left(\frac{N_s}{N_r}\right)^2 H_{\mathrm{rv}}(s-j\omega_1)H_{\mathrm{ri}}(s-j\omega_1)+j\frac{3}{4}\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\frac{N_s}{N_r}\mathbf{I}_{s0}^{*}\left[\left(\mathbf{I}_{r0}-\frac{N_s}{N_r}\frac{L_s}{L_m}\mathbf{I}_{s0}\right)H_{\mathrm{ri}}(s-j\omega_1)-j\mathbf{I}_{r0}K_{\mathrm{rd}}+\mathbf{M}_{r0}\right]T_p(s-j\omega_1)-\frac{3}{4}\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\left(\frac{N_s}{N_r}\right)^2\mathbf{I}_{s0}^{*}T_q(s-j\omega_1)}$$

DFIG with GFL control:

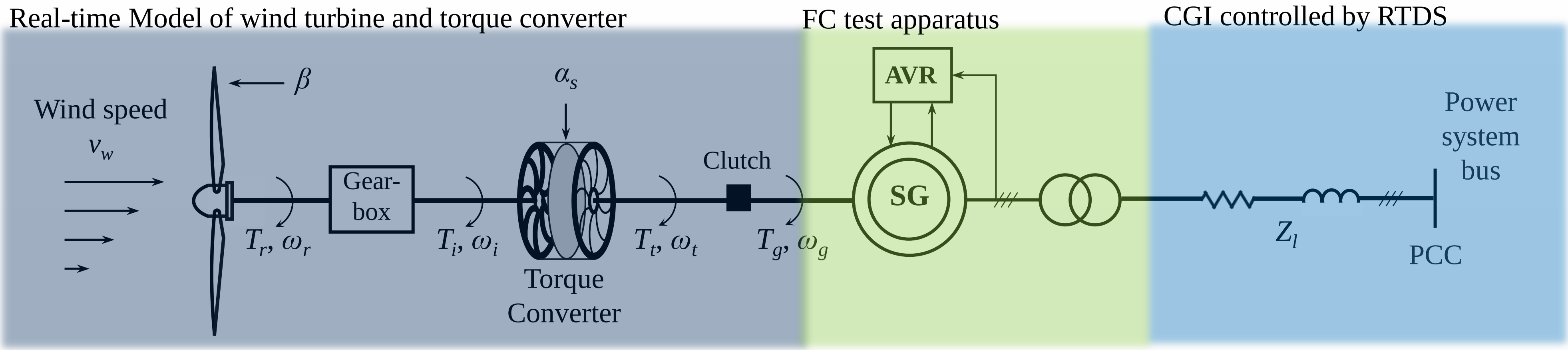
$$Z_{\mathrm{sp}}(s)=\frac{R_s+\frac{R_r'}{\sigma_p(s)}+s(L_{\mathrm{ls}}+L_{\mathrm{lr}}')+\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\frac{N_s}{N_r}\left\{\frac{N_s}{N_r}\left[H_{\mathrm{ri}}(s-j\omega_1)-jK_{\mathrm{rd}}\right]+\frac{3}{2}V_1 G_p(s-j\omega_1)H_p(s-j\omega_1)H_{\mathrm{ri}}(s-j\omega_1)\right\}}{1-\frac{1}{2}\frac{k_m V_{\mathrm{dc}}}{\sigma_p(s)}\frac{N_s}{N_r}\left\{\mathbf{I}_{r0}\left[H_{\mathrm{ri}}(s-j\omega_1)-jK_{\mathrm{rd}}\right]+\mathbf{M}_{r0}\right\}\frac{T_{PLL}(s-j\omega_1)}{V_1}}$$

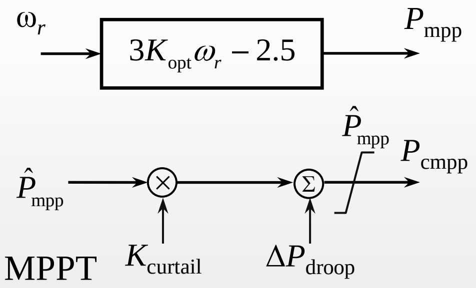
Sync wind:

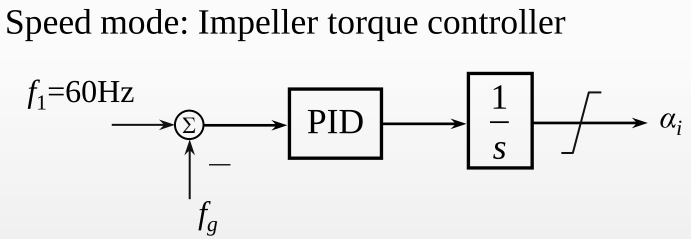
$$Z_{\mathrm{tp}}(s)=R_s+sL_{\mathrm{ls}}$$

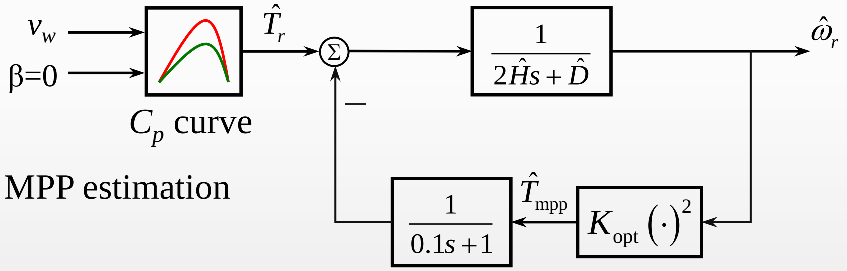
PHIL Tests of Synchronous Wind Operation

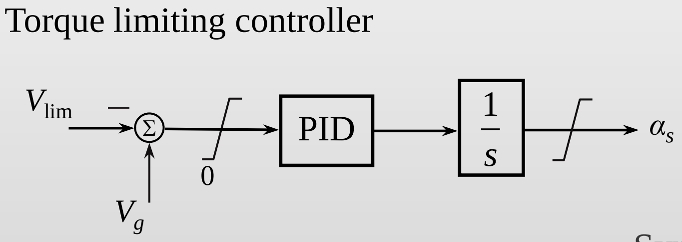
SyncWind Testbed with Torque Converter Model

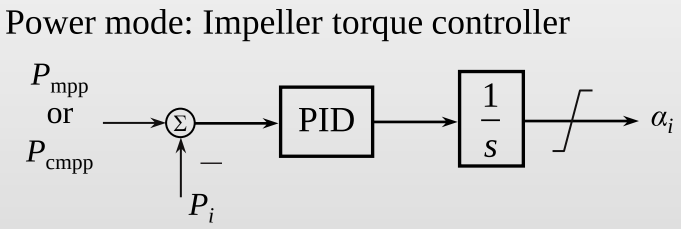


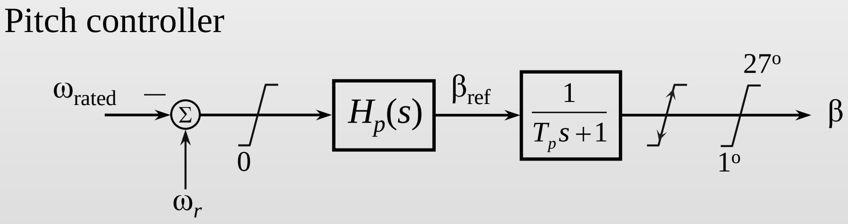








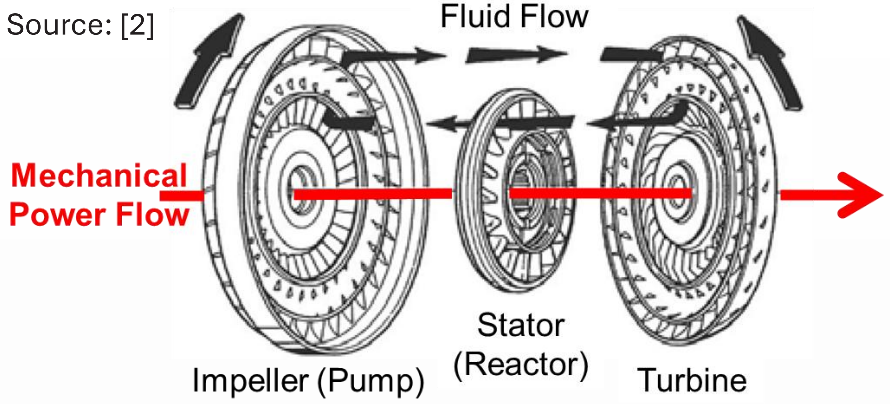


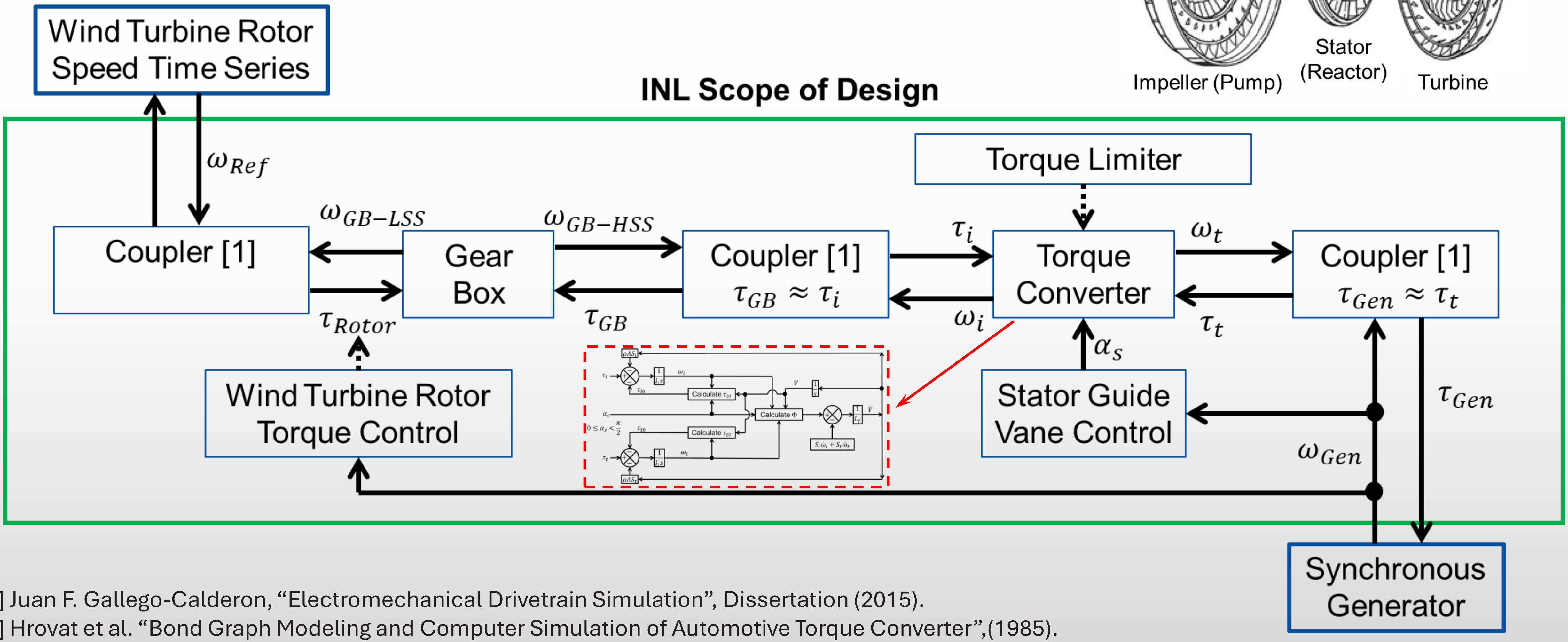


SyncWind Torque Converter available at: https://github.com/IdahoLabResearch/Type_5_Wind_Turbine_Drivetrain

Hydraulic Torque Converter

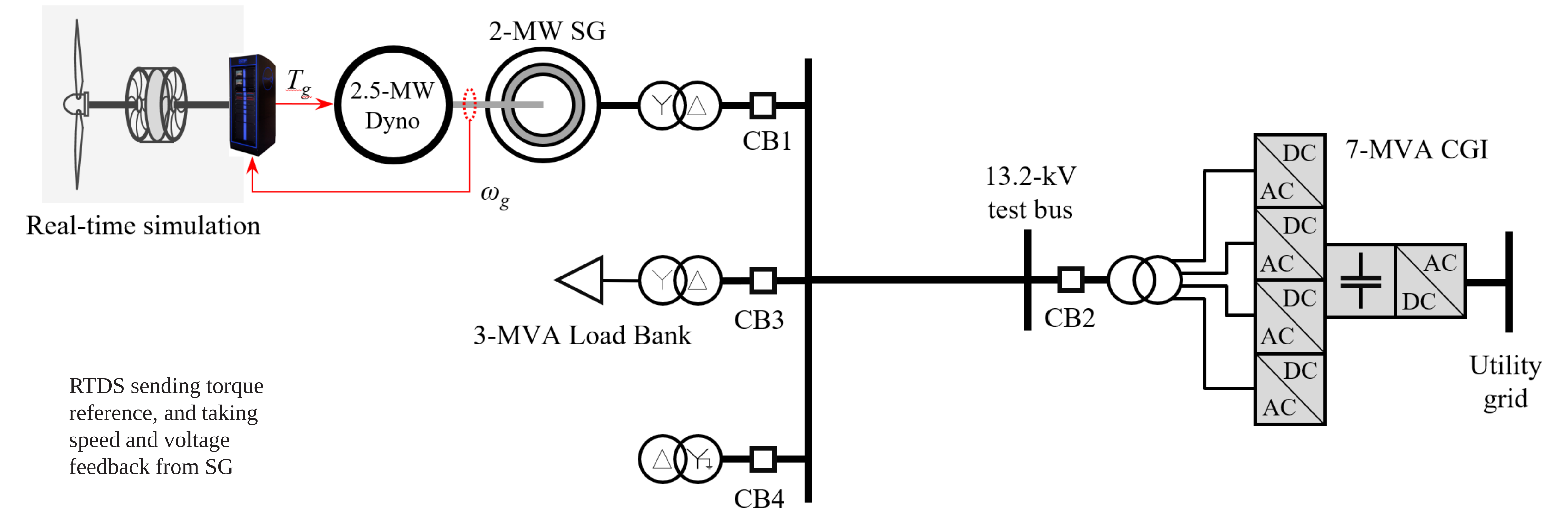
Image Source: [2]





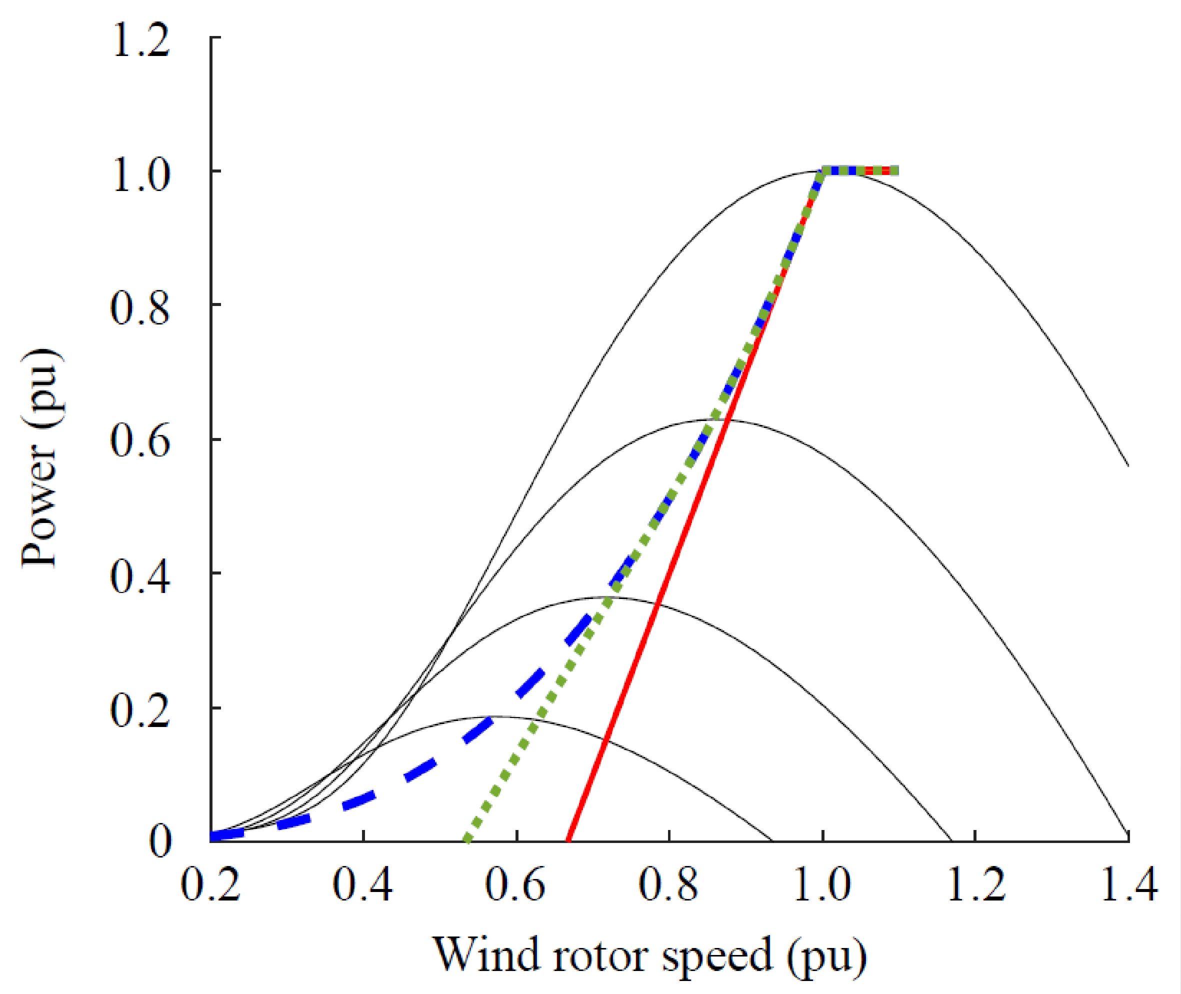
[1] Juan F. Gallego-Calderon, "Electromechanical Drivetrain Simulation", Dissertation (2015).
[2] Hrovat et al. "Bond Graph Modeling and Computer Simulation of Automotive Torque Converter",(1985).

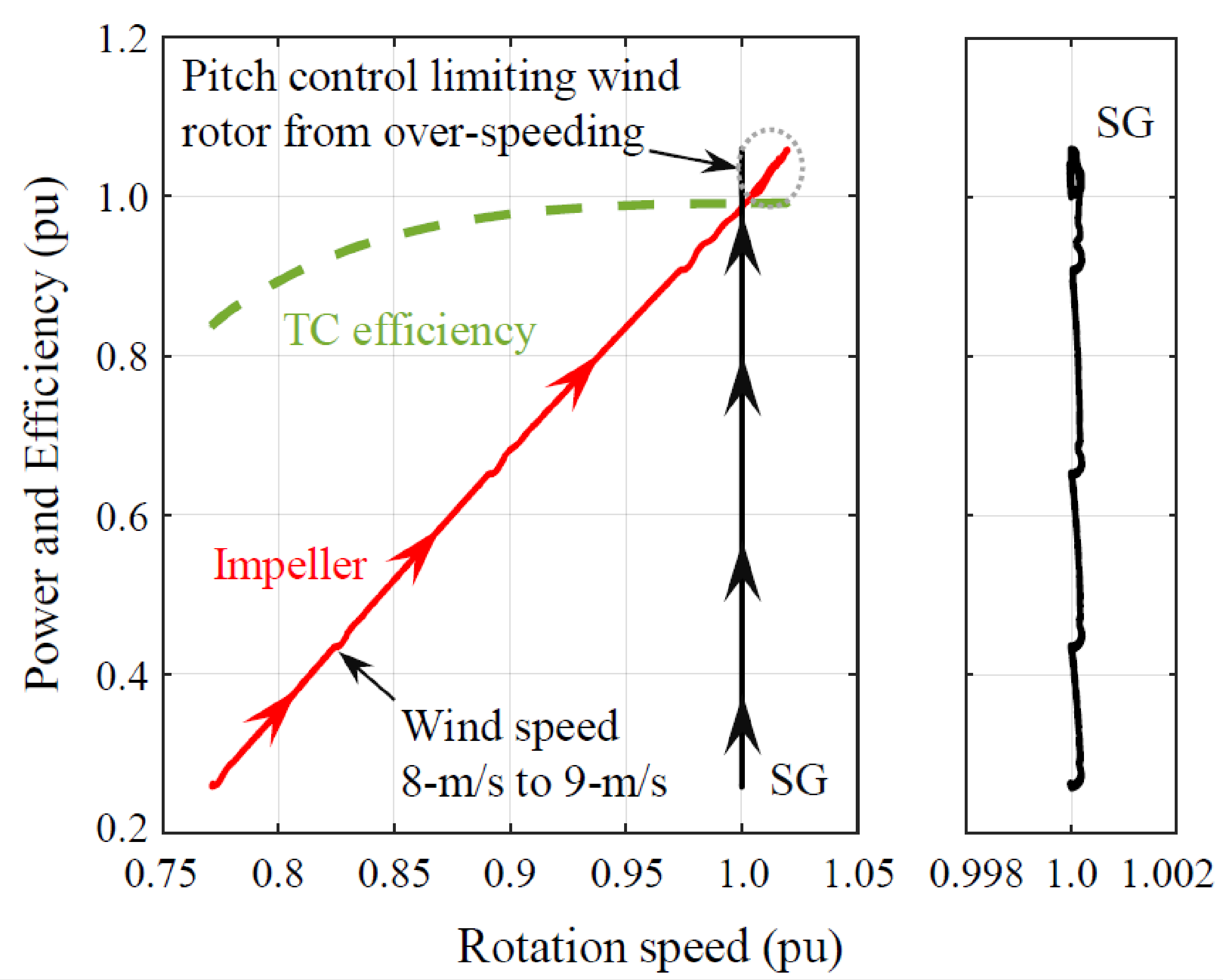
SyncWind Testbed with Torque Converter Model



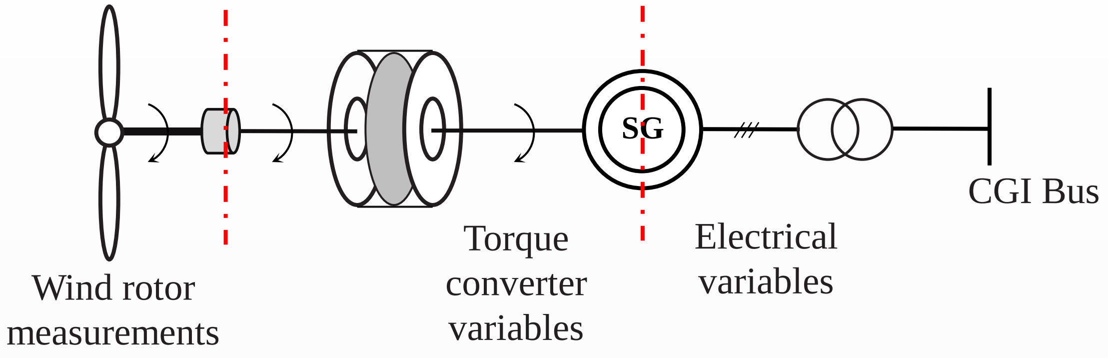
- CGI is maintaining the SG's speed when Type-5 wind is operating in power control model.
- Type-5 wind can be switched to speed control model for islanding operation, in conjunction with load bank.

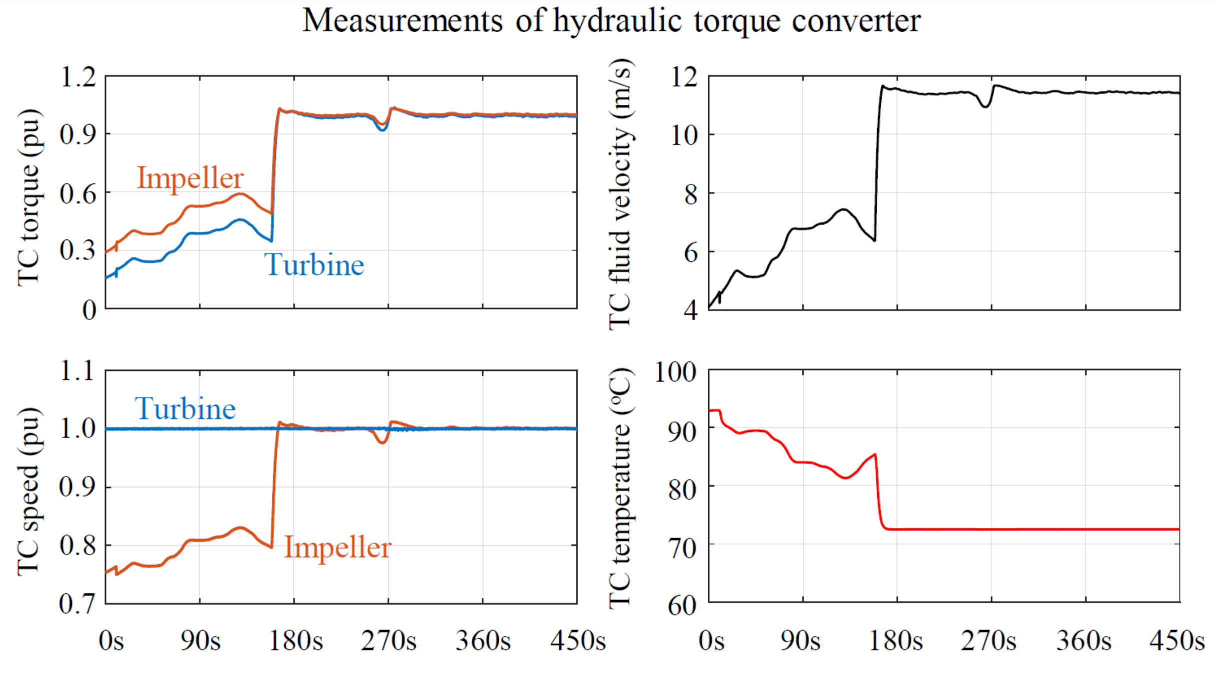
SyncWind Operation with Torque Converter Model

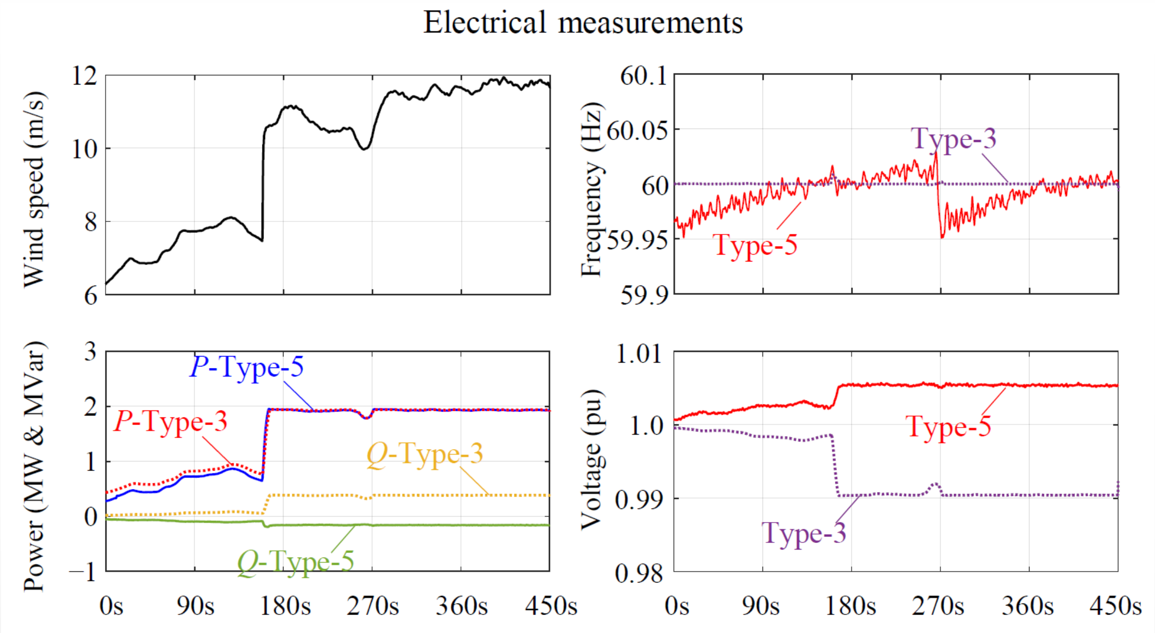


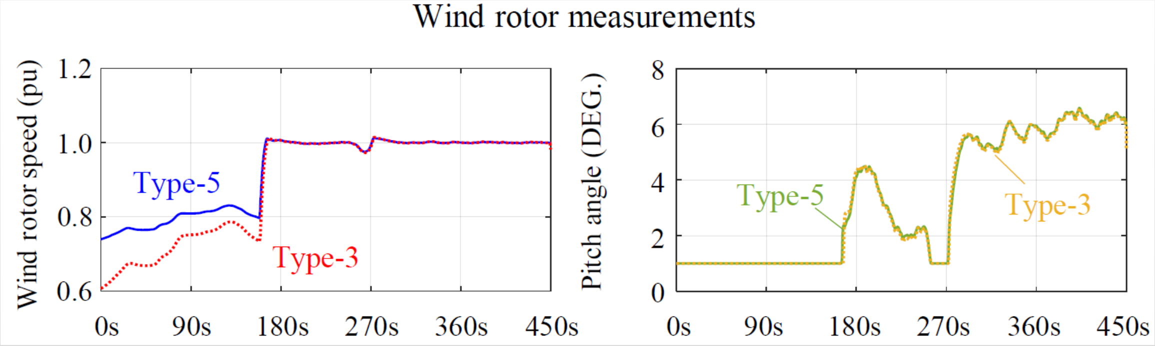


SyncWind under Variable Wind Condition



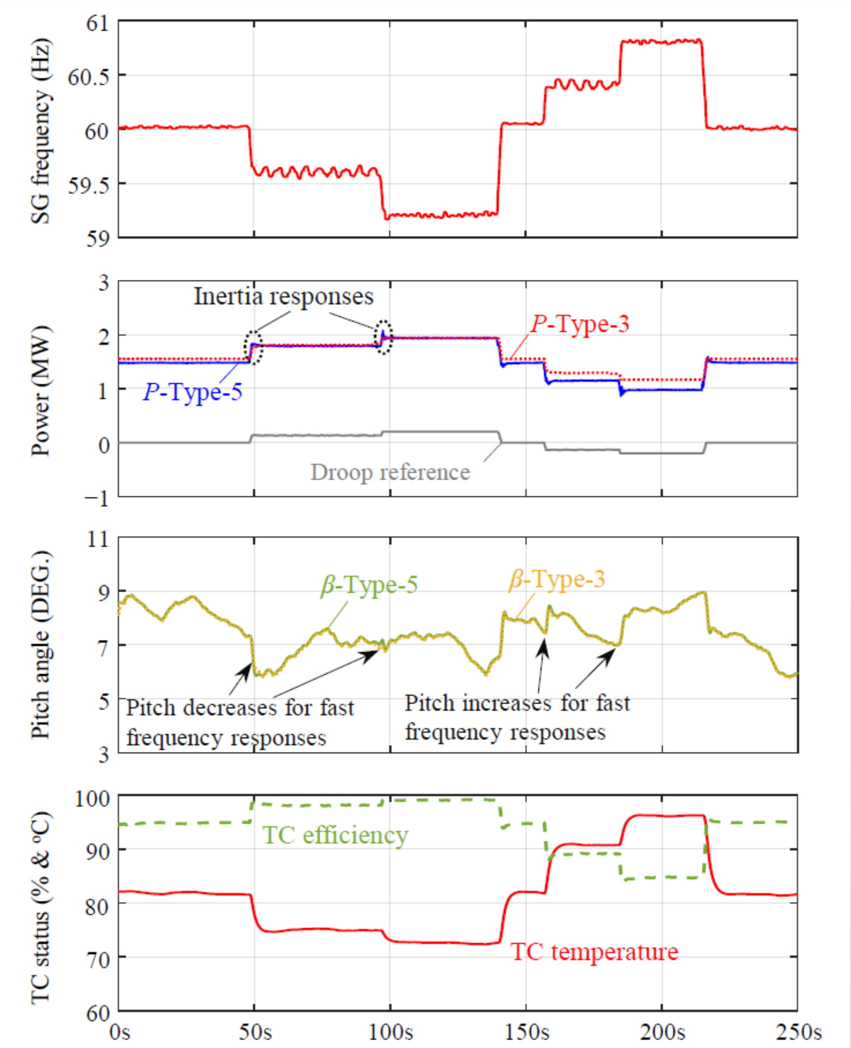




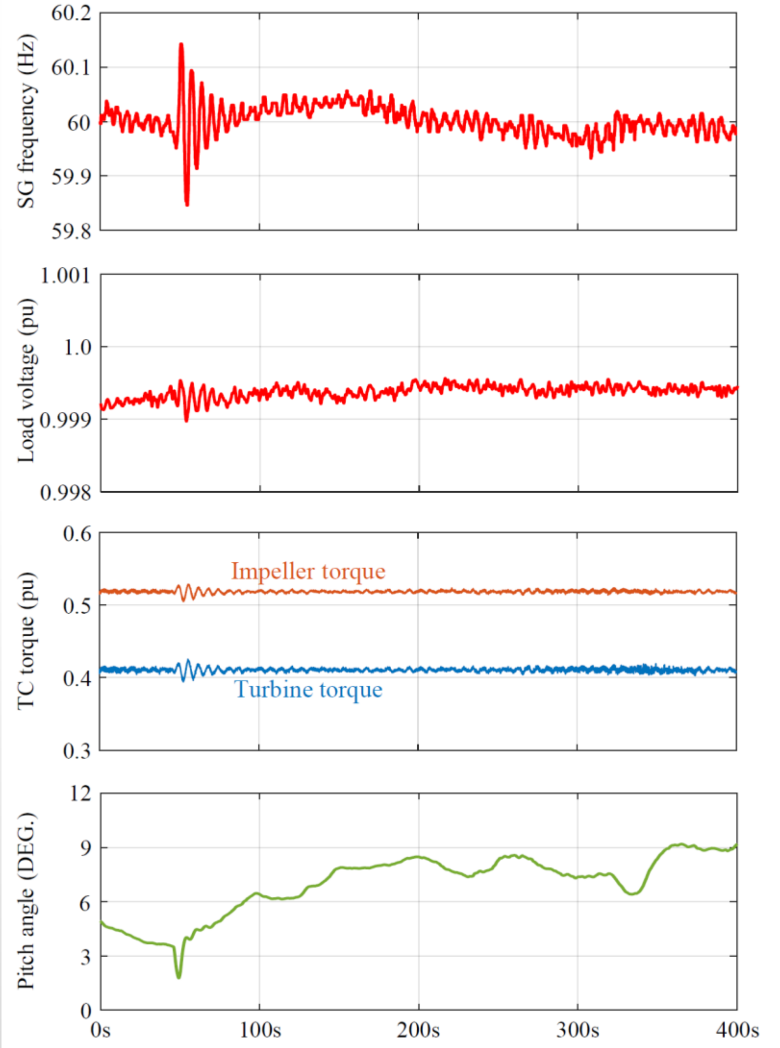


SyncWind Grid-forming/supporting Controls

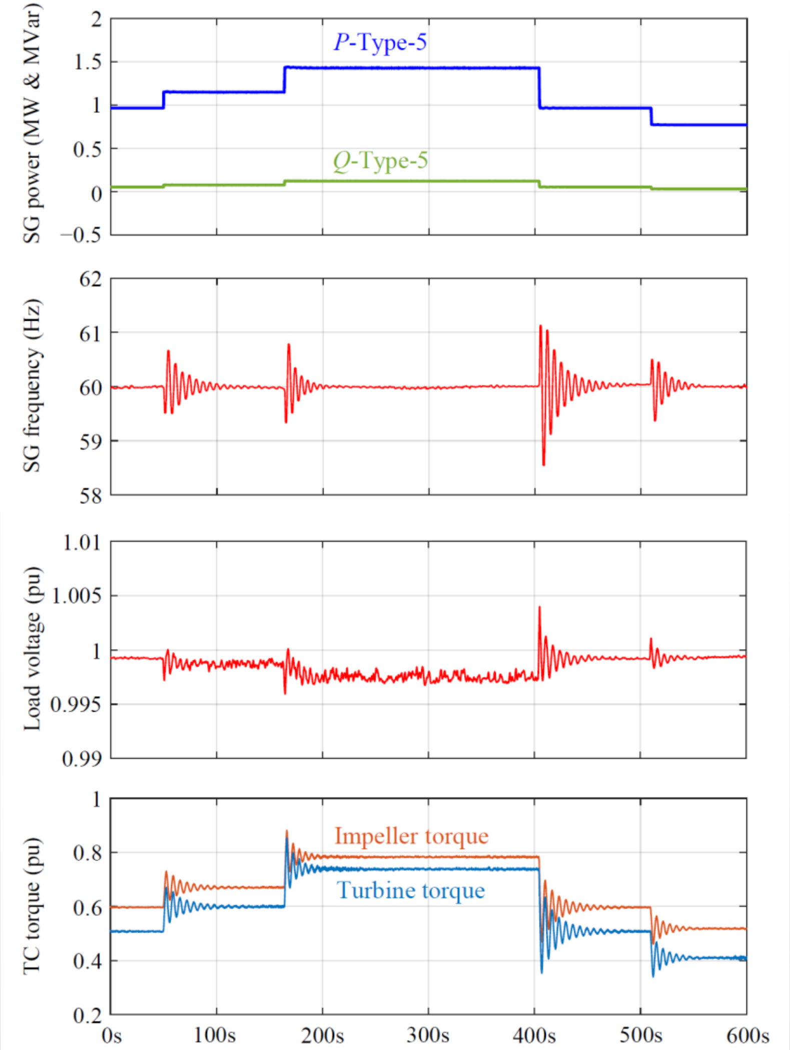
- Frequency droop control



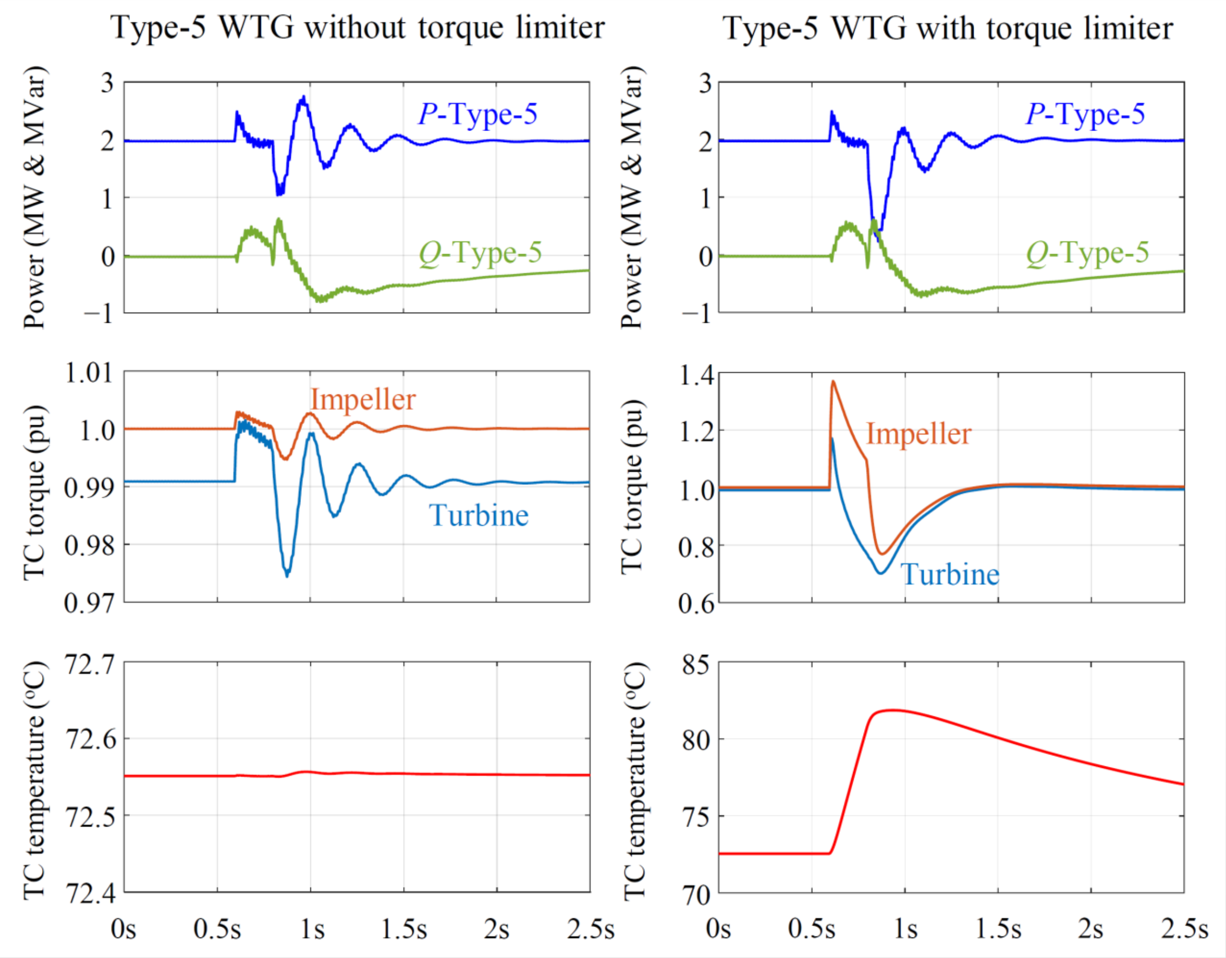
- Islanded operation under variable wind



- Islanded operation under variable load

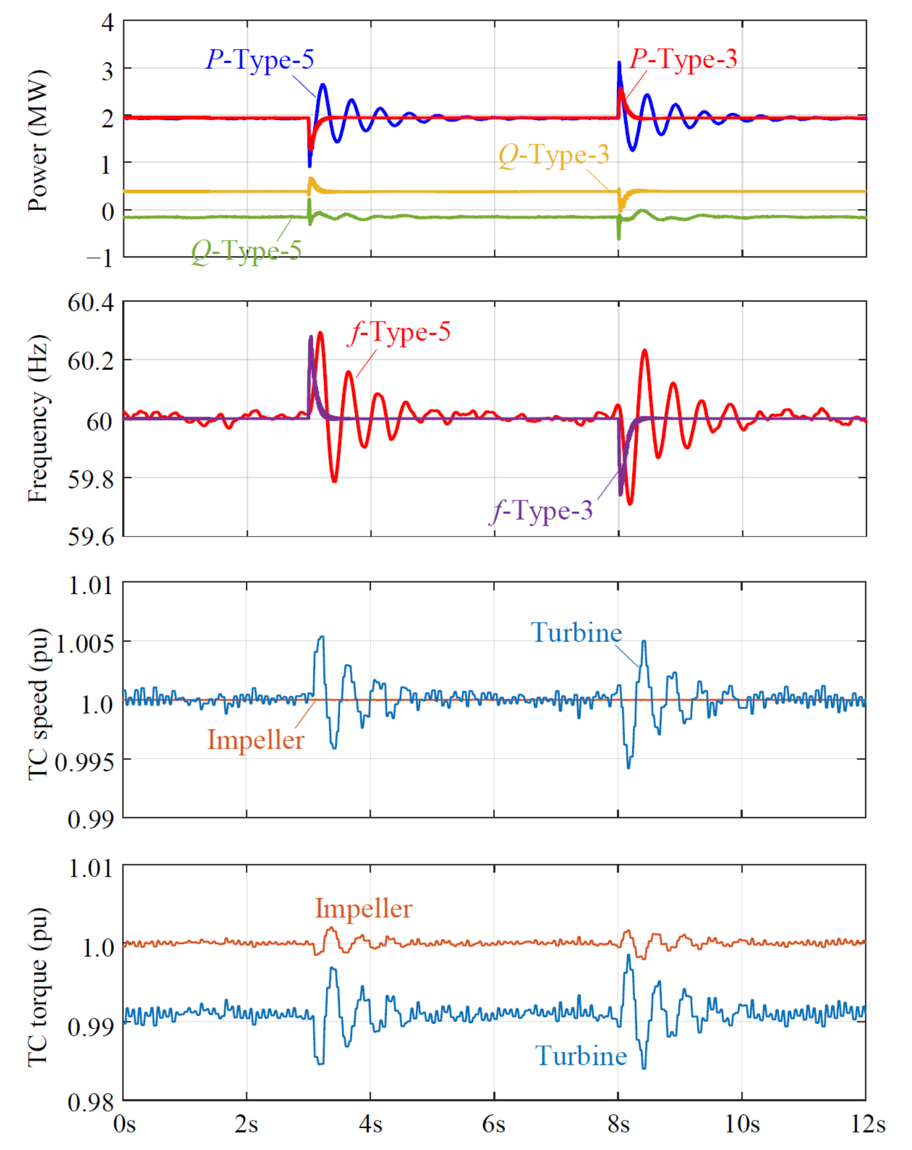


SyncWind Grid-forming/supporting Controls



- LVRT of SyncWind with/without torque limiter

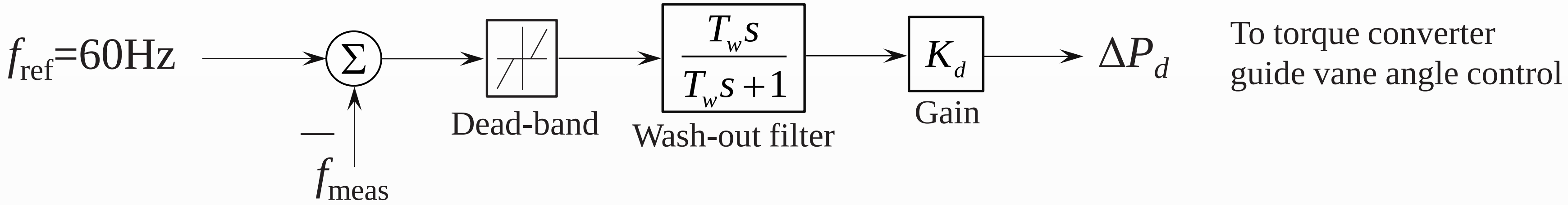
- Phase jump of SyncWind



PHIL Tests of SyncWind Oscillation Damping

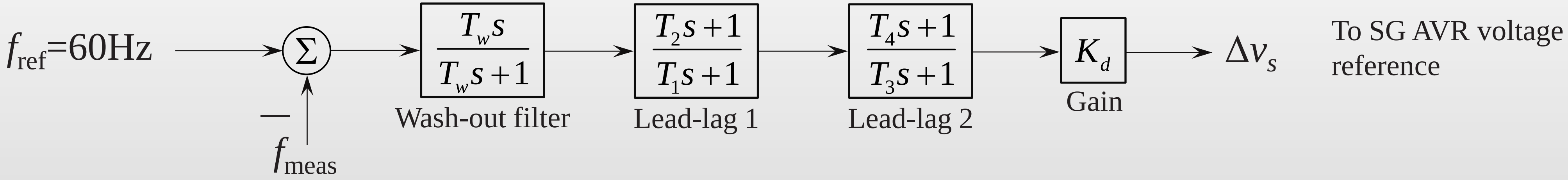
WindSG Power Modulation

- Active power modulation for interarea oscillation damping



  – No wind curtailment, ΔP_d will use kinetic energy in wind rotor.

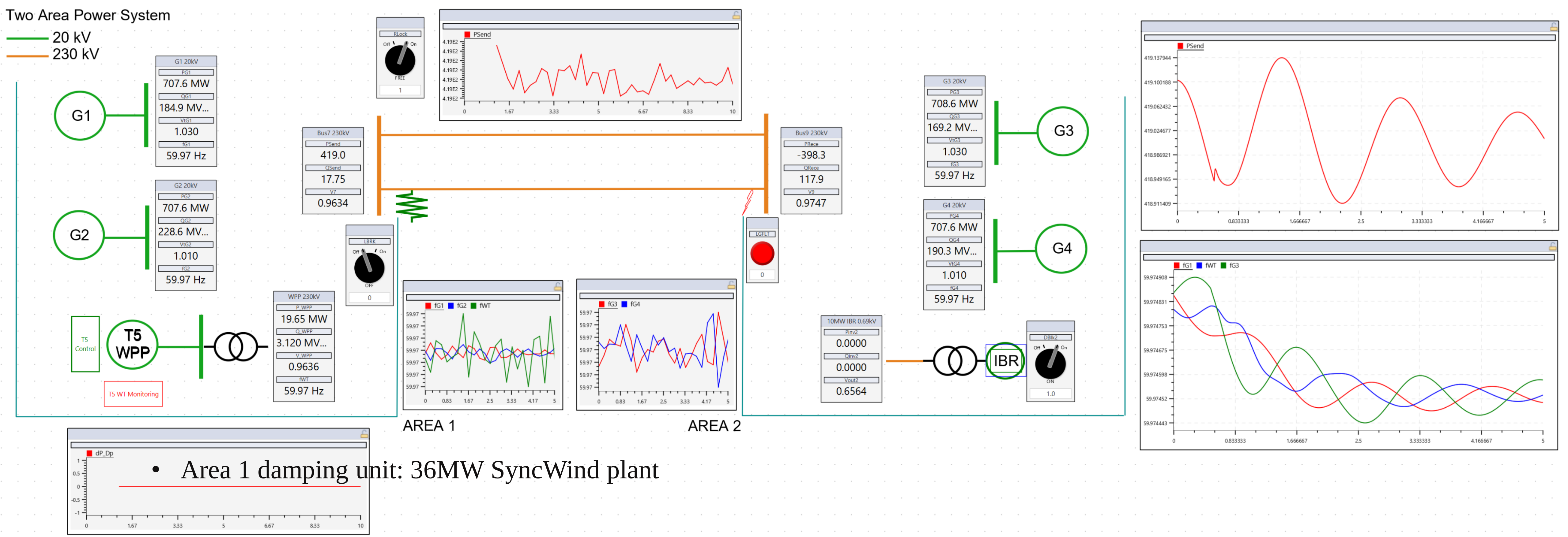
- Reactive power modulation for interarea oscillation damping



  – Use typical PSS model, modulate reactive power through adjusting SG field voltage.

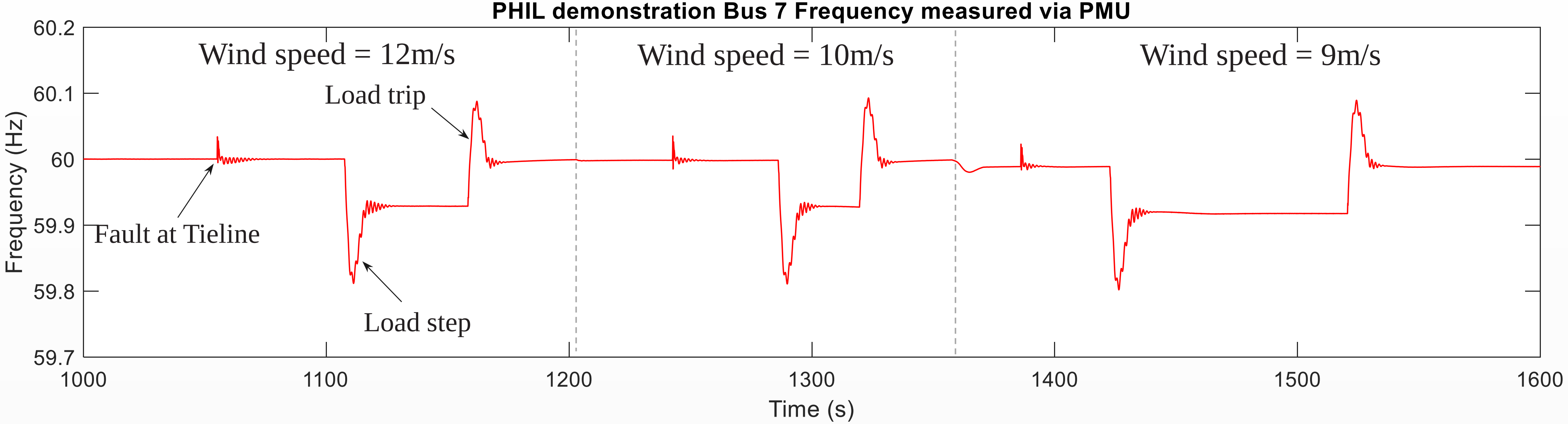
SyncWind Interarea Oscillation Damping

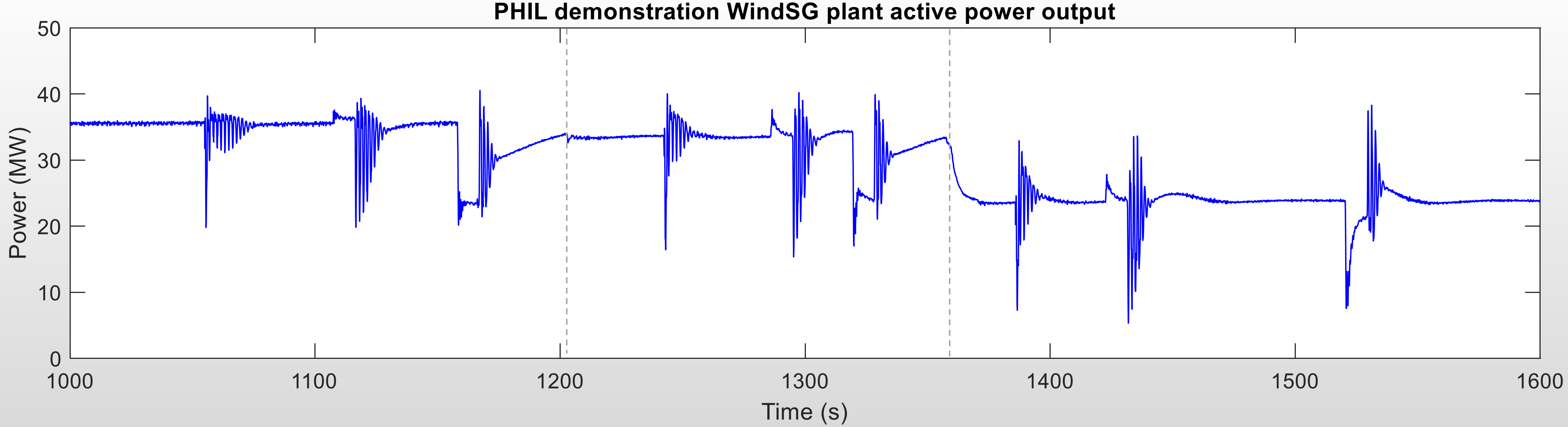
- CGI emulates the Bus 7 behavior of the Kundar two area model simulated in RTDS.
- 36MW WindSG wind power plant is integrated in the over 2.5GW system.



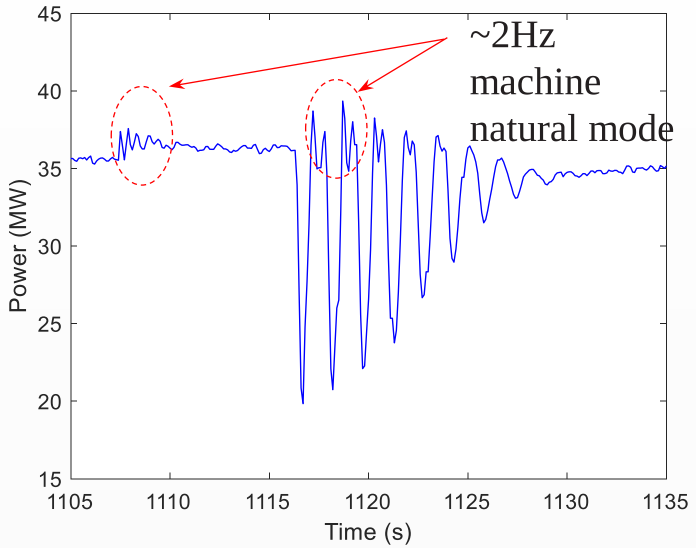
- Area 1 damping unit: 36MW SyncWind plant

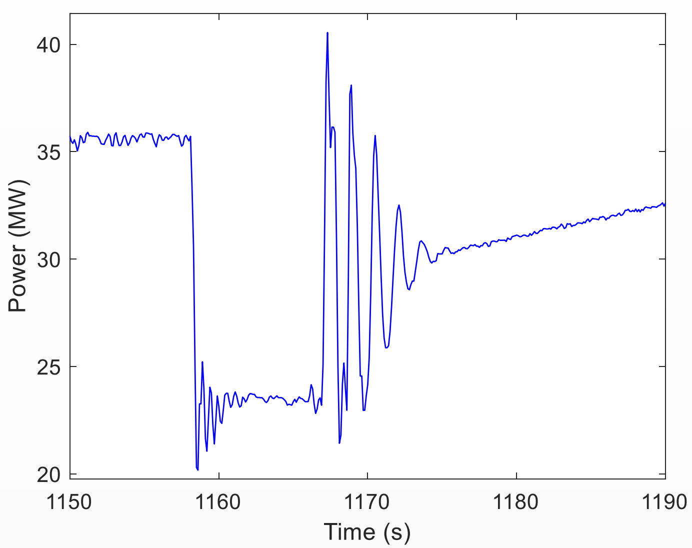
- Active Power Modulation

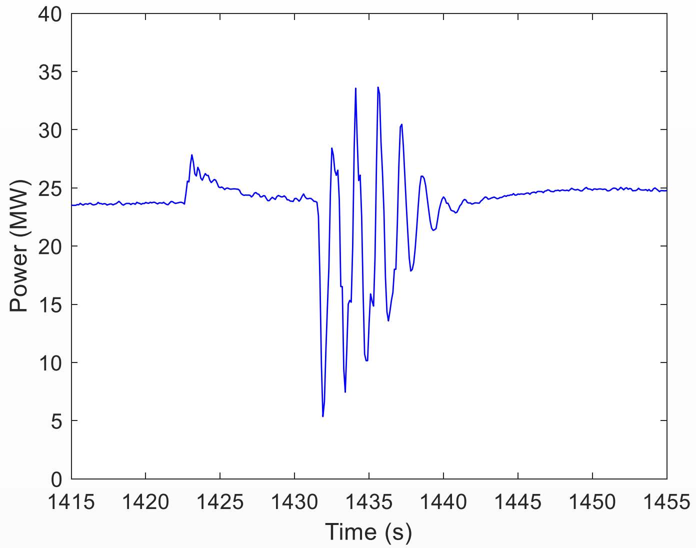


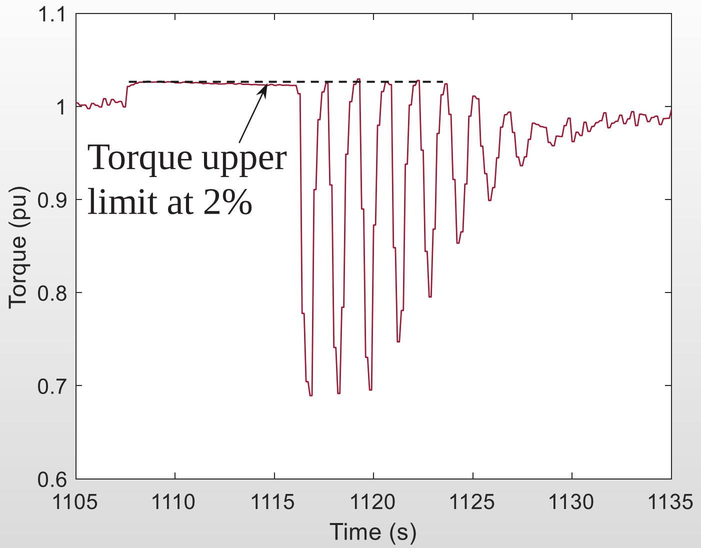


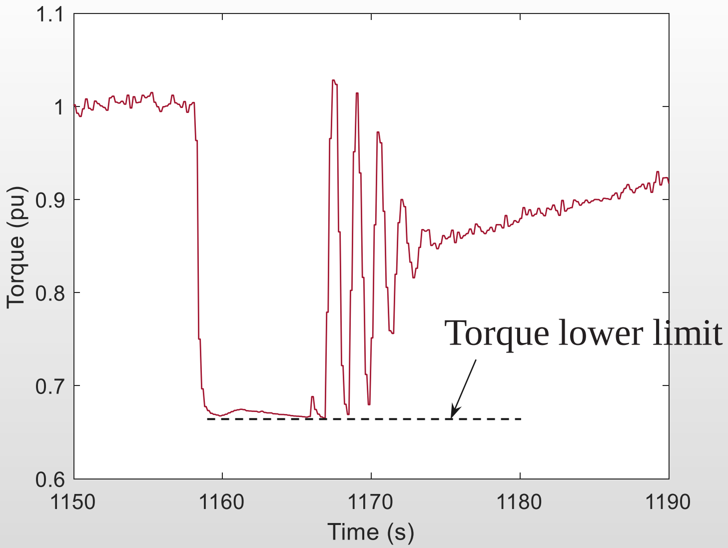
- Full power output with frequency drop
- Full power output with frequency surge
- Lower power output with frequency drop

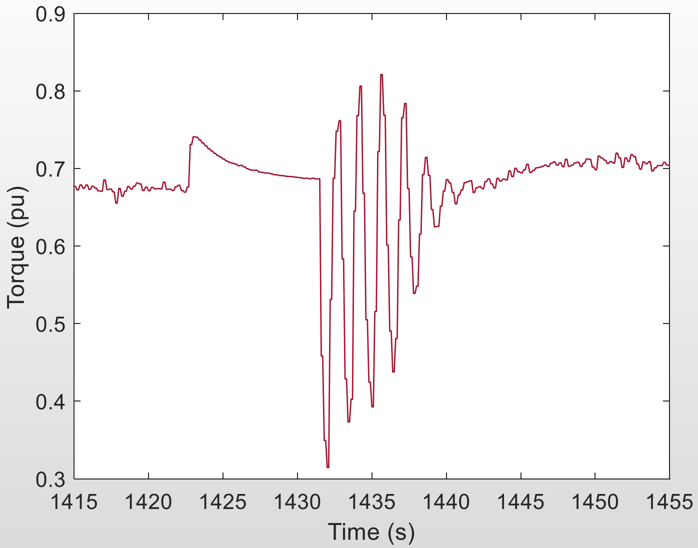




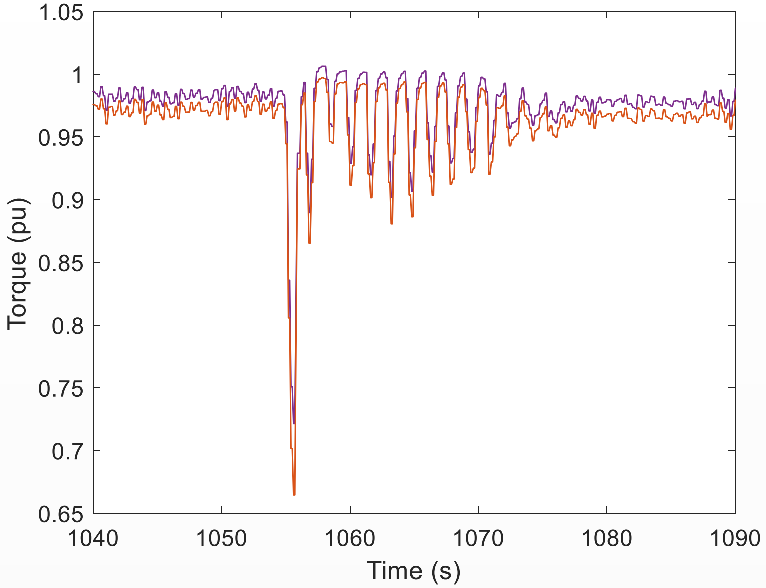


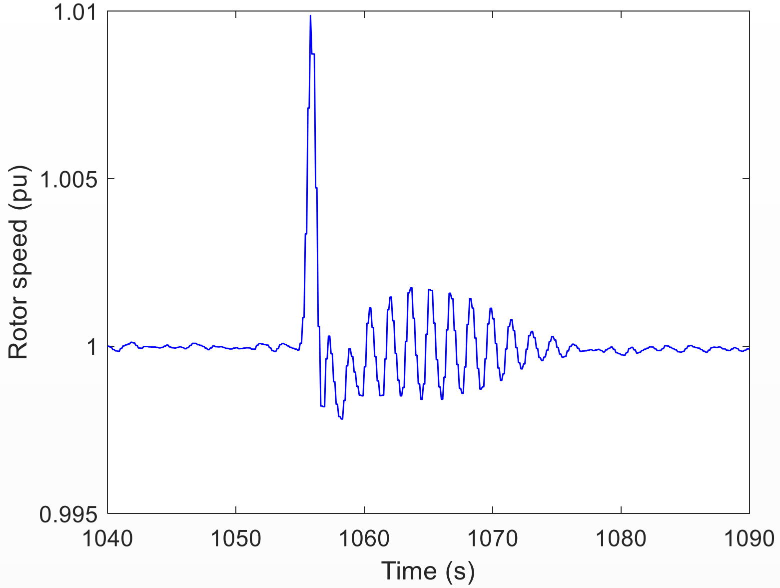


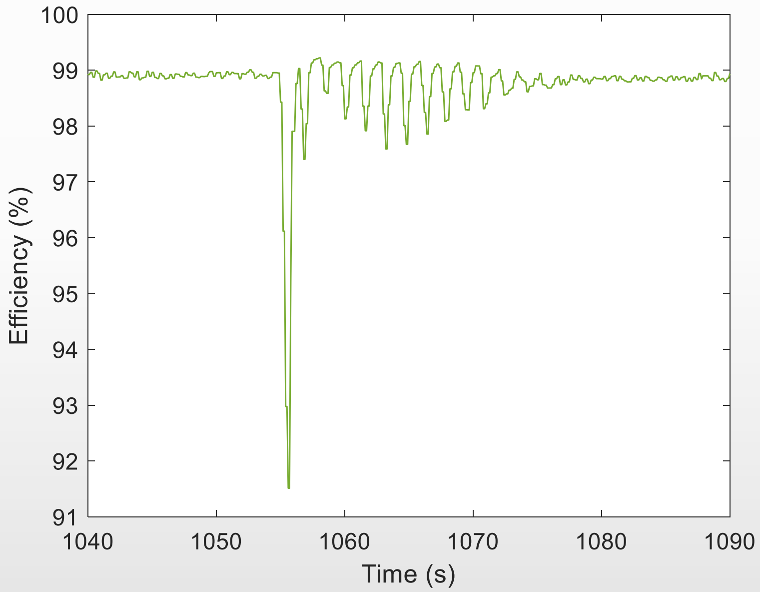


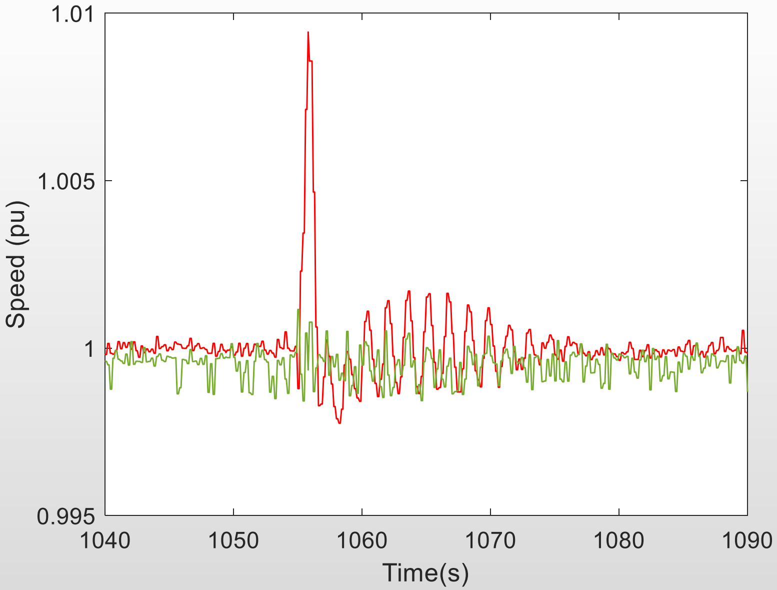


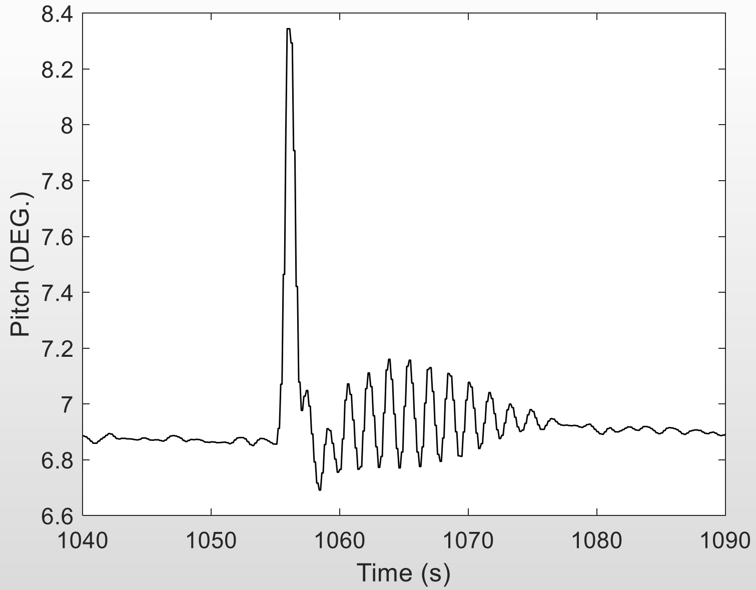
SyncWind Torque Converter Simulated in RTDS under Tie-line fault, wind speed = 12m/s





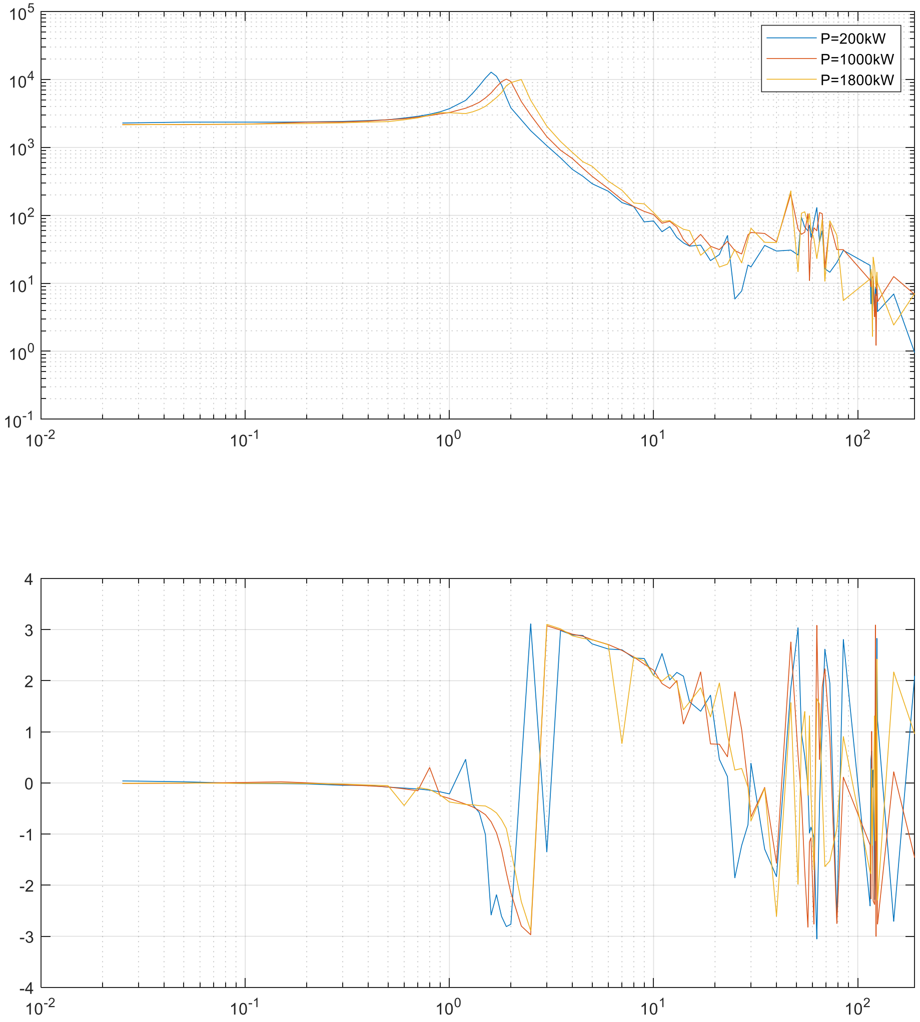




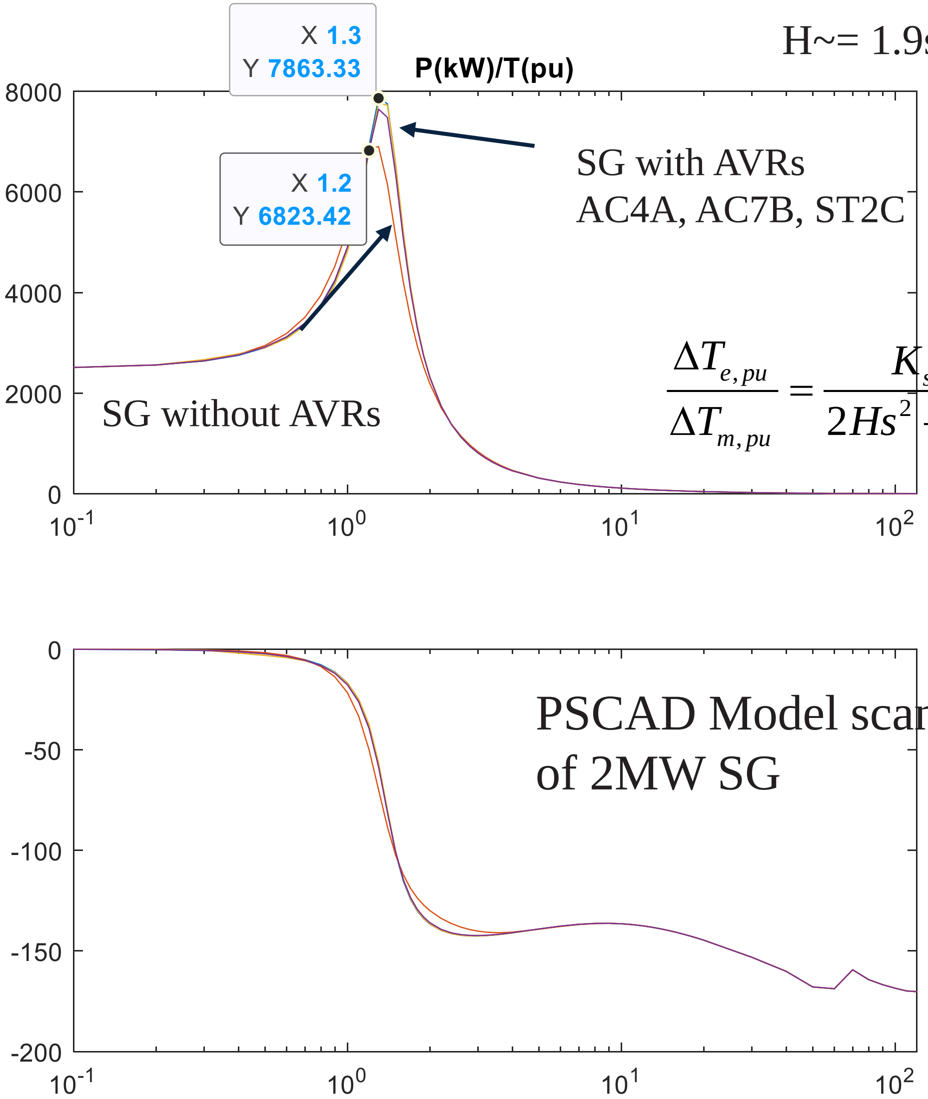


SG Natural Oscillation Mode

- 2MW SG Torque to Power Bode Plot

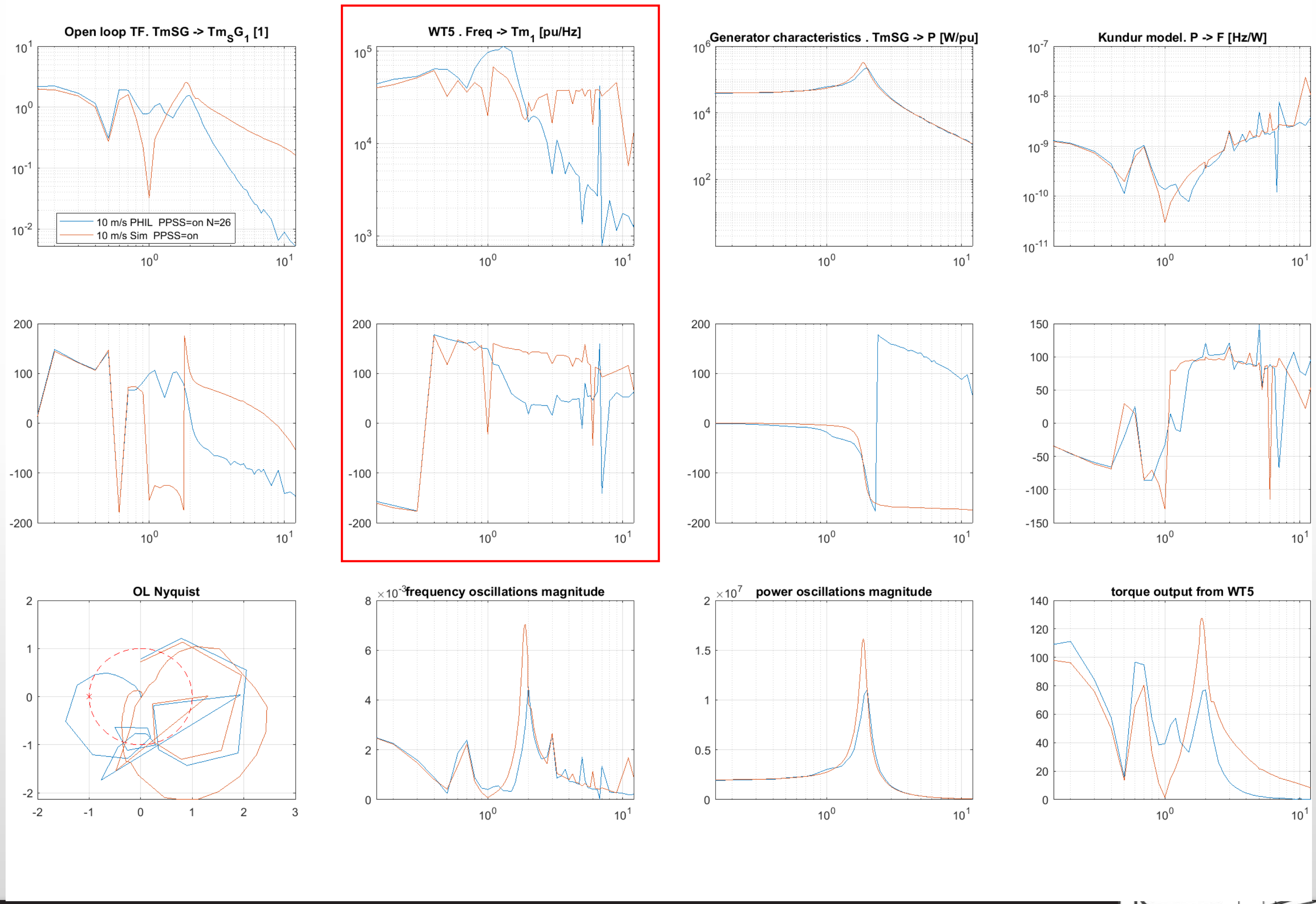


H~= 1.9s

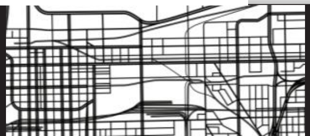


$$\frac{\Delta T_{e,pu}}{\Delta T_{m,pu}} = \frac{K_s \omega_n}{2Hs^2 + \omega_n K_s}$$

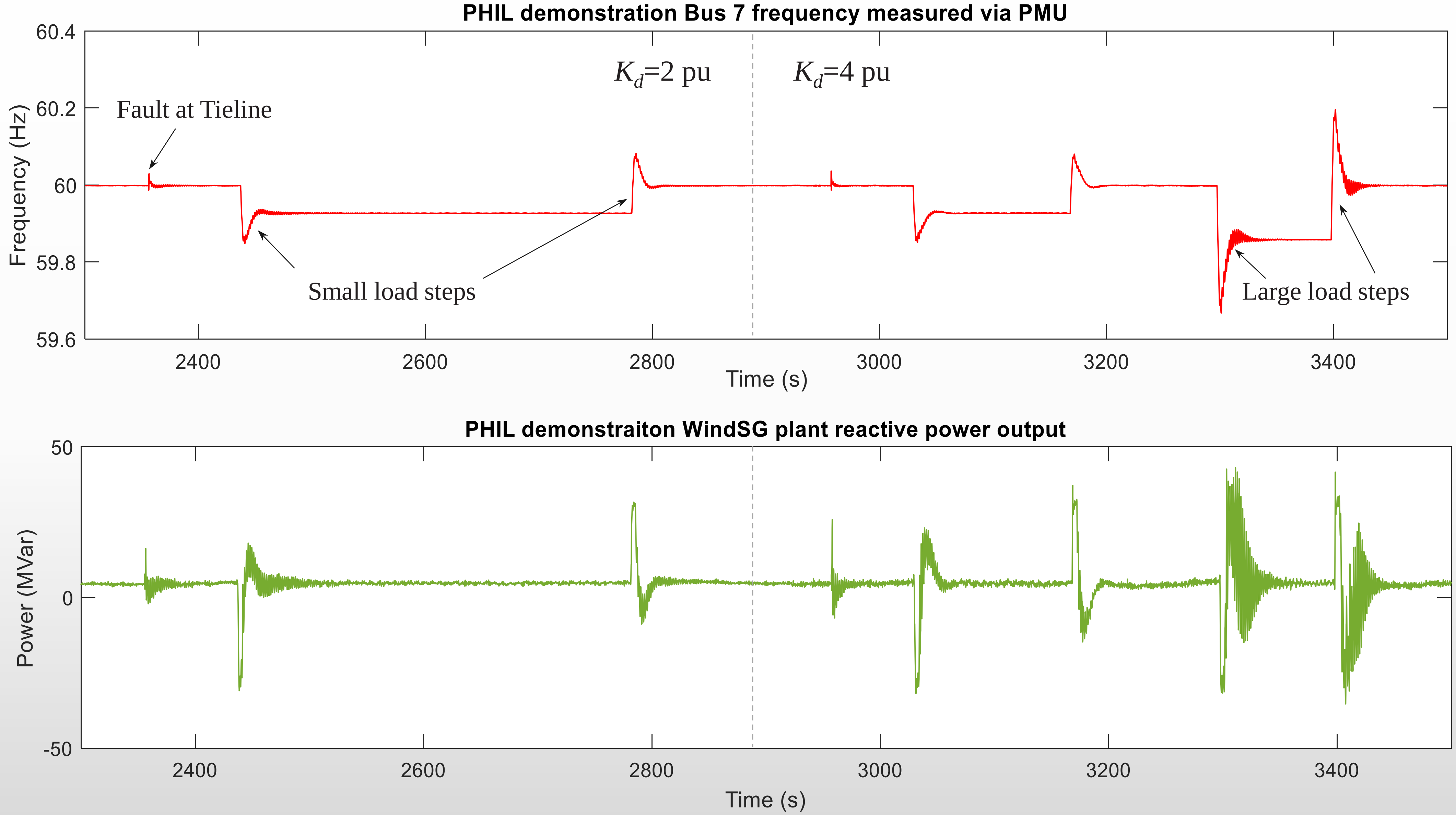
Impact of Frequency Measurement Bandwidth



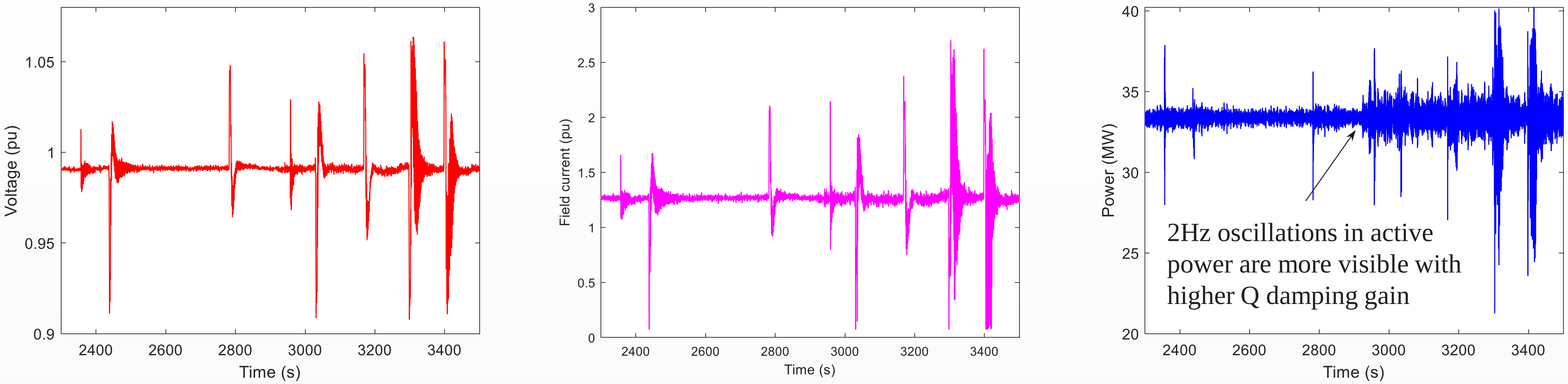
Sim vs PHIL graphs shows that PHIL had large phase shift in WT5 controls due to slow PLL used for initial frequency measurements



- Reactive Power Modulation

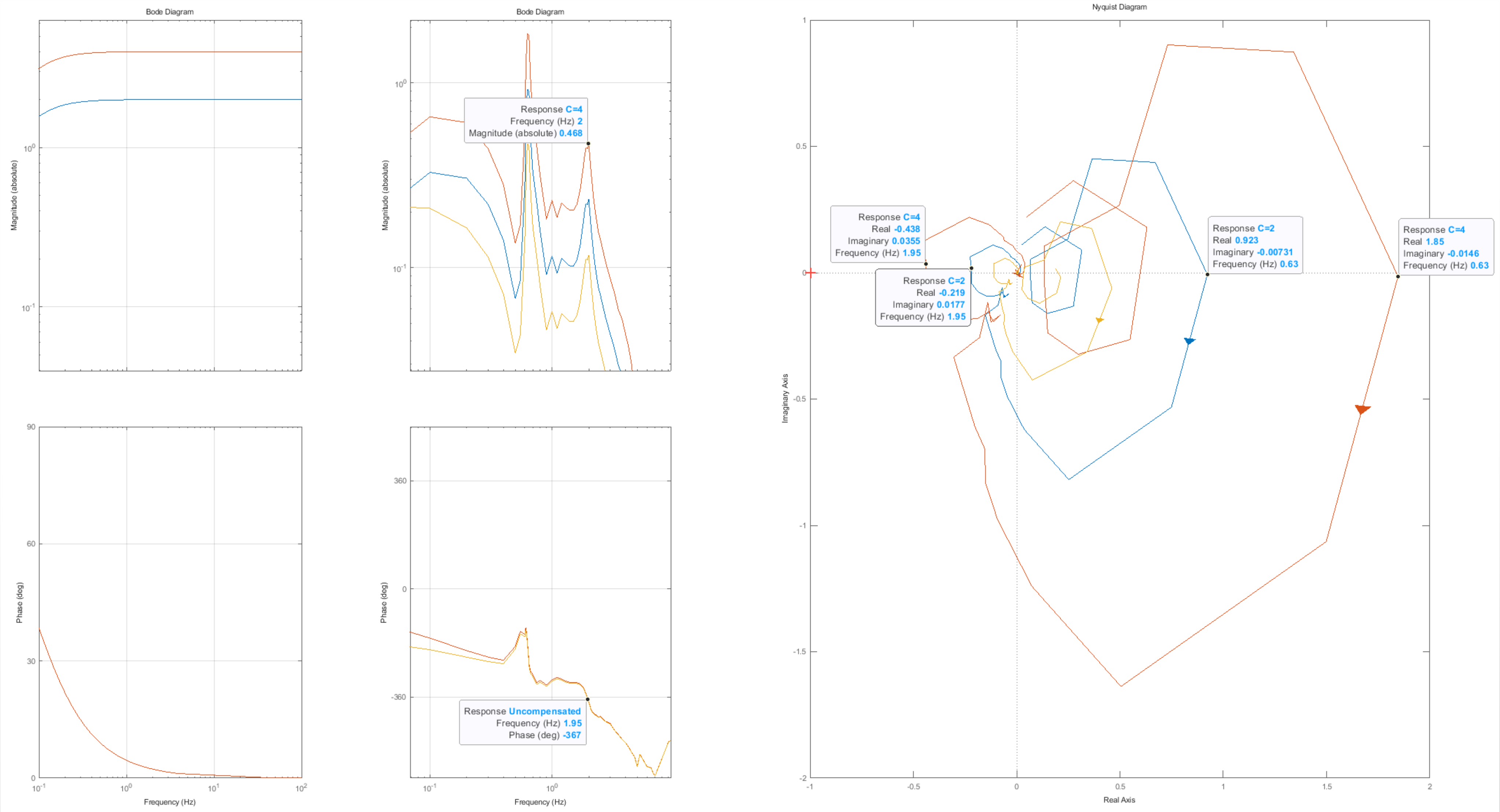


SG Voltage and Field Current Measurements



- Q modulated damping adjusts Bus 7 voltage based on frequency oscillation and further changes the power of the resistive load to provide oscillation damping.
- SyncWind plant's active power is not impacted in this damping case.
- Its effectiveness depends on system load condition.

PHIL PSS Compensator Tunning



Summary

- Modern power systems face a completely different scenario than the one 20 years ago, and such shift raised awareness of enhancing grid-strength under various energy mix.

- “WindSG: Wind power as a real Synchronous Generator” developed and tested a high-fidelity model of a Type 5 WTG in the PHIL setup using a 2-MW SG driven by a 2.5-MW dynamometer. A Type 5 WTG offers a unique GFM solution to address many grid integration and grid strength problems by keeping the grid synchronous.

- RTDS plays a critical role in implementing the governor/hydraulic torque converter of the SyncWind and further carried out PHIL demonstration on SyncWind operation and oscillation damping.

Thank you

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