Grid-Forming Type 3 Wind Turbine – Design Considerations and Prototype Demonstration Results

Dustin Howard
GE Energy Consulting

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Summary

- Overview of Grid-Forming (GFM) capabilities of Wind Turbines
- NREL Testbench Description for 2.5MW Type III Wind Turbine
- Response of GFM WTG to Phase Jumps
- Response of GFM WTG to ROCOF
- Response of GFM WTG to LVRT
- Next Steps & Conclusions

GFM Capabilities of Wind Turbines

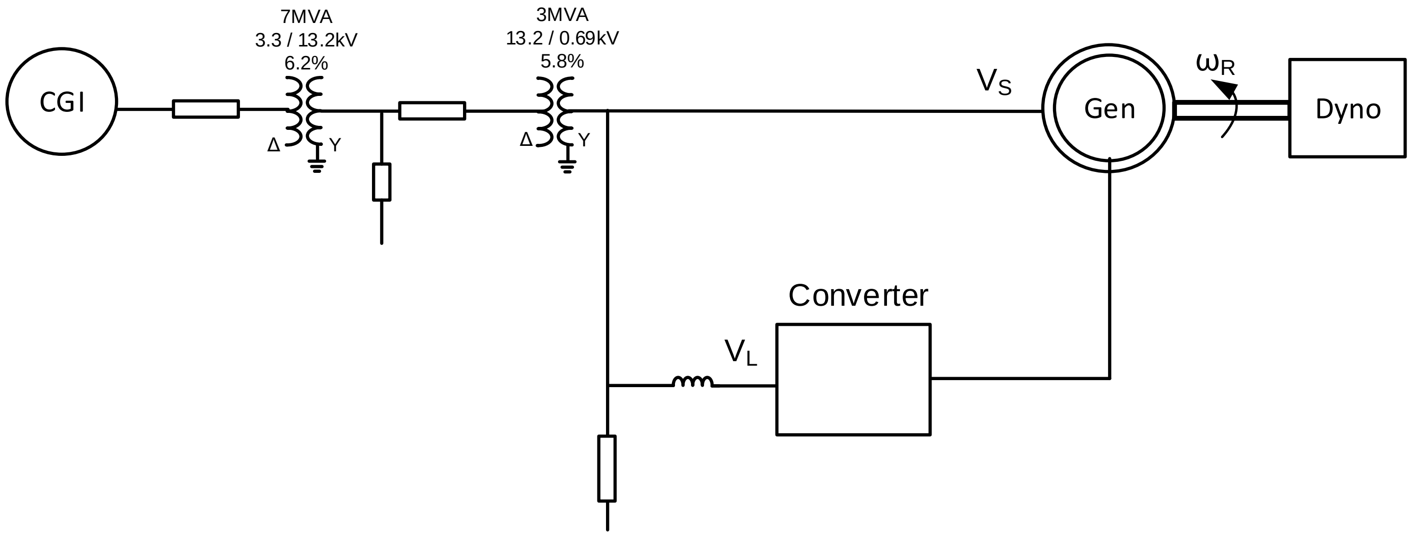
- Grid-Forming Capability – what can wind turbines do?

		Grid Following (GFL) Wind Turbine	Grid Forming (GFM) Wind Turbine	Grid Forming (GFM) Wind Turbine + BOP Battery/Diesel Generator/WTG Energy Storage
Core GFM	Voltage Source behind X Characteristic	No	Yes	Yes
	Phase Jump/Synchronizing Power	No	Yes	Yes
	Inertial Power	"Pseudo" Inertia Capability	Yes	Yes
	Frequency Droop	Yes	Yes	Yes
Advanced GFM	Blackstart	No	No	Yes
	Standalone power source (SCR = 0)	No	No	Yes

- Core grid-forming performance aspects may be achievable with minimal/no hardware upgrades
- Important implications for **existing fleet** of wind turbines + keeping costs low for **new installations**
- Test campaign assessing "off the shelf" WTG grid-forming capability without extra equipment

GFM Type 3 WTG Prototype Demonstration

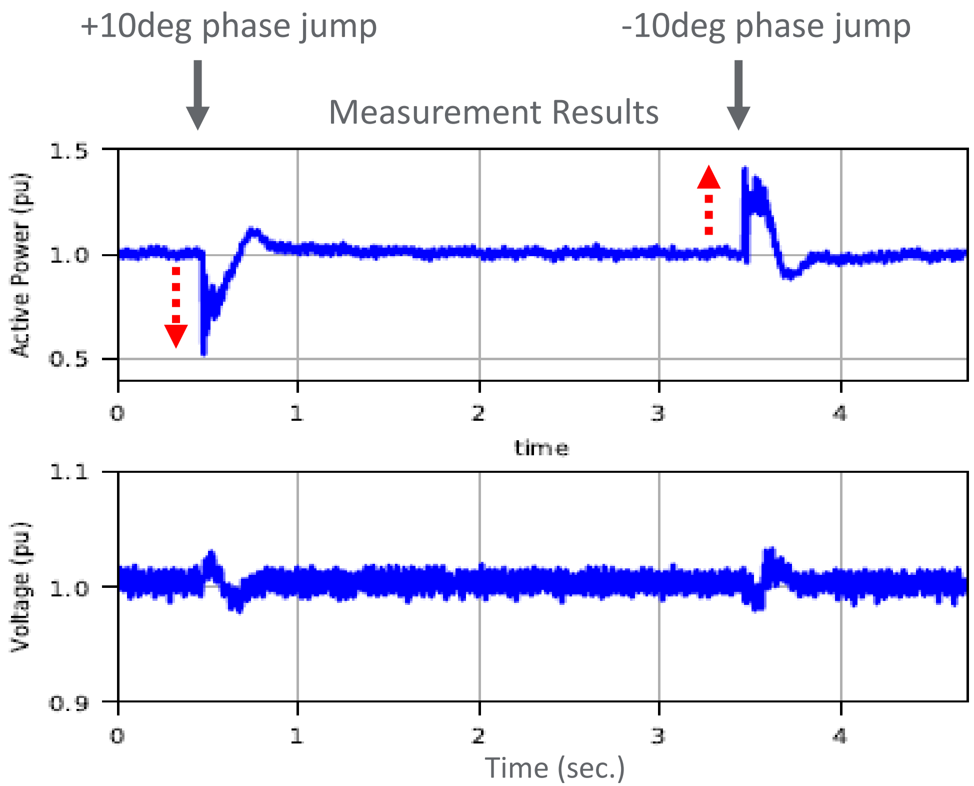
- Type 3 Grid-Forming WTG Test Bench at NREL
  - AC Voltage created by CGI
  - Dynamometer regulating speed
  - Tests evaluated include grid frequency/phase changes, LVRT, HVRT
- 2.5MW "off the shelf" Type 3 WTG hardware
  - Converter controls developed over ~2 years to incorporate grid-forming algorithms that coordinate with limitations of the hardware



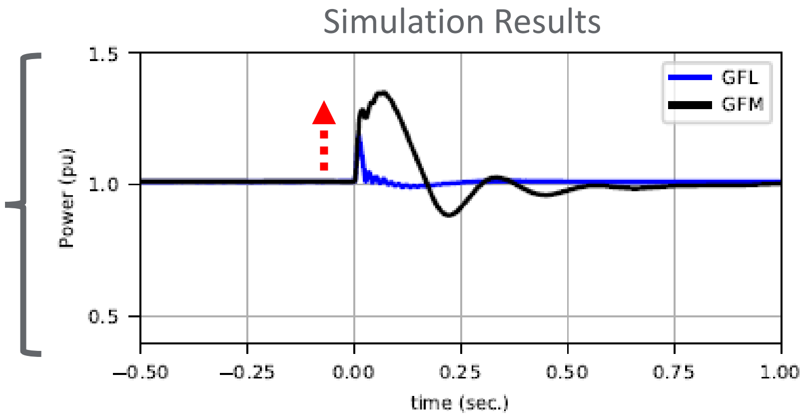
Lab environment with fully controllable voltage source conducive to testing WTG response severe grid events that are impractical to test in field

Phase Jump Response of GFM Type 3 WTG

- Phase Jump Response
  - Controls designed to oppose changes in grid phase angle similar to a synchronous generator while also:
    - Avoiding equipment overloads (electrical and mechanical)
    - Avoiding trips
  - Phase jump power varies based on
    - Initial conditions
    - Phase jump magnitude
  - Response may be asymmetric for +/- phase jumps based on initial conditions



Phase Jump Response Comparison b/w GFL and GFM

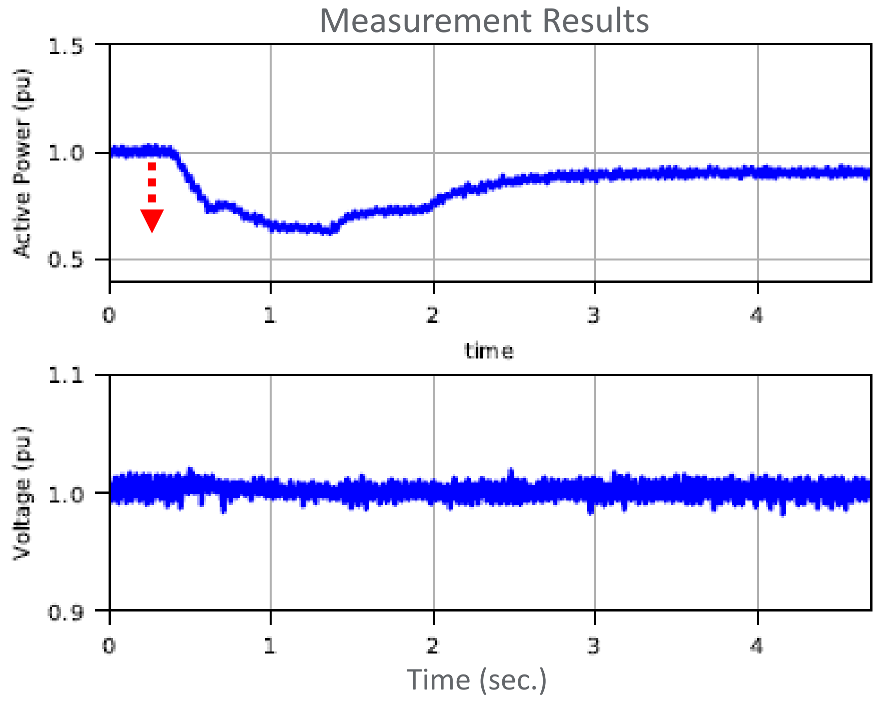


ROCOF Response of GFM Type 3 WTG

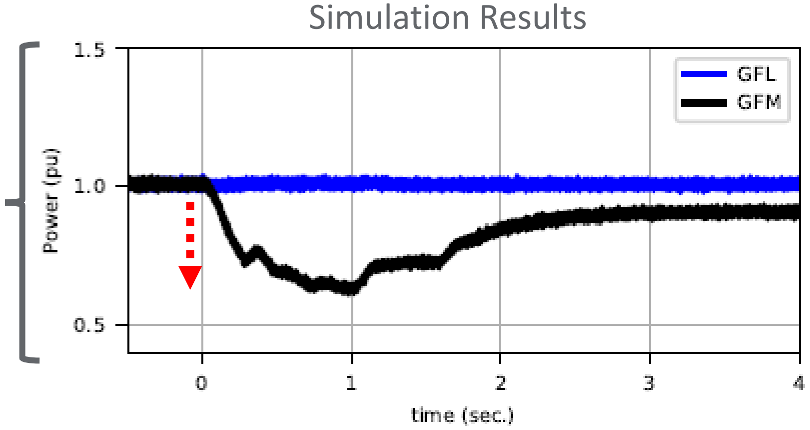
- ROCOF Response
  - Controls designed to provide inertial power response like a synchronous generator
    - Amount of power change depends on rate of frequency change & frequency deviation
  - Controls also designed to avoid equipment overloads (electrical and mechanical) and trips
  - Significant variation in “inertial power” capability with:
    - Operating speed limitations
    - Stored energy related to rotor speed^2
    - Energy input based on wind conditions
    - Proximity to equipment limits relative to initial conditions

Phase Jump and ROCOF response demonstrates key performance aspects of synchronous machines that increase system inertia and improve grid strength, but subject to complex equipment limiting aspects

+1Hz/sec ROCOF
From 60 to 61Hz



ROCOF Response Comparison b/w GFL and GFM

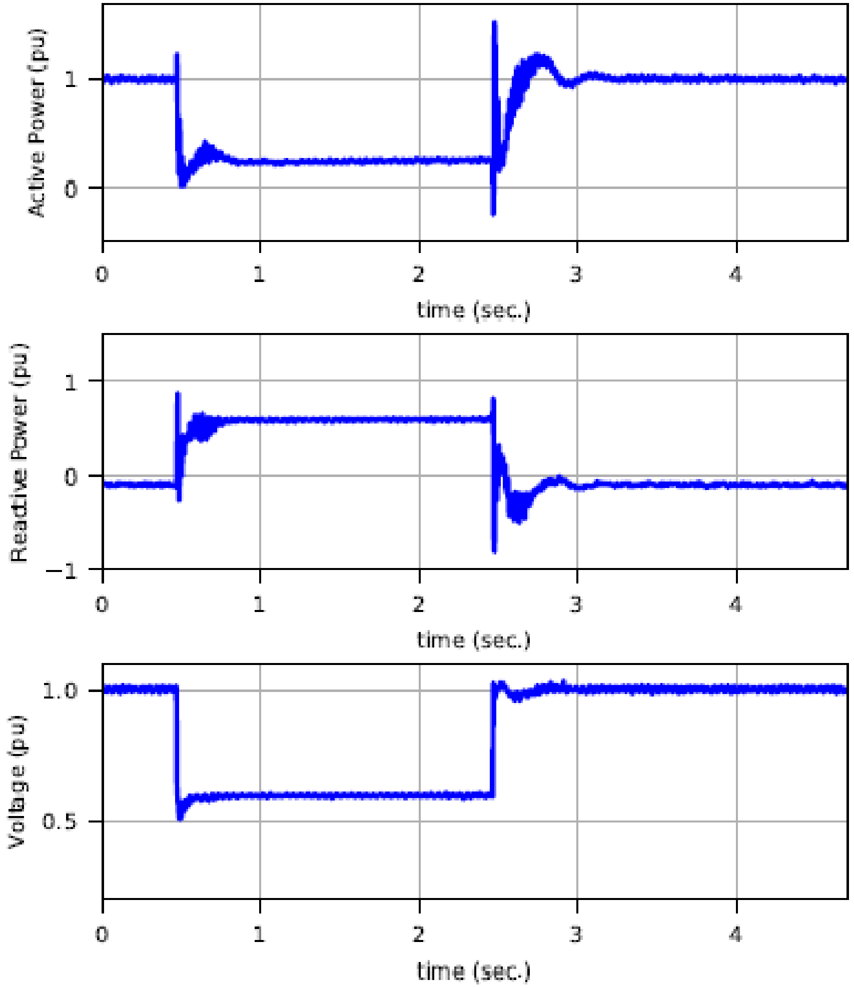


LVRT Response of GFM Type 3 WTG

- LVRT Response
  - Voltage source characteristic of system supports grid voltage during faults
    - Current limits of system still enforced by controls
  - Mode switching from is GFM to GFL is avoided to reduce risk of mode “toggling” – No mode switching
  - Active/Reactive current injection based on impedances of system, fault impedance, and residual voltage level (similar to synchronous machine, but subject to current limits)

LVRT capabilities similar between GFM and GFL systems, but current dynamics during and after fault may be quite different due to different control designs

Measurement Results



Next Steps and Conclusions

Next Steps

- Ongoing research into evaluating GFM impacts to mechanical controls and drivetrain components
- Full turbine prototype tests planned for 2022/23

Conclusions

- Tremendous capability with wind resources to mitigate key risks with energy transition – reducing system inertia and weakening grid
- Important considerations for grid-forming performance based on equipment (electrical + mechanical) limitations and initial operating conditions
- Grid requirements should consider both existing resource capabilities/hardware together with new resources so as to not limit access to markets
- Higher levels of grid forming penetration can likely be achieved faster with Core GFM capabilities