GE VERNOVA

GRID FORMING IN DFIG-BASED WIND TURBINES

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Agenda

- Wind GFM Prototype Testing
- GFM Response in DFIG Wind Turbines
- Inertial Capability of GFM DFIG
- Conclusions

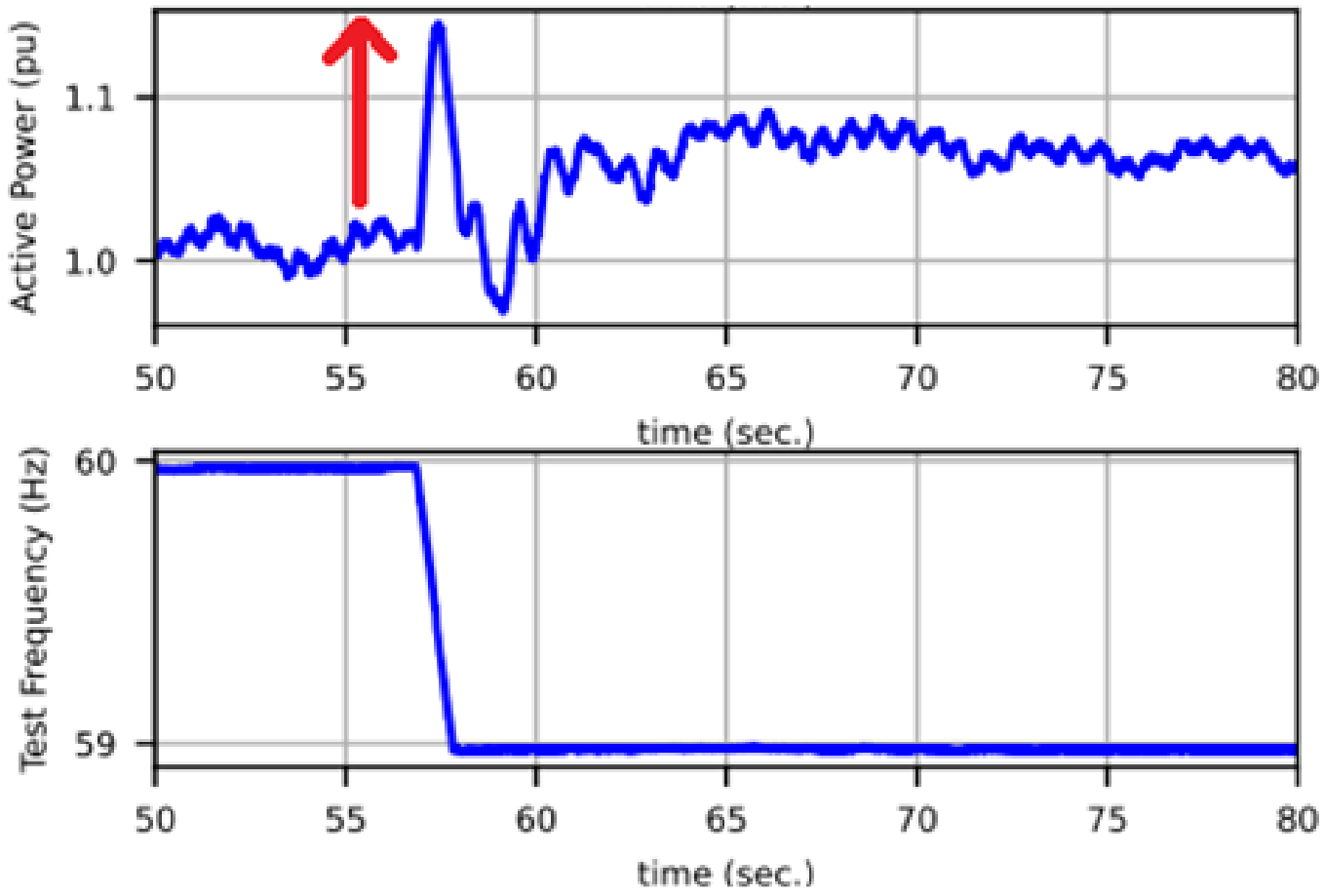
Prototype Tests

- Turbine Prototype (Lubbock, TX, USA)
  - Standard GE 2.8 MW DFIG
  - Prototype GFM Controls
  - Connected to Local Grid
- Preparation Steps (~2-3 years)
  - GFM Control design and careful coordination with equipment/energy limits of particular turbine hardware
  - Rigorous simulation validation on multiple simulation platforms
  - Electrical subsystem testing
  - Regression testing
  - Creation of test plan
  - Review/approval with engineering leadership

2.8MW Prototype Turbine, Lubbock TX, USA

Prototype Results

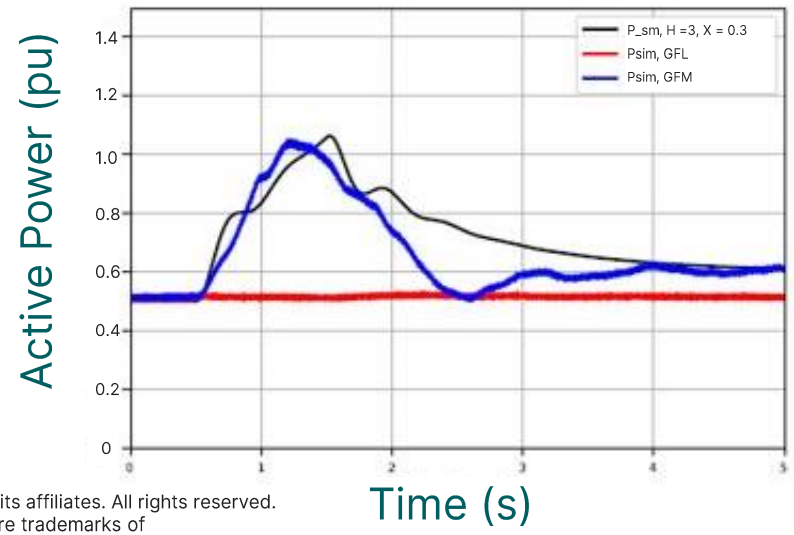
- Turbine Prototype
  - Standard GE 2.8 MW DFIG
  - Prototype GFM Controls
  - Connected to Local Grid
- ROCOF Test
  - WTG Running at Rated Power before ROCOF
  - Immediate Increase in Power to ~1.15 pu due to Inertial Response
  - Power Reverts to Higher than Initial Conditions due to Droop



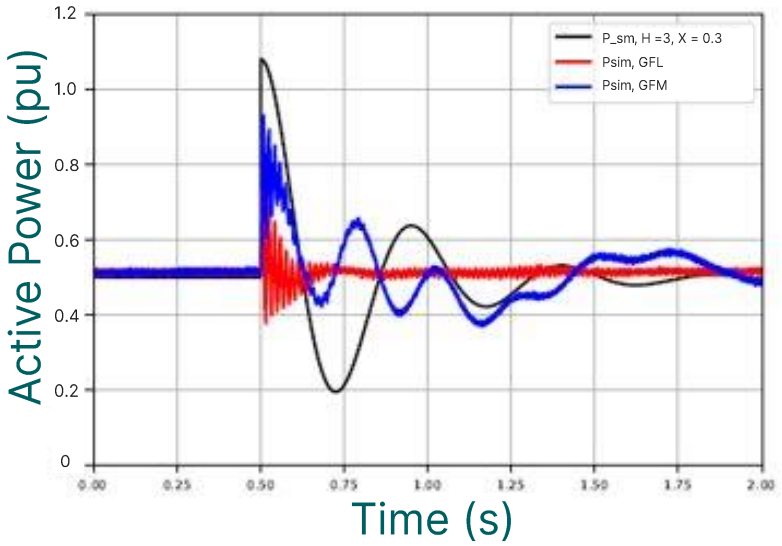
GFM Grid Strengthening

- **Voltage Angle Strengthening:** Maintain positive-sequence phase angle approximately fixed during transient conditions and when equipment limits are not being reached
- **Voltage Magnitude Strengthening:** Maintain positive-sequence voltage amplitude approximately fixed during transient conditions and when equipment limits are not being reached

-1Hz/sec ROCOF to 59Hz

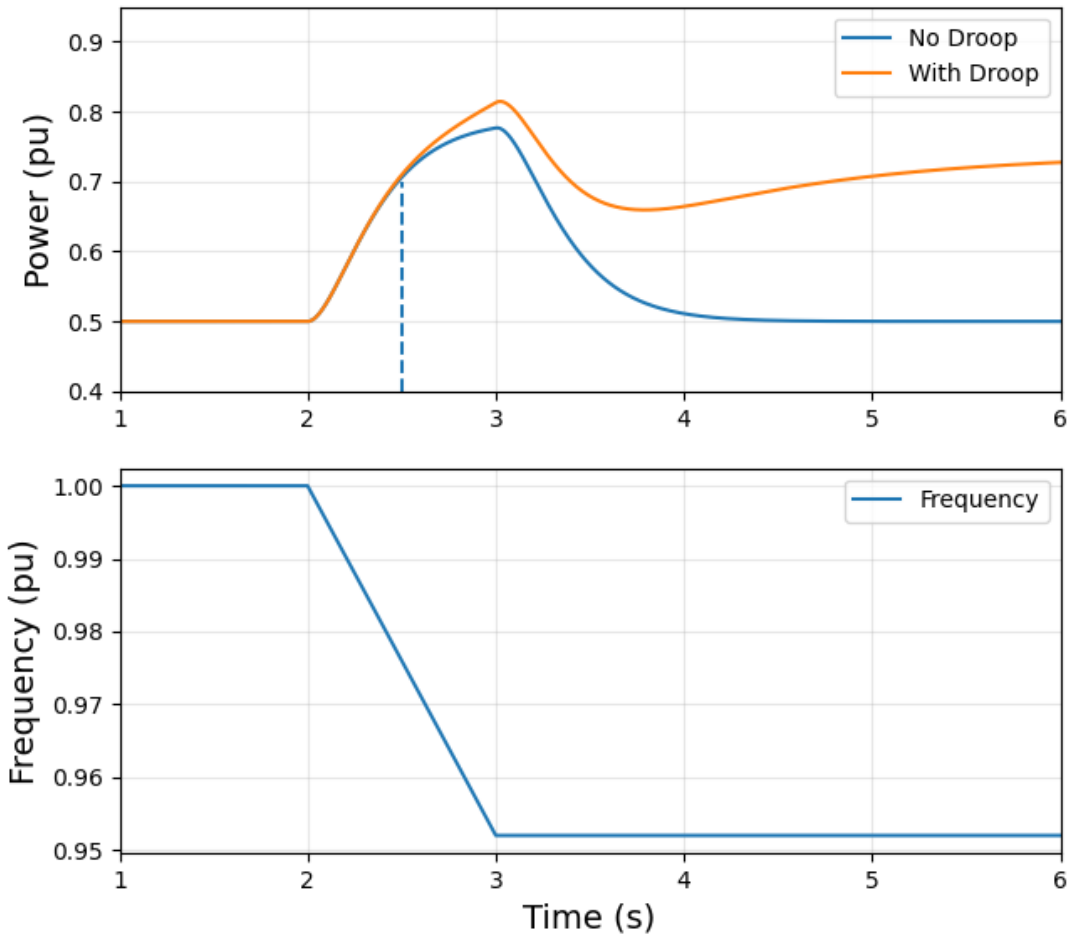


-10deg phase jump

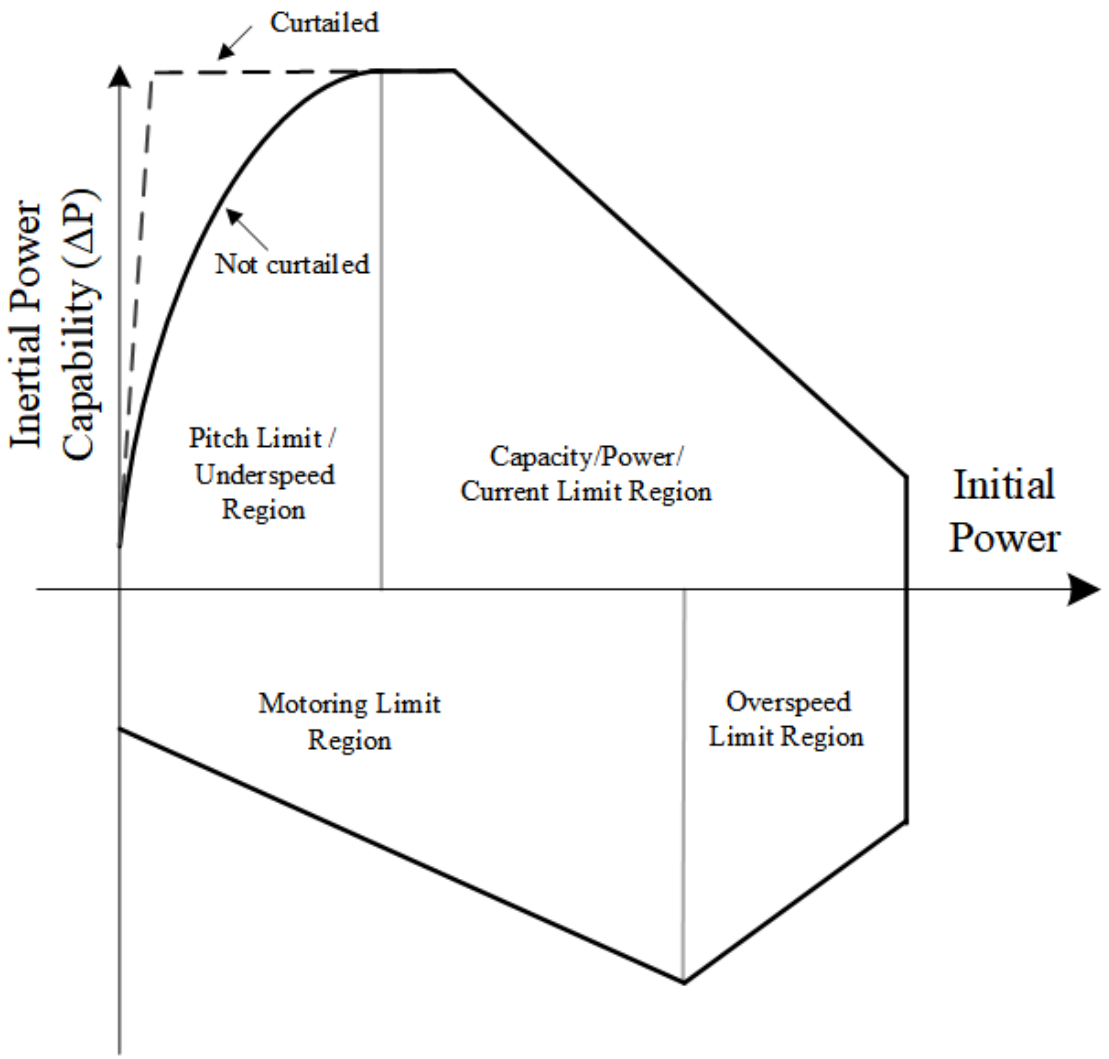


How to Define Inertial Contribution?

- Fast and Slow Dynamics
  - Phase Jump Response
  - Plant Droop, Pitch Blade Angle
- Testbed for Inertial Contribution Limits
  - Apply ±3 Hz/s ROCOF with Strong Grid
  - Measure Inertial Power at 500 ms
  - Keep Applying ROCOF to Determine Limits
- Example of Synchronous Generator With and Without Frequency Droop
  - Frequency Droop Washes out by 500ms



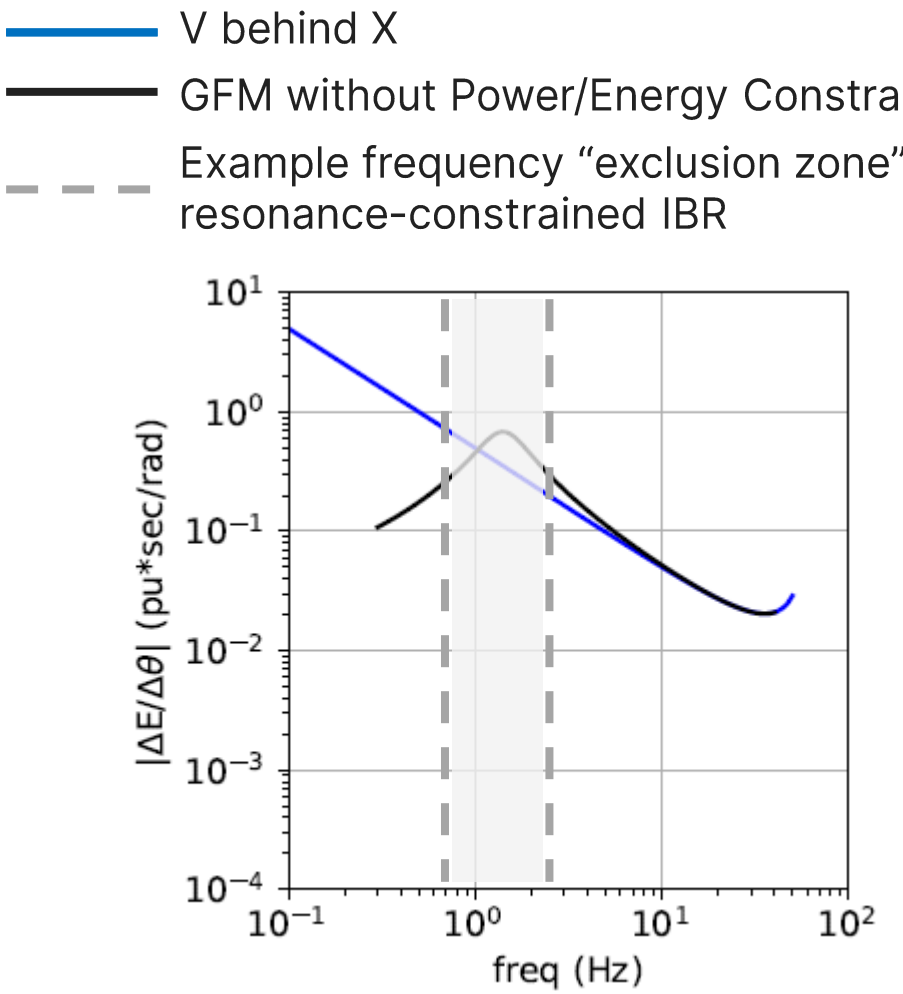
Qualitative Inertial Capability Curve



- Inertial Capability Curve of DFIG
  - Does Not Represent Specific Product or Configuration
- Different Than BESS or Other WTGs
  - E.g. BESS Contributes Maximum Inertia at Zero Initial Power
  - DFIG Doesn't Operate in Sustained Negative Initial Power
- Curtailed vs Not Curtailed Limits
- Capability Limiting Factors
  - Overspeed/underspeed limits,
  - Blade pitch angle response time,
  - Hardware Capacity Limits

Practical Power/Energy Limitations

- DC Energy – Constrained Devices
  - DC storage is negligible in typical IBR
  - Without curtailment or specially designed hardware with additional storage, DC-Energy constrained IBR cannot meet the ΔP/Δθ characteristics of V behind X for dynamics relevant for positive-sequence
  - Example DC – Constrained Devices: solar, statcoms, wind turbines operating in ‘statcom’ mode
- Resonance – Constrained Devices
  - Mechanical systems often have resonances in certain frequency ranges that may require frequency “exclusion zones” to avoid overstimulation of resonance
  - Outside this exclusion zone, IBR may exhibit V behind X characteristics (even without curtailment)
  - Example Resonance-Constrained IBR may include: wind turbines, pumped hydro



Conclusions

- Fault Ride-Thru Performance of GFM Wind Largely Similar to GFL Wind
- Inertial Contribution Needs to be Carefully Defined so it Does Not Exclude Equipment Beneficial for Grid Stability
- Mechanical limitations, in addition to current limitations, should be considered in GFM requirements to avoid making GFM IBR with rotating machines overly expensive