Grid-Forming Capability and Design Considerations for Wind Turbines

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Summary

- Overview of Grid-Forming (GFM) Capabilities of Wind Turbines
- Grid-Strengthening Capabilities: GFM Wind vs. Sync. Generators
- Inertial Response Capabilities for GFM Wind
- Important Design Tradeoffs
- Island Operation Scenarios and WTG Technology Capability
- 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	Strengthens Grid	No	Yes	Yes
	Inertial Power Response	"Pseudo" Inertia Capability	Yes	Yes
	Frequency Droop	Yes	Yes	Yes
Advanced GFM	Blackstart	No	No	Yes
	Standalone power source (SCR = 0)	No	No	Yes

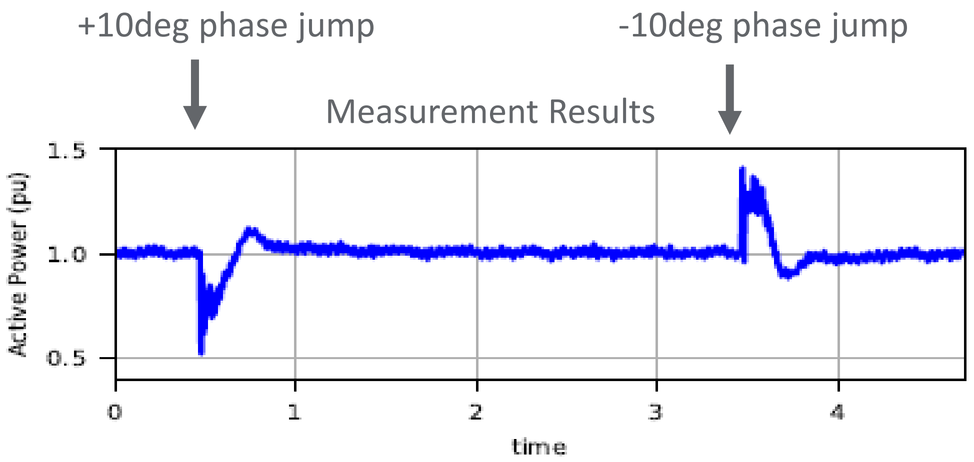
- Core grid-forming performance aspects may be achievable with minimal/no hardware upgrades, but significant time/resource investment required to coordinate algorithms with hardware limitations
- Important implications for **existing fleet** of wind turbines + keeping costs low for **new installations**

Grid-Strengthening Capabilities: GFM Wind vs. Sync. Gen

- Grid-Forming wind designed to behave as voltage source behind reactance around fundamental frequency
  - Effectively has a grid-strengthening impact compared to GFL for small variations in grid voltage
  - Impedance characteristic may be ‘tunable’ to an extent, but with tradeoffs
  - Significant variation in ‘grid-strengthening’ capabilities with initial conditions, equipment limits, and severity of disturbances
  - Some short-term overload capability

Grid-Strengthening Aspect	Grid Forming (GFM) Wind Turbine with Core Capabilities	Sync. Generator
Steady-State Voltage Source behind X Characteristic	Yes	Yes
Phase Jump/Synchronizing Power	Yes, subject to strict equip. limits	Yes
Max. Short-Circuit Current Contribution	~1.1 pu Type 4, ~1.1 – 2.0 pu Type 3	> 4pu
Reduces likelihood of IBR control interactions	Yes, for small-signal interactions	Yes

Example Phase Jump Power Contribution from Type 3 GFM WTG



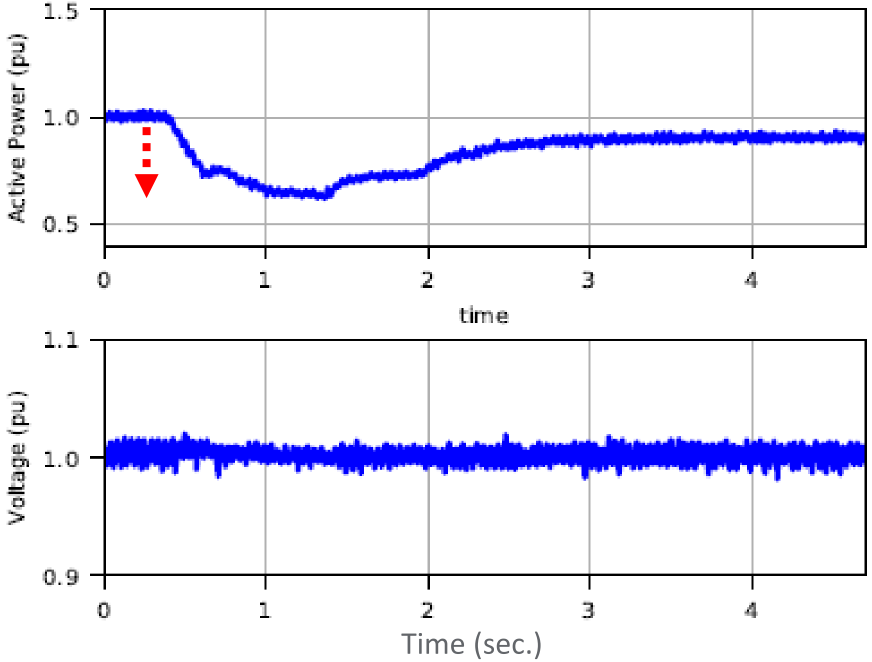
Inertial Response Capabilities of GFM Wind

- 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

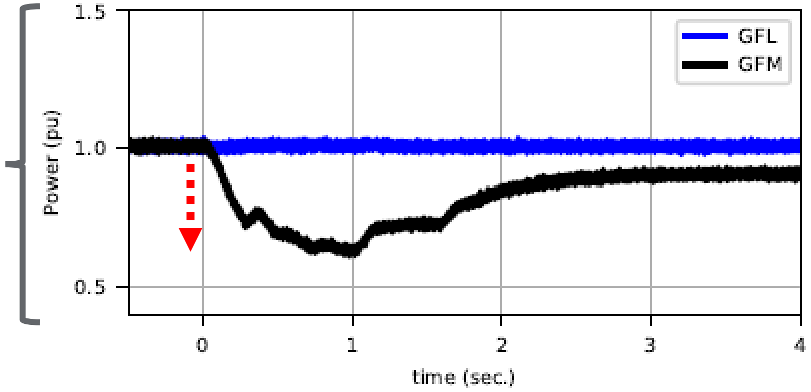
+1Hz/sec ROCOF
From 60 to 61Hz

Measurement Results



Simulation Results

ROCOF Response Comparison b/w GFL and GFM

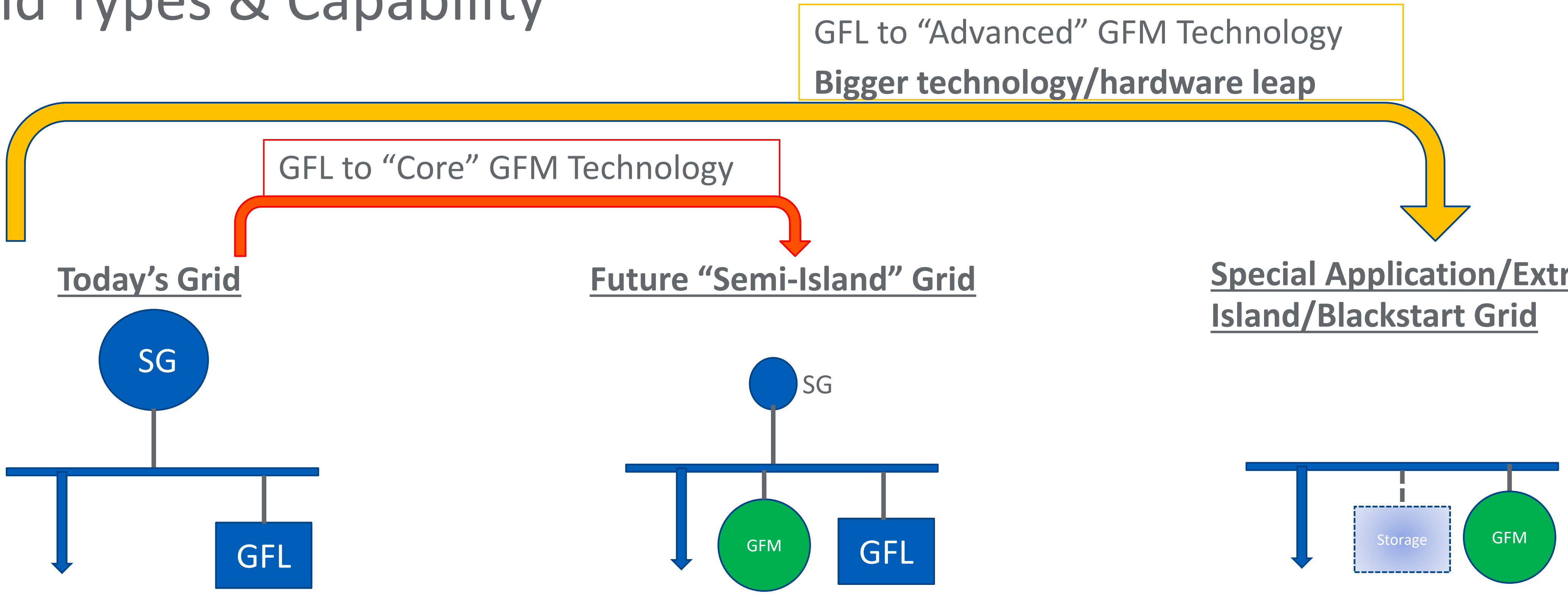


Important Design Tradeoffs with ROCOF/Phase Jump Response

- GFM Resources Designed with Higher Virtual Inertia helps reduce Grid ROCOF
  - Tradeoff is higher likelihood of hitting equipment limits during ROCOF event
- GFM Resources Designed with Lower Impedance helps improve grid strength
  - Tradeoff is higher likelihood of hitting equipment limits for phase jumps
  - ‘Virtual’ impedances may be useful for maximizing grid support
- Good design tradeoff may be low impedance/high inertia designs that avoid equipment limits for small to medium ROCOF/Phase jump events, with response to severe events focused on avoiding abrupt mode changes as equipment limits are approached

Performance requirements for **severe** ROCOF/Phase Jump events should avoid unintentionally encouraging low inertia and/or high impedance designs

Island Types & Capability



GFL to “Advanced” GFM Technology

Bigger technology/hardware leap

GFL to “Core” GFM Technology

Today’s Grid

- High Penetration of Sync. Generation
- High Inertia, Low Impedance (SCR > 2)
- GFL Power Generation Compensated by Dispatchable Sync. Machines

Future “Semi-Island” Grid

- Few Sync. Generators, Some GFM IBR, large amounts of GFL IBR
- Periods of operation with Low Inertia, High Impedance (0.5 < SCR < 2)
- GFM Power Generation participates in Gen/Load Balance, with periods of load-constrained generation

Special Application/Extreme Island/Blackstart Grid

- Zero Inertia, Zero SCR
- Power generation dictated by loads only
- Significant variation in application-specific requirements

Requirements dictating most extreme versions of GFM island capability may slow down energy transition

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