Photo by Dennis Schroeder, NREL 55200

NREL
Transforming ENERGY

Grid Forming Wind Power

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Main Reliability Challenges in Evolving Grid: Importance of Grid Strength

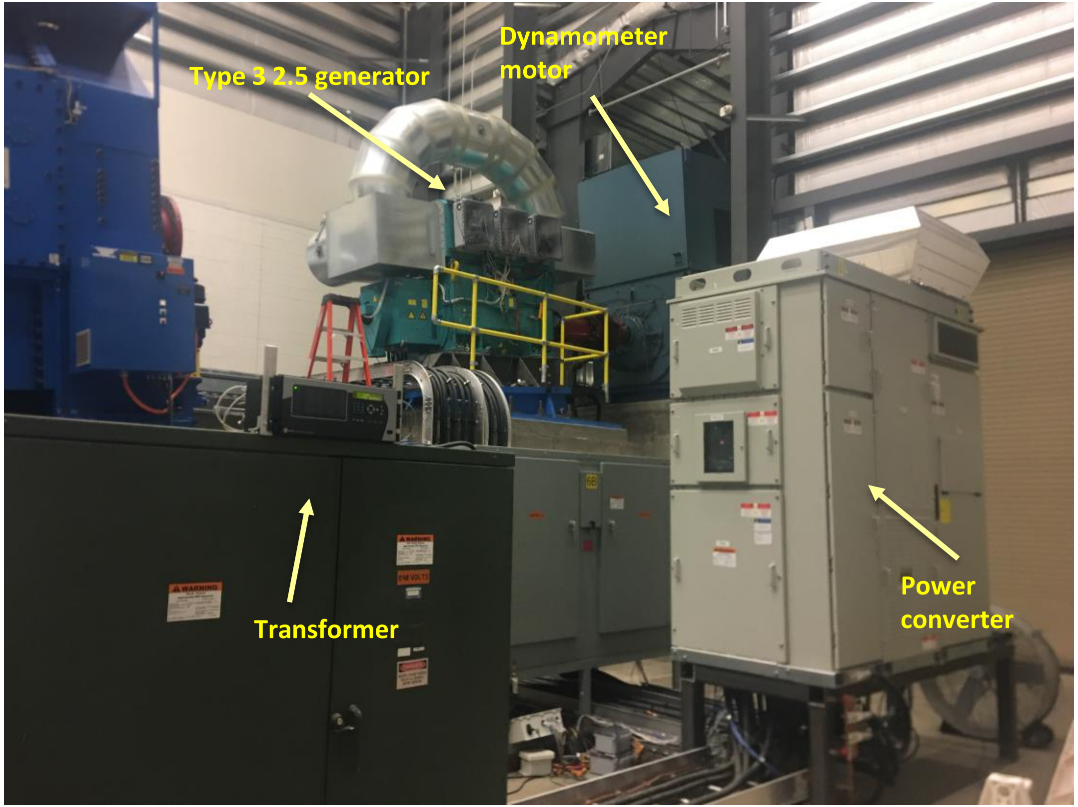
A power system with low system strength are expected to exhibit the following behavior:

- Undamped voltage and power oscillations.
- Degradation in IBRs fault ride-through capabilities.
- Protection system malfunctioning due to reduced levels of short circuit current.
- Longer voltage recovery after voltage faults and disturbances.
- Larger transient voltage steps caused by switching capacitor or inductor banks.
- Dynamic voltage control stability issues.
- Increased levels of harmonic distortion in the grid.
- Deeper voltage dips and higher over-voltages during transients / More severe transient characteristics of the system.
- Black start, islanded operation, issue of inrush currents

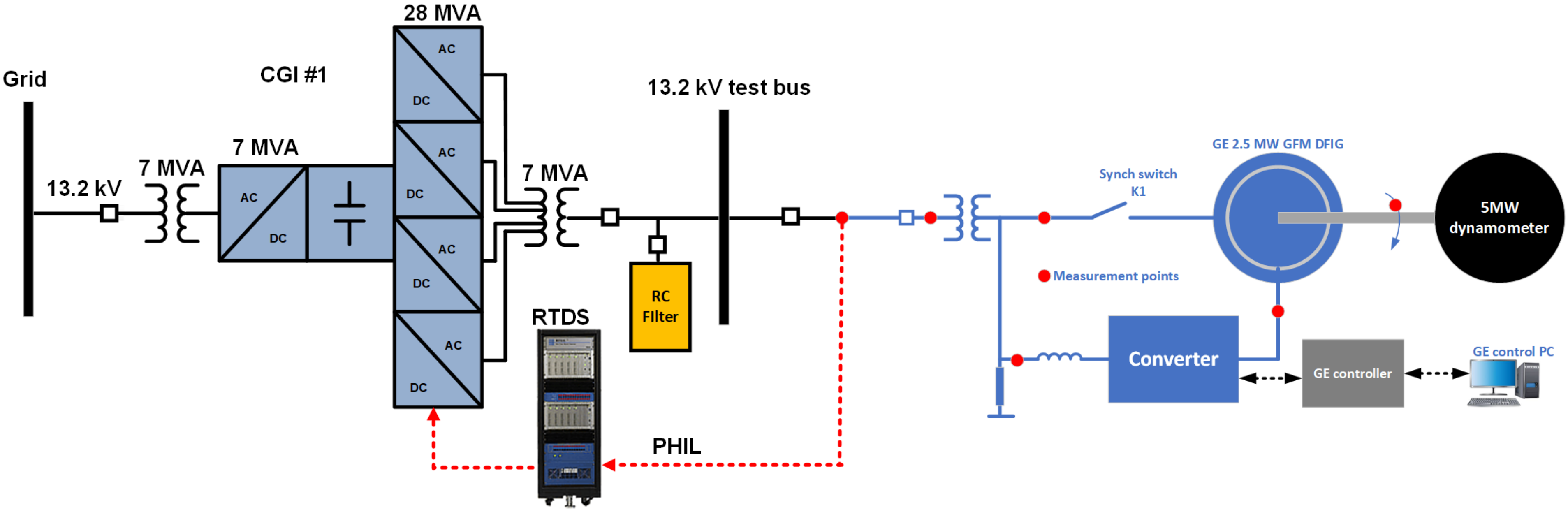
Is grid forming by IBRs going to help? If so, how much do we need it?

GRM Wind Project

- DOE WETO funded 3-year NREL/GE project
- Develop, deploy and demonstrate GFM controls in 2.5 MW Type 3 wind turbine generator
- Drivetrain installed on NREL 5 MW dynamometer and tests using 7 MVA MV gird simulator (CGI)

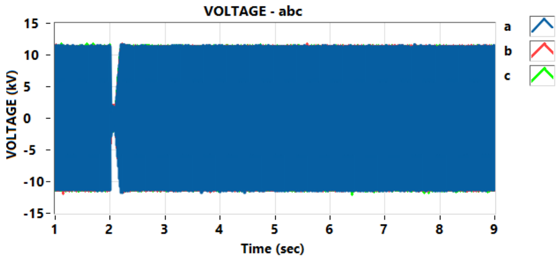


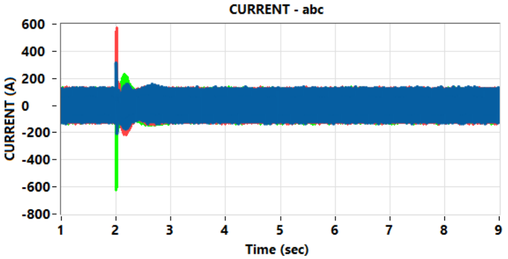
NREL Test Platform

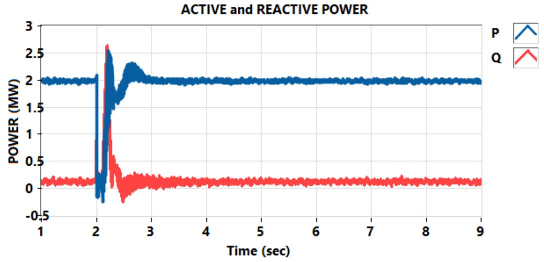


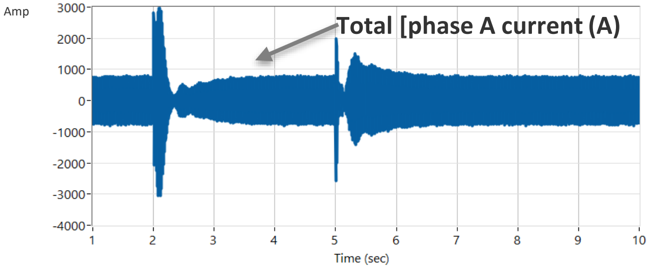
- Testing under controlled grid conditions:
  - Grid strength emulated by CGI PHIL
  - Balanced and unbalanced LVRT and HVRT
  - Frequency variations, phase jumps
  - Islanded operation
- RTDS and PSCAD model validation

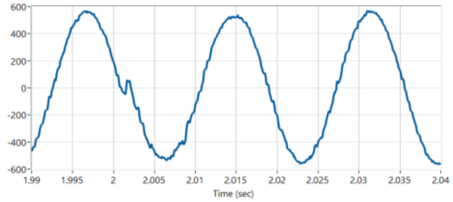
LVRT and 30º phase-jump

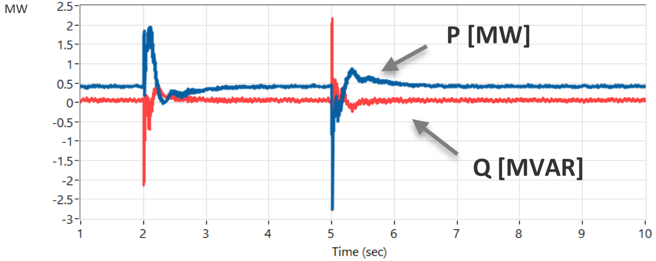


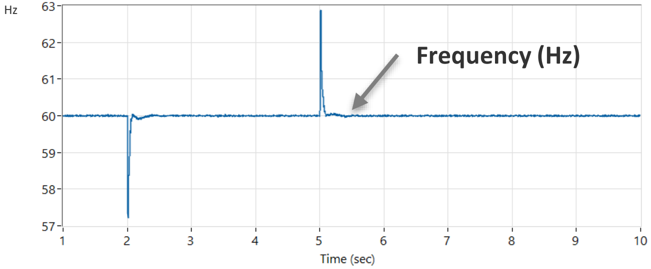








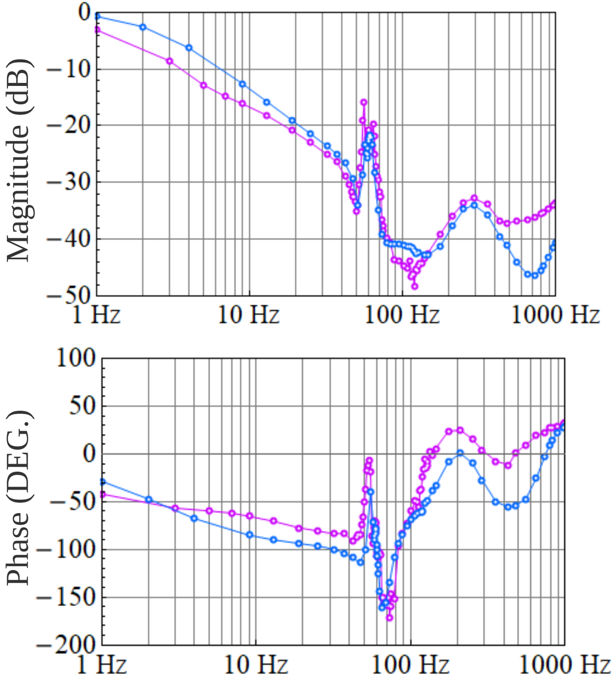


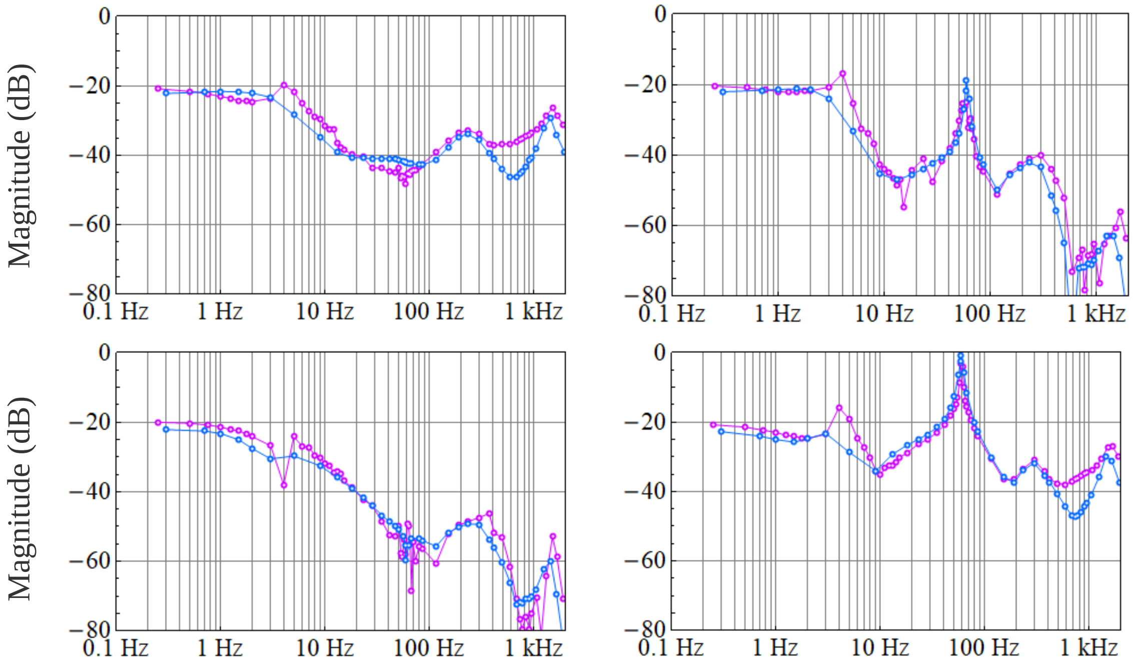


Type 3 GFM WTG Impedance Characteristic: Model and Test Comparison

$Y_p(s)$: +ve Seq. Admittance

- $\mathbf{Y}_{PN}(s)$: Sequence Admittance Matrix

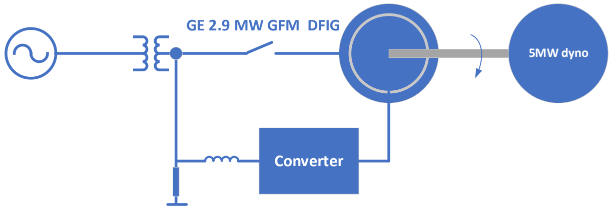




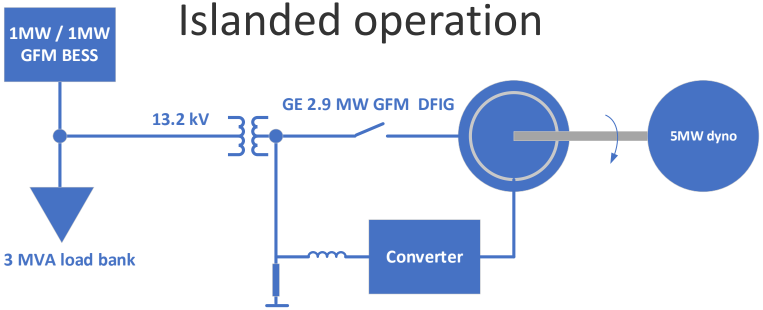
PSCAD (2.7MW, 1497 rpm) CGI (2 MW, 1460 rpm)

Type 3 GFM testing configurations

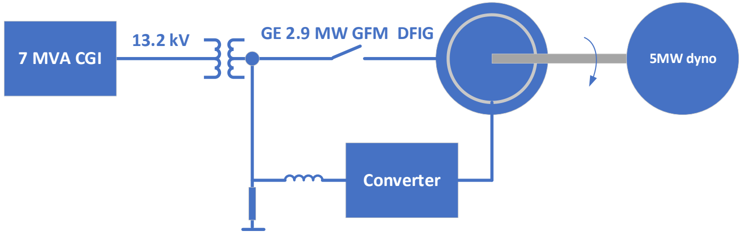
Grid connected



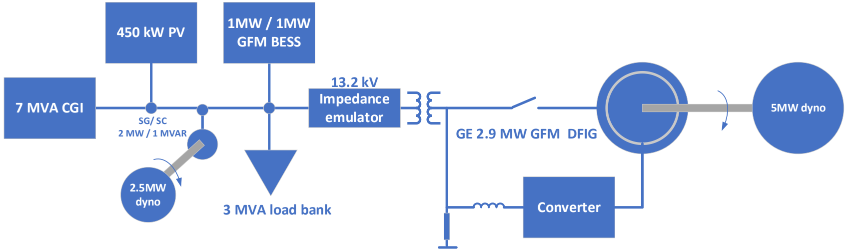
Islanded operation



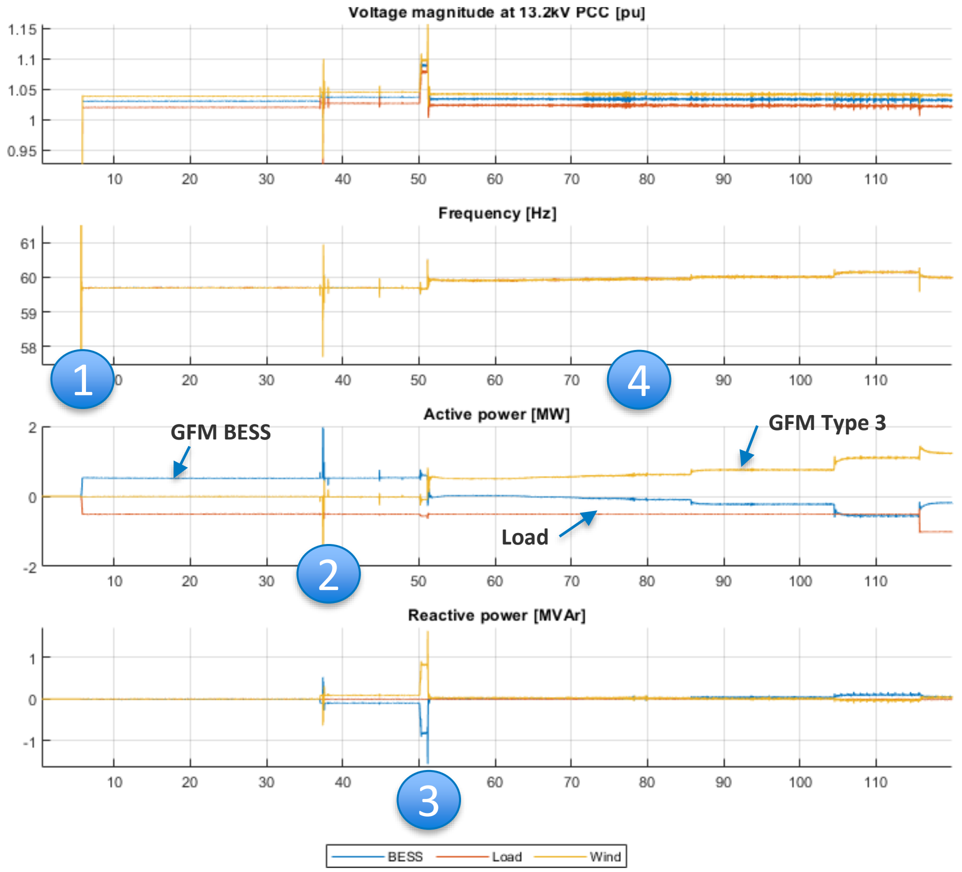
Connected to simulated grid



Multi-technology island

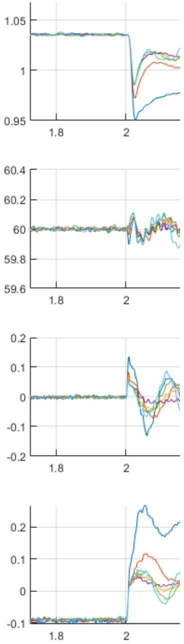


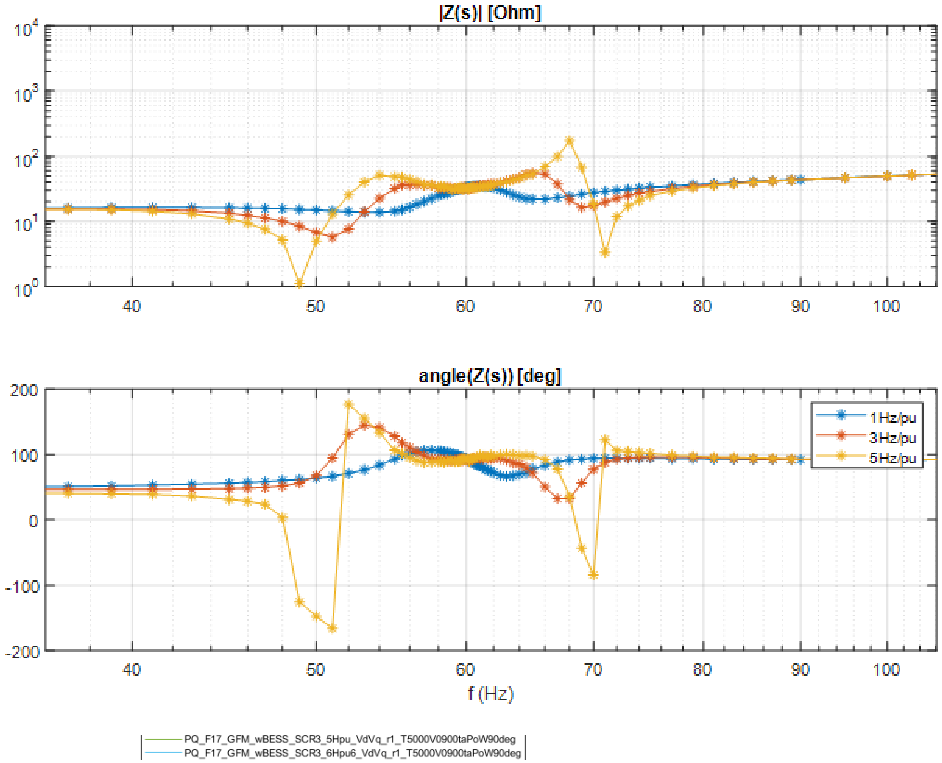
Black start with GFM BESS

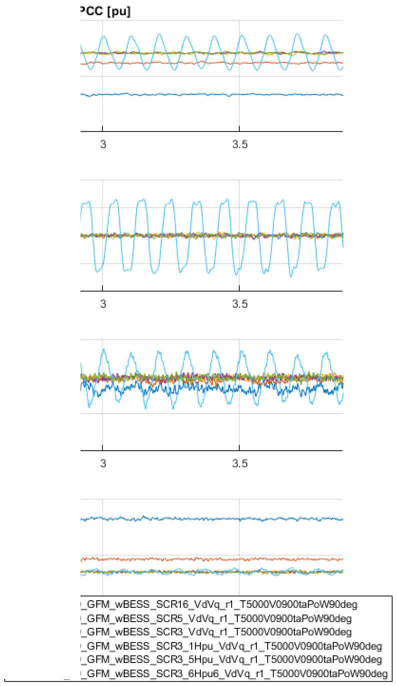


1. GFM BESS starts with 500kW loads and voltage ramps
2. Spike up to 2MVA observed on BESS during GFM Type 3 first synchronization – SMA has overcurrent capabilities to ride through it
3. Closing of second breaker causes initially large reactive power injection that needs to be handled by SMA
4. After that GFM Type 3 controls reactive power much better and active power is ramped up

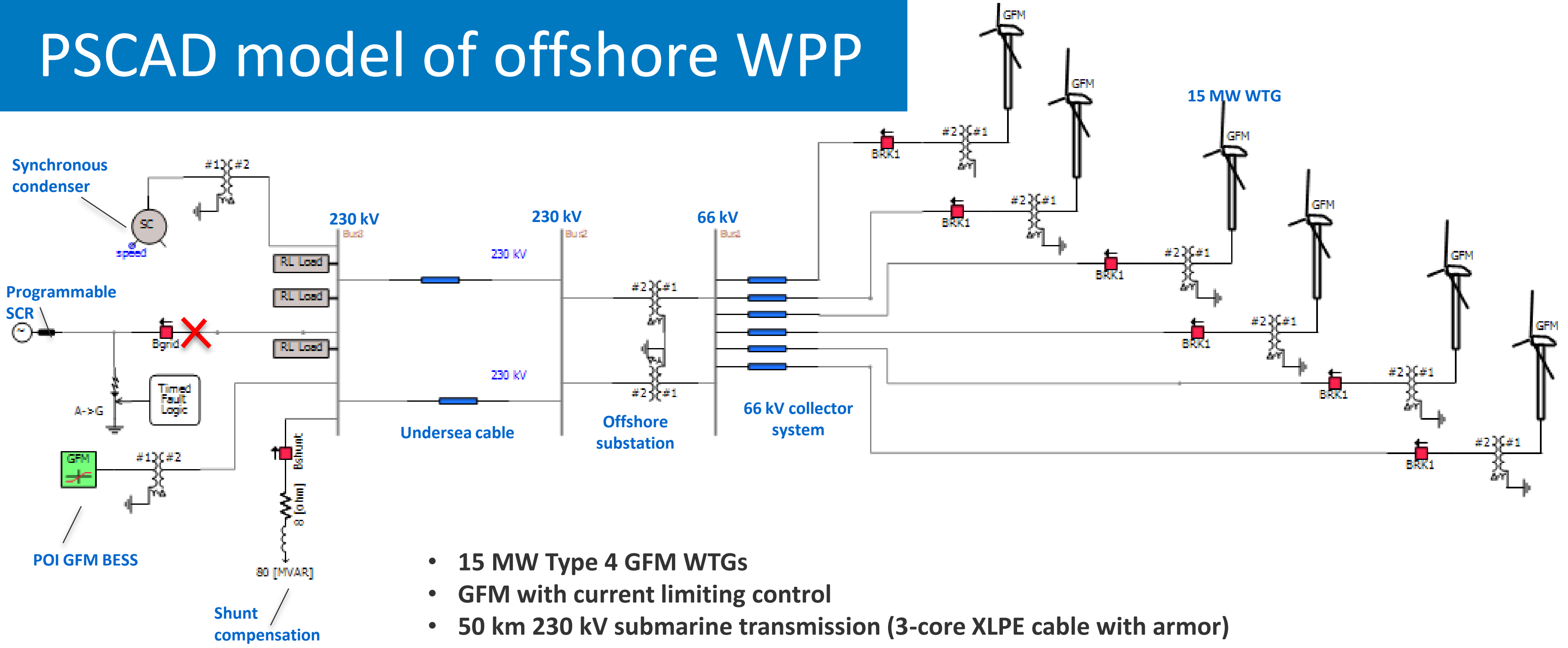
Response of GFM BESS + GFM Type 3 WTG to voltage steps





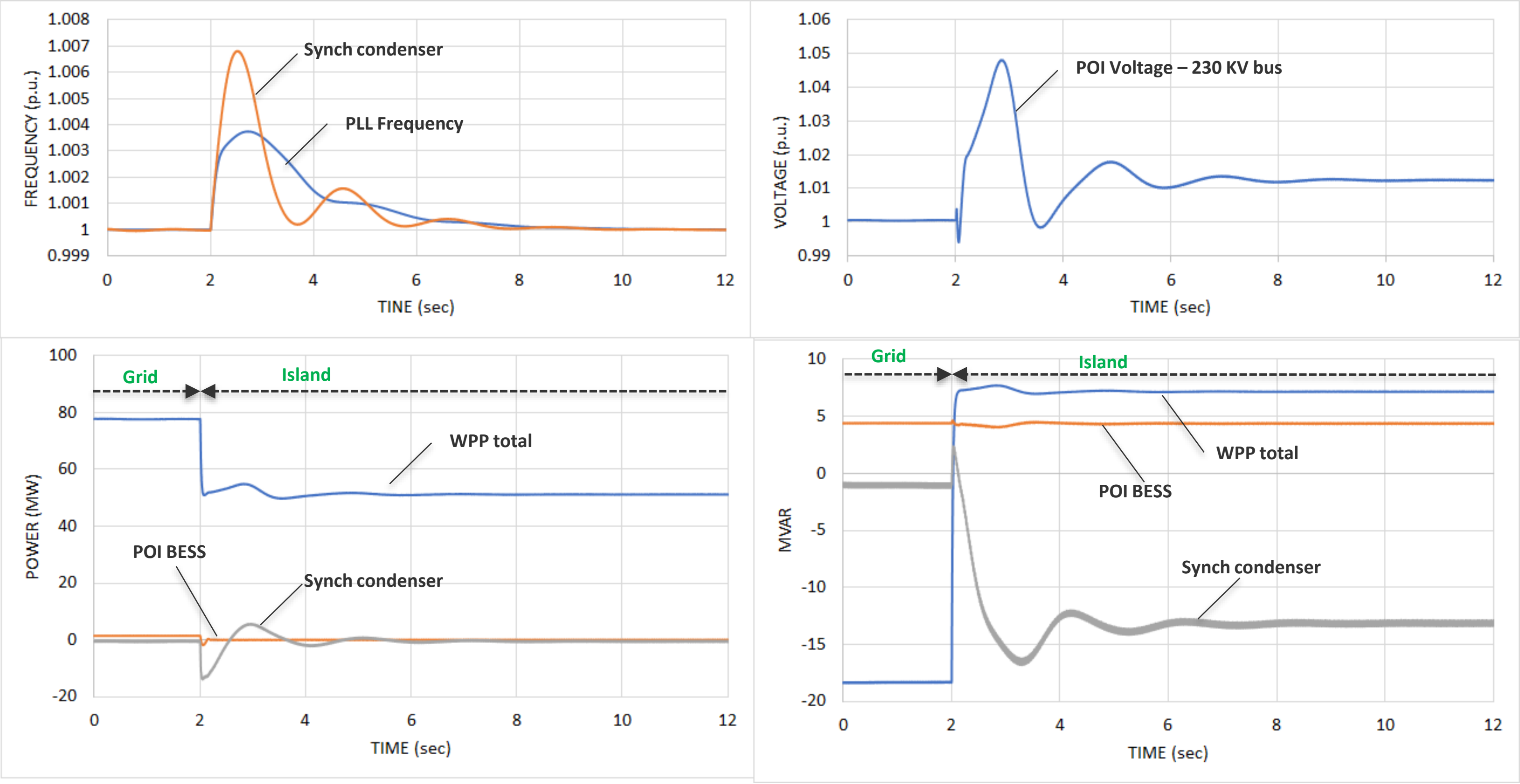


PSCAD model of offshore WPP



- 15 MW Type 4 GFM WTGs
- GFM with current limiting control
- 50 km 230 kV submarine transmission (3-core XLPE cable with armor)
- 66 kV collector system
- Shunt compensation at receiving end
- POI SCR range: 2-50
- Enhancing systems modeled at POI: GFM BSS, synchronous condenser

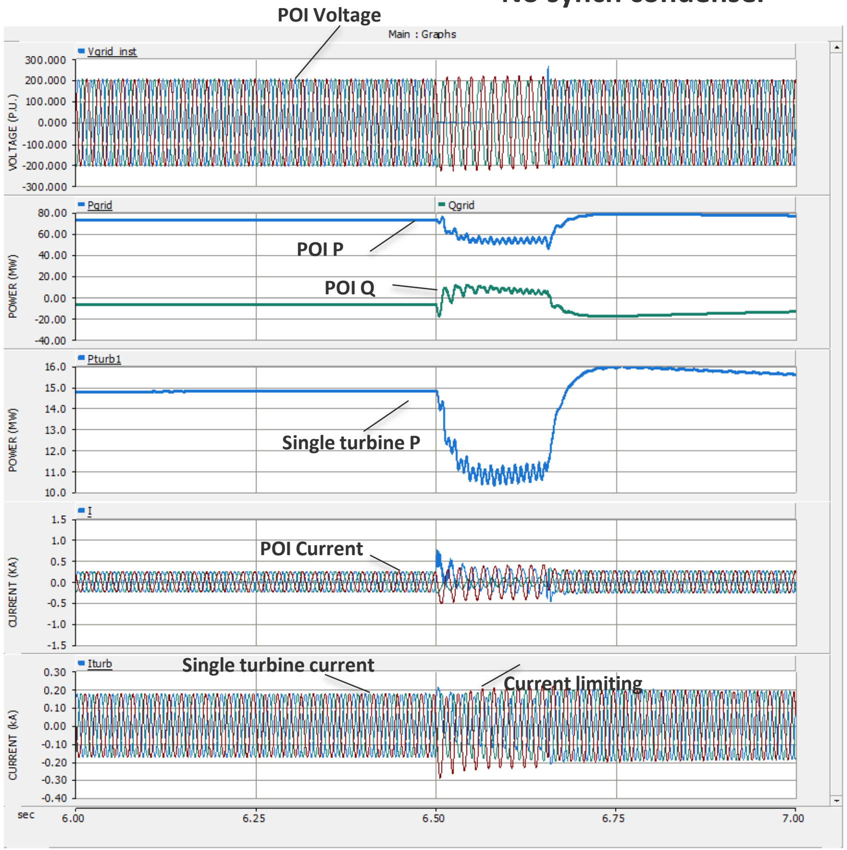
Offshore GFM WPP – islanded operation



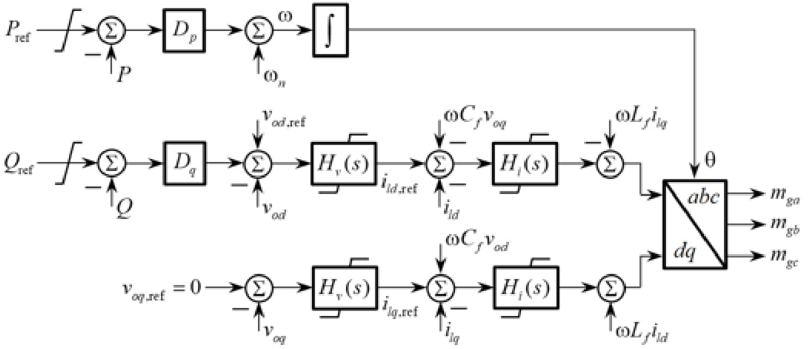
GFM WPP LVRT

SCR=3

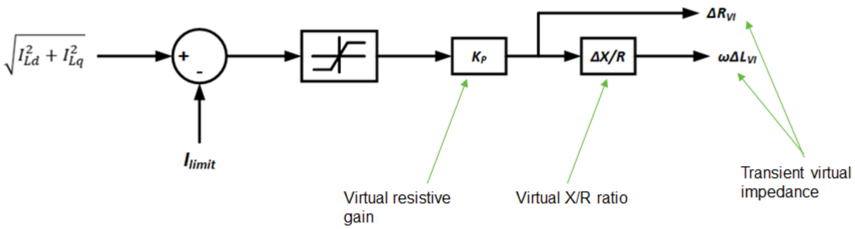
1-phase fault
No synch condenser



Direct current control method

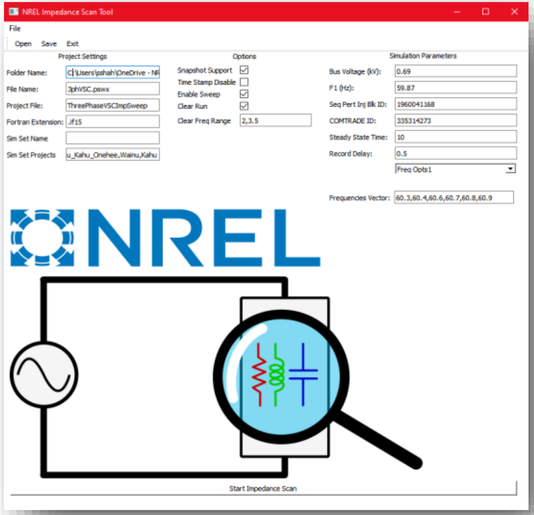


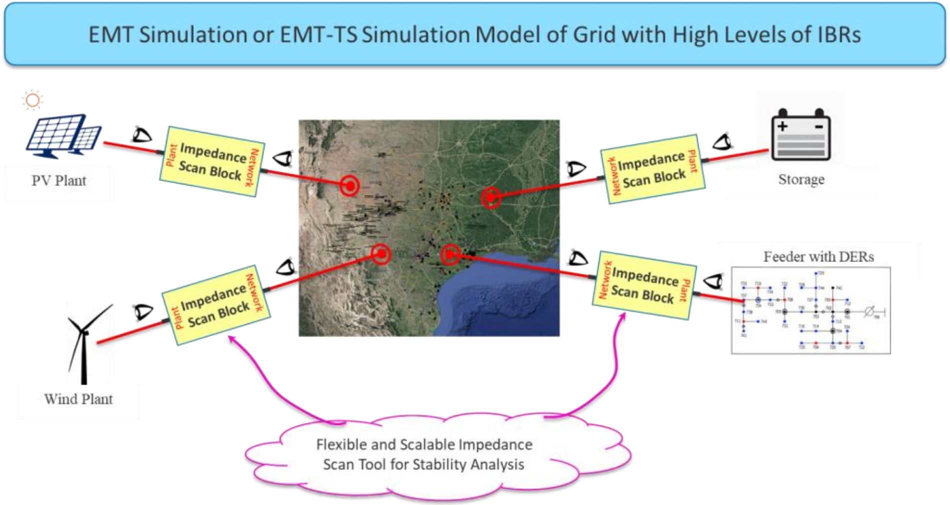
Virtual impedance current limiting method



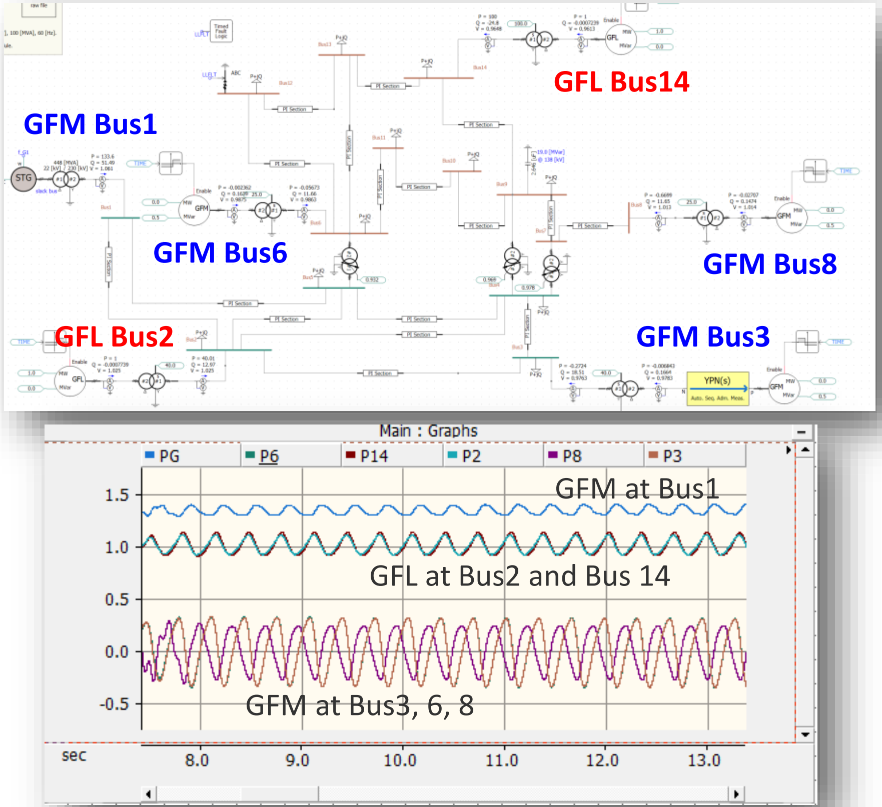
NREL's Impedance Scan Tool

- Evaluates Impact of IBRs on System Stability, Control Interactions, and Oscillations
- Works with all IBR models – black-box user-defined, real code, and generic EMT models





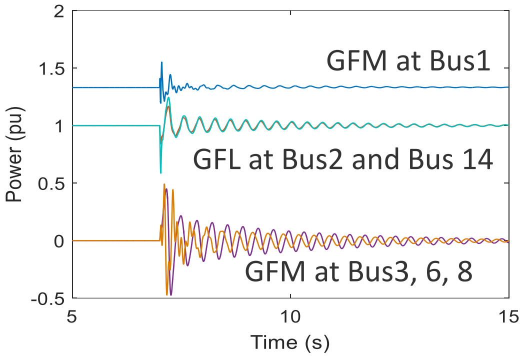
14-bus System with 6 IBRs (4 GFM and 2 GFL)



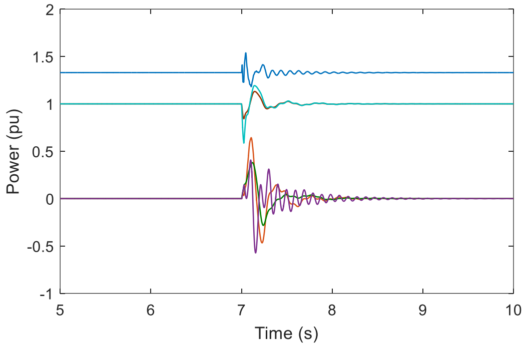
- In this example all IBRs oscillate at 3.2 Hz following a fault event
  - What is the role of GFL vs GFM IBRs in system-wide 3.2 Hz oscillations?
  - How to define the minimum capacity of GFM resources required in a 100% IBR grid to ensure stable operation without oscillations?

Capacity of GFM IBRs Required for Stability

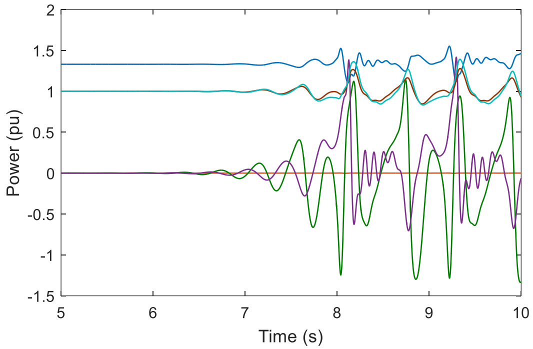
Original Design of GFM IBR3



Improved GFM Control at IBR3 (higher voltage control bandwidth)



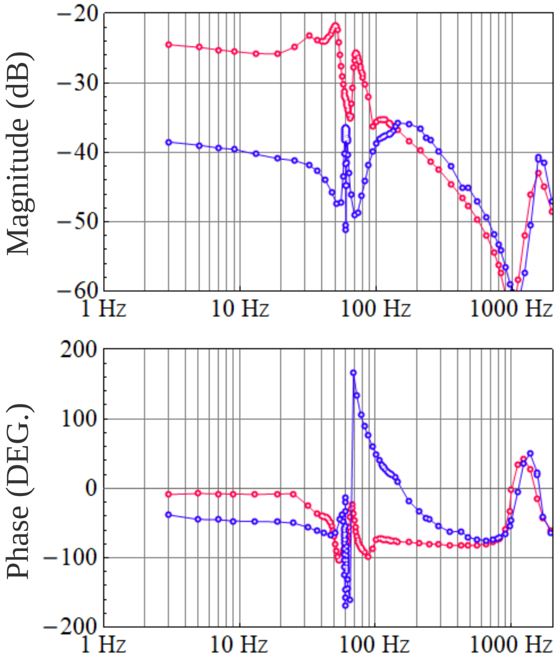
IBR3 Mode Changed to GFL



- NREL's impedance scan tool shows not only how any selected IBR impacts dynamic stability of the system, but it also shows the impact of control modes (e.g., GFM vs GFL) and control parameters of IBRs and guides the control design process to mitigate stability problems.

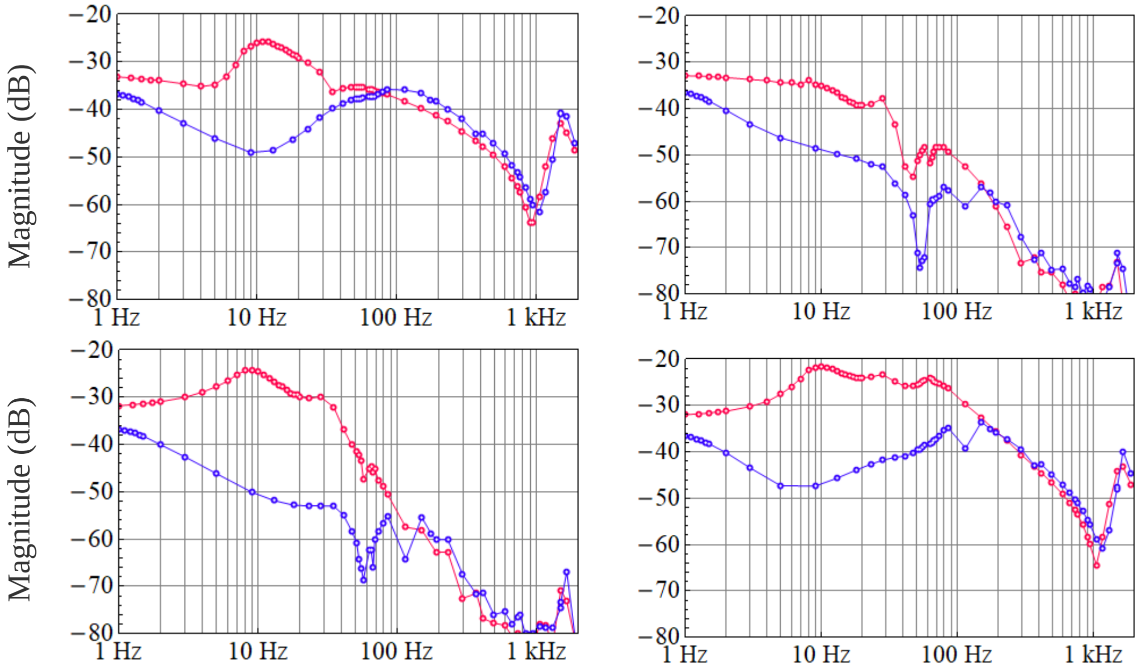
Impedance Scan of a 2 MW Inverter

$Y_p(s)$: +ve Seq. Admittance



GFL Mode

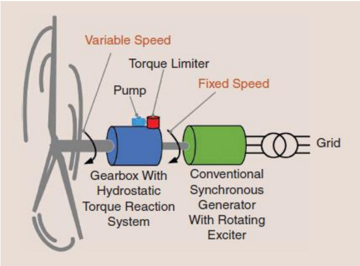
$\mathbf{Y}_{PN}(s)$: Sequence Admittance Matrix



GFM Mode

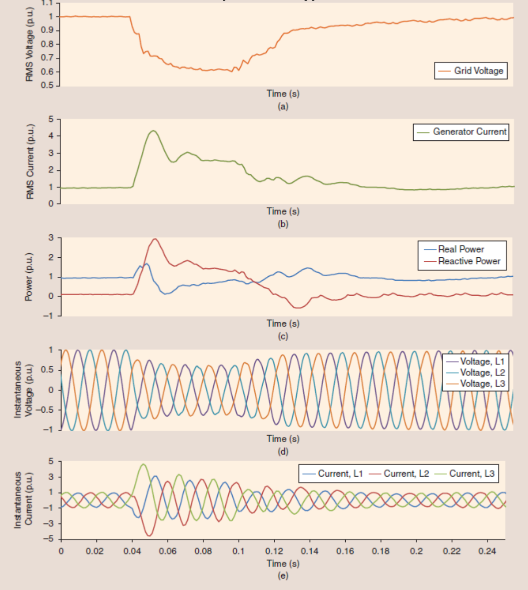
Synchronous Wind Concept

Type 5 wind turbine with Torque Limiter



- WETO-funded project
- Evaluate system level benefits of Type-5 wind

Measured Fault Response of Type 5 Wind Power Plant



A Comparison of Advantages fore 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 permanent magnet generators	Mass produced, global maintenance network and workforce exists, no dependence 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, G Henderson - IEEE Electrification Magazine, 2022

Summary and Future Plans

- GFM technology for IBRs is gaining traction in the energy industry as the grid continues to evolve with increasing shares of IBRs and retiring conventional generators. GFM control by IBRs can replace some of the services that synchronous generators have been providing.
- Mainstream wind power based on Type-3 and Type-4 electric topologies, as an IBR technology, is fully capable of providing GFM services
- GFM resources are fast acting
  - In most cases they improve small-signal stability, avoid control interactions and oscillations, and enable stable operation of grids with high as well as low penetration of IBRs
  - They bring additional value for frequency and voltage control for high IBR grids – GFM control does not significantly add value to frequency/voltage control for low IBR grids.
- Value of GFM increases with penetration of IBRs – industry needs to take long-term view to avoid substantial cost in future of not promoting GFM control for IBRs
- **Large-scale field demonstration** of GFM operation is needed
- Standardization

Thanks you

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