Advanced Grid Support BESS Functional Specification and Test Protocol

ERCOT IBRWG Meeting July 12, 2024

Andrew Isaacs

ELECTRANIX

SPECIALISTS IN POWER SYSTEM STUDIES

Background

- Electranix contracted to develop functional specification and test frame work for GFM **BESS** within the ERCOT system
- Achieved by exhaustive testing of four commercially available OEM-provided BESS GFM models
- Approach does not specify specific control topologies, instead provides detailed list of tests to demonstrate functional behaviour (control agnostic)
- This presentation represents Electranix Recommendations.

Technical Memorandum:
DRAFT Advanced Grid Support BESS Functional Specification and Test Protocol

Date: **July 3, 2024**

Prepared For: **ERCOT**
Prepared By: **Kasun Samarawickrama**
Lukas Unruh
Andrew L. Isaacs

ELECTRANIX
SPECIALISTS IN POWER SYSTEM STUDIES

Project Team

- Electranix:
  - Andrew Isaacs, Vice President
  - Kasun Samarawickrama, Senior Studies Engineer
  - Lukas Unruh, Senior Studies Engineer
- ERCOT:
  - Operations: Shun Hsien (Fred) Huang, Yunzhi Cheng, Amro Quedan, Ali Yazdanpanah
  - Planning: Sun Wook Kang, John Schmall, Poria Astero, Scott Zuloaga, Jonathan Rose

Electranix GFM Specification Experience

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems

September 2023

HAWAIIAN ELECTRIC FACILITY TECHNICAL MODEL REQUIREMENTS AND REVIEW PROCESS

August XX, 2021

Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework

January 2024

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Need for Grid-Forming

NERC White Paper: *GFM controls can provide grid stabilizing characteristics that support reliable operation of the BPS under increasing penetration of IBRs. Enabling GFM in BPS-connected BESS allows for system-wide enhancement of stability margins as these resources are interconnected. Therefore, system stability enhancements can be achieved at much lower cost than through the addition of transmission assets*

White Paper: Grid Forming Functional Specifications for BPF-Connected Battery Energy Storage Systems
https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf

Functional Definition - GFL

Grid-Following: Most inverter based resources currently in service rely on fast synchronization with the external grid (termed Grid-Following) in order to tightly control their active and reactive current outputs. If these inverters are unable to remain synchronized effectively during grid events or under challenging network conditions, they are unable to maintain controlled, stable output.

What technology uses Grid-Following?

- *Current generation wind turbines*
- *Current generation transmission connected PV*
- *DER*
- *Most BESS applications*
- *LCC HVDC*
- *Most VSC HVDC*
- *Current generation STATCOMs and SVCs*

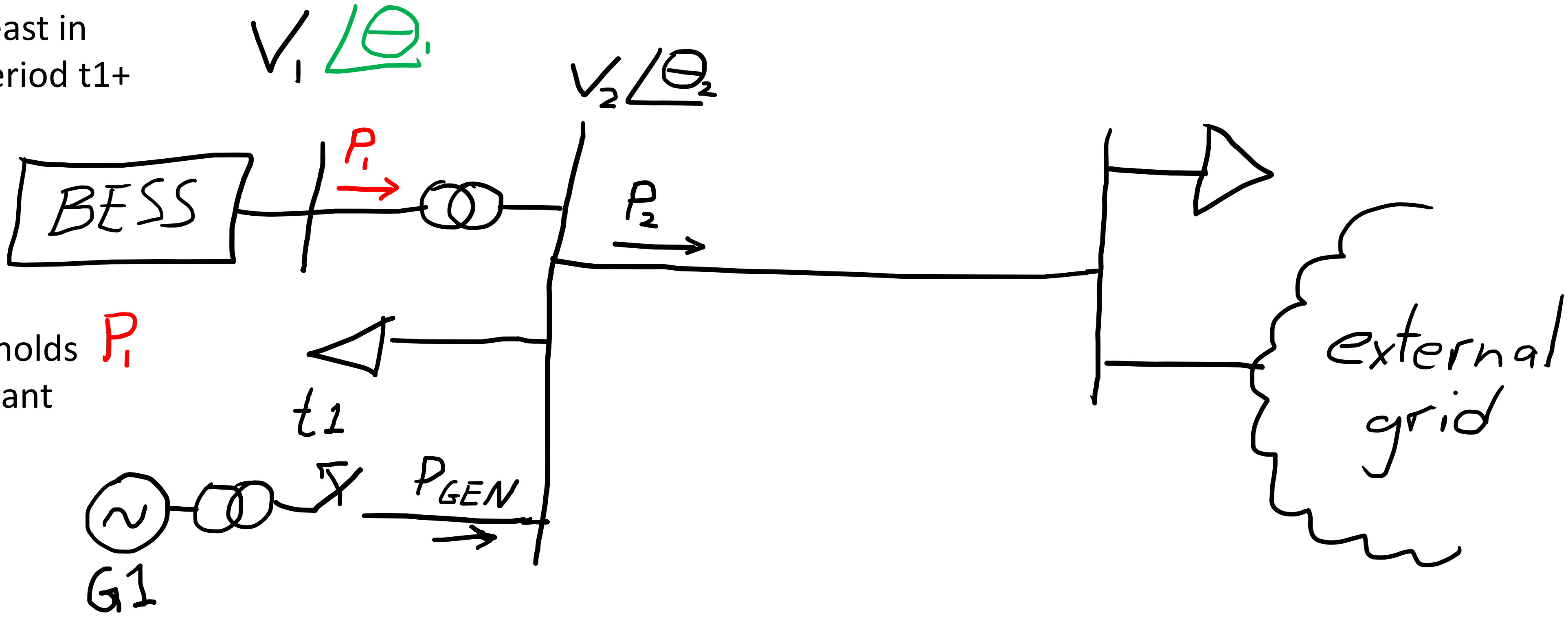
Functional Definition - GFM

- *Grid-Forming: Inverter controls maintain a constant or near-constant voltage phasor at the inverter terminals in the timeframe immediately after changes occur in the system, maintaining synchronism with the grid and continuing to provide normal grid supporting functions and services required of conventional IBRs at all times. Requirements for performance apply at the POI, as per GFL resources.*

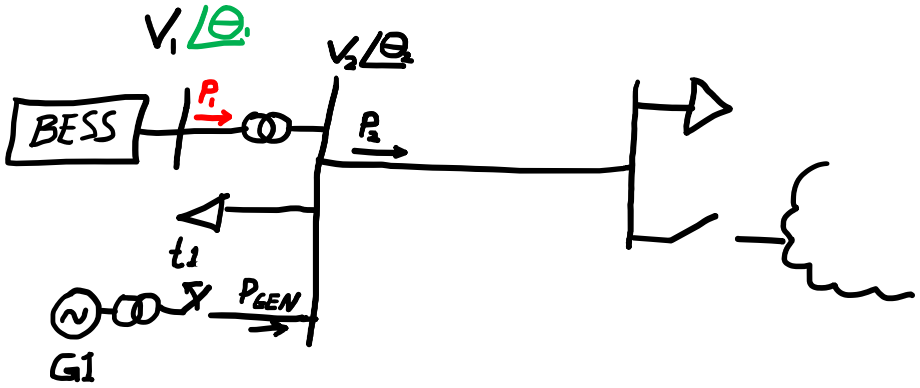
What does that actually mean in a system?

Grid-Forming holds Θ_1 constant… at least in the transient period t1+

Grid-Following holds P_1 (currents) constant during t1+



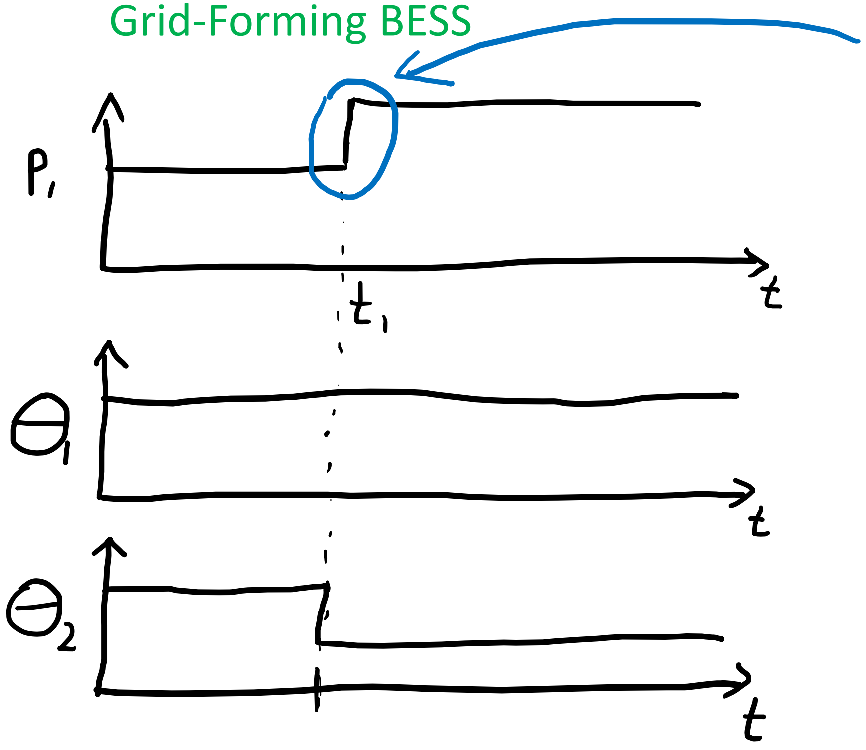
What does it look like when you disconnect the generator G1? (Island system)



Grid-Following BESS

(grid instability and tripping at weak grids)

Grid-Forming BESS

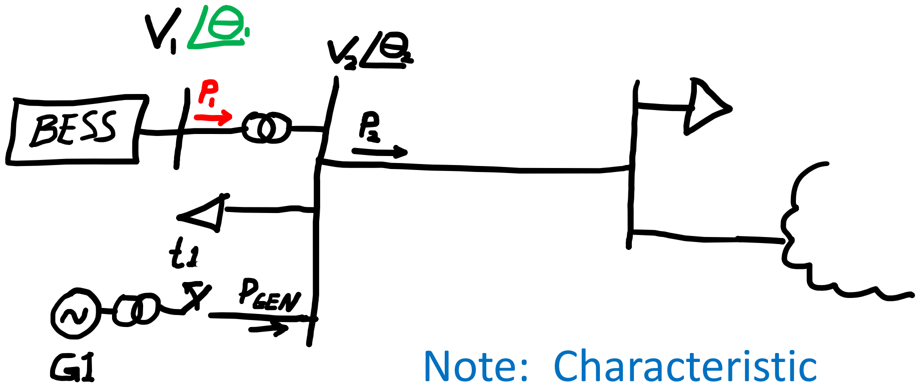


Note: Characteristic Phase-Jump Power

Note: Grid-Forming BESS performance is contingent on having sufficient current and energy headroom when the angle changes!! If there is no headroom, the plant will respond according to its control strategy and should do no harm to the grid.

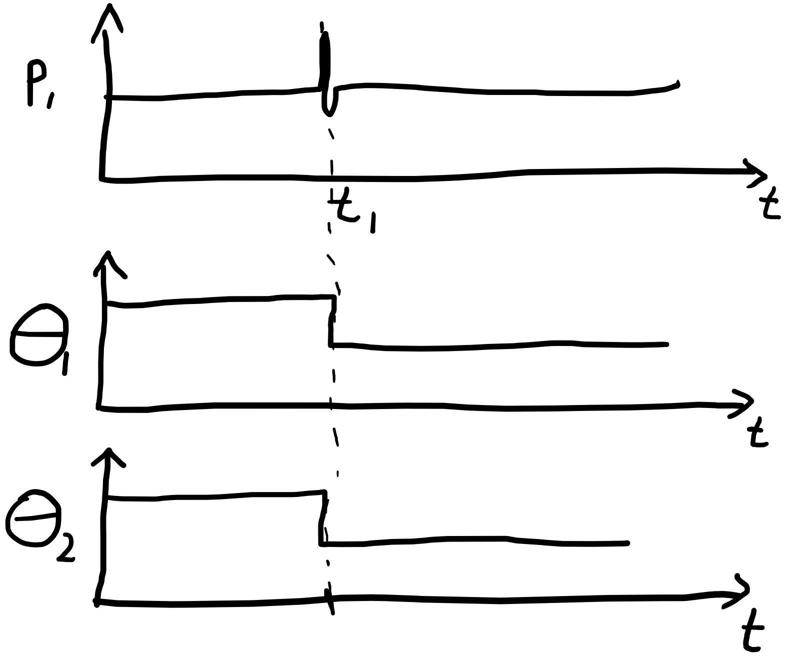
If we re-connect the island, and…

add power control/grid synchronization

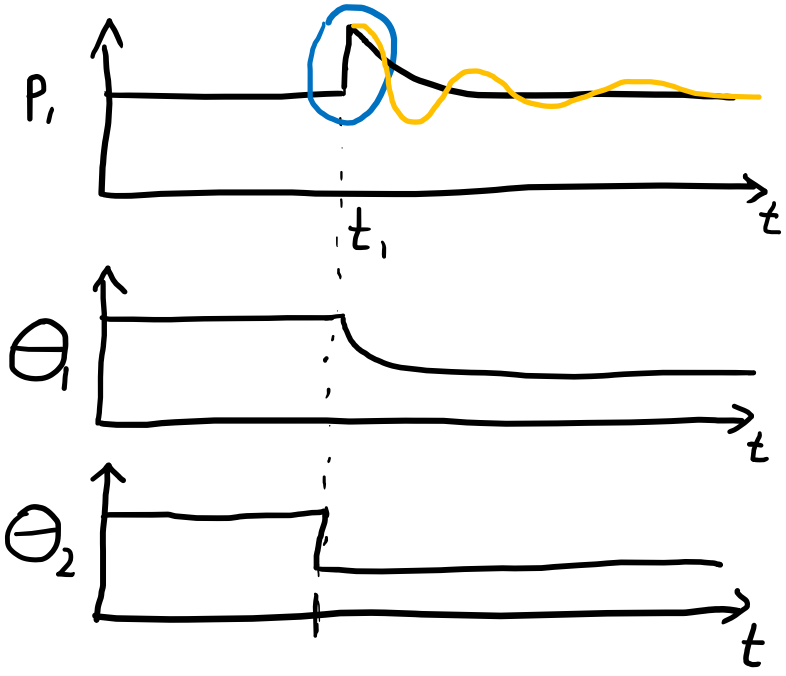


Note: Characteristic Phase-Jump Power

Grid-Following BESS



Grid-Forming BESS



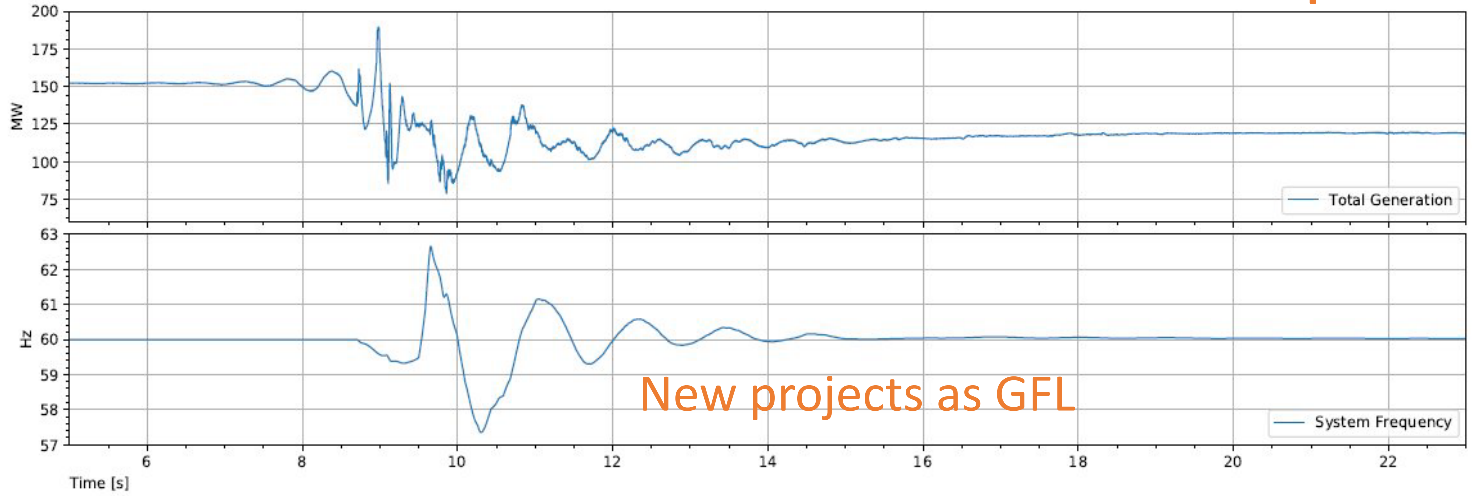
Note: Synchronous machine-type response if desired

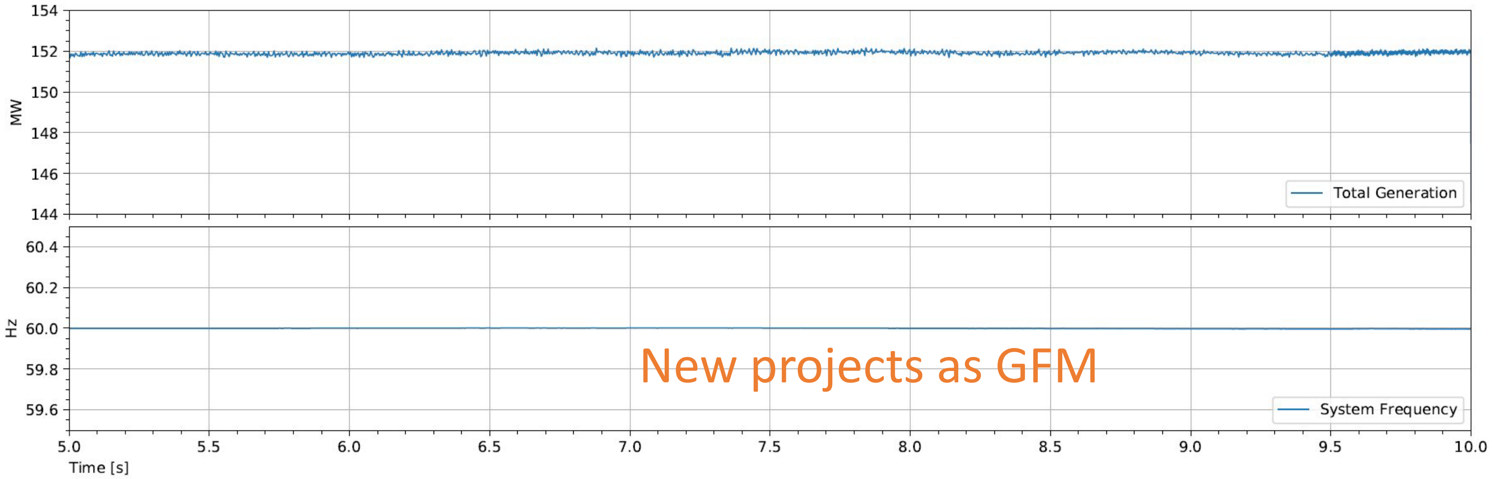
Note: Grid-Forming BESS performance is contingent on having sufficient current and energy headroom when the angle changes!!

Benefits of GFM BESS

- Better performance in weak systems
- Better damping at sub-synchronous frequencies
- Better (fast and stable) grid voltage and frequency support
- Black-start capable (not in scope of this project)

Maui Island Example





Why GFM for BESS now but not PV and Wind?

- BESS may be changed from GFL to GFM via software control change only
- It may not be easy for non-BESS resources to be GFM today. Technical hurdles include impact on mechanical systems for wind, MPPT/energy controllers modifications for PV, and others
- BESS does not face the same constraints, and naturally operates with current and energy headroom much of time. As long as the device is not at current or energy limits, it can respond
- BESS GFM is commercially available now

Functional Capability Requirements for GFM

- All IBRs (GFL and GFM) are required to have:
  - Active power dispatchability
  - Steady state voltage control
  - Dynamic reactive power support
  - Active power frequency control
  - Disturbance ride-through capability
- Additional characteristics required of GFM:
  - Resistance to instantaneous changes in the power network by providing appropriate active and reactive power output in the near-instantaneous time frame. This provides inertia-like energy response to assist with system wide frequency control, and provides additional voltage stability in systems with weak characteristics.
  - Provision of positive damping characteristics in problematic sub-synchronous frequency ranges, which is important to help mitigate subsynchronous resonance challenges related to series capacitors in the ERCOT system.
- <u>Proposed tests are intended to allow GFM BESS to meet success criteria without requiring significant extra rating or hardware beyond their standard capacity rating. Many of the tests could be extended to show additional benefit if additional current or energy headroom were available.</u>

IEEE 2800 Capability and GFM in ERCOT

- As ERCOT moves to adopting IEEE 2800-2022, should note areas of standard which could conflict with inherent GFM control.
- Note: IEEE 2800 acknowledges this and makes provisions (from section 1.4): *It is not the intent of this standard to limit the adoption of technologies and controls (**e.g., grid forming**) that are currently being developed… Due consideration should be given to the benefits of the new technology and controls in deciding which requirements of this standard should be adopted and **which may be exempted**. This should be done in coordination between IBR owner and TS owner/TS operator.*

IEEE 2800 Capability and GFM in ERCOT

Areas for further examination:

- Power may not be limited to max export limits for frequency / phase jump events because BESS current limits or installed AC BESS capacity exceeds plant export limit
- Automatic inadvertent islanding detection not possible
- Initial voltage / frequency control response is automatic and immediate
- Fault current magnitude and active/reactive priority cannot easily be transiently prescribed (but is probably beneficial and correct anyway)

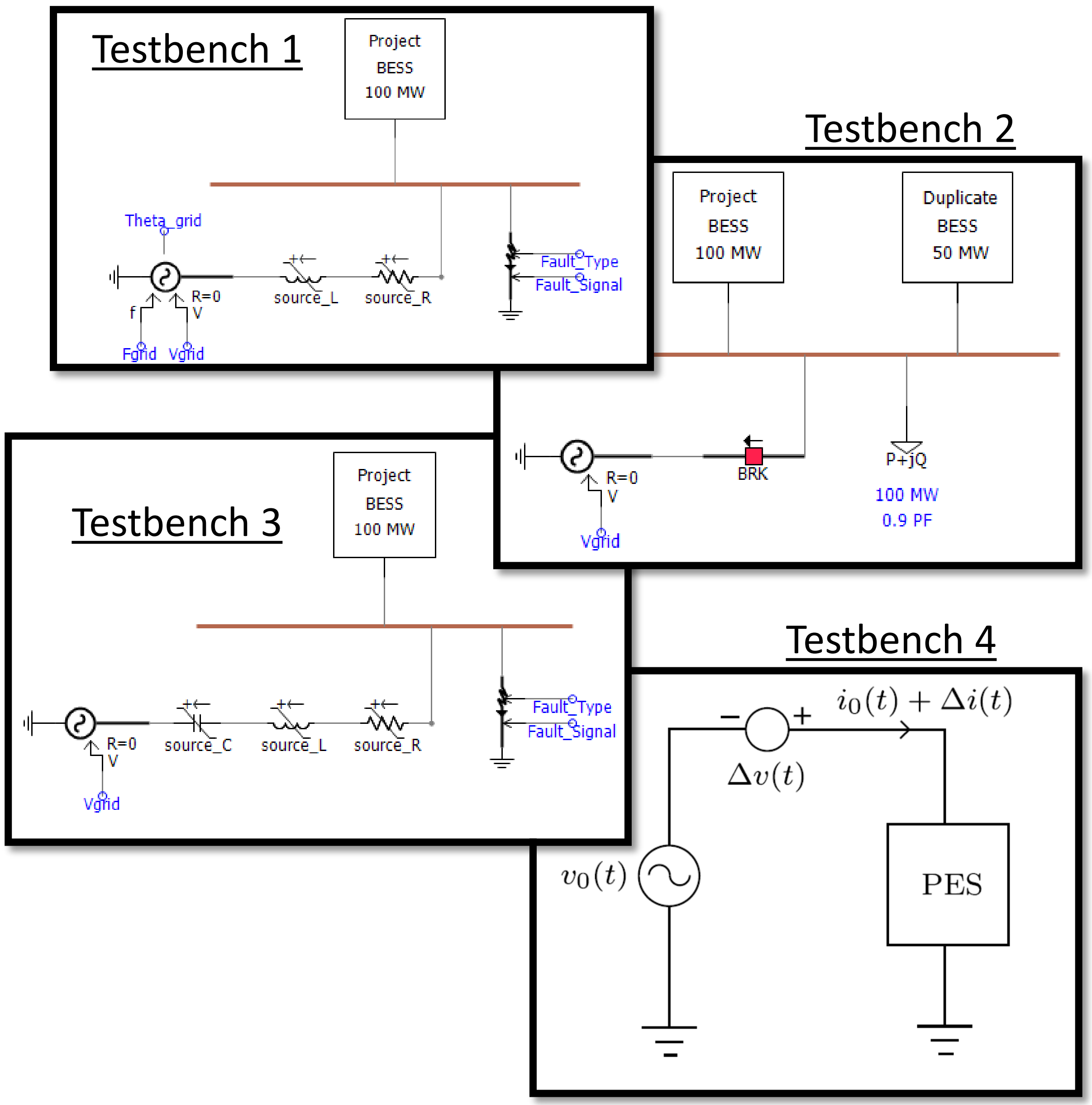
Testbench Summary

Testbench 1: Single Machine Variable Impedance (SMVI) system. Voltage source behind an impedance with precise control over voltage magnitude, frequency, angle, and the series impedance

Testbench 2: Simplified Network With Load (SNWL). This is a simple power system testbench consisting of a voltage source, a constant impedance load, and a copy of the GFM device under test.

Testbench 3: Single Machine Variable Impedance with Series Compensation (SMVI_SC) system. Voltage source behind an impedance with a series capacitor with precise control over voltage magnitude, and the capacitance in series with the source.

Testbench 4: Perturbed voltage source. This is a special voltage source with a mechanism for perturbing its terminals with variable frequency voltage quantities, suitable for performing so-called “frequency scans” to determine the frequency-variant impedance and Q/V characteristics of the plants



Testing Assumptions

- Model quality should be high (usable and accurate), according to ERCOT requirements, including state of charge (SOC) and DC modeling if it is determined to impact performance
- The Plant is able to meet existing requirements for GFL interconnections, including but not exclusively:
  - Fault ride through and recovery
  - Voltage control
  - Frequency control
  - Stability

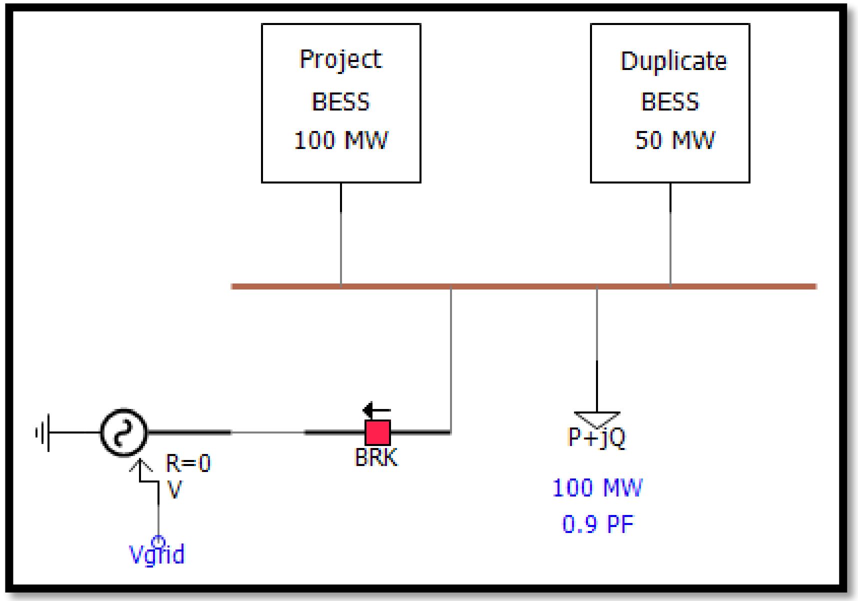
GFM Capability Test Protocols

Test #	Test Name	Testing for:	Test Type	Testbench System
1	Loss of synchronous machine - discharging	GFM core functions (BESS only)	Pass / Fail	2 - SNWL
2	Loss of synchronous machine - charging	GFM core functions (BESS only)	Pass / Fail	2 - SNWL
3	Loss of synchronous machine - limit test	GFM core functions, limits (BESS only)	Pass / Fail	2 - SNWL
4	Loss of synchronous machine - power balance	GFM core functions	Pass / Fail	2 - SNWL
5	Large ROCOF up and down	Control stability	Pass / Fail	1 - SMVI
6	SCR step-down with fault	Control stability	Pass / Fail	1 - SMVI
7	Angle step change	GFM core functions	Pass / Fail	1 - SMVI
8	Series compensation step test	Control stability in series com. network	Pass / Fail	3 - SMVI_SC
9	Voltage step up and down	GFM core functions	Pass / Fail	1 - SMVI
10	Energy response test	Transient energy response	Informational	1 - SMVI
11	Frequency scan	Damping, impedance trend	Informational	4 - PVS

Note: "Informational" tests may not have sufficient testing experience to qualify as pass/fail, but add more understanding to behaviour. Tests may be revised as needed.

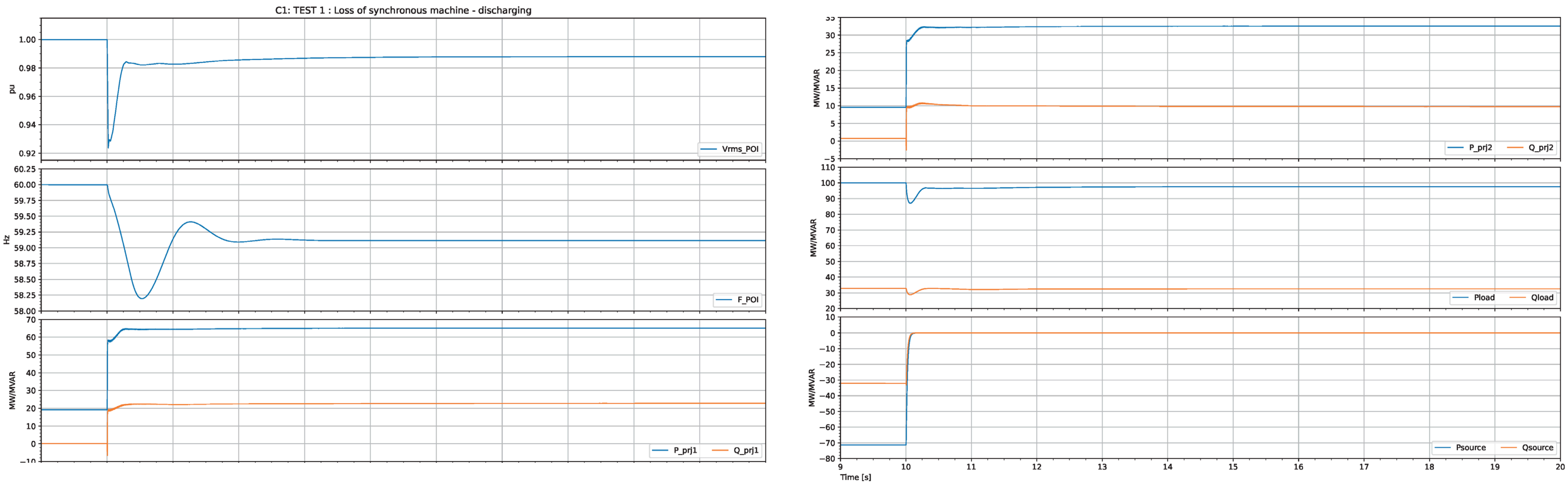
Example Test Protocol: Loss of Last Synchronous Machine (Test #1)

- Same tests proposed in NERC GFM specification white paper
- Tests for core GFM functions
- Note that this is not a test of Blackstart capability



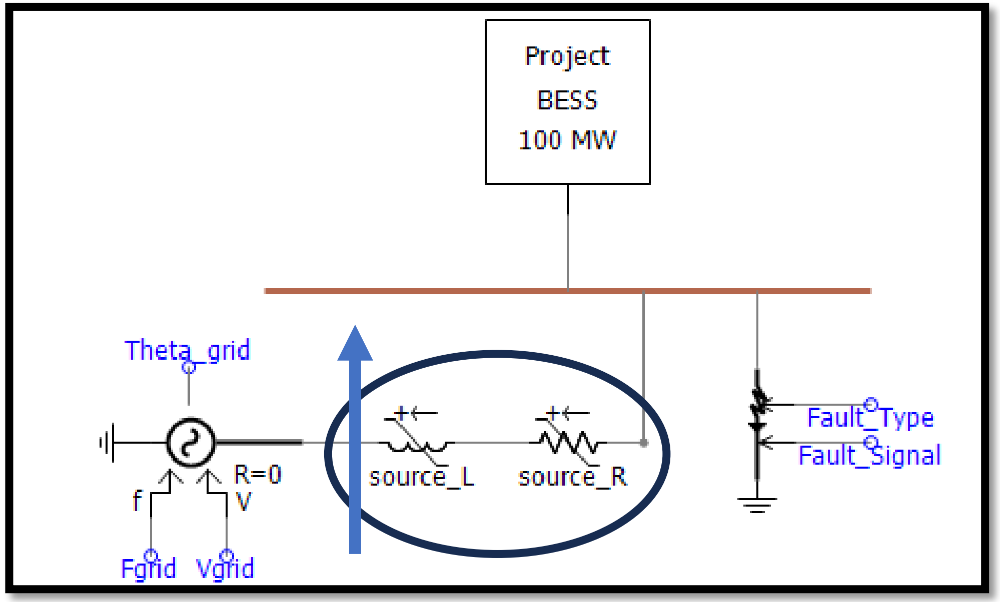
Test 1 (Loss of synchronous machine - discharging) – Setup and Success Criteria (Testbench 2)	
Testbench setup	
The project plant is dispatched at 20% of its maximum discharge power limit.	
The duplicate plant is dispatched at 20% of its maximum discharge power limit	
The load (constant impedance) is set to 100% of the project 1 active power limit, with a power factor of 0.95	
The voltage source is supplying 100% of the reactive power to the load	
Voltage and frequency of the voltage source are fixed at 1 pu	
Test Sequence	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the voltage source (no fault).	
Success Criteria	
Post-Trip	**Pass/Fail**
a. Immediately following the trip, plant output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels. For example, oscillations should be damped within 10 seconds, and quantities not exceed nominal ranges for more than a few cycles, and should reach settled values within 5 seconds.	
b. Voltage settles to a stable operating point.	
c. The final voltage is as expected based on the droop and deadband settings.	
d. Frequency settles to a stable operating point.	
e. The final frequency is as expected based on the droop and deadband settings.	
f. Any oscillation shall be settled.	
g. Any distortion observed in phase quantities should dissipate over time.	
h. Active power from each plant should move immediately to meet the load requirement and settle according to its frequency droop setting. Note that response time to 90% of initial change in instantaneous active power[1] should occur within 15ms	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. RMS voltage does not deviate beyond [0.8, 1.1] pu for longer than 0.1s throughout the test . These voltage bounds and the time threshold are based on preliminary testing, may be adjusted as more experience with this requirement is gained.	

Loss of Last Synchronous Machine Example



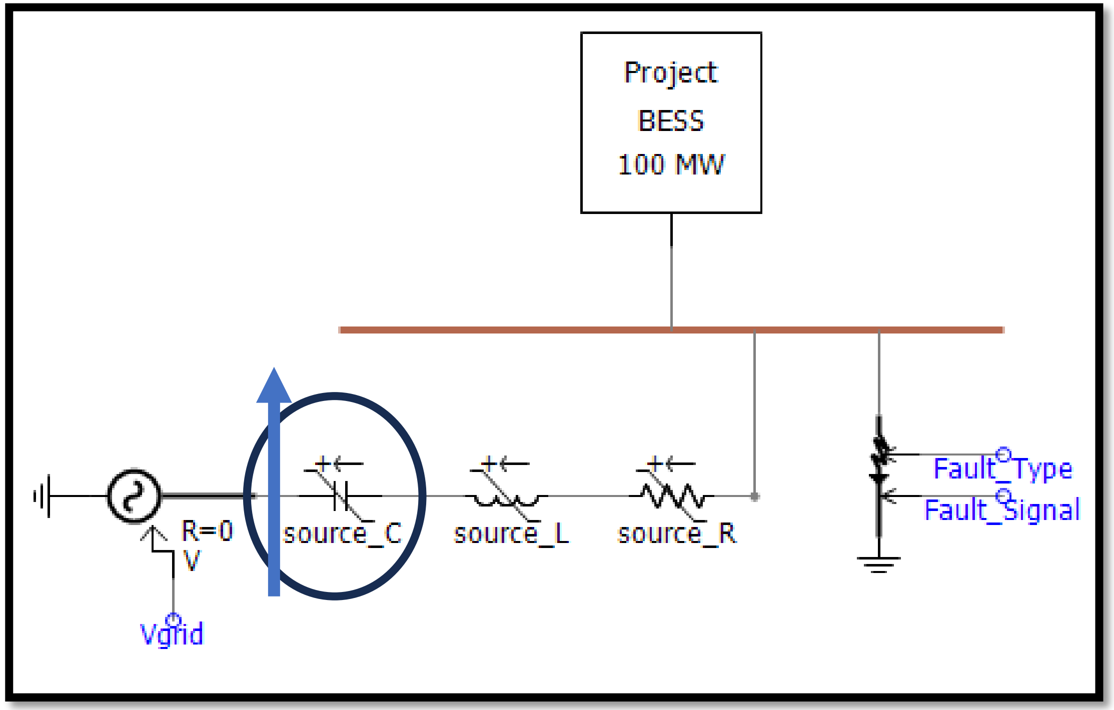
Test #6: SCR Step Down with Fault (pass/fail)

- Testing GFM core functions
- Incrementally increase grid impedance, applying brief faults at each step
- Plant required to perform well down to an SCR of 1.25
- For reference, GFL resources required to perform well to SCR of 3 according to current MQT



Test #8: Series Compensation Step (unique ERCOT test) (pass/fail)

- Testing control stability in series compensated system
- Step increases in series capacitor, up to 70% compensation
- GFM expected to remain stable throughout test
- Test may be extended depending on degree of damping desired



Test #10: Energy Response Test (informational)

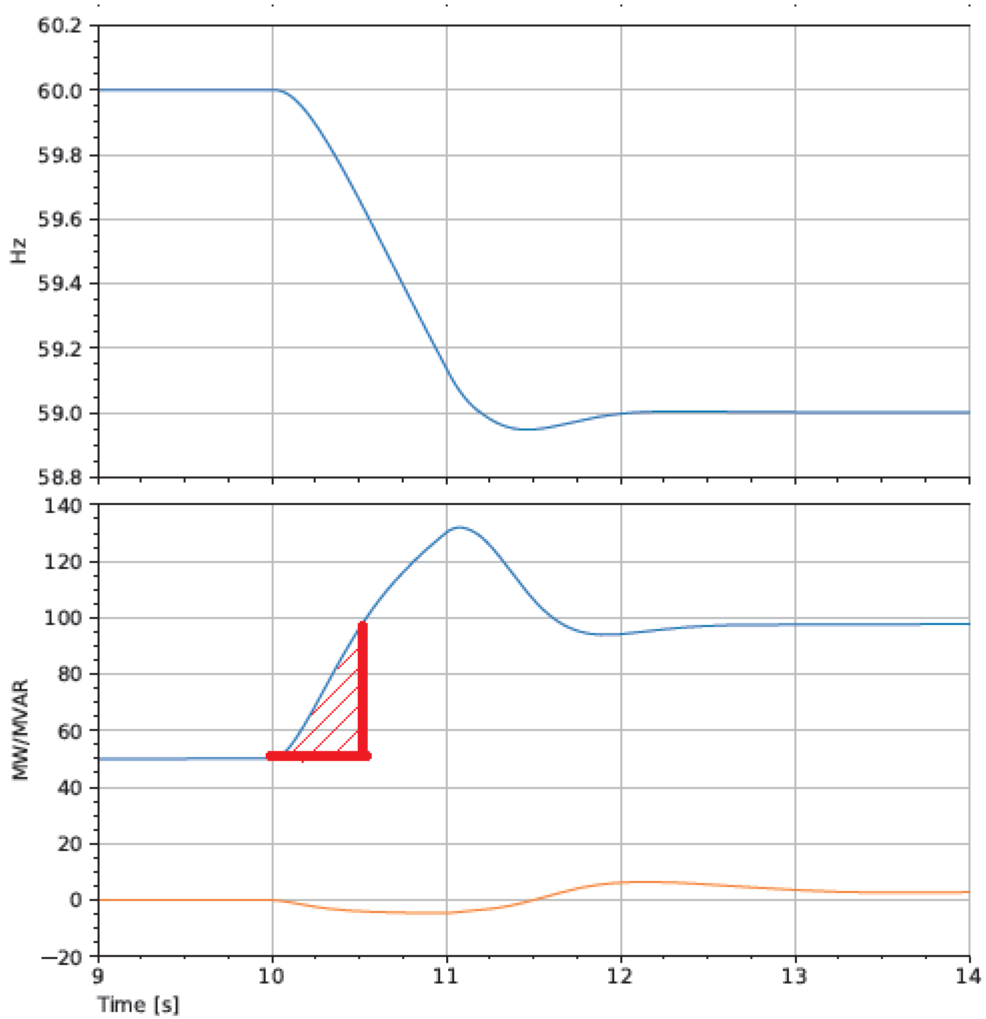
- Quantifies short-term (first 0.5s) energy provided by GFM for frequency events
- System frequency ramps +/- 1 Hz at 1 Hz/s
- Test setup so that there is 50% power headroom
- Energy constant calculated as:

$$Energy\ Constant = \frac{\Delta E}{RoCoF}$$

Where;

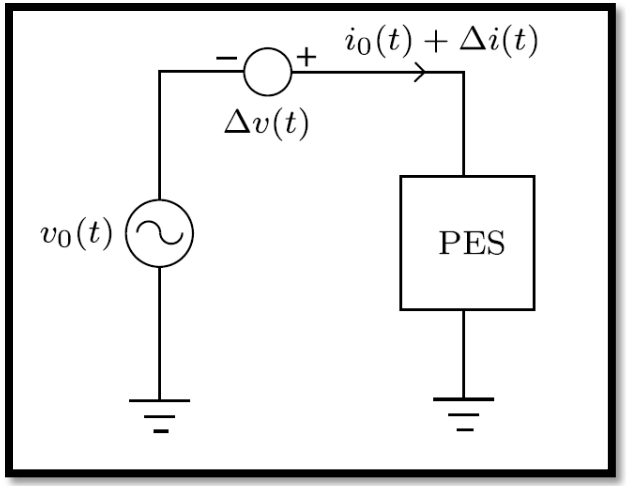
ΔE = Area under the ΔP (pu) curve (i.e. $P - P_{Pre-Disturbance}$) for a period of 0.5s from RoCoF application (pu.s)

$RoCoF = 1/60\ (pu/s)$

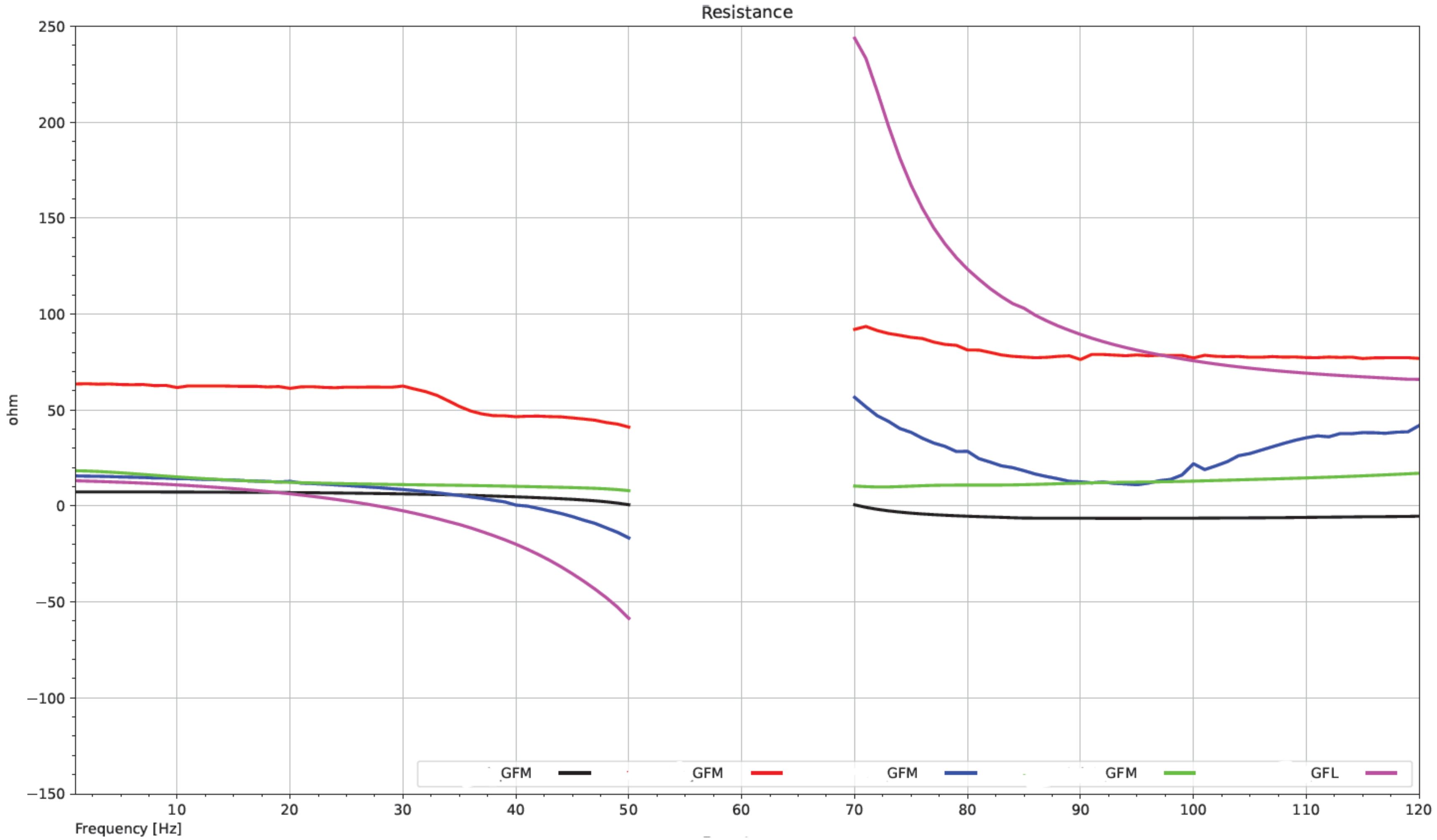


Test #11: Frequency Scan Tests (informational)

- Seek to get information about small-signal behaviour of GFM by external perturbations
- Two types of scans:
  - Impedance scan to assist in confirming damping.
    - Expecting positive resistance up to 50 Hz
  - Q/V scan to assist in confirming core GFM functionality
    - Expecting voltage-source like characteristic over certain frequency range



Impedance Scan Result



Preliminary -- Summary of OEM GFM BESS Performance[(1)]

Case #	Test #	Test Type	OEM				
			GFM1	GFM2	GFM3	GFM4	GFL
C1	Test 1	Pass / Fail	Pass	Pass	Pass	Pass	Fail
C2	Test 2		Pass	Pass	Pass	Pass	Fail
C3	Test 3		Pass	Pass	Pass	Pass	Fail
C4	Test 4		Pass	Pass	Pass	Pass	Fail
C5	Test 5		Pass	Pass	Pass[1]	Pass	Pass[2]
C6	Test 6		Pass	Pass[3]	Pass	Pass	Fail
C7	Test 7.1		Pass	Pass	Pass	Pass	Fail
C8	Test 7.2		Pass	Pass[4]	Pass	Pass	Fail
C9	Test 8.1		Pass	Pass	Pass	Pass	Fail
C10	Test 8.2		Fail[5]	Pass	Pass	Pass	Fail
C11	Test 8.3		Fail[5]	Pass	Pass	Pass	Fail
C12	Test 9		Pass	Pass	Pass	Pass	Fail
C13	Test 10.1	Infor-mational	Acceptable	Acceptable	Acceptable	Acceptable	Clarification Required
C14	Test 10.2						
C15	Test 11.1		Acceptable[6]	Acceptable	Clarification Required[7]	Acceptable	Clarification Required
C16	Test 11.2						
C17	Test 11.3						
C18	Test 11.4		Acceptable[8]	Acceptable[8]	Acceptable[8]	Acceptable[8]	Clarification Required
C19	Test 11.5						
C20	Test 11.6						

1 The plant is on a limit during the 57 Hz frequency region. This is visible when it is coming out of the limit due to GFL like characteristics.

2 The plant is in compliance with success criteria but does not show GFM characteristics in the responses observed as expected.

3 A poorly damped low frequency oscillation was observed in the active power when the SCR drop below 2.0. Control tuning may require.

4 The current limit of the inverter is being hit due to -30 deg phase jump since the pre disturbance active power is at 100%. Therefore, the initial power jump did not reach the expected values. As per the success criteria, the large phase jumps (> 10 deg) does not require to comply with initial power jump requirement if they are on a limit.

5 This model seems to have an issue during charging and close to zero dispatch levels (i.e. the model does not ride through a regular 3LG 6 cycle fault while charging or zero dispatch levels). This is not related to series capacitor test but any test with faults being applied while the plant is charging may affect.

6 Negative damping was observed between 50 Hz-55Hz and in the region between 65-120 Hz. The negative damping in the super synchronous range may affect parallel resonances.

7 Negative damping was observed between 40 Hz-50Hz

8 Relatively flat region was observed in the angle of the Q/V plot but the flat region was not significant in the |Q/V| plot.

Pass or Acceptable
Fail or Clarification Required
Marginally Pass or Acceptable

(1). ERCOT appreciates the support by the OEMs, including Power Electronics, SMA, Sungrow, and Tesla. The results in the table do not indicate any limitation or certification of any OEMs.

Additional Content

Test Protocols:

Test #	Test Name	Testing for:	Test Type	Testbench System
1	Loss of synchronous machine - discharging	GFM core functions (BESS only)	Pass / Fail	2 - SNWL
2	Loss of synchronous machine - charging	GFM core functions (BESS only)	Pass / Fail	2 - SNWL
3	Loss of synchronous machine - limit test	GFM core functions, limits (BESS only)	Pass / Fail	2 - SNWL
4	Loss of synchronous machine - power balance	GFM core functions	Pass / Fail	2 - SNWL
5	Large ROCOF up and down	Control stability	Pass / Fail	1 - SMVI
6	SCR step-down with fault	Control stability	Pass / Fail	1 - SMVI
7	Angle step change	GFM core functions	Pass / Fail	1 - SMVI
8	Series compensation step test	Control stability in series com. network	Pass / Fail	3 - SMVI_SC
9	Voltage step up and down	GFM core functions	Pass / Fail	1 - SMVI
10	Energy response test	Transient energy response	Informational	1 - SMVI
11	Frequency scan	Damping, impedance trend	Informational	4 - PVS

Test 1 (Loss of synchronous machine - discharging) – Setup and Success Criteria (Testbench 2)	
Testbench setup	
The project plant is dispatched at 20% of its maximum discharge power limit.	
The duplicate plant is dispatched at 20% of its maximum discharge power limit	
The load (constant impedance) is set to 100% of the project 1 active power limit, with a power factor of 0.95	
The voltage source is supplying 100% of the reactive power to the load	
Voltage and frequency of the voltage source are fixed at 1 pu	
Test Sequence	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the voltage source (no fault).	
Success Criteria	
Post-Trip	**Pass/Fail**
a. Immediately following the trip, plant output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels. For example, oscillations should be damped within 10 seconds, and quantities not exceed nominal ranges for more than a few cycles, and should reach settled values within 5 seconds.	
b. Voltage settles to a stable operating point.	
c. The final voltage is as expected based on the droop and deadband settings.	
d. Frequency settles to a stable operating point.	
e. The final frequency is as expected based on the droop and deadband settings.	
f. Any oscillation shall be settled.	
g. Any distortion observed in phase quantities should dissipate over time.	
h. Active power from each plant should move immediately to meet the load requirement and settle according to its frequency droop setting. Note that response time to 90% of initial change in instantaneous active power[1] should occur within 15ms	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. RMS voltage does not deviate beyond 0.8 pu for longer than 0.1s throughout the test . These voltage bounds and the time threshold are based on preliminary testing, may be adjusted as more experience with this requirement is gained.	

Test 2 (Loss of synchronous machine - charging) – Setup and Success Criteria (Testbench 2)	
Testbench setup	
The project plant is dispatched at half of its maximum charge power limit.	
The duplicate plant is dispatched at half of its maximum charge power limit.	
The load (constant impedance) is set to 50% of the project 1 active power limit, with a power factor of 0.95	
The voltage source is supplying 100% of the reactive power to the load	
Voltage and frequency of the voltage source are fixed at 1 pu	
Test Sequence	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the voltage source (no fault).	
Success Criteria	
Post-Trip	**Pass/Fail**
a. Immediately following the trip, plant output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels. For example, oscillations should be damped within 10 seconds, and quantities not exceed nominal ranges for more than a few cycles, and should reach settled values within 5 seconds.	
b. Voltage settles to a stable operating point	
c. The final voltage is as expected based on the droop and deadband settings.	
d. Frequency settles to a stable operating point	
e. The final frequency is as expected based on the droop and deadband settings.	
f. Any oscillation shall be settled.	
g. Any distortion observed in phase quantities should dissipate over time.	
h. Active power from each plant should move immediately to meet the load requirement and settle according to its frequency droop setting. Note that response time to 90% of initial change in instantaneous active power should occur within 15ms	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. RMS voltage should not deviate beyond 0.8 pu for longer than 0.1s throughout the test. These voltage bounds and the time threshold are based on preliminary testing, may be adjusted as more experience with this requirement is gained.	

Test 3 (Loss of synchronous machine - limit test) – Setup and Success Criteria (Testbench 2)	
Testbench setup	
The project plant is dispatched at 0 MW.	
The duplicate plant is dispatched at its maximum discharge power limit.	
The load (constant impedance) is set to 100% of the project 1 active power limit, with a power factor of 0.95	
The voltage source is supplying 100% of the reactive power to the load	
Voltage and frequency of the voltage source are fixed at 1 pu	
Test Sequence	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the voltage source (no fault).	
Success Criteria	
Post-Trip	**Pass/Fail**
a. Immediately following the trip, plant output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels. For example, oscillations should be damped within 10 seconds, and quantities not exceed nominal ranges for more than a few cycles, and should reach settled values within 5 seconds.	
b. Voltage settles to a stable operating point	
c. The final voltage is as expected based on the droop and deadband settings.	
d. Frequency settles to a stable operating point	
e. The final frequency is as expected based on the droop and deadband settings.	
f. Any oscillation shall be settled.	
g. Any distortion observed in phase quantities should dissipate over time.	
h. Active power from each plant should move immediately to meet the load requirement and settle according to its frequency droop setting. Note that response time to 90% of initial change in instantaneous active power should occur within 15ms. Active power from the duplicate plant should not exceed its max discharge power limit at steady state. Duplicate plant output may exceed momentarily depending on available active power and temporary overload capability.	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. RMS voltage should not deviate beyond 0.8 pu for longer than 0.1s throughout the test. These voltage bounds and the time threshold are based on preliminary testing, may be adjusted as more experience with this requirement is gained.	

Test 4 (Loss of synchronous machine – power balance)– Setup and Success Criteria (Testbench 2)	
Testbench setup	
The plant is dispatched at half of its maximum discharge power limit.	
The duplicate plant is dispatched at half of its maximum discharge power limit.	
The load (constant impedance) is set to 75% of the project 1 active power limit, with a power factor of 0.95	
The voltage source is supplying 100% of the reactive power to the load	
The voltage source active power is set to approximately zero	
Voltage and frequency of the voltage source are fixed at 1 pu	
Test Sequence:	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the voltage source (no fault).	
Success Criteria	
Post-Trip	**Pass/Fail**
a. Immediately following the trip, plant output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels. For example, oscillations should be damped within 10 seconds, and quantities not exceed nominal ranges for more than a few cycles, and should reach settled values within 5 seconds.	
b. Voltage settles to a stable operating point	
c. The final voltage is as expected based on the droop and deadband settings.	
d. Frequency settles to nominal	
f. Any oscillation shall be settled.	
g. Any distortion observed in phase quantities should dissipate over time.	
h. Active power from each plant should settle back to pre-trip levels	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. RMS voltage should not deviate beyond 0.8 pu for longer than 0.1s throughout the test. These voltage bounds and the time threshold are based on preliminary testing, may be adjusted as more experience with this requirement is gained.	

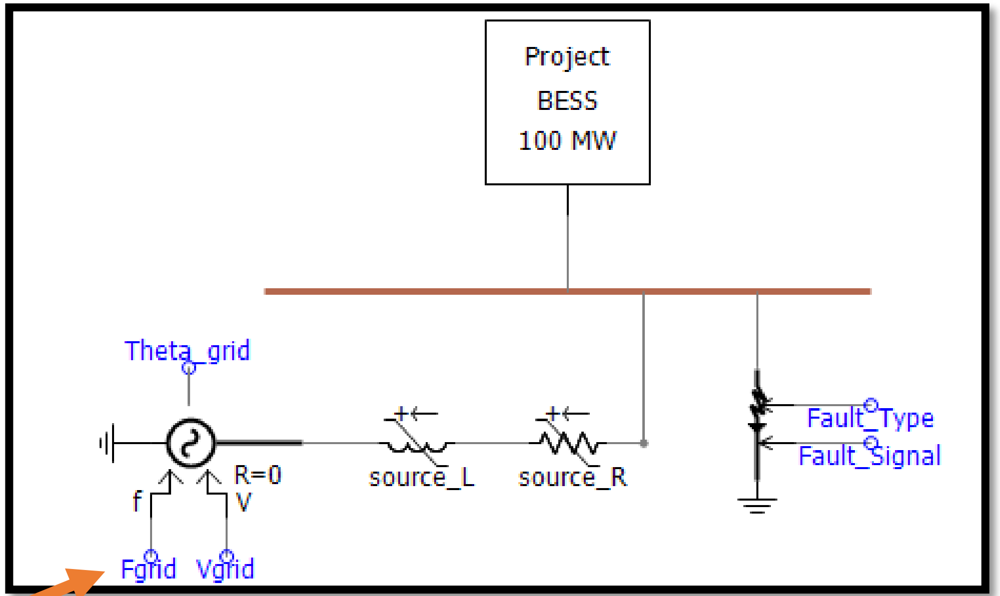
Tests #2 – 4: more Loss of Last Synchronous Machine (pass/fail)

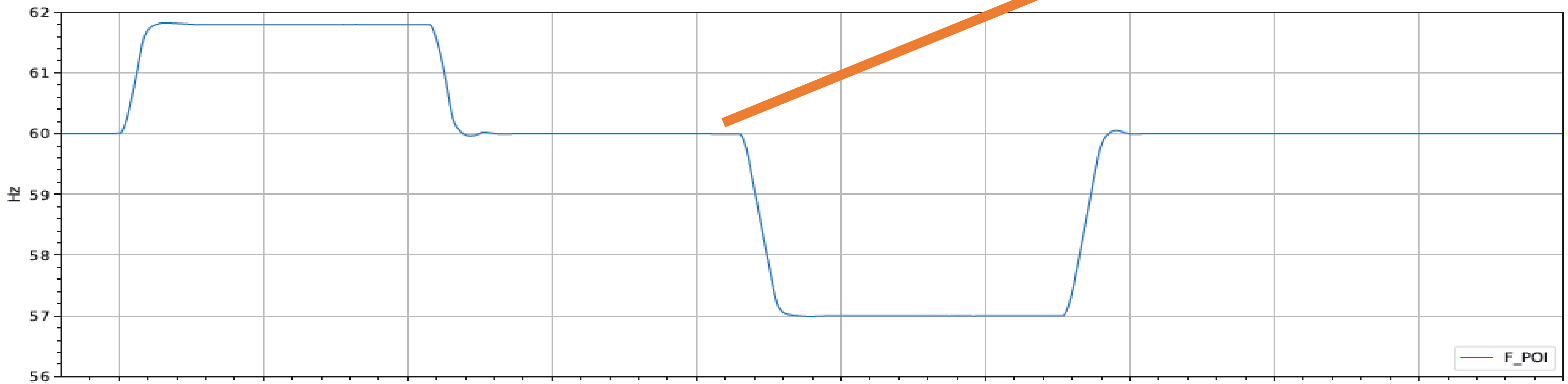
- Test 2: Both plants initially charging
- Test 3: One plant initially discharging at Pmax limit, other at 0 MW
  - Shows response of plant being pushed to beyond limit
- Test 4: Both plants discharging to match load
  - Plants only picking up reactive load. Can be used to test non-BESS

Test 5 (RoCoF up and down)– Setup and Success Criteria (Testbench 1)	
Testbench setup	
SCR at connection point is set to 10. System Equivalent X/R is set to 6.	
Initial dispatch of generation is 50% of nominal power.	
Only the project plant, no duplicate.	
Test Sequence:	
1. Ramp up the frequency from 60 Hz to 61.8 Hz at +5 Hz/s. Stay at 61.8 Hz for 5 seconds	
2. Ramp down the frequency from 61.8 Hz to 60 Hz at -5 Hz/s. Stay at 60 Hz for 5 seconds	
3. Ramp down the frequency from 60 Hz to 57 Hz at -5 Hz/s. Stay at 57 Hz for 5 seconds	
4. Ramp up the frequency from 57 Hz to 60 Hz at +5 Hz/s	
Success Criteria	**Pass/Fail**
a. Plant real and reactive power output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels for any significant amount of time.	
b. Voltage settles to a stable operating point when frequency is not ramping	
c. Active power should settle according to its frequency droop and deadband settings when frequency is not ramping	
d. Any oscillation shall be settled.	

Test #5: Stability of Plant with Changing Frequency (pass/fail)

- Fast frequency ramping up/down
- Checking for control stability ("Plant output should be well controlled")
- Some methods of GFM control can have problems with large, fast frequency ramps



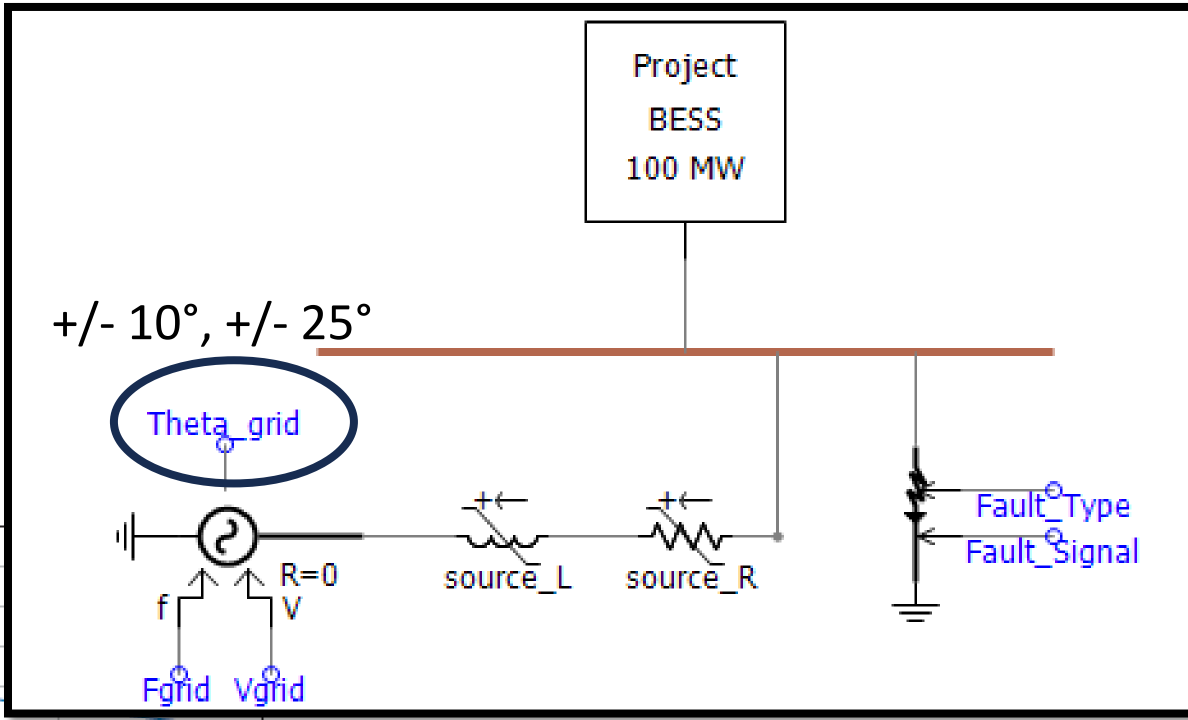


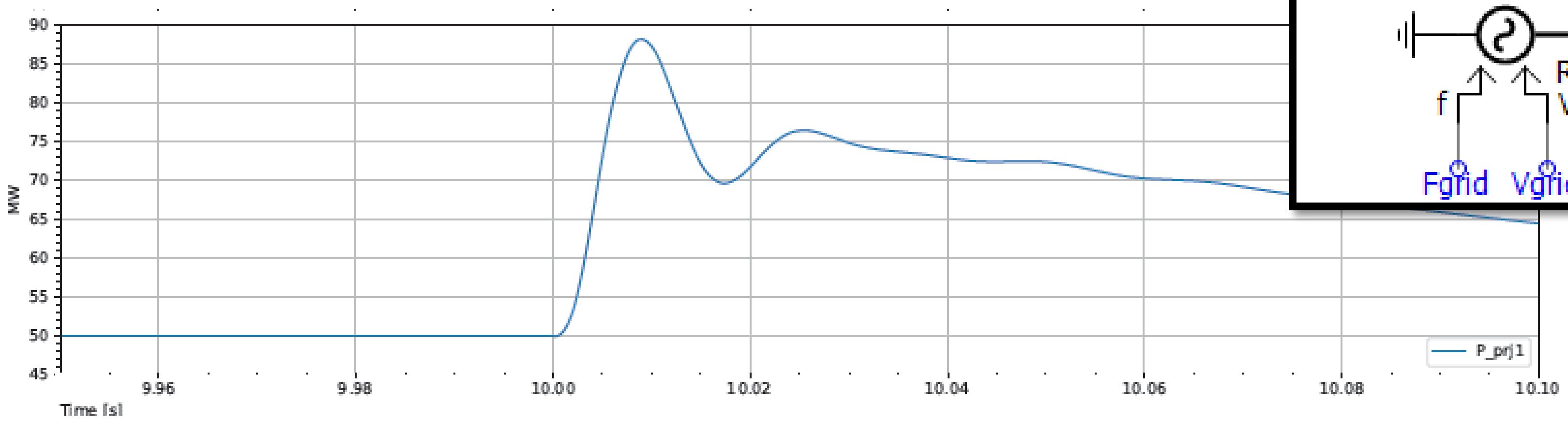
Test 6 (SCR Ramp Down with Fault) – Setup and Success Criteria (Testbench 1)	
Testbench setup	
Initial SCR at connection point is set to 20. System Equivalent X/R is set to 6.	
Initial dispatch of generation is 100% of nominal power.	
Only the project plant, no duplicate.	
Test Sequence:	
SCR at connection point stepped down repeatedly in this progression: 20, 10, 3, 2, 1.5, 1.25	
A 3 phase bolted 6-cycle fault is applied just before each SCR transition. The SCR transition occurs at fault clearing time	
Success Criteria	**Pass/Fail**
a. Plant real and reactive power output should be well controlled and plant should not trip or reduce power (outside of the fault period) for any extended period of time down to an SCR of 1.25	

Test 7 (Angle step change) – Setup and Success Criteria (Testbench 1)	
Testbench setup	
SCR at connection point is set to 3, system equivalent X/R ratio is set to 6	
Only the project BESS, no duplicate.	
The following initial active and reactive power scenarios will be considered for the GFM plant: 1. P=50%, Q=approximately zero 2. P=max, Q=approximately zero	
Test Sequence:	
1. Angle of the voltage source behind the equivalent grid impedance is decreased instantaneously by 10 degrees	
2. A few seconds later, angle of voltage source is increased by 10 degrees	
3. A few seconds later, repeat steps 1 & 2 with a +/- 25 degree phase angle change	
Success Criteria	**Pass/Fail**
a. Instantaneous active power output of the plant should quickly respond to oppose the angle change for each of the 10 degree voltage phase angle jumps , with a peak active power change of at least 0.2 pu on the rated active power base (e.g. a 100 MW rated plant should temporarily increase active power output from 50 MW to at least 70 MW when source voltage angle is decreased by 10 degrees, and should temporarily decrease active power from 50 to 30 MW or below when voltage source angle is increased by 10 degrees) **Note:** If the plant is on a limit and the phase jump is larger than 10 deg and in the direction towards exceeding its limit, above initial power jump criteria may not apply.	
b. For each of the 10 degree voltage phase angle jumps, response time to 90% of initial change in instantaneous active power should occur within 15 ms	
c. Active power does not return to the pre disturbance level within 50 ms	
d. if active power / current reaches limits for the 25 degree phase change, the plant should return to pre-event power levels in a stable manner.	
e. Any oscillation shall be settled.	
f. Any distortion observed in phase quantities should dissipate over time.	

Test #7: Angle Step Change (pass/fail)

- Testing GFM core functions
- Step changes in system angle
- GFM power expected to respond within 15 mS and be sustained for at least 50 mS for 10 degree step

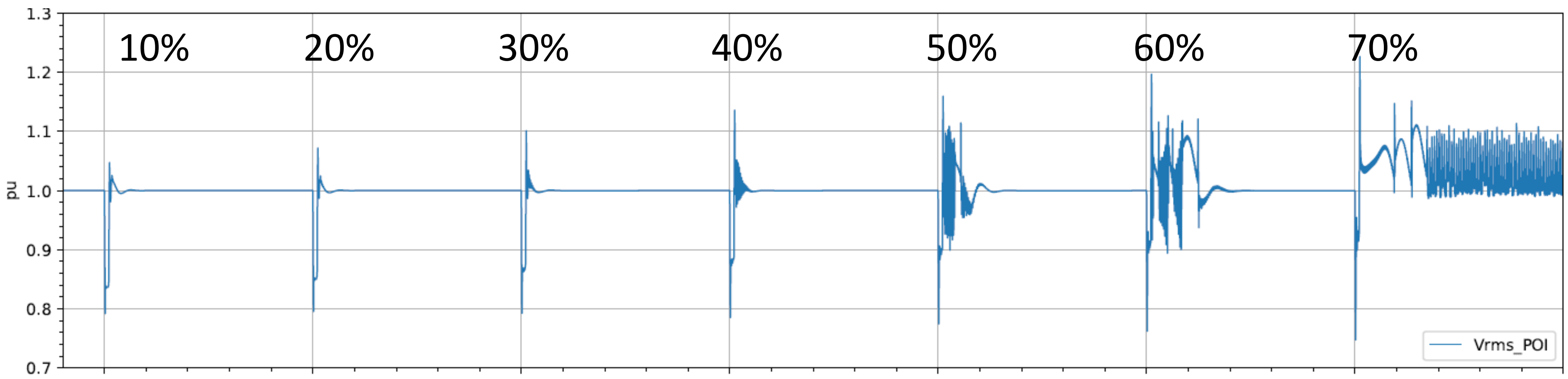




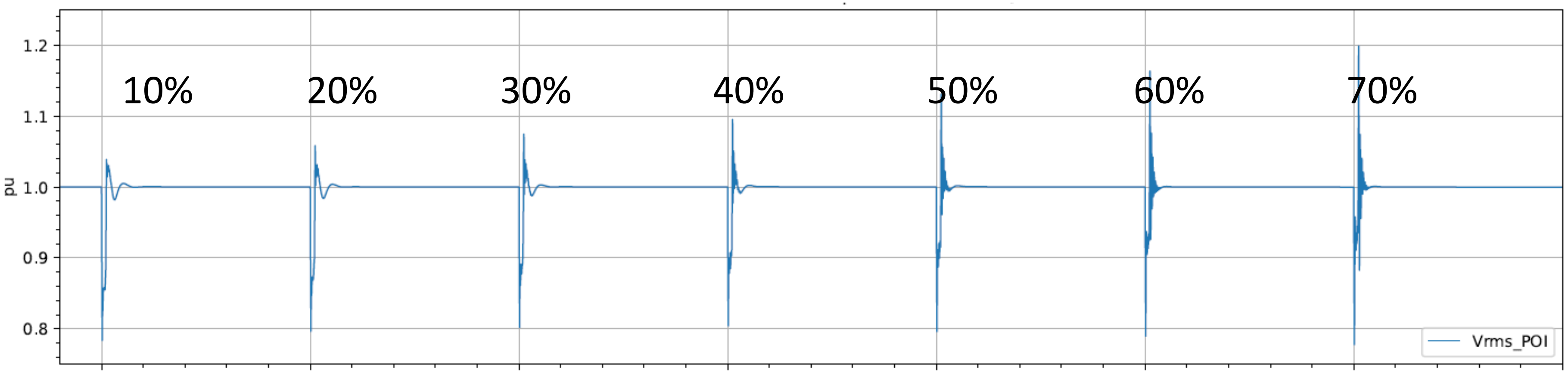
Test 8 (Series Compensation Step Test) – Setup and Success Criteria (Testbench 3)	
Testbench setup	
Initial SCR at connection point is set to 5 (capacitor bypassed).	
Initial X/R ratio at connection point is set to 15 (capacitor bypassed).	
Series capacitor should be initially by-passed and configured to compensate for 10% of the network equivalent X when first un-bypassed.	
The following initial active and reactive power scenarios will be considered for the GFM plant: 1. P=max, Q=approximately zero 2. P=min (if PV or Wind) P=0 (if BESS), Q=approximately zero 3. P=max charge (if BESS), Q=approximately zero	
Only the project plant, no duplicate	
Test Sequence:	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Apply balanced high impedance (resistive) fault at POC, (approximate retained voltage 0.9 pu)	
3. Clear fault after 3 cycles and un-bypass series capacitor (initially 10% compensation)	
4. Simulate 5 seconds following fault inception	
5. Repeat fault in step 2.	
6. Clear fault after 3 cycles and increase the compensation level by 10%	
7. Repeat fault in step 4.	
6. Repeat step 5-7, incrementing compensation by 10% each time until total compensation level is 70%. *Note: As series capacitance is added, SCR will increase and X/R will decrease. In addition, the series resonant frequency of the grid impedance will become higher with approximate range of 20 Hz - 50 Hz (Series resonance frequency of the entire test setup including the impedances between POI and terminal will be approximately around 13 Hz - 35 Hz).*	
Success Criteria	**Pass/Fail**
a. Plant real and reactive power output should be well controlled and plant should not trip or reduce power for any extended period of time at any compensation level.	
b. Oscillations should be damped across the tested range of series compensation	
Note: Unstable levels of series compensation are not expected or allowed, but if they are identified, they may be compared against the frequency scan results from Test 11.	

Test 8: Series Compensation

- GFL...



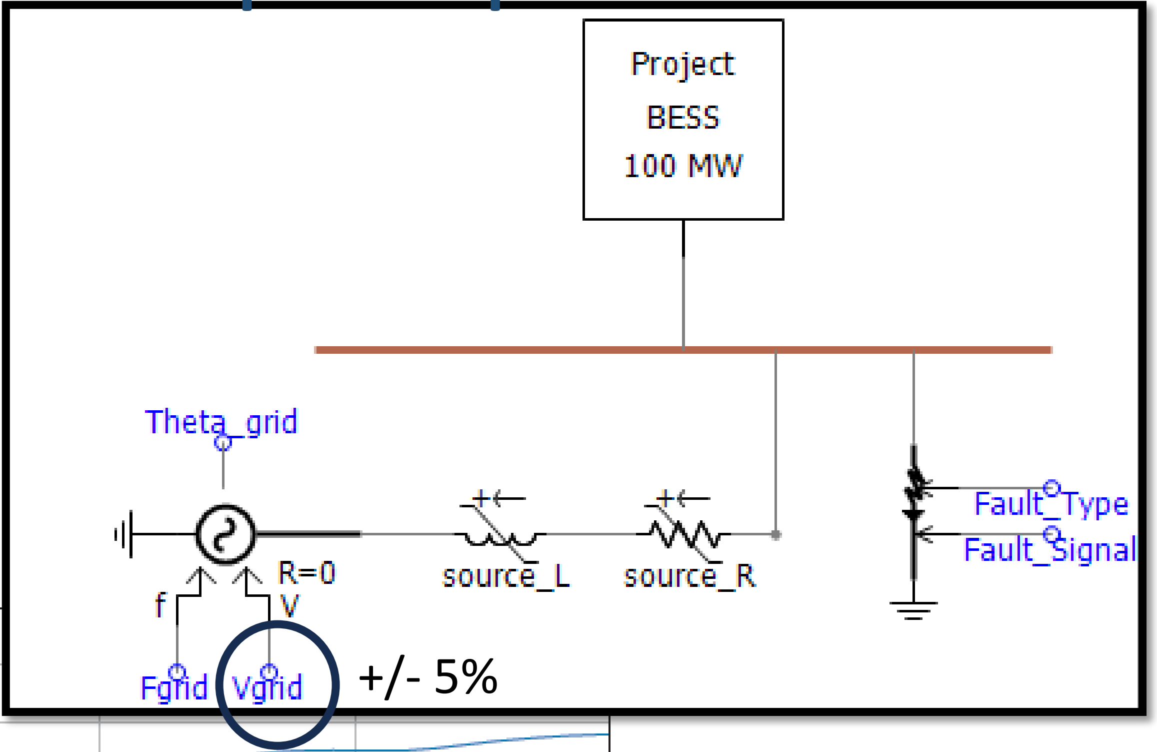
- GFM!

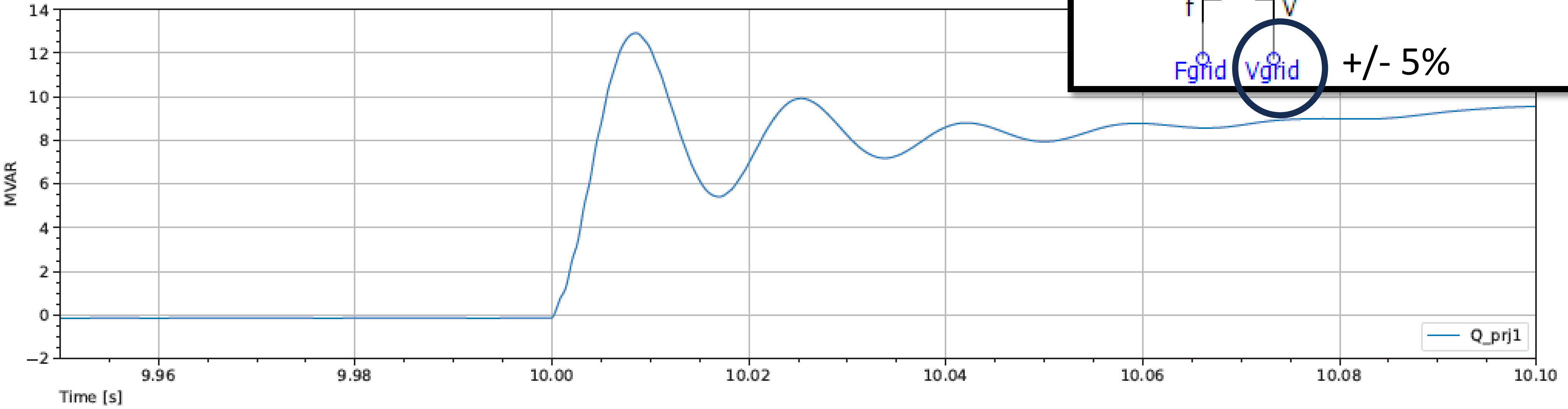


Test 9 (Voltage magnitude step change) – Setup and Success Criteria (Testbench 1)	
Testbench setup	
SCR at connection point is set to 3, system equivalent X/R ratio is set to 6	
Initial dispatch of generation is 100% of nominal power.	
Only the project BESS, no duplicate.	
Test Sequence:	
1. Magnitude of the voltage source behind the equivalent grid impedance is decreased instantaneously by 5%	
2. A few seconds later (once the transient is settled), magnitude of voltage source is increased by 5%	
Success Criteria	**Pass/Fail**
a. Instantaneous reactive power output of the plant should quickly respond to oppose the voltage step change for each of the 5% voltage steps, with a initial peak reactive power change of at least 0.05 pu on the rated power base (e.g. a 100 MW rated plant with 0 MVAR initial output should temporarily increase reactive power output from 0 MVAr to at least 5 MVAr when source voltage magnitude is decreased by 5%). **Note**: The initial peak reactive power change may affect (and may not meet the success criteria) for plants with large collector system reactance and/or filter reactance.	
b. For each of the 5% voltage steps, response time to 90% of initial change in instantaneous reactive power should occur within 15 mS	
c. Reactive power does not return to the pre disturbance level within 100 ms. Note: This test assumes that the PPC is in voltage control mode. Adjustments for this test may be required for very fast or otherwise unusual PPC configurations.	
e. Any oscillation shall be settled.	
f. Any distortion observed in phase quantities should dissipate over time.	

Test #9: Voltage Magnitude Step Response (informational)

- Informational test, assists in confirming GFM core functions
- +/- 5% step changes in system voltage
- GFM power expected to respond within 15 mS and be sustained for at least 100 mS





Test 10 (Energy Response Test)– Setup and Success Criteria (Testbench 1)	
Testbench setup	
SCR at connection point is set to 3. System Equivalent X/R is set to 6.	
Initial dispatch of generation is 50% of nominal power.	
Only the project plant, no duplicate.	
Test Sequence:	
1. Ramp down the frequency from 60 Hz to 59 Hz at -1 Hz/s.	
2. Ramp up the frequency from 60 Hz to 61 Hz at +1 Hz/s.	
Success Criteria	**Comments**
a. Energy Constant (calculated as below) should be greater than 2.5 $Energy\ Constant = \frac{\Delta E}{RoCoF}$ $Where;$ $\Delta E = Area\ under\ the\ \Delta P\ (pu)\ curve\ (i.e.\ P - P_{Pre-Disturbance})\ for\ a\ period\ of\ 0.5s\ from\ RoCoF\ application\ (pu.s)$ $RoCoF = 1/60\ (pu/s)$	
b. Plant real and reactive power output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels for any significant amount of time.	
c. Voltage settles to a stable operating point when frequency is not ramping	
d. Active power should settle according to its frequency droop and deadband settings when frequency is not ramping	
e. Any oscillation shall be settled.	

Test 11 (Frequency Scan Tests) – Setup and Success Criteria (Testbench 4)	
Testbench setup	
Connect the plant under test to an ideal 3-phase voltage source set at rated Point of Interconnection (POI) voltage and nominal frequency.	
The following initial active and reactive power scenarios will be considered for the GFM plant: 1. P=max, Q=approximately zero 2. P=min (if PV or Wind) P=0 (if BESS), Q=approximately zero 3. P=max charge (if BESS), Q=approximately zero	
Test Sequence:	
Perform impedance scans between 1 Hz and 120 Hz according to procedures described in Appendix 1	
Perform Q/V frequency scans between 1 Hz and 120 Hz according to procedures described in Appendix 1	
Success Criteria	**Comments**
Impedance Scan: Typical impedance response of a Grid Forming Converter: Resistance is positive between zero and 50 Hz.	
Q/V Scan: A region with flat Q/V response (in both magnitude and angle) should be identified. The angle of Q/V response within the flat region (identified above) should be around 180 degrees.	

Rationale for Energy Response criteria

Per the swing equation, inertia will be H = (ΔP- D*Δw) /(2*ROCOF), ΔP = ΔE/t and t = 0.5 s, therefore, ΔP = 2*ΔE, and H = ΔE /ROCOF (if D is neglected). In other terms, the above equation will calculate the actual inertia of a synchronous machine if the area measurement is taken during the steady state of the ROCOF (i.e once the initial transient is settled). Note that the inertia measurement used in this test is a function of time, not a strict inertia calculation, and may better be termed "energy response." In the future, a more detailed criteria may be required to merge energy response/inertia and frequency response capability.

In the success criteria:

- 0.5 s duration is selected to distinguish the actual inertia/energy response vs typical frequency response (i.e. PFR or FFR response). Beyond 0.5 seconds, the PPC may enter the control, and we are testing a more general frequency response.

- 2.5 is a theoretical choice to distinguish GFM from GFL. The number is selected as per the droop-based GFM inverter with droop considered to be less than or equal to 5%.

Rationale for 15ms response time for P

In Test 1, the response time to 90% of the initial change in instantaneous active power must be within 15 ms.

These numbers were selected based on Test 7 (phase angle jump). Any change in the electrical characteristic of a voltage source-based system will result in immediate power changes. If there are no energy storage components in the circuit (i.e. capacitors, inductors), this change should happen within one time step. In reality, this could be few milliseconds. 15 ms is based on a worst-case impedance of the network between POC and inverter terminals (see note b below).

a. Instantaneous active power measurement should not have a filtering delay of more than 0.001s in order to adequately observe the peak, which may only be visible very briefly.

b. Success criteria was selected such that even a plant with an extreme impedance up to 40% (on plant MW rating base, X/R of 8) can meet the criteria.

c. This criterion may not be as important for Test 1 as it is for Test 7, however, leaving such performance requirements in Tests 1-4 may improve the general quality of control response.

Rationale for choice of SCR levels

For some tests (eg. angle step change), the degree of change in power is dependent on the system impedance. It must be precisely defined for any quantitative evaluation to be made, and a value needed to be chosen. Generally, this value was selected to provide a reasonably weak connection (eg. 3.0), while not being so weak that other factors would begin to impact or complicate the tests.

In other tests (eg. test 8 – series compensation), the SCR will change from the beginning of the test to the end, and so values need to be selected that are reasonable throughout the range of the test.

For test 6 – SCR reduction test, it is important to test at the extreme ends to ensure stability in both strong and weak systems.

Rationale for <100ms and >50ms time thresholds for return to pre-disturbance (tests 9 and 7).

In GFL inverters, the current may respond briefly as a GFM converter before the phase tracking control engages, but will be quickly controlled such that the real and reactive powers return to pre-disturbance (approximately) levels before 100ms in the case of Test 9. This applies as well in the Case of Test 7 (angle step), but requiring a minimum time to recover imposes a sort of energy response shape on the controls that is difficult for GFL.