Going the Distance:

Moving AC Power from Large Inverter-Based Generation Pockets to Load Centers

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GridLAB

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Agenda

- Motivation of our Effort
- Theories & Approach to Analysis
- Simulation Results
- Key Findings

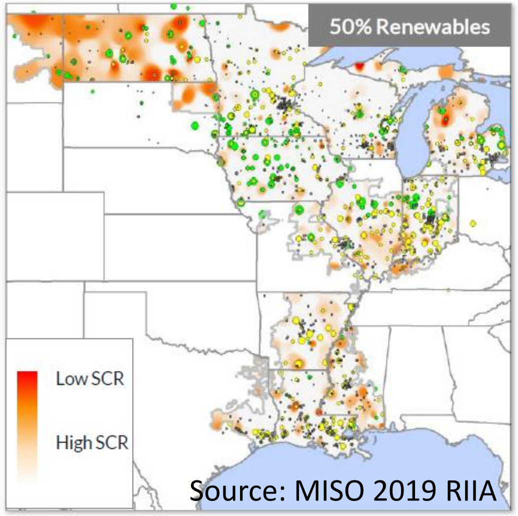
Context

- MISO RIIA's study highlighted many technical challenges for integrating very high-levels of renewables, among those – **grid strength** and **voltage weakness** – even at 30% renewable energy levels

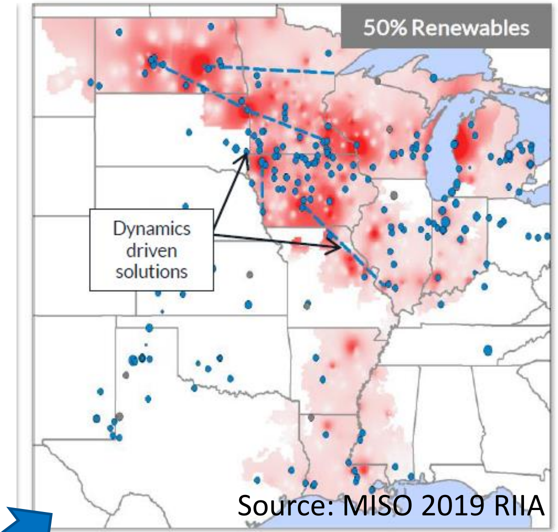
- At 30% energy, there are many times of nearly 100% instantaneous penetration of renewables, and most are inverter-based resources (IBR) like wind and solar

- NREL's GFM Roadmap identifies many challenges, some overlap with RIIA

Grid Strength



Dynamics – Voltage Weakness



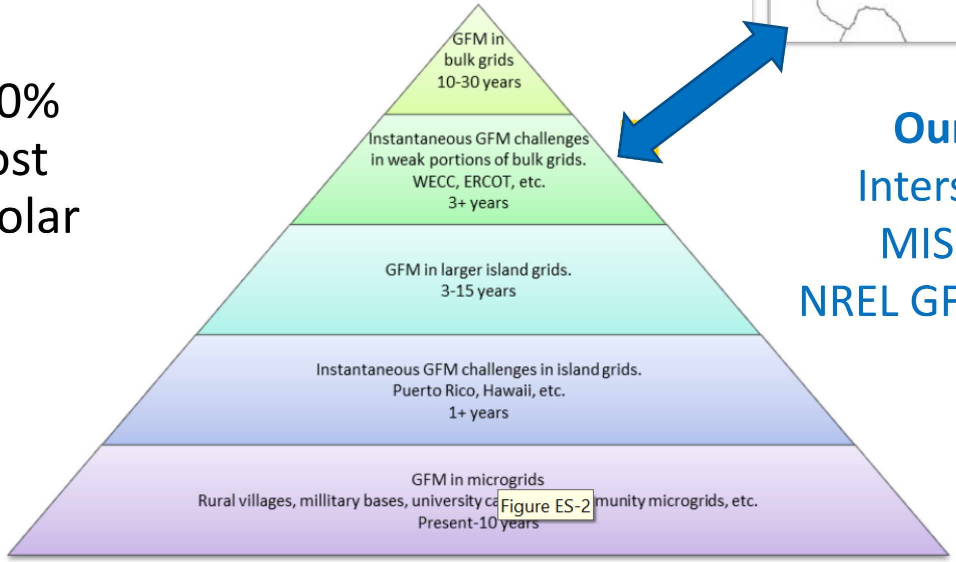


Figure ES-2. (b) Incorporating grid-forming controls into the electric grid will take place gradually after key functionalities have been demonstrated and confidence has been gained by operating them in smaller microgrids and island power systems.

Source: NREL GFM Roadmap, January 2021

Our Focus:
Intersection of
MISO RIIA &
NREL GFM Roadmap

Objective of this Effort

How to export power over long distances from regions with predominantly IBR?

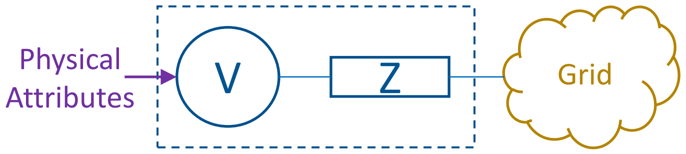
Key Questions:

- *What phenomena limit transfer?*
- *What GFM IBR can (and can't) do to raise limits?*
- *What to look for during (planning) studies?*
- *What tools will best meet the needs (especially, how simple and robust can we make/expect mainstream planning simulations)?*

Brief Technology Overview

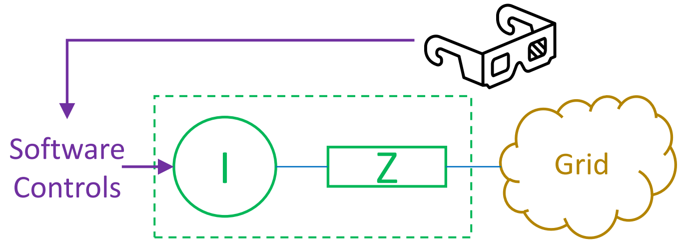
Synchronous Machines (SM)

- Behaves like a voltage source (inherent, physics-defined response)
- Stored energy in rotating mass and magnetic field (relatively small amount – seconds at rated)
- Ability to release energy quickly (3-5x current rating)



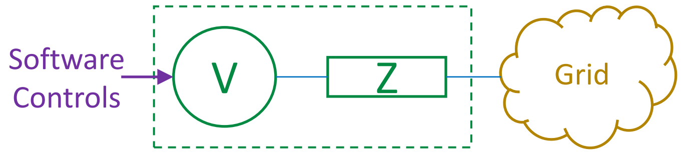
Grid-Following Inverters (GFL)

- Behaves like a current source (sense-then-respond, software-defined response)
- Stored energy varies (cycles at rated for PV, more with wind, hours with battery)
- Limited ability to release energy (1 – 1.5x current rating)

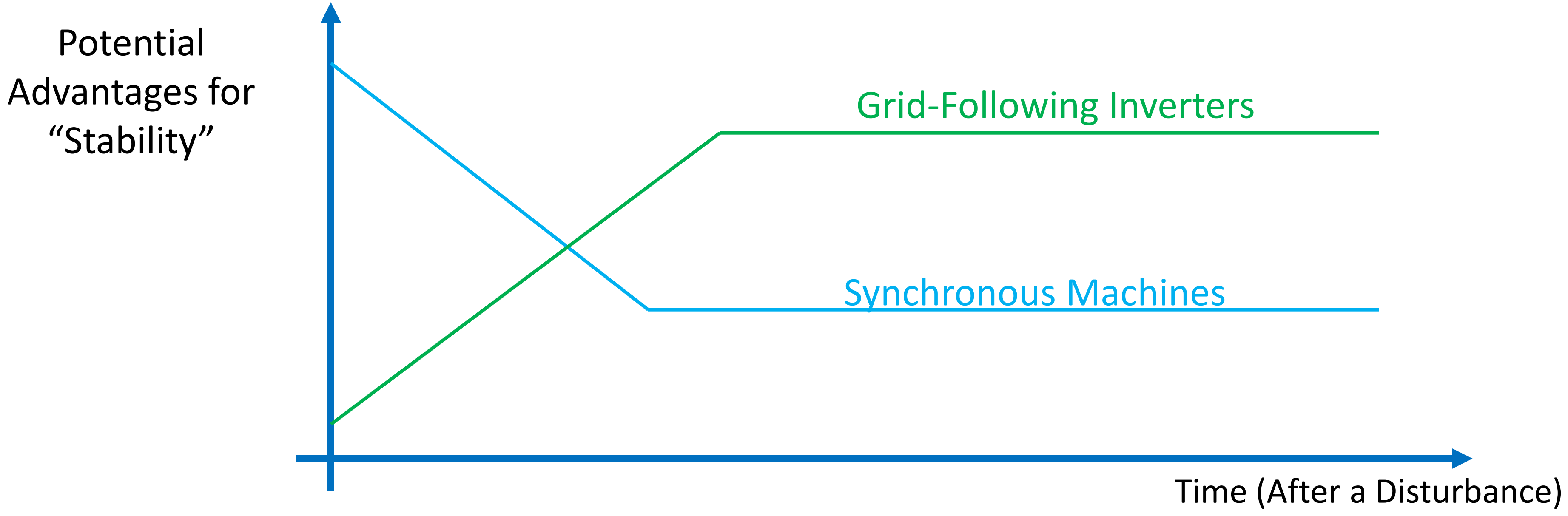


Grid-Forming Inverters (GFM)

- Behaves like a voltage source (inherent-like, software-defined response)
- Stored energy varies (cycles at rated for PV, more with wind, hours with battery)
- Limited ability to release energy (1 – 1.5x current rating)



Our Theory



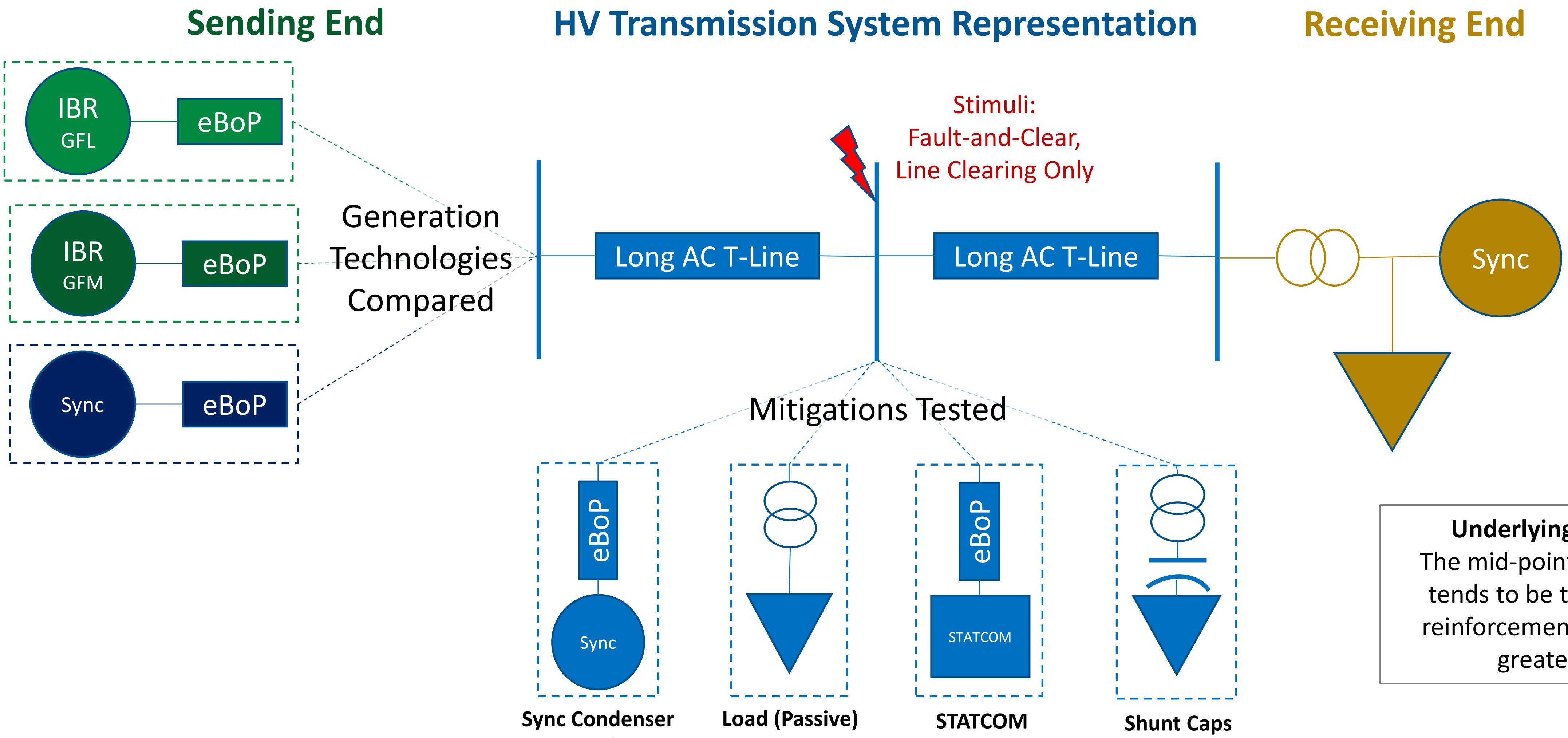
Very short time frames (<~0.1 sec):

- GFL closed-loop controls are challenged to maintain stability margin
- Synchronous machines have an inherent “open-loop” behavior that is stable

Longer time frames (> ~0.1 sec):

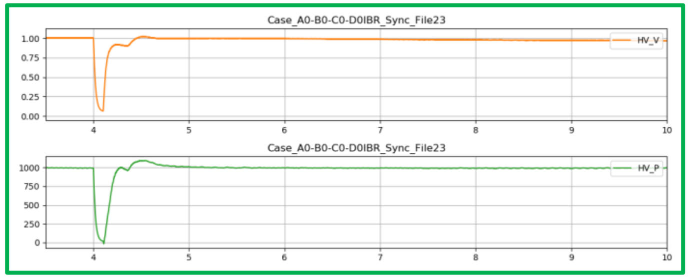
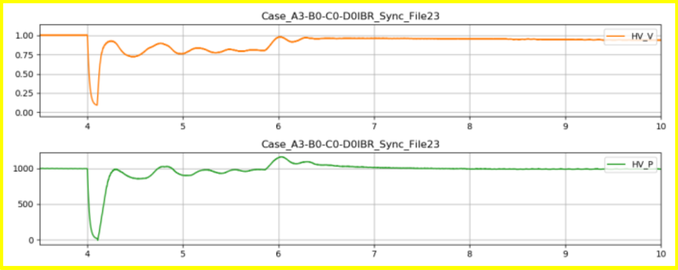
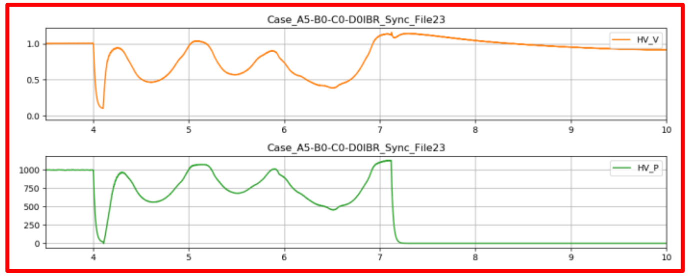
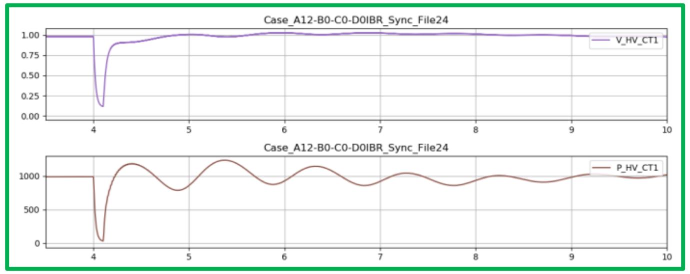
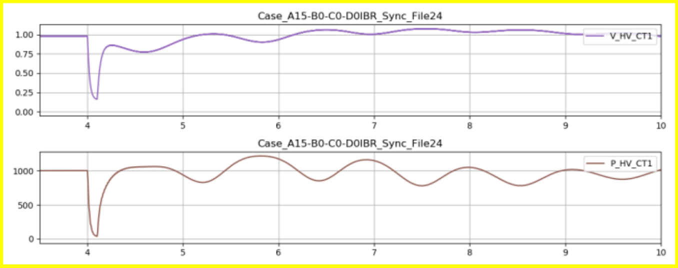
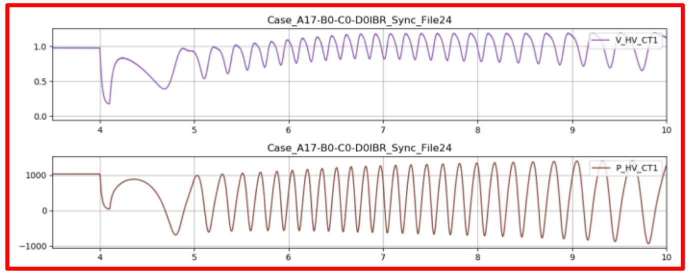
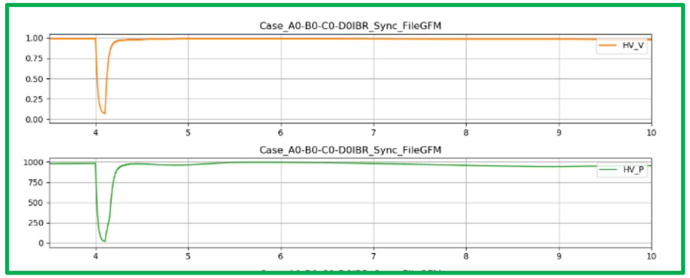
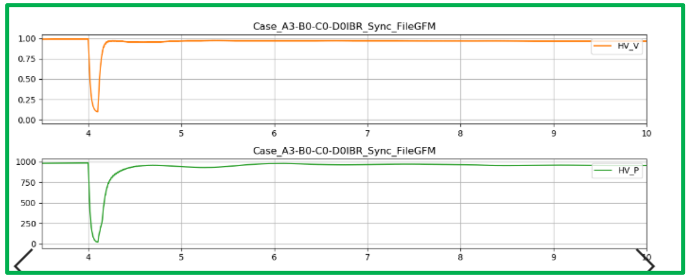
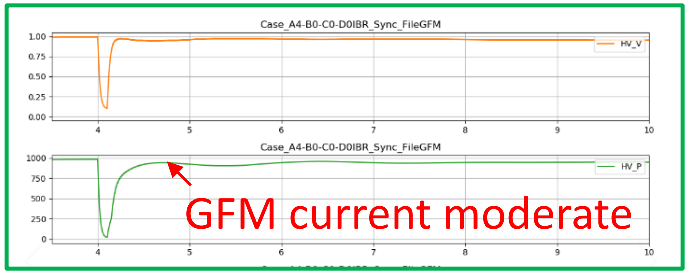
- GFL have developed advanced control strategies that can provide voltage regulation, active power response, transient stability, and damping that are as good or better than synchronous machines
- Synchronous machines may be subject to first-swing instability and may lack damping, some of which can be mitigated (for instance, PSS)

Our Approach



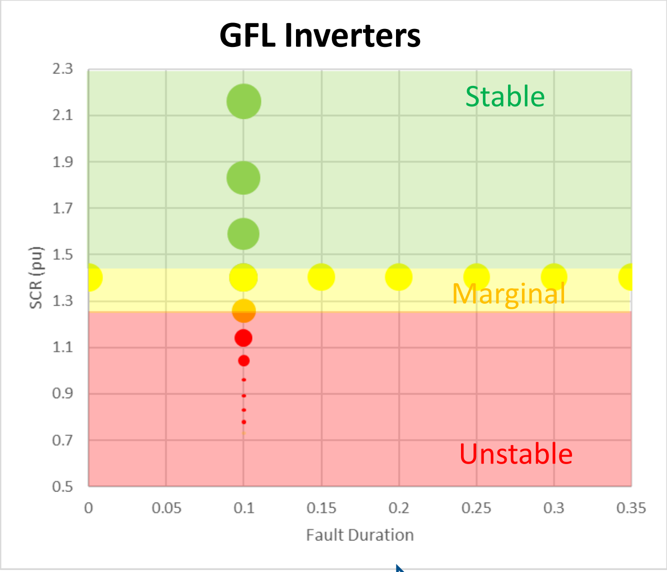
Underlying assumption:
The mid-point of transmission tends to be the "soft" spot – reinforcements here yield the greatest benefit

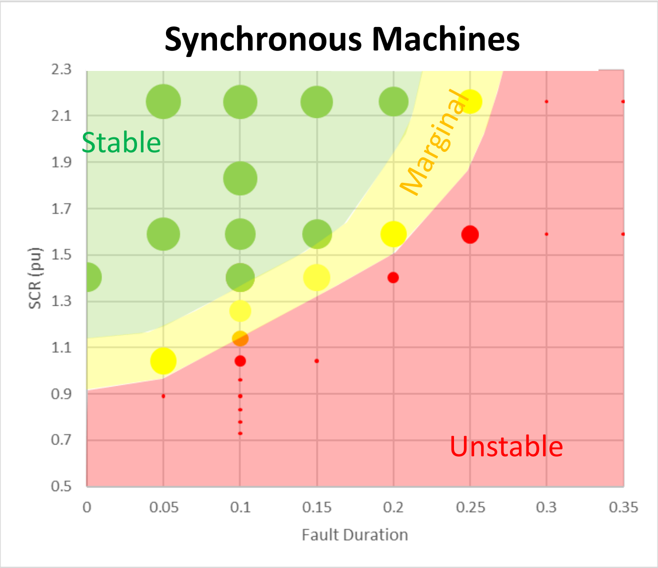
Grid Strength Impact

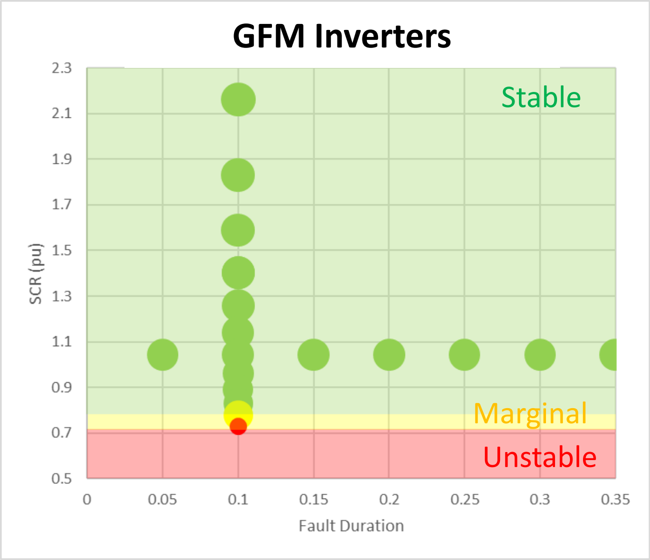
	Soft Grid (SCR = 2.2)	Marginal Grid (SCR = 1.4)	Weak Grid (SCR = 1.1)
GFL-IBR			
Synchronous Generator			
GFM-IBR			

Technology Performance Comparison

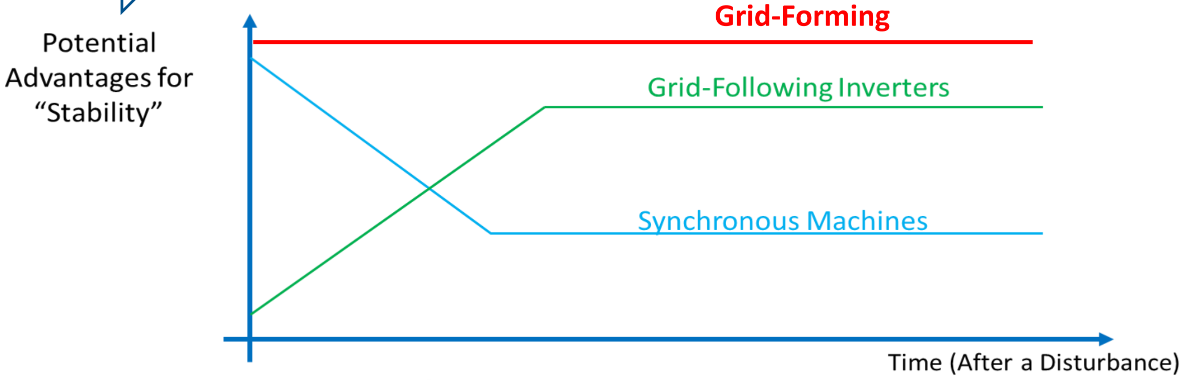
Stronger grid







More severe events



GFM inverters **show promise** for being the "best of both worlds" for grid stability

...many questions remain

A Closer Look at Equipment Responses

Resource Step-Test Responses

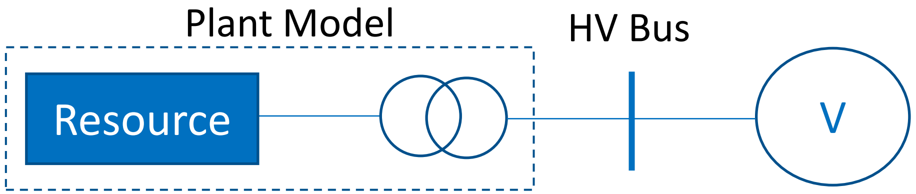
- Each resource is tested independently
- Repeatable stimuli
- Can be applied to exercise different behaviors

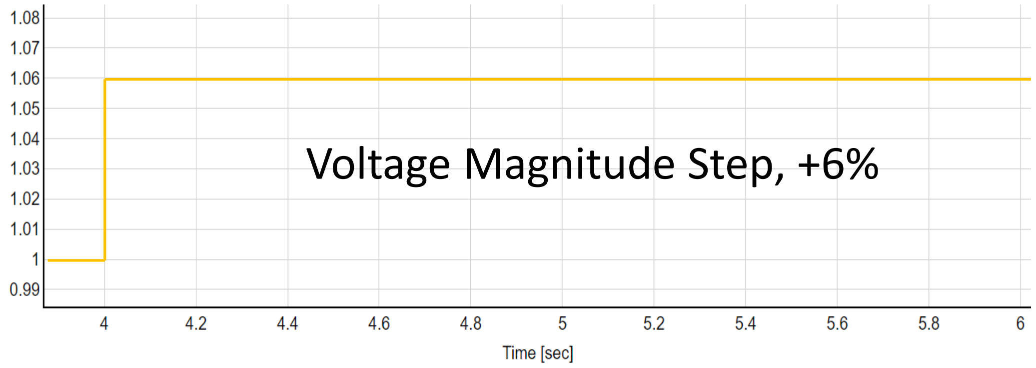
Voltage Magnitude Step

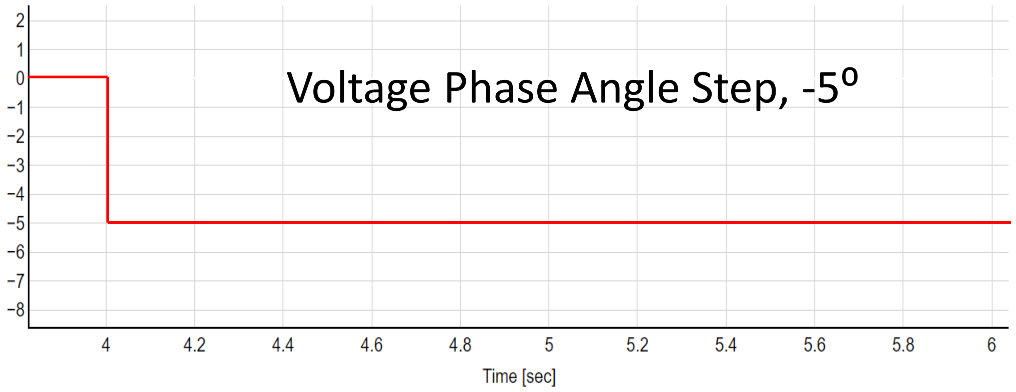
- Intended to exercise the reactive power response
- Small signal stimuli applied

Voltage Phase Angle Step

- Intended to exercise the active power response
- Small signal stimuli applied

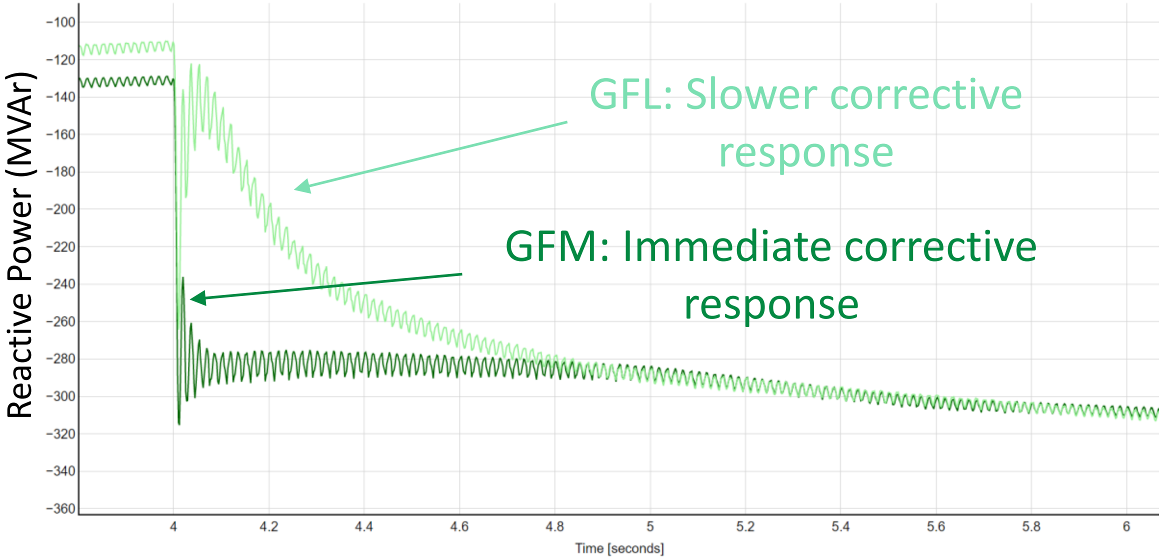




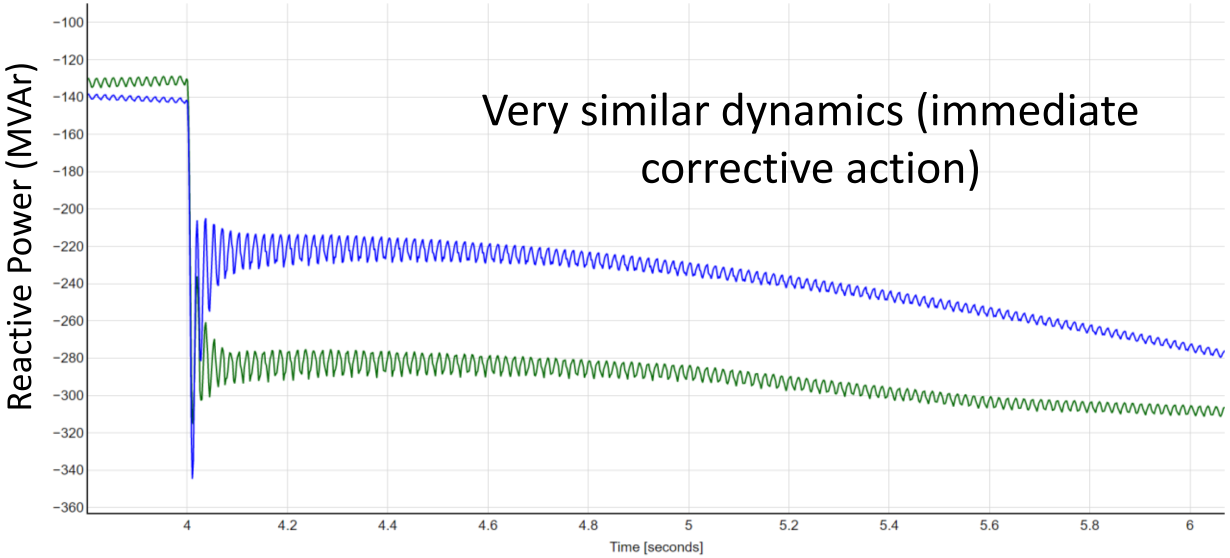


Voltage Magnitude Step Responses

GFM v. GFL Inverters



GFM v. SM

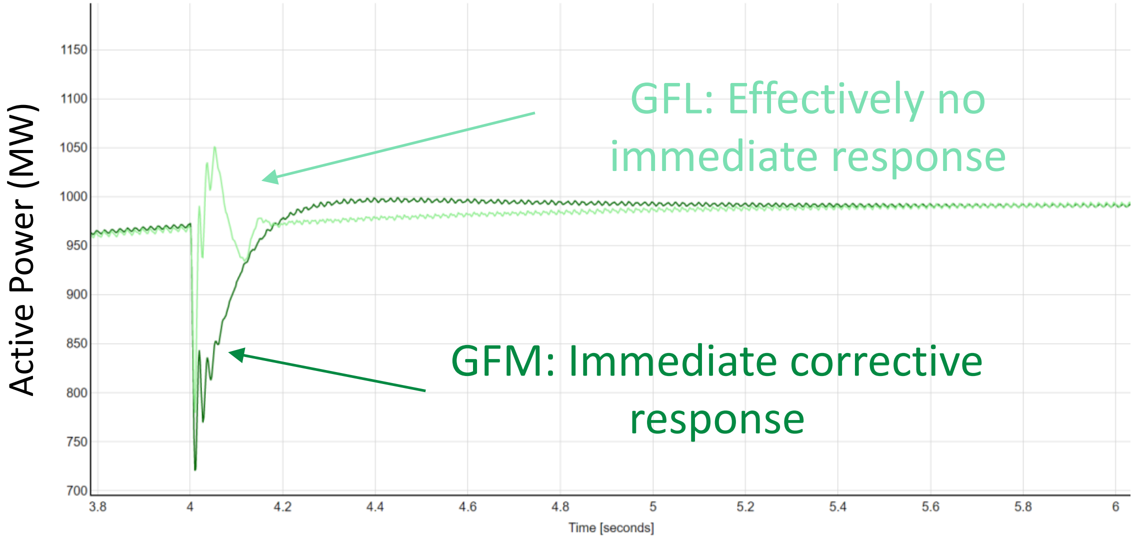


Note: The traces plotted here and in subsequent slides show small 60Hz oscillations due residual DC components and very little filtering of power quantities to show fast dynamics

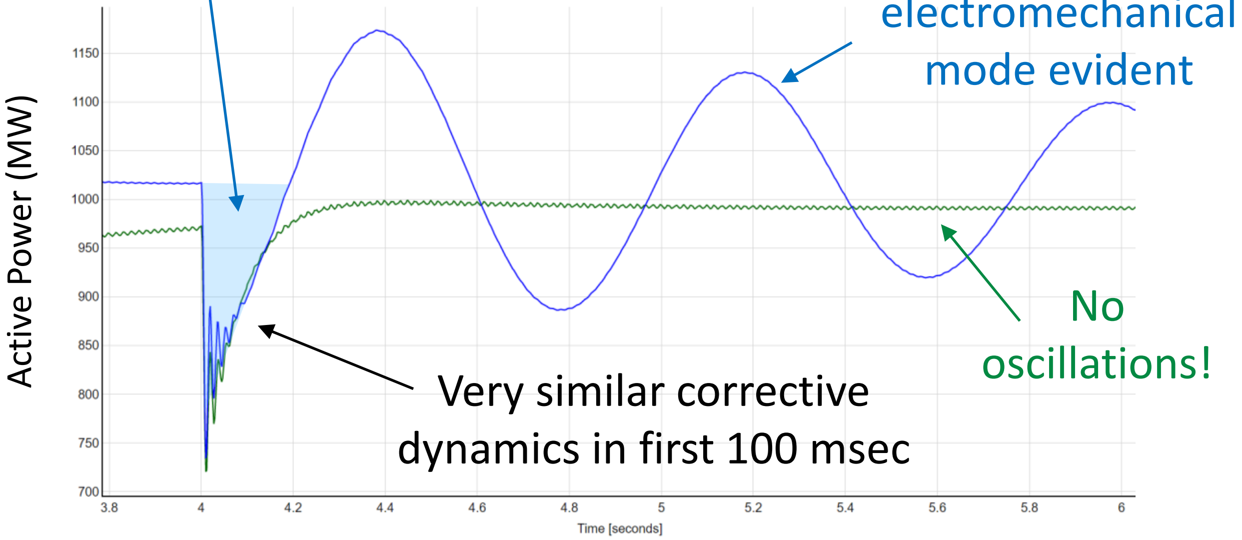
Evidence of grid strengthening behavior from synchronous machines and from GFM inverters

Voltage Phase Angle Step Responses

GFM v. GFL Inverters



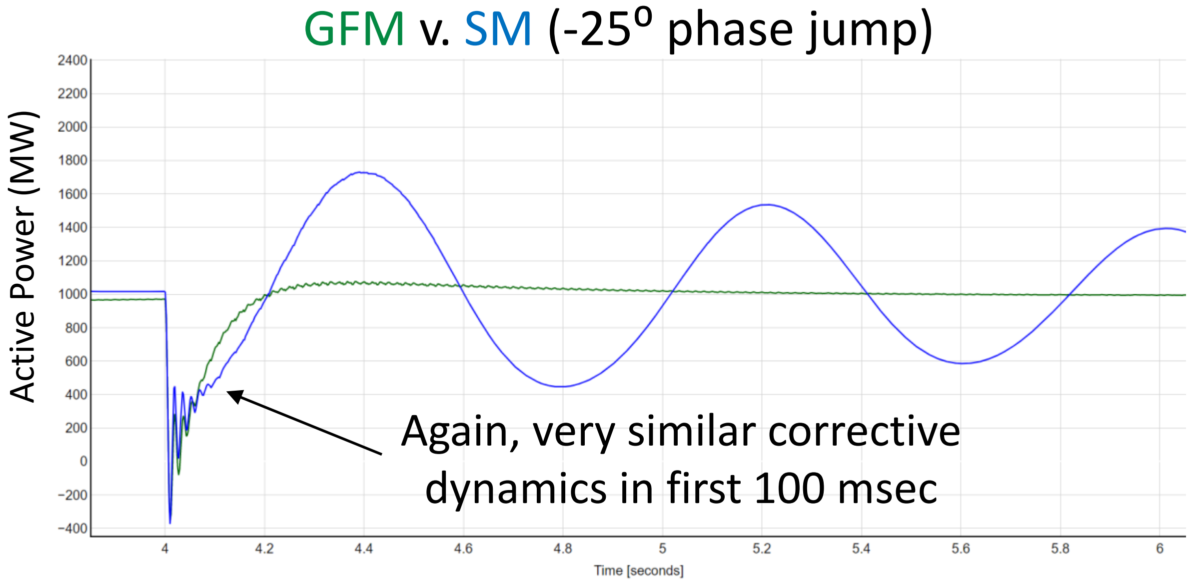
GFM v. SM

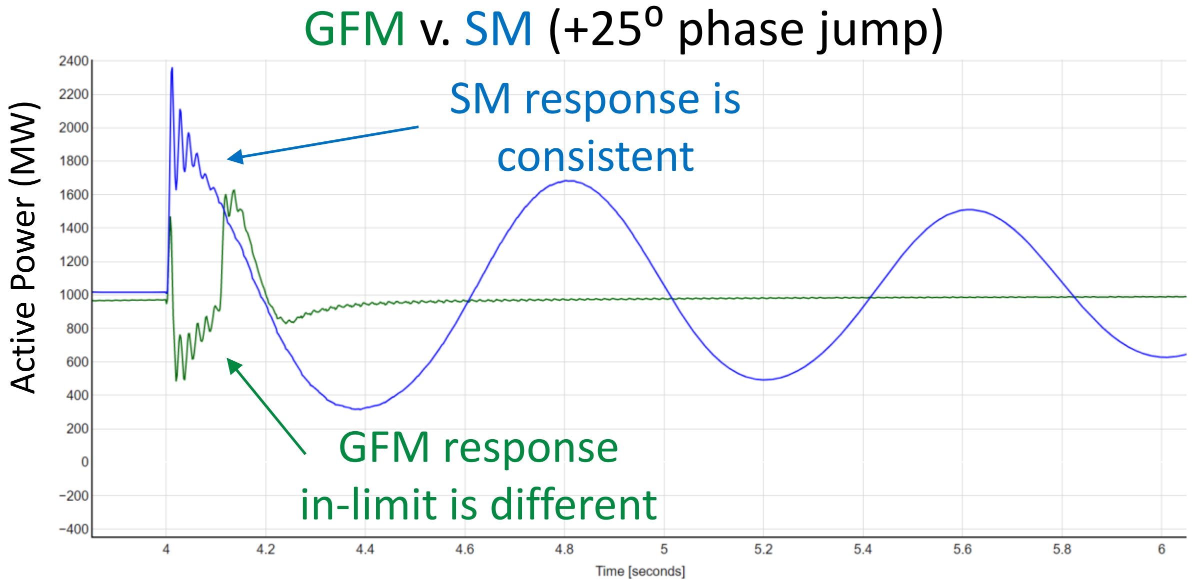


Evidence of true inertial response from synchronous machines and GFM inverters, but very different damping characteristics!

A Closer Look at Equipment Responses & Limits

Consider a BIG whack to the resource: a 25⁰ phase angle jump event

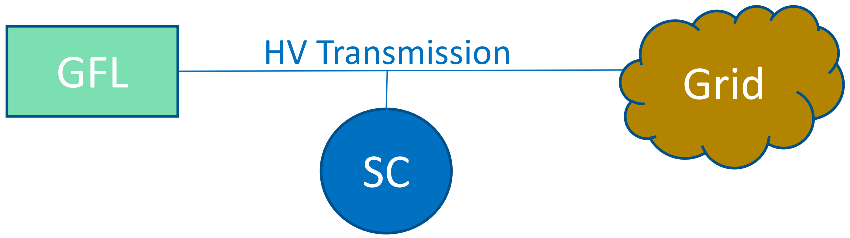




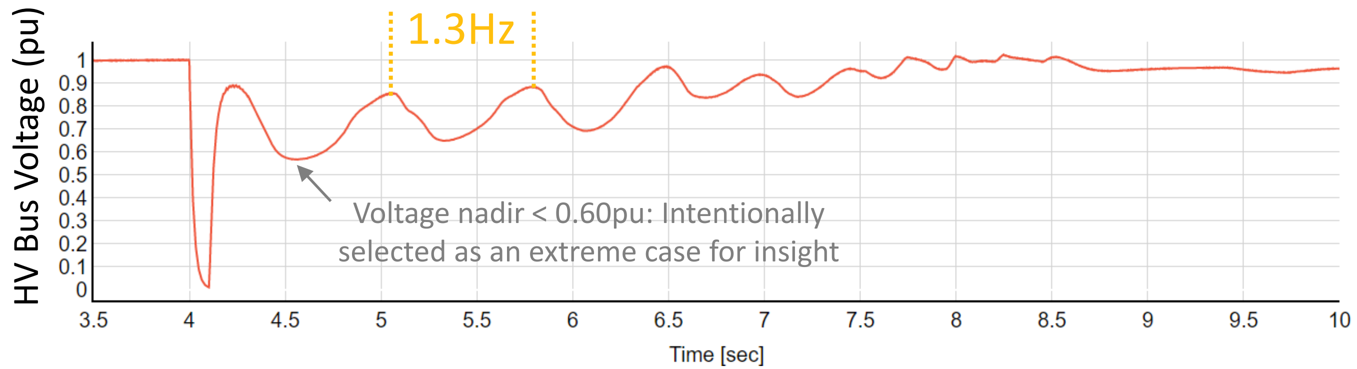
All resources have limits; behavior at the limit may differ.

Resource behavior at their limit – and impact (if any) to the grid – needs to be better understood.

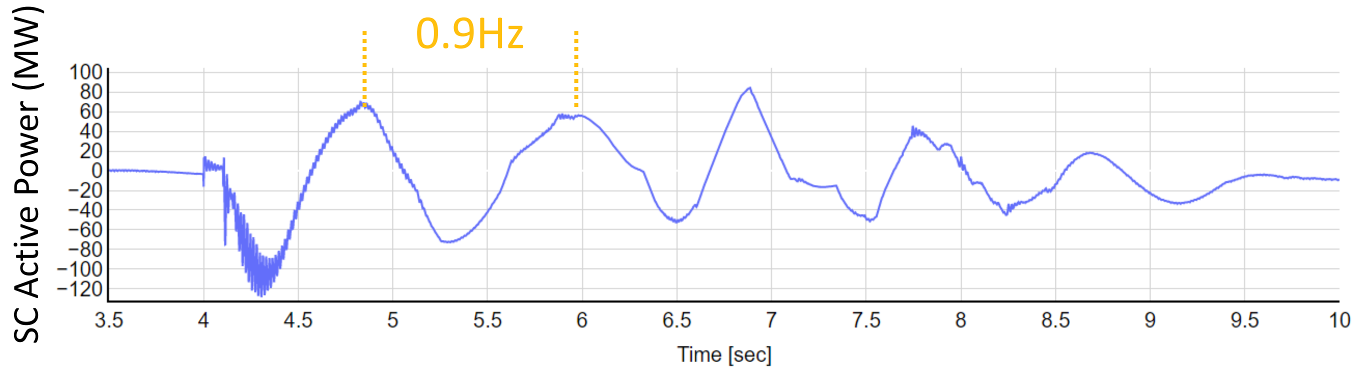
Dynamics Can Get Complicated



Consider the case: GFL + synchronous condenser



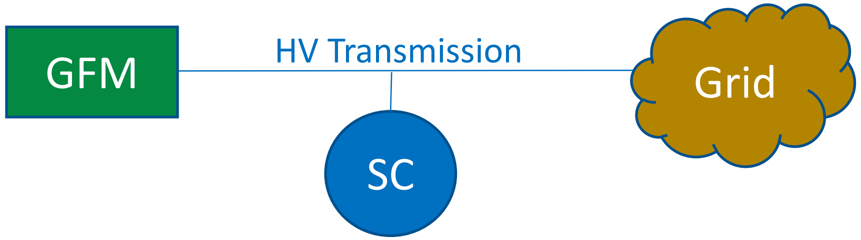
Voltage swings, dominated by the control of GFL



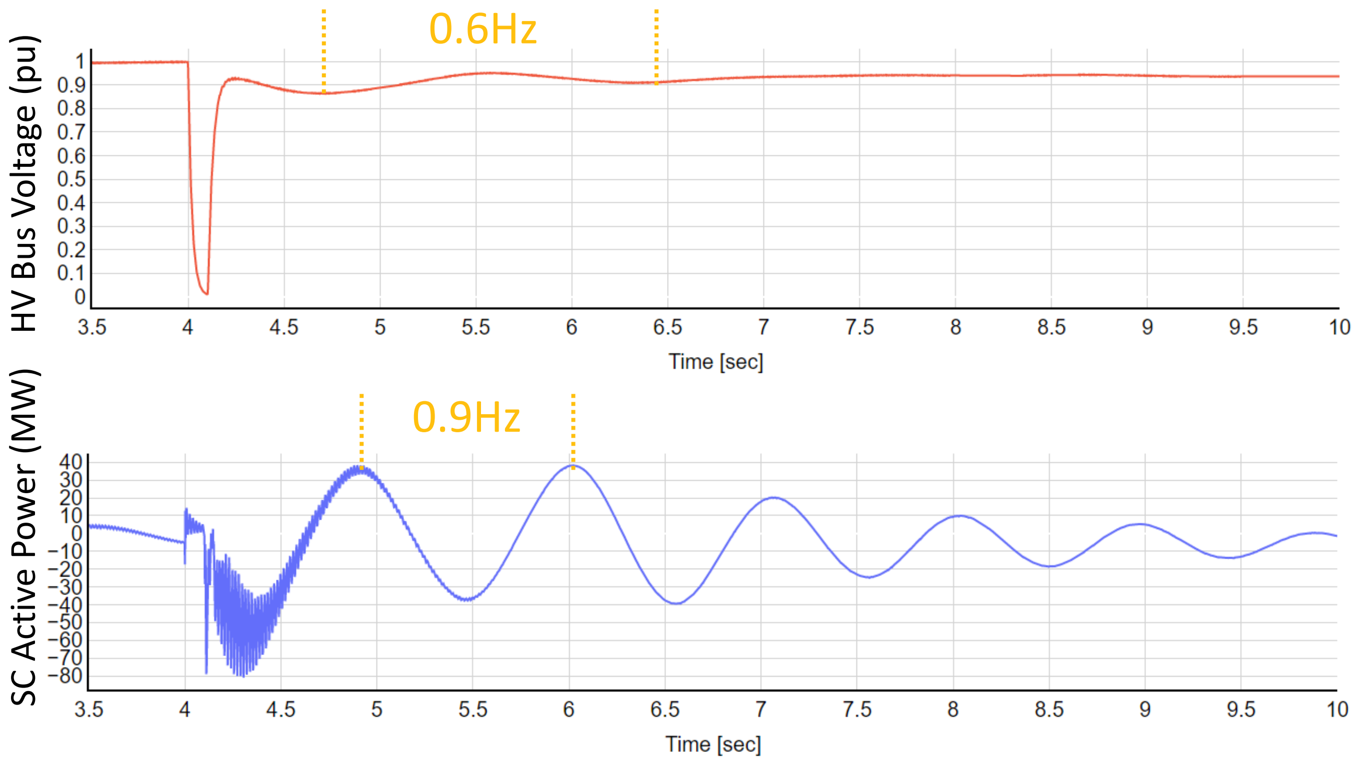
Power swings of the condenser, dominated by electro-mechanical swings of synchronous condenser

Two distinct modes observed → GFL is interacting with the synchronous condenser, resulting in complex dynamics

Dynamics: SC + GFM



Consider the case: GFM + synchronous condenser



The simulation conditions were identical to those used for GFL + SC

Voltage swings are **much smaller** relative to the GFL + SC case

Power swings of the condenser are roughly half the magnitude as the GFL + SC case

Simpler, sinusoidal dynamics → GFM is more decoupled from synchronous condenser (less interaction)

Summary of Key Findings

Characterizing Resource Performance

- Sync machines and GFL can have similar stability limits for power transfer
- GFM shows improved stability over both GFL and sync machines; GFM swings benign
- Sync machines are sensitive to fault duration; IBR are not → CCT may be a misleading stability metric for IBR
- GFM shows similar step characteristics to synchronous machines, but behavior in-limit is different. High current rating not needed for good stability performance.

Characterizing Network Mitigations

- All technologies are sensitive to grid strength
- The transmission network tends to be "soft" in the middle; and for the GFL, soft at the sending end, too
- Sync condensers improve GFL stability, but location matters, and sync condensers introduce additional dynamics!
- Complex relationship between fault location, SC location, SC inertia, and IBR controls. SC at the IBR resource may not always best for stability!

More to Come

- Generalize findings for a variety of IBR and HV transmission systems (this analysis is a starting point; single IBR + simple topology; single snapshot of both GFL & GFM controls here).

Thank You! Questions?

Special thanks to the support provided by Ric O'Connell at GridLAB!

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