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

January 2024

A set of simulation test methods to guide the assessment of a grid-forming inverter's compliance to the core capabilities in AEMO's May 2023 'Voluntary Specification for Grid-forming Inverters'

Important notice

Purpose

AEMO has prepared this document to provide information about testing grid-forming inverters to the core requirements set out in the Voluntary Specification for Grid-forming Inverters[1], as at the date of publication.

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[1] AEMO. 2023 Voluntary Specification for Grid-forming Inverters, May 2023. At https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E

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1 Introduction

1.1 Context

As the generation mix in Australia's power systems shifts away from synchronous machines toward inverter-based resources, the technologies and processes that maintain its stable operation also need to evolve. Grid-forming inverters (GFMI) with a firm energy source behind them may be able to replace many of the capabilities historically provided by synchronous generators.

In order to increase the pace of GFMI integration, there is urgent need for industry alignment on the specification of GFMI and testing frameworks for proving compliance.

1.2 Background

In May 2023, AEMO published the *Voluntary Specification for Grid-forming Inverters*[2] (Voluntary Specification) as a statement of voluntary threshold requirements for 'core' technical capabilities that power electronic devices should have in order to be categorised as grid-forming inverters. It also described the 'additional' technical capabilities which, although often desirable, may not be required from all grid-forming inverters.

The Voluntary Specification provides qualitative descriptions of these core and additional capabilities, and does not present methods to evaluate performance against these capabilities. To further progress the integration of GFMI in Australia, it was identified that the key next step of this work should be the development of a test framework to quantitatively evaluate performance of GFMI against the core capabilities in the specification.

1.3 Purpose

This 'Test Framework for Grid-forming Inverters' provides an informative framework for testing equipment and control modes in simulation, to determine whether they can meet the requirements of the core capabilities listed in the Voluntary Specification and thereby provide the benefits expected from GFMI topologies.

This document accompanies the Voluntary Specification as a preliminary set of documents to provide guidance to stakeholders while the regulatory environment around grid-forming technology develops.

1.4 Scope

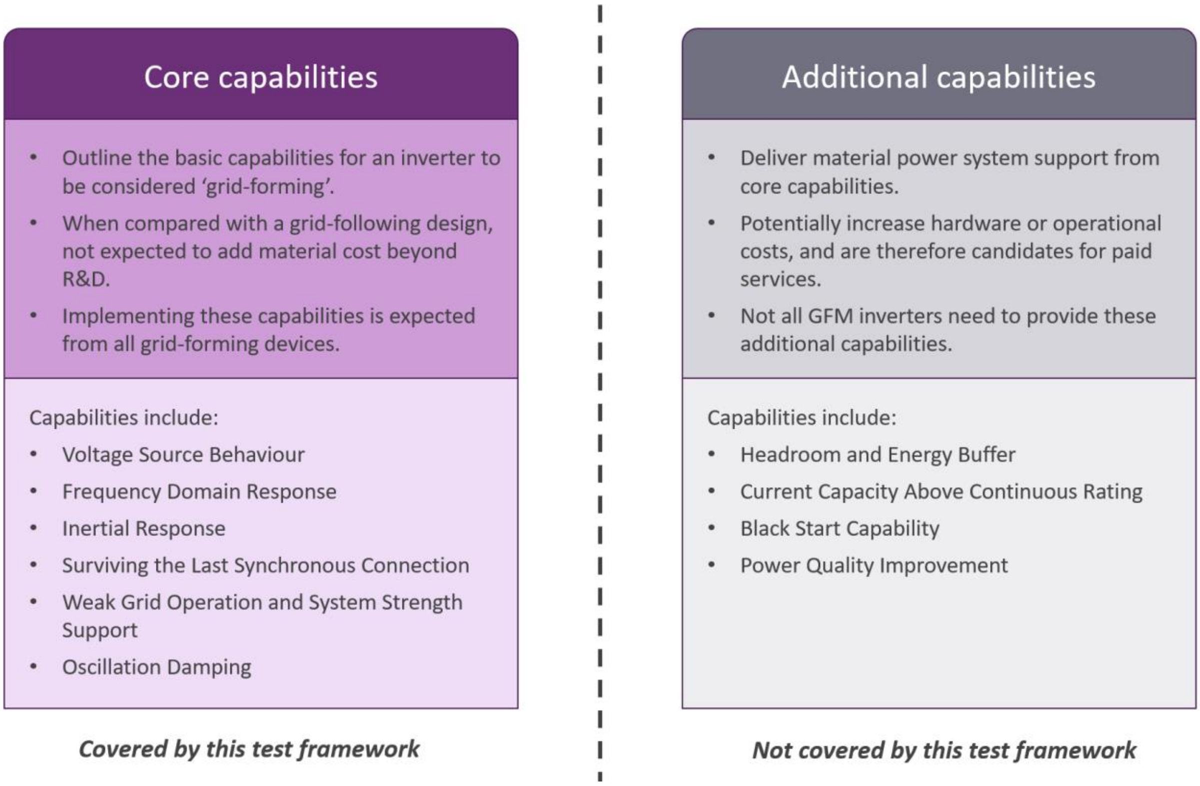
The test framework outlined in this document provides a minimal set of simulation tests which may be used to determine whether a GFMI resource meets the criteria set out as core capabilities in the Voluntary Specification, summarised in Figure 1. Each test is presented with a reference to:

- The Voluntary Specification
- A described simulation testbench

[2] At https://aemo.com.au/newsroom/news-updates/aemo-report-highlights-electric-vehicle-benefits-and-challenges?sc_site=Corporate

- Testbench configuration
- Criteria for assessment.

Figure 1 Coverage of capabilities from Voluntary Specification



The intended audience for this document is original equipment manufacturers (OEMs) and project developers of GFM plant, and any other stakeholders involved with planning, running, or reporting on GFMI performance in the project planning phase. Although voluntary in nature, this document may also be of relevance to parties seeking to procure services from GFMI, who may wish to incorporate elements of this framework into agreements with GFM plant developers and operators.

It is critical to note that this framework is in addition to existing performance requirements, such as those specified in the National Electricity Rules (NER), and does not seek to substitute or replace those requirements. These tests are specifically designed to evaluate GFMI capability, and many other tests are required to establish the plant's overall performance and confirm conformance with NER technical requirements.

Ideally, it is desirable for a full specification to have measurable assessment criteria against all tests. However, this document seeks to strike a balance between providing clear assessment criteria against the need to provide some flexibility as GFMI control methodologies, and industry understanding of them, evolves. In this document AEMO has aimed to avoid introducing unrealistic thresholds or creating bounds that could limit future innovation. The thresholds and bounds presented in the assessment criteria are primarily based on engineering judgement rather than any specific regulatory requirements, and are provided for guidance only at this time.

This document does not intend to validate a specific plant's grid forming capability under all network or operational conditions. Instead, it defines a minimum set of tests that can be used to assess an inverter's ability to meet the core threshold requirements. Parties seeking to demonstrate or require performance criteria from a GFM plant will need to consider further tests or requirements to meet their specific needs, such as:

- Additional capabilities as listed in the Voluntary Specification
- Regulatory requirements relevant to the plant's point of connection
- Service specifications

While AEMO aims to be technology agnostic in specifying GFM technology, some of the tests described in this document may necessitate that the inverter is paired with a sufficient source of stored energy, such as a battery energy storage system (BESS). As such, for technologies without reasonable energy storage behind the inverter, this document can be considered as an informative base for future development of a specification with broader application as the maturity of other technologies progresses.

1.5 How to get involved

Stakeholders wishing to provide feedback on this document, to actively contribute to future work, or to be notified of future updates on AEMO's grid-forming inverter work can contact AEMO at FutureEnergy@aemo.com.au.

2 Test systems

2.1 Simulation testbench summary

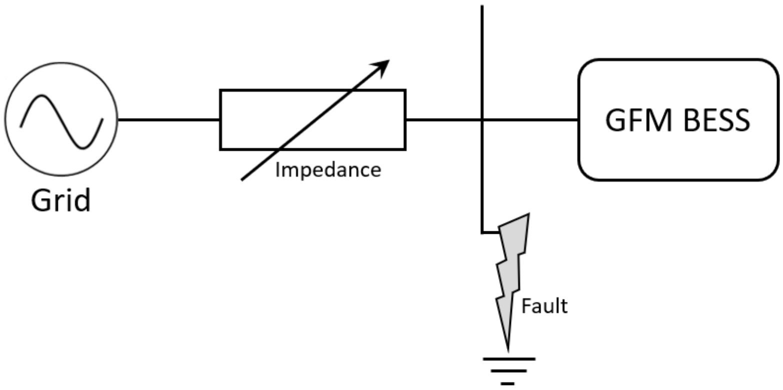
In order to specify tests on a GFM plant, first it is necessary to describe the test systems which must be created. There are 3 test systems which are referred to in this framework, summarized as follows:

- Testbench 1: Single Machine Variable Impedance (SMVI) system – This is a voltage source behind an impedance with precise control over voltage magnitude, frequency, angle, and the impedance in series with the source.
- Testbench 2: Simplified network with load – This is a simple power system testbench consisting of a synchronous machine, a constant impedance load, and a copy of the GFMI device under test.
- Testbench 3: 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 “impedance scans” to determine the frequency-variant impedance characteristics of the controls.

2.2 Testbench 1: Single Machine Variable Impedance (SMVI)

The test system used for Testbench 1 consists of an ideal voltage source connected to the device being tested through a controllable series impedance, as well as a variable impedance fault component shown in Figure 2. The source must have inputs for voltage (including magnitude, phase, and frequency), and the series impedance must be variable such that the connection point strength and voltage may be set.

Figure 2 Testbench 1 (SMVI) test system example

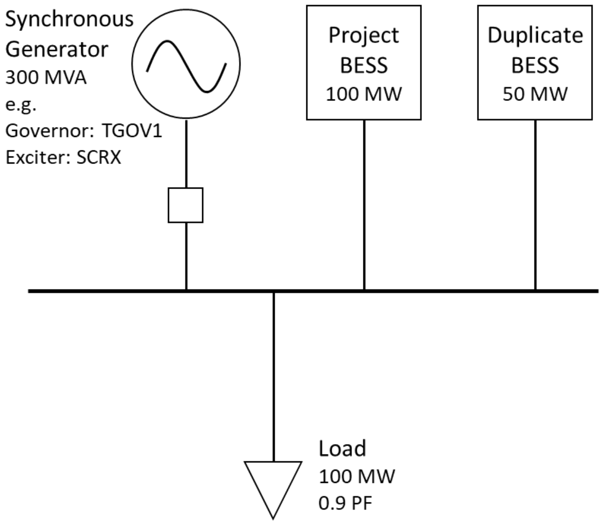


2.3 Testbench 2: Simplified network with load (SNWL)

The test system used for Testbench 2 is described in the draft guideline produced by NERC in March 2023[3]. The system (see Figure 3) consists of the following components connected to a single bus without any impedance:

- A synchronous generator with a simple excitation system model (e.g. SCRX) and turbine-governor model (e.g. TGOV1), with circuit breaker to disconnect the generator.
- A constant impedance load with both active and reactive power (inductive) components, with a maximum power factor of 0.9.
- The Grid-forming (GFM) plant model under test.
- A duplicate of the GFM plant model, rated at or near half (MVA and MW) of the model. It is presumed that the original (fully rated) GFM plant is representative of the device being tested, however both the fully rated and half rated devices are needed to determine whether the device will perform as expected. Separate models for each can be used, or one model may be scaled down to half-rating if appropriate. The half-rated model is used in these tests to demonstrate effective coordination of multiple GFM devices, as well as to allow one plant to be dispatched at a limit while the other carries load balancing burdens.

Figure 3 Testbench 2 (SNWL) test system example configured for a 100 MW GFM BESS [AB]



A.BESS ratings and synchronous generator ratings are for example only.
B.NERC. 2023 White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems, September 2023 At https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf

The combined MVA rating of the GFM plant models must be sufficient to fully supply the load upon disconnection of the synchronous generator. The synchronous generator MVA rating must be sufficient to simultaneously serve the load and charge both the GFM plants at their rated maximum charge power. For the purposes of this test system, both GFM plant models should be in voltage control mode with the same voltage and frequency droop settings and set points. All protection settings in the GFM plant should reflect the equipment planned to be installed in the field; however, settings should be set as wide as possible within the equipment ratings and

[3] NERC. Draft Whitepaper “Defining Grid Forming Capability in Interconnection Requirements for BPS-Connected Battery Energy Storage Systems – Functional Specifications, Verification, and Modelling”, June 2023. At https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf

capabilities since the tests are intended to subject the GFM plant to extreme frequency, voltage, and phase jump events.

2.4 Testbench 3: Perturbed voltage source (PVS)

This testbench is intended to be used for the (informational) impedance scan method described in Appendix A2, and is not required for the seven tests defined in Section 3.

Power electronic systems (PES) are widely used in modern power systems in different forms, such as wind turbine systems, solar/PV systems, battery energy systems, HVDC and FACTS devices. These PES are equipped with fast controllers that can interact with the electrical network over wide frequency ranges. Such interaction can be unstable and requires detailed study and analysis.

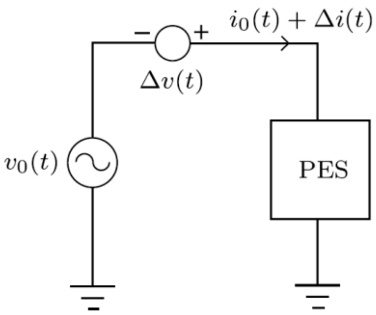
Most of these oscillations are small-signal instabilities and can be analysed using linear system analysis techniques like the state-space method. In realistic scenarios, building a state-space model of a system with PES is problematic and to certain extent impossible as most PES controllers are vendor provided black-box models. Even if the controller is known, writing equations for building a state-space model is difficult as these PES controllers are not standardised and an additional step of linearisation is required as PES are non-linear systems.

Impedance scanning as described in the Voluntary Specification is a pragmatic approach of obtaining a small-signal model of PES from a time-domain simulation. In this method, a small voltage at a particular frequency is used to perturb the system in the time-domain simulation and the corresponding output current is recorded. Using discrete Fourier transform (DFT) on the perturbed voltage and the output current, the corresponding frequency components are extracted, and the admittance/impedance of the system can be calculated at that frequency.

Figure 4 shows a PES connected to an ideal voltage source $v_0(t)$. At steady state, a perturbation voltage (Δv(t)) of small magnitude is applied in series with the voltage source. The corresponding current $i_0(t) + \Delta i(t)$ is recorded where $i\_0(t)$ is the nominal steady state current and $\Delta i(t)$ is the small change in the current due to small voltage perturbation. Using DFT on applied voltage and the output current, the admittance/impedance frequency response can be calculated as given below.

$$Y(j\omega) = \frac{\Delta I(j\omega)}{\Delta V(j\omega)} \ or \ Z(j\omega) = \frac{\Delta V(j\omega)}{\Delta I(j\omega)}$$

Figure 4 A PES connected to an ideal voltage source



2.5 Testing assumptions

The following assumptions are implicit in the proposed tests:

- Model quality should be high (usable and accurate), and in accordance with AEMO requirements[4]. Discussion of Control Hardware-In-the-Loop (CHIL) for performance benchmarking is included in Appendix A1.
- While the Framework does not test for compliance to requirements under Schedule 5.2 of the National Electricity Rules (NER) [5], it does assume that the plant can meet existing requirements for GFL interconnections according to the NER, including but not exclusively:
  - Fault ride through and recovery
  - Voltage control
  - Frequency control
  - Stability

Note that the Framework does not seek to replace or substitute those requirements specified in the NER.

The tests assume the performance inherently possible with BESS or hybrid plants with BESS. GFMI candidates with limited energy storage or with limited ability to adjust their active power output may not be able to perform tests 1, 2 and 3 as described, but may be able to perform acceptably during all other tests. Such devices may include E-STATCOMs, synchronous condensers, and possibly future PV and wind technologies.

Discussion on the use of generic GFL inverters in test systems

The AEMO Voluntary Specification states that a GFM inverter should provide system strength support to nearby grid-following (GFL) inverters and enhance their stable operation during and following power system disturbances.

The set of tests specified in this document do not seek to explicitly demonstrate GFM plant stabilising GFL plant. Such a test would be difficult to design and tune in a way that robustly proved system strength contribution from the grid-forming plant, due to the diversity of potential drivers and modes of instability in GFL plant.

Instead, in aggregate, the set of tests is designed to show that the GFM plant meets the core requirements set out in the Voluntary Specification. Plant that complies with all the tests in section 3 is considered to be inherently capable of providing system strength, which in turn could help stabilise nearby GFL plant. Any specific stability considerations for a given point of connection will need to be discussed as part of the connection process.

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[4] As defined in AEMO. 2018 Power System Model Guidelines, Final report and determination, June 2018. At https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-security-market-frameworks-review/2018/power_systems_model_guidelines_published.pdf?la=en&hash=A3DDF450DBEE1E7C1D7E2E379461538A

[5] AEMC. 2023 National Electricity Rules (NER) Version 200, May 2023. At https://energy-rules.aemc.gov.au/storage/rules/84ed4172617975de6c9e693eac6bd32d78edc04c/assets/files/NER%20-%20v200%20-%20Contents_cover.pdf

3 Grid-forming inverter simulation tests

In order to successfully be deemed GFMI according to the AEMO Voluntary Specification, the following core capabilities must be present. Additional capabilities are possible and are discussed in the Voluntary Specification but are not tested in this framework.

Table 1 Voluntary specification core capabilities

Core Function Reference	Description
A	Voltage Source Behaviour[6]
B	Frequency Domain Response
C	Inertial Response
D	Surviving the Last Synchronous Connection
E	Weak Grid Operation and System Strength Support
F	Oscillation Damping[7]

To verify the GFMI capability of a plant according to the Voluntary Specification core requirements, the following tests should be conducted. Appendix A3 provides example results. Beyond the scope of the Voluntary Specification, additional tests may be needed on a case-by-case basis to further demonstrate specific capabilities or to address local concerns. These tests are intended to provide a general confidence that the plant meets the definition of GFM as laid out in the Voluntary Specification. They will not be sufficient in every case to determine whether a specific GFM topology or configuration is suitable for a specific purpose, particularly for sites with special requirements. They will not in isolation confirm whether the plant is compliant with all relevant performance requirements for interconnection, and the following requirements may also apply:

- National Electricity Rules (NER)
- Dynamic Model Acceptance Test (DMAT) Guideline

Table 2 shows a summary of the tests outlined in this section. Each of these tests is defined in further detail below. Tests 1-7 are intended to provide complete coverage of core functions A-F described in Table 1, noting that each test evaluates aspects of performance for multiple core functions. To be compliant with the Voluntary Specification core requirements, a GFMI must pass all tests 1-7.

Table 2 Summary of GFMI Tests

Test Number	Test Name	Testing for	Core Function Reference	Testbench System
1	Loss of synchronous machine – discharging	GFMI basic functions (BESS only)	A,C,D,E,F	2 - SNWL
2	Loss of synchronous machine – charging	GFMI basic functions (BESS only)	A,C,D,E,F	2 - SNWL
3	Loss of synchronous machine – limits	GFMI basic functions, limits (BESS only)	A,C,D,E,F	2 - SNWL

[6] As described in: S. Shah, et al, “A Testing Framework for Grid-Forming Resources.” 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA

[7] For the purpose of this document, oscillation damping here refers to damping in sub-synchronous range.

Test Number	Test Name	Testing for	Core Function Reference	Testbench System
4	Loss of synchronous machine – power balance	GFMI basic functions	A,C,D,E,F	2 - SNWL
5	RoCoF up and down	Control stability	C,E	1 - SMVI
6	SCR ramp down with fault	Control stability	A,C,E,F	1 - SMVI
7	Angle step change	GFMI basic functions	A,C,E,F	1 - SMVI
Appendix A2	Impedance scan[8]	(Informational) Damping, impedance trend and system strength support	B,F	3 - PVS

3.1 Test 1 – Loss of Synchronous Machine – Discharging

Tests 1 through 3 have been proposed in the June 2023 NERC Whitepaper[9] as applicable to GFM BESS. When correctly applied, these tests are suitable to confirm basic grid-forming characteristics of a BESS resource. Note that these tests are not directly applicable to non-BESS GFM resources.

Table 3 Protocol for Test 1 – Loss of Synchronous Machine – Discharging

Test 1 (Loss of synchronous machine - discharging) – Setup and Success Criteria Testbench 2	
Initial Dispatch	
• 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 is set to 100% of the project 1[10] active power limit, with a power factor of 0.95.	
• The synchronous machine is supplying 100% of the reactive power to the load.	
Test Sequence:	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the synchronous generator (no fault).	
Success Criteria	
Pre-Trip:	**Pass/Fail**
a. Both plants active power outputs match dispatched levels.	
b. Synchronous generator active power output matches the rest of the load.	
c. Frequency is 1 pu.	
d. Voltage at Bus 1 should be within 5% of nominal.	
e. There should not be oscillations in the RMS quantities.	
f. Reactive power output from all devices should be within limits.	

[8] This test has been included as an Appendix as this area of work is still in an early stage of its development. Understanding is still maturing across the engineering community.

[9] Draft NERC Whitepaper "Defining Grid Forming Capability in Interconnection Requirements for BPS-Connected Battery Energy Storage Systems – Functional Specifications, Verification, and Modelling." June 2023

[10] Nominated as 'Project BESS' in the example test bed shown in Figure 3

Test 1 (Loss of synchronous machine - discharging) – Setup and Success Criteria Testbench 2	
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 any significant amount of time.	
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 adequately damped in line with definition presented in the NER[11].	
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[12] should occur within 50ms[13].	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. 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.	

3.2 Test 2 – Loss of Synchronous Machine – Charging

Table 4 shows the sequence of events applied to testbench 2, including success criteria.

Table 4 Protocol for Test 2 – Loss of Synchronous Machine – Charging

Test 2 (Loss of synchronous machine - charging) – Setup and Success Criteria Testbench 2
Initial Dispatch
• 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 is set to 50% of the project 1 active power limit, with a power factor of 0.95.
• The synchronous machine is supplying 100% of the reactive power to the load.
Test Sequence:
1. Run until the system is stable at the given power flow conditions, without oscillations.
2. Trip the synchronous generator (no fault).
Success Criteria

[11] AEMC. 2023 National Electricity Rules (NER) Version 200, May 2023. At https://energy-rules.aemc.gov.au/ner/477/glossary/a.

[12] 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.

[13] Site specific response may need to be slower to ensure system security. Intent is to ensure inherent initiation of active power response.

Test 2 (Loss of synchronous machine - charging) – Setup and Success Criteria Testbench 2	
Pre-Trip:	**Pass/Fail**
a. Plants active power outputs match dispatched levels.	
b. Synchronous generator active power output matches the rest of the load.	
c. Frequency should be 1 pu.	
d. Voltage at Bus 1 should be within 5% of nominal.	
e. There should not be oscillations in the RMS quantities.	
f. Reactive power output from all devices should be within limits.	
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 any significant amount of time.	
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 adequately damped in line with definition presented in the NER[14].	
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 50ms[15].	
i. Reactive power from each plant should move immediately and settle according to its voltage droop setting.	
j. Voltage should not deviate outside of [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.	

3.3 Test 3 – Loss of Synchronous Machine – Limit Test

Table 5 shows the sequence of events applied to testbench 2, including success criteria.

Table 5 Protocol for Test 3 – Loss of Synchronous Machine – Limit

Test 3 (Loss of synchronous machine - limit test) – Setup and Success Criteria
Initial Dispatch
• The project plant is dispatched at 0 MW.
• The duplicate plant is dispatched at its maximum discharge power limit.
• The load is set to 100% of the project 1 active power limit, with a power factor of 0.95.

[14] AEMC. 2023 National Electricity Rules (NER) Version 200, May 2023 At https://energy-rules.aemc.gov.au/ner/477/glossary/a

[15] Site specific response may need to be slower to ensure system security.

Test 3 (Loss of synchronous machine - limit test) – Setup and Success Criteria	
• The synchronous machine is supplying 100% of the reactive power to the load.	
Test Sequence:	
1. Run until the system is stable at the given power flow conditions, without oscillations.	
2. Trip the synchronous generator (no fault).	
Success Criteria	
Pre-Trip:	**Pass/Fail**
a) Plants active power outputs match dispatched levels.	
b) Synchronous generator active power output matches the rest of the load.	
c) Frequency should be 1 pu.	
d) Voltage at Bus 1 should be within 5% of nominal.	
e) There should not be oscillations in the RMS quantities.	
f) Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
a) Immediately following the trip, plants 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.	
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 adequately damped in line with definition presented in the NER[16].	
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 50ms. Active power from the duplicate plant should not exceed its max discharge power limit at steady state. Duplicate plant output may exceed temporarily 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) Voltage should not deviate outside of [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.	

3.4 Test 4 – Loss of Synchronous Machine – Power Balance

Test 4 is very similar to Tests 1-3, except it is configured with zero power in and out of the synchronous machine, such that the GFM device and load is balanced. This test is more feasible for GFM devices with very little energy storage or active power margin than tests 1-3.

[16] AEMC. 2023 National Electricity Rules (NER) Version 200, May 2023 At https://energy-rules.aemc.gov.au/ner/477/glossary/a

Table 6 Protocol for Test 4 – Loss of Synchronous Machine – Power Balance

Test 4 (Loss of synchronous machine – power balance)– Setup and Success Criteria Testbench 2			
Initial Dispatch			
•	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 is set to 75% of the project 1 active power limit, with a power factor of 0.95.		
•	The synchronous machine is supplying 100% of the reactive power to the load.		
Test Sequence:			
1.	Run until the system is stable at the given power flow conditions, without oscillations.		
2.	Trip the synchronous generator (no fault).		
Success Criteria			
Pre-Trip:			**Pass/Fail**
a.	Plants active power outputs match the load.		
b.	Synchronous machine active power output is zero or close to zero.		
c.	Frequency should be 1 pu.		
d.	Voltage at Bus 1 should be within 5% of nominal.		
e.	Phase voltage and current waveform should not be distorted.		
f.	There should not be oscillations in the RMS quantities.		
g.	Reactive power output from all devices should be within limits.		
Post-Trip:			**Pass/Fail**
a.	Immediately following the trip, plants 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.		
c.	The final voltage is as expected based on the droop and deadband settings.		
d.	Frequency settles to nominal.		
e.	Any oscillation shall be settled.		
f.	Any distortion observed in phase quantities should dissipate over time.		
g.	Active power from each plant should settle back to pre-trip levels.		
h.	Reactive power from each plant should move immediately and settle according to its voltage droop setting.		
i.	Voltage should not deviate outside of [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.		

3.5 Test 5 – Stability of Plant with Changing Frequency

Test 5 is intended to test stability of the GFM plant in response to changing frequency in both directions (increasing and decreasing frequency)[17].

Table 7 Protocol for Test 5 – RoCoF Up and Down

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 frequency from 50 Hz to 51 Hz at 4 Hz/s. Stay at 51 Hz for 5 seconds.	
2. Ramp frequency from 51 Hz to 50 Hz at 4 Hz/s. Stay at 50 Hz for 5 seconds.	
3. Ramp frequency from 50 Hz to 49 Hz at 4 Hz/s. Stay at 49 Hz for 5 seconds.	
4. Ramp frequency from 49 Hz to 50 Hz at 4 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 adequately damped[18] in line with definition presented in the NER	

3.6 Test 6 – SCR Step Down with Fault

Test 6 is very similar to existing tests applied for connection assessment, with a key difference that in the existing DMAT test protocols the test is informational rather than “pass/fail”, and is allowed to trip at SCR = 1 or lower. This this test specifies that for GFM, stability of the resource down to the minimum level of 1.25[19] is required as a “pass” criterion.

[17] Note that it is not a method of quantifying the “inertial” response of the plant to change in frequency. The “inertial” response may be observed in the test output in some cases, however depending upon the exact implementation of the GFM controls, inertial behaviour may be muted, and testing of “quantifiable inertia” is problematic for some controls without modification to plant-level and inverter-level controls.

[18] AEMC. 2023 National Electricity Rules (NER) Version 200, May 2023 At https://energy-rules.aemc.gov.au/ner/477/glossary/a

[19] An SCR of 1.25 was selected as the lower limit as it is below the SCR stability threshold of typical GFL devices but is above power transfer limits. Testing an SCR drop to (or near) 1.0 is possible as an informative test but may require an active power dispatch reduction to respect power transfer limitations.

Table 8 Protocol for Test 6 – SCR Step Down with Fault

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:	
1. SCR at connection point stepped down repeatedly in this progression: 10, 3, 2, 1.5, 1.25.	
2. A 6-cycle 2 phase-to-ground fault is applied with a minimum fault depth of 0.5pu 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.	

3.7 Test 7 – Angle Step Change – Speed of Response

This test applies a step change to the angle of the connection system so that the active power response time and magnitude may be measured.

Table 9 Protocol for Test 7 – Angle Step Change

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.	
• Initial dispatch of generation is 50% of nominal power.	
• Only the project BESS, no duplicate.	
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. Angle of the voltage source behind the equivalent grid impedance is decreased instantaneously by 30 degrees.	
4. A few seconds later, angle of voltage source is increased by 30 degrees.	
5. Angle of the voltage source behind the equivalent grid impedance is decreased instantaneously by 60 degrees.	
6. A few seconds later, angle of voltage source is increased by 60 degrees.	
Success Criteria	**Pass/Fail**

Test 7 (Angle step change) – Setup and Success Criteria Testbench 1		
a.	Instantaneous active power output[20] 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)[21].	
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 15ms[22].	
c.	Active power settles to pre-disturbance level shortly after all phase jumps.	
d.	If active power / current reaches limits for the 60 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.	

[20] 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

[21] Plant impedance from inverter terminals to connection point is a factor in the theoretical maximum phase jump a plant may provide, however the 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.

[22] A +/- 60 degree phase angle change is severe and only feasible in a small subset of network locations. Testing should focus around the 20-30 degree phase angle jumps. For larger steps, the test should still be applied but the determination of pass/fail should be situational and subject to actual connection point condition.

A1. Discussion of Control Hardware-In-the-Loop (CHIL) application to GFM controls

Hardware-In-the-Loop (HIL), or Control Hardware-In-the-Loop (CHIL) is a simulation technique which embeds control hardware within a simulation environment for ease of testing and design. CHIL techniques have been used for power systems control testing for decades, and require powerful EMT computers to allow the simulated environment to run at the same speed as the control hardware ("real time"). Traditionally, CHIL simulation environments have been used to test control hardware in factory environments and sometimes benchmark the performance against model performance. Recent standardisation efforts have been pushing manufacturers to advance the model benchmarking use case for CHIL, giving increased confidence in model accuracy. These standardisation efforts (note IEEE 2800-2022 and draft standard IEEE 2800.2) aim to provide concrete guidance for which tests should be applied to validate models and confirm performance where possible.

It is notable that these recent standardisation efforts for model validation are more focused on model validation (comparison between CHIL responses and model responses), and less on performance characteristics of the device under test. This is because most criteria for plant performance apply at a plant level (including transformers, multiple inverters, collectors, plant controllers, etc), and are difficult to exhaustively test in a CHIL environment. Once the individual unit controllers are tested under varying conditions using CHIL and compared favourably against unit level model performance, it is assumed that the aggregated plant models may be sufficiently accurate once assembled, at least with respect to the inverter models.

These concepts apply equally to GFL and GFM control hardware, and at the present time, standards for CHIL validation which apply to existing or conventional GFL controls will apply also to GFM. CHIL use in this context is useful for model validation and validated models are then tested for appropriate performance.

A2. Impedance scan method

This test is intended to provide a characterisation of the control impedance as it varies with frequency. It has been included as an Appendix as this area of work is still in an early stage of development and its understanding is still maturing across the engineering community.

This test should be performed on GFM controls to build understanding of the performance of the system, including oscillation damping, voltage source behaviour, and other impacts.

As GFM control is a non-linear system, the nominal voltage at fundamental frequency ($v_0(t)$) is used to set-up the operating point.

Signal selection

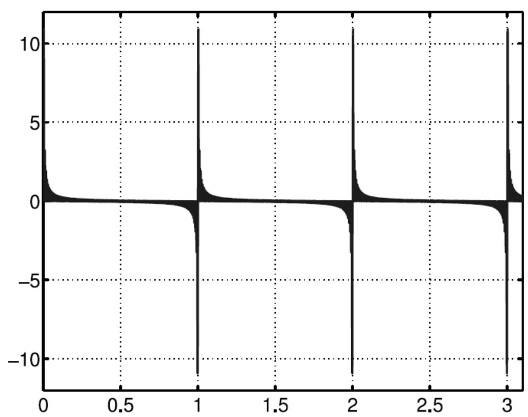
The injected voltage $\Delta v(t)$ can be of single frequency or of multiple frequencies. To avoid repeated simulations, $\Delta v(t)$ consisting of multiple frequencies may be preferred, but for maximum accuracy and stability of results, single frequencies may be used. The combination of signals of different frequencies is given below,

$$\Delta v(t) = a \sum_{l=l_0}^{N} sin(2\pi f_d\, l\, t + \delta_l)$$

where 'a' is the amplitude of each sinusoid and δ_l is the phase of each sinusoid. 'f_d' is the frequency resolution and the resultant signal $\Delta v(t)$ is periodic with time-period of $T_d=1/f_d$. Such a signal is called a wideband signal or a multi-sine signal.

If signals are added while keeping phase δ_l same for all sinusoids, then the resultant signal have periodic spikes of large magnitude as shown in Figure 5. This type of signal injection may disturb the operating point of the PES.

Figure 5 Response of Δv(t) keeping phase angle same for each sinusoid

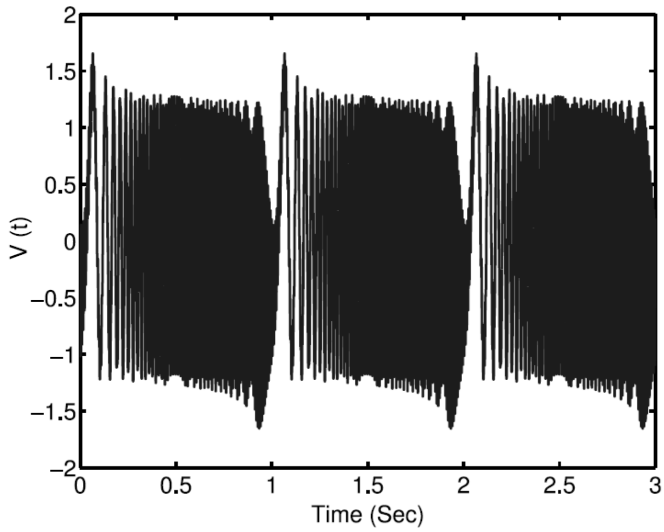


Alternatively, a signal with uniform magnitude in the given time range can be obtained by changing the phase angle of each sinusoid using the formula as given below.

$$\delta_l = -\frac{(l-l_o)(l-l_o+1)}{(N-l_o+1)}\pi$$

The new signal is plotted with this new formulation as shown in Figure 6 and the signal has more uniform magnitude in the whole time range.

Figure 6 Response of Δv(t) varying phase angle for each sinusoid



Injection signal magnitude

The magnitude of the signal injected should not be large enough to change the operating point of the PES, and the magnitude should not be so small that it will impact the impedance calculation due to low signal to noise ratio.

Selection of injection variable

For a three phase PES, the signal can be injected using sequence variables or DQ variables. Using sequence-based injection, sequence impedances (positive, negative, and zero sequence) can be extracted. Similarly using DQ variables, a DQ impedance/admittance model can be obtained. In this report, sequence-based signal injection is described in detail.

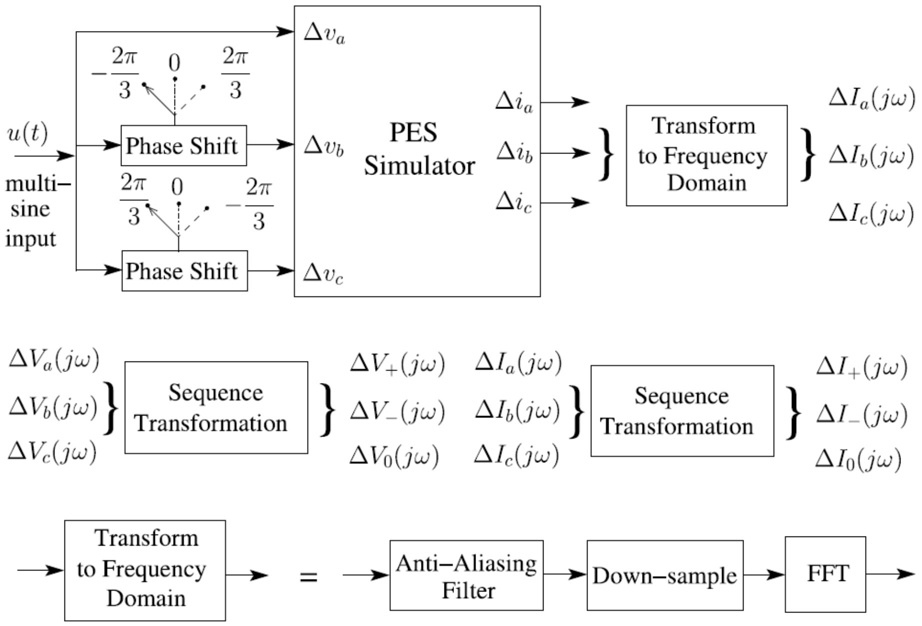
Sequence variable-based impedance scanning technique[23]

In this technique, a sequence impedance matrix is extracted, i.e., positive, negative, and zero sequence impedances. The complete procedure is shown in Figure 7. Positive, negative, and zero sequence perturbation is applied independently to the PES simulator. To perform this, the PES system will be simulated three times. For each three phase multi-sine signal, the phases of each sinusoid are shifted by the appropriate 120 degree angle to get positive and negative sequence variables, while for the zero sequence the phase shift is kept at zero.

As a PES simulator works in the phase domain, the measured voltage and the current is in the phase domain, so additional phase to sequence transformation is used to convert from the phase domain to the sequence domain. Once sequence variables are obtained, a fast Fourier transform (FFT) is used to extract frequency components in the input voltage and output current signal. As PES simulators run at very small time-steps (microseconds), down-sampling with anti-aliasing filter may be required for efficient FFT processing.

[23] As described in: A. M. Kulkarni, M. K. Das and A. M. Gole, "Frequency scanning analysis of STATCOM - network interactions," 2016 IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, 2016, pp. 1-6, doi: 10.1109/ICPES.2016.7584088.

Figure 7 Procedure for sequence based impedance scanning technique



At A. M. Kulkarni, M. K. Das and A. M. Gole, "Frequency scanning analysis of STATCOM - network interactions," 2016 IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, 2016, pp. 1-6, doi: 10.1109/ICPES.2016.7584088.

Additional notes

It should be noted that for sequence-based scanning using a multi-sine signal, certain precautions are required. If the difference between the maximum frequency and the minimum frequency is higher than the fundamental frequency (50 Hz), then independent impedance scanning with a gap of 50 Hz is required to avoid any harmonic interference[24]. For example, to scan a system from 1 to 150 Hz, three independent scans are required, 1-50 Hz, 51-100 Hz and 101 Hz to 150 Hz.

Although positive, negative, and zero sequence impedances/admittances can be obtained using impedance scan, for screening or stability studies such as sub-synchronous controller interaction (SSCI) evaluation, positive sequence impedance is a useful and relatively intuitive metric.

As the converter controller is sensitive to the injection frequencies near to fundamental frequency, this may result in erroneous scan results in this range. It is advisable to avoid conducting impedance scans in the narrow range of +/-5 Hz around the fundamental frequency.

At the present time, AEMO desires the frequency range to be at least between 1 and 100 Hz.

Example Positive Sequence Impedance Scans for BESS in GFL and GFM Mode

Figure 8 to Figure 11 show a dynamic impedance scan of a 50 Hz GFL BESS model. The impedance scan range is from 1 Hz to 1000 Hz with a frequency resolution of 1 Hz. For this positive sequence impedance scan, a multi-sine signal is used. To avoid harmonic interference, multiple independent scans are performed with a gap of 50 Hz, i.e. 1-50 Hz, 51-100 Hz etc.

[24] As described in: M. K. Das and A. M. Kulkarni, "Dynamic phasor based frequency scanning for grid-connected power electronic systems." Sādhanā 42 (2017): 1717-1740.

Similarly, Figure 12 to Figure 15 show a dynamic impedance scan of a 60Hz GFM BESS model and allow a comparison with GFL response, ignoring the different assignment of fundamental frequency between the two inverter types. GFM plant is observed to be generally inductive with positive resistance across the entire frequency range.

Figure 8 BESS in GFL mode - Positive sequence scan from 1 to 1000 Hz (R and X) (45 Hz to 55 Hz scan is avoided) (50Hz fundamental frequency)

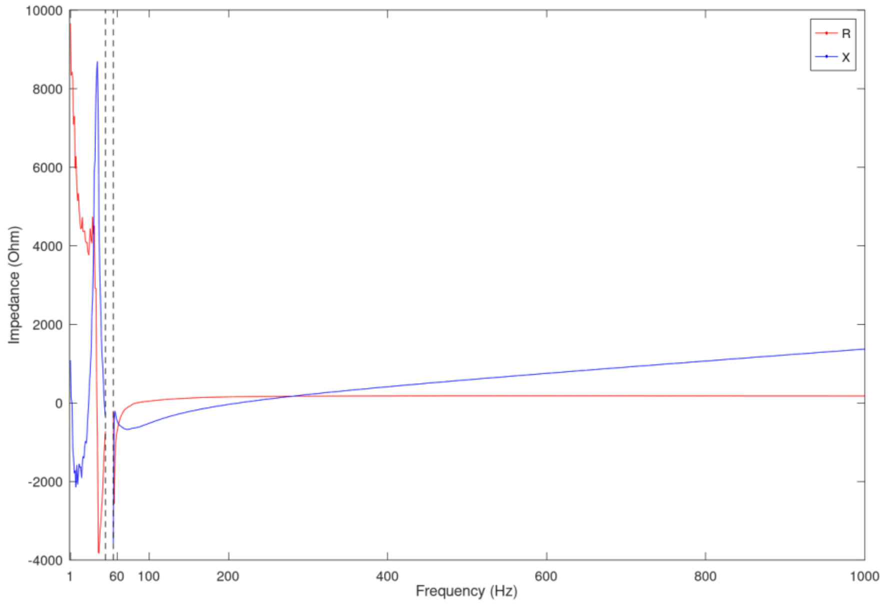


Figure 9 BESS in GFL mode - Positive sequence scan from 1 to 120 Hz (R and X) (45 Hz to 55 Hz scan is avoided) (50Hz fundamental frequency)

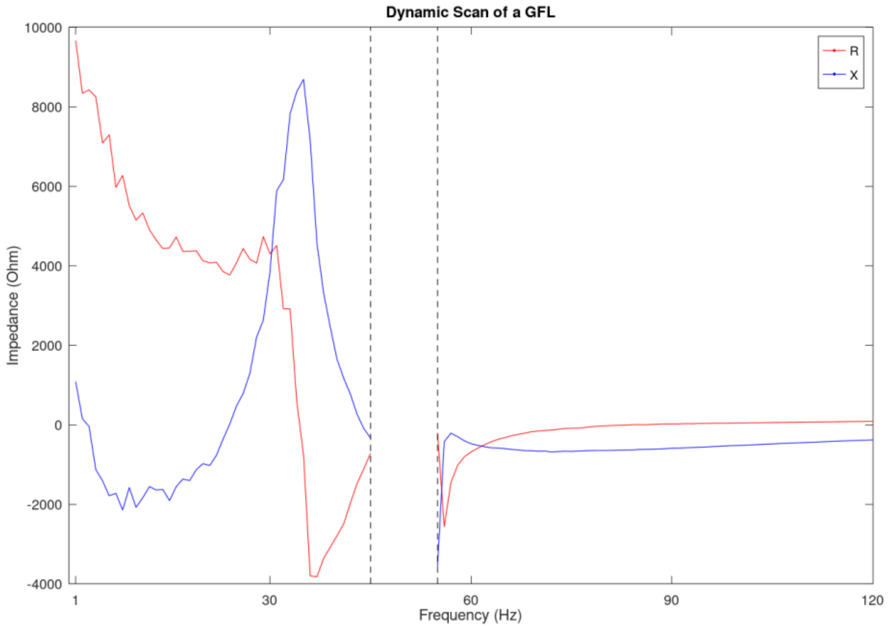


Figure 10 BESS in GFL mode - Positive sequence scan from 1 to 1000 Hz (magnitude and phase) (45 Hz to 55 Hz scan is avoided) (50Hz fundamental frequency)

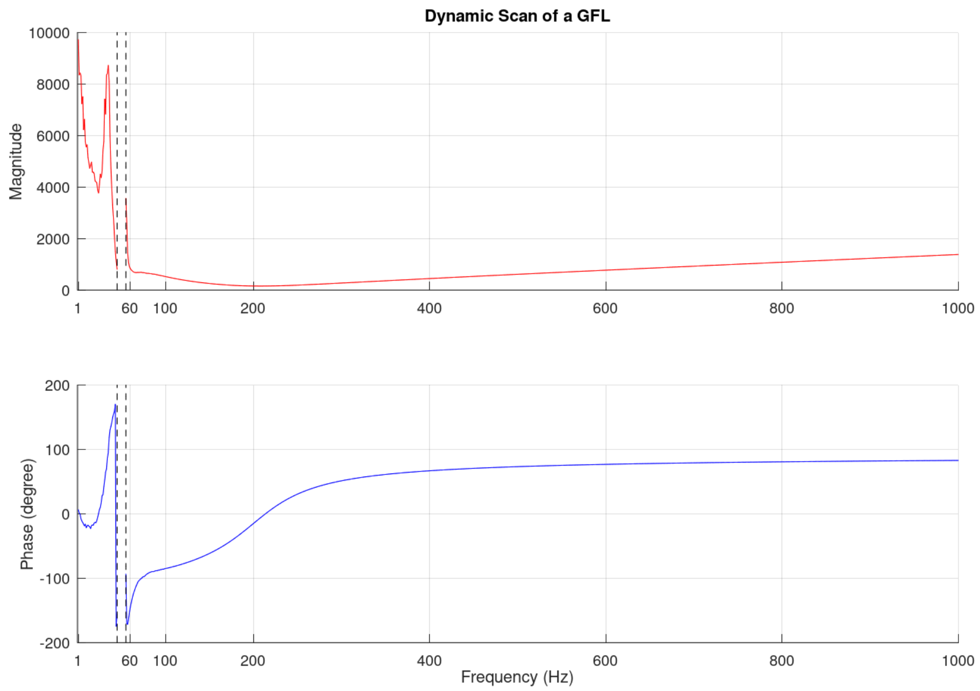


Figure 11 BESS in GFL mode - Positive sequence scan from 1 to 120 Hz (magnitude and phase) (45 Hz to 55 Hz scan is avoided) (50Hz fundamental frequency)

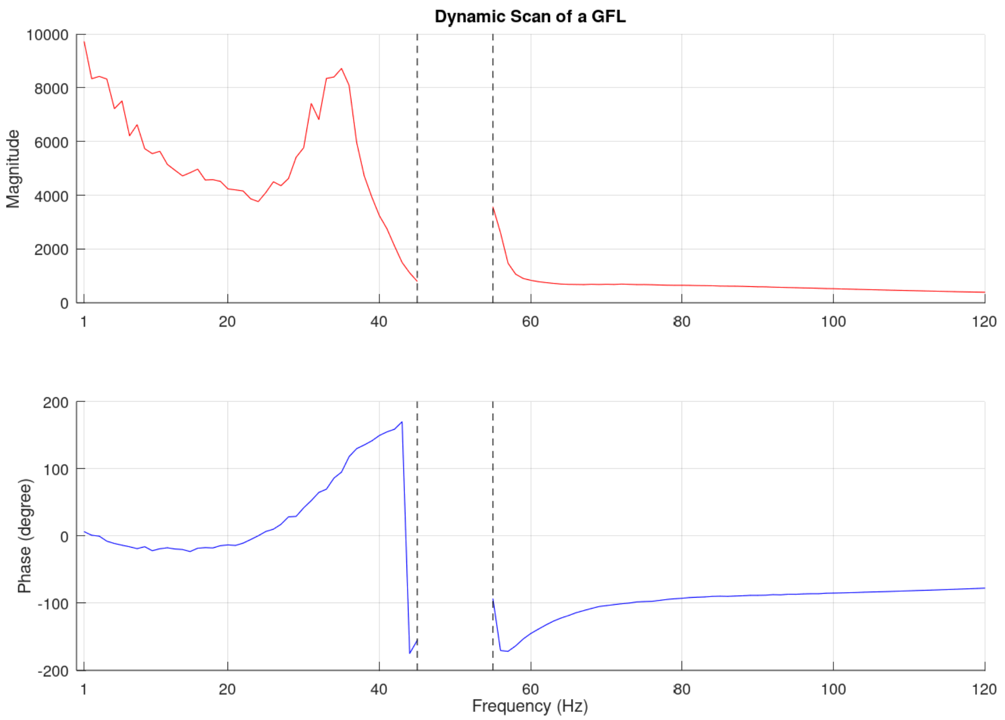


Figure 12 BESS in GFM mode - Positive sequence scan from 1 to 1000 Hz (R and X) (55 Hz to 65 Hz scan is avoided) (60Hz fundamental frequency)

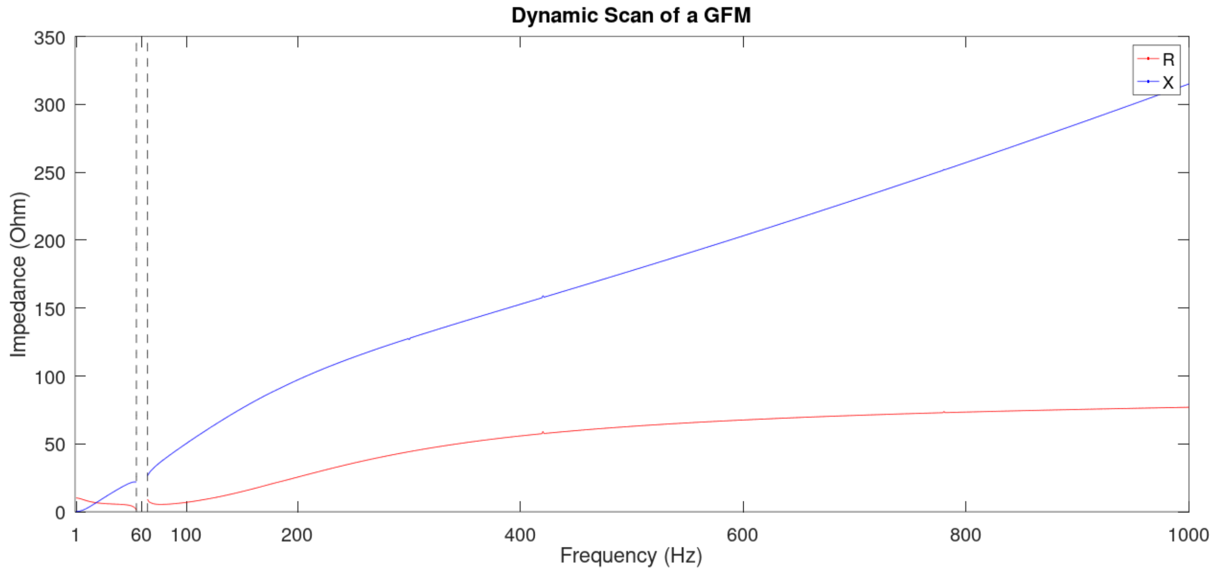


Figure 13 BESS in GFM mode - Positive sequence scan from 1 to 120 Hz (R and X) (55 Hz to 65 Hz scan is avoided) (60Hz fundamental frequency)

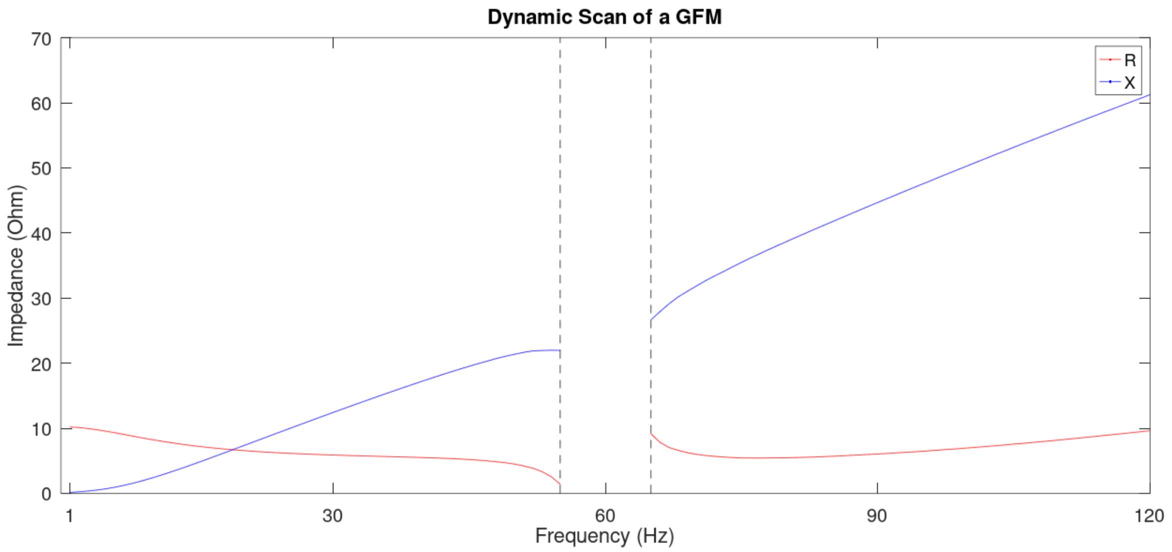


Figure 14 BESS in GFM mode - Positive sequence scan from 1 to 1000 Hz (magnitude and phase) (55 Hz to 65 Hz scan is avoided) (60Hz fundamental frequency)

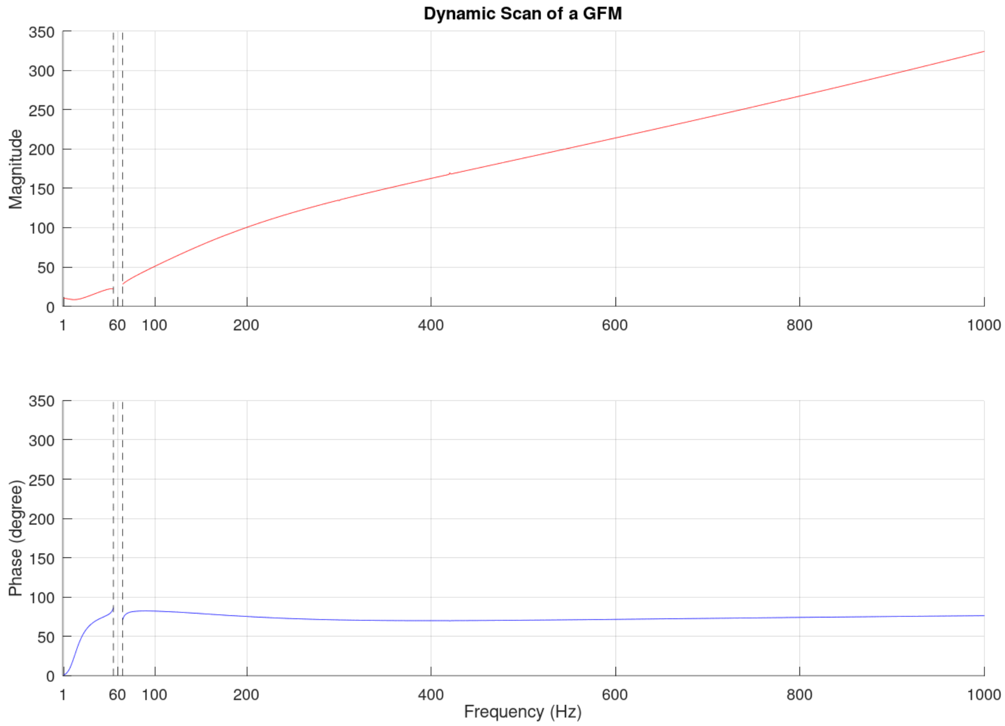
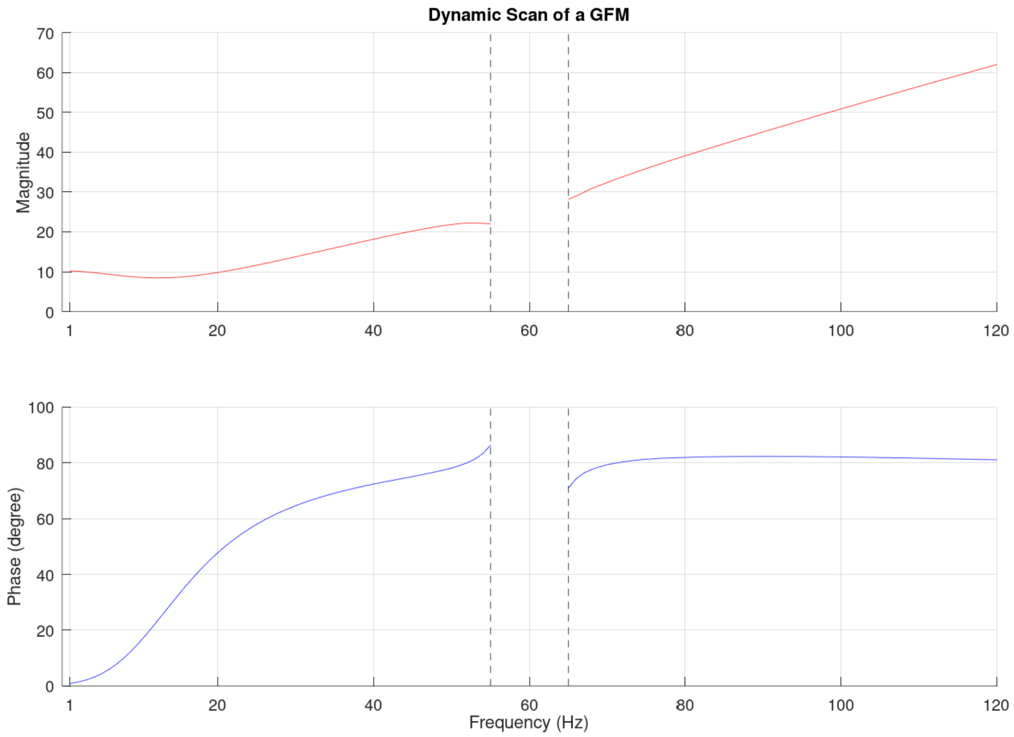


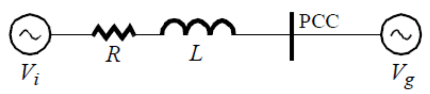
Figure 15 BESS in GFM mode - Positive sequence scan from 1 to 120 Hz (magnitude and phase) (55 Hz to 65 Hz scan is avoided) (60Hz fundamental frequency)



Discussion of Q(s)/V(s) impedance scans to identify voltage source behaviour in GFM Controls

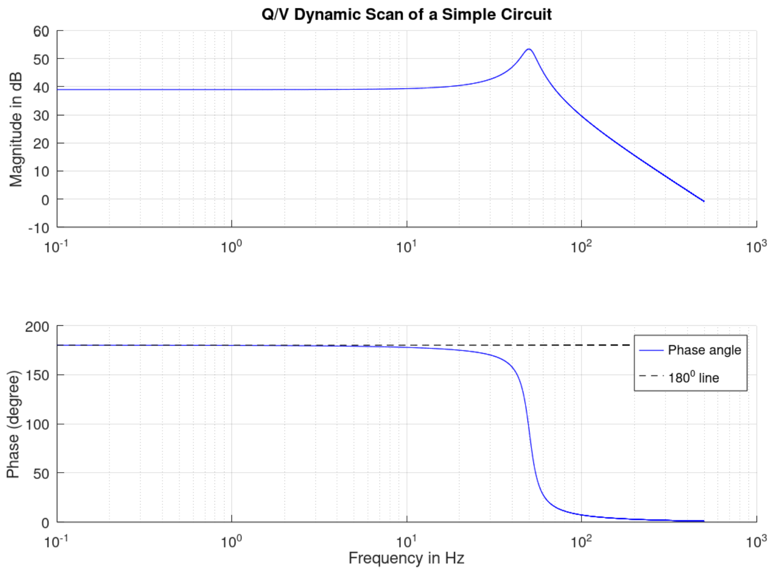
As described in the Voluntary Specification, GFM devices are expected to react near-instantly to changes in grid voltage (magnitude and phase). This near-instant response of GFMs is possible as the voltage phasor generated by GFM controls remains nearly constant during the sub-transient period. Using an impedance scan, such voltage source behaviour of GFM can be characterised as given in the IEEE paper, "A Testing Framework for Grid-Forming Resources"[25]. A Q(s)/Vm(s) and P(s)/theta(s) impedance scan is used for such analysis, where P and Q are the active and reactive power flows, and Vm and theta are the magnitude and phase of the grid side voltage.

Figure 16 A simplified model of a converter connected to a grid



The IEEE paper describes how it is possible to analyse a simple circuit and the corresponding Q(s)/V(s) frequency response. Figure 16 shows the equivalent circuit for a converter (left side) connected to a grid (right side). The internal impedance between grid and converter is represented using a simple series R-L circuit. Assuming the converter is generating a fixed AC voltage phasor, the magnitude and phase plot for the frequency response of Q(s)/Vm(s) is shown in Figure 17, where perturbation is applied to the grid voltage magnitude and the reactive power is measured at the grid side.

Figure 17 Q/Vm frequency response of a simple voltage source circuit



The frequency response of this simple circuit appears as a second order low pass filter with resonant/cutoff frequency around fundamental frequency (50 Hz). Around the cut-off frequency, the frequency response is significantly affected by the resistance of the internal impedance. For frequencies below the cut off frequency (50 Hz), the magnitude of Q(s)/Vm(s) remains almost constant and the phase of Q(s)/Vm(s) is near to 180 degrees. From this we may conclude that if a converter can hold the voltage phasor constant, we may expect a

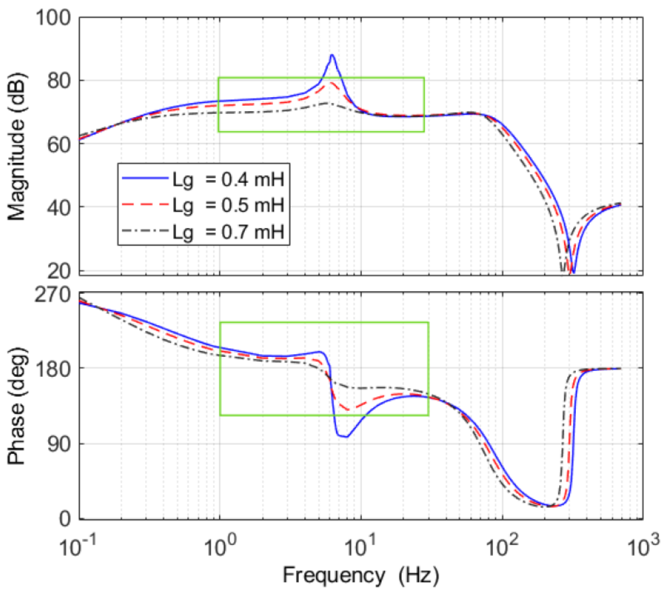
[25] As described in: S. Shah, et al, "A Testing Framework for Grid-Forming Resources." 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA

similar Q(s)/V(s) frequency response. GFM controllers can hold the internal voltage phasor constant in the sub-transient period and subsequently adjust the voltage to match the grid condition. At lower frequency ranges, a constant magnitude and 180-degree phase response of the Q/Vm transfer function is expected from a GFM response.

In principle, it may therefore be possible to specify voltage source behaviour using the frequency response of Q(s)/Vm(s) from low frequency (1-5 Hz) to fundamental frequency (50 Hz), or within some frequency band of interest[26]. However, more research is needed to accurately find the frequency range and magnitude/phase plot tolerances for proper characterization of GFM vs GFL responses.

For example, GFM devices may have resonances at low frequencies which significantly change the Q/Vm frequency response around the resonance frequency as shown in Figure 18(resonance around 7 Hz). This may create difficulty in characterising GFM behaviour. By proper controller tuning of GFMs, such resonances can be avoided.

Figure 18 Q/Vm frequency response GFM (GFM has resonance around 7 Hz)[27]



Calculating Q(s)/Vm(s) Frequency Response

As an example, a sample converter is connected to a voltage source and a small perturbation at a particular frequency is applied to the magnitude of the grid voltage. Due to this small perturbation, the corresponding change in the reactive power flow is measured. Using DFT, the frequency components present in the reactive power flow at the perturbation frequencies are extracted and used for calculating the frequency response of the Q(s)/Vm(s) transfer function.

A 50 Hz sinusoidal voltage phasor with voltage magnitude V_0 and phase angle a can be represented as follows:

$v(t)=V_0*\sin(2\pi 50t+a)$

[26] As described in: S. Shah, et al, “A Testing Framework for Grid-Forming Resources.” 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA

[27] Extracted from: S. Shah, et al, “A Testing Framework for Grid-Forming Resources.” 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA

Applying a small perturbation to the magnitude of the voltage phasor and the corresponding signal becomes:

$v(t) = [V_0 + m*\sin(2\pi f_p t)] *\sin(2\pi 50t + a)]$

Where 'f_p' and 'm' are the frequency and magnitude of the perturbation signal.

P(s)/q(s) Frequency Response

By holding constant the magnitude of the grid voltage, the phase angle can be perturbed and the corresponding active power flow can also be measured. Using angle perturbation, the frequency response of P(s)/q(s) transfer function can be obtained.

Example Comparison of Q(s)/Vm(s) frequency response of a BESS operating in GFM vs. GFL Mode

Figure 19 and Figure 20 represent the Q(s)/Vm(s) frequency response of a BESS operating in GFM and GFL mode respectively. The operating grid frequency is 50 Hz and impedance scan is performed from 1 Hz to 500 Hz. The frequency response from 1 to 50 Hz is used for the analysis which is shown in a dotted square box in the figures below. For a GFM device, at low frequencies (5-50 Hz), the magnitude of Q/Vm transfer function is relatively constant and the phase angle is close to 180 degrees. However, different behaviour is observed in the case of a GFL device.

Figure 19 Q/Vm frequency response of a GFM inverter

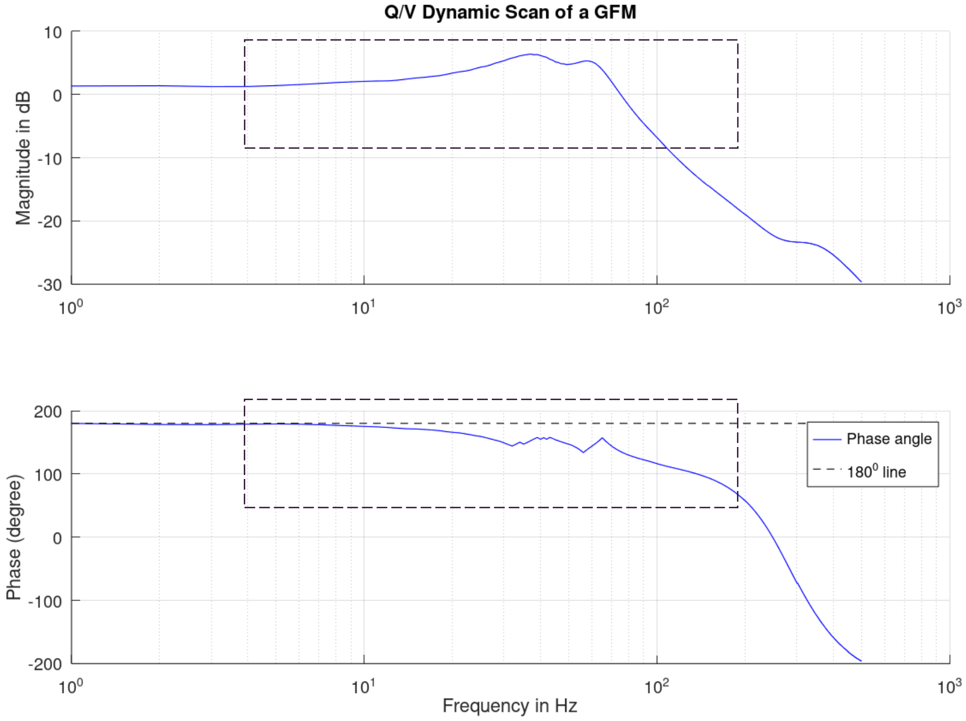
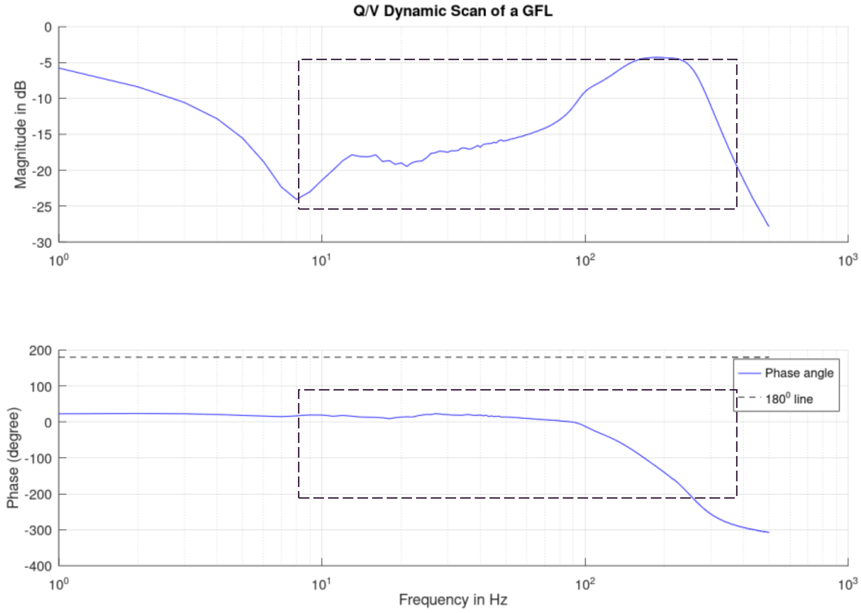


Figure 20 Q/Vm frequency response of a GFL inverter



A3. Example results

Two different models of GFM plant are used to obtain example results in line with the test sequences described in Section 3. Differences in behaviour of the two models is due to both the control schemes employed by the OEM in GFMI design, and the projects' specific tuning. GFM Model 1 uses a very small droop for both voltage and frequency, thus, both voltage and frequency are controlled tightly to their nominal values. GFM Model 2 has looser droop settings and allows for some deviation in voltage and frequency.

Test 1 – Loss of Synchronous Machine – Discharging

Figure 21 Example results of Test 1 for two GFM BESS models

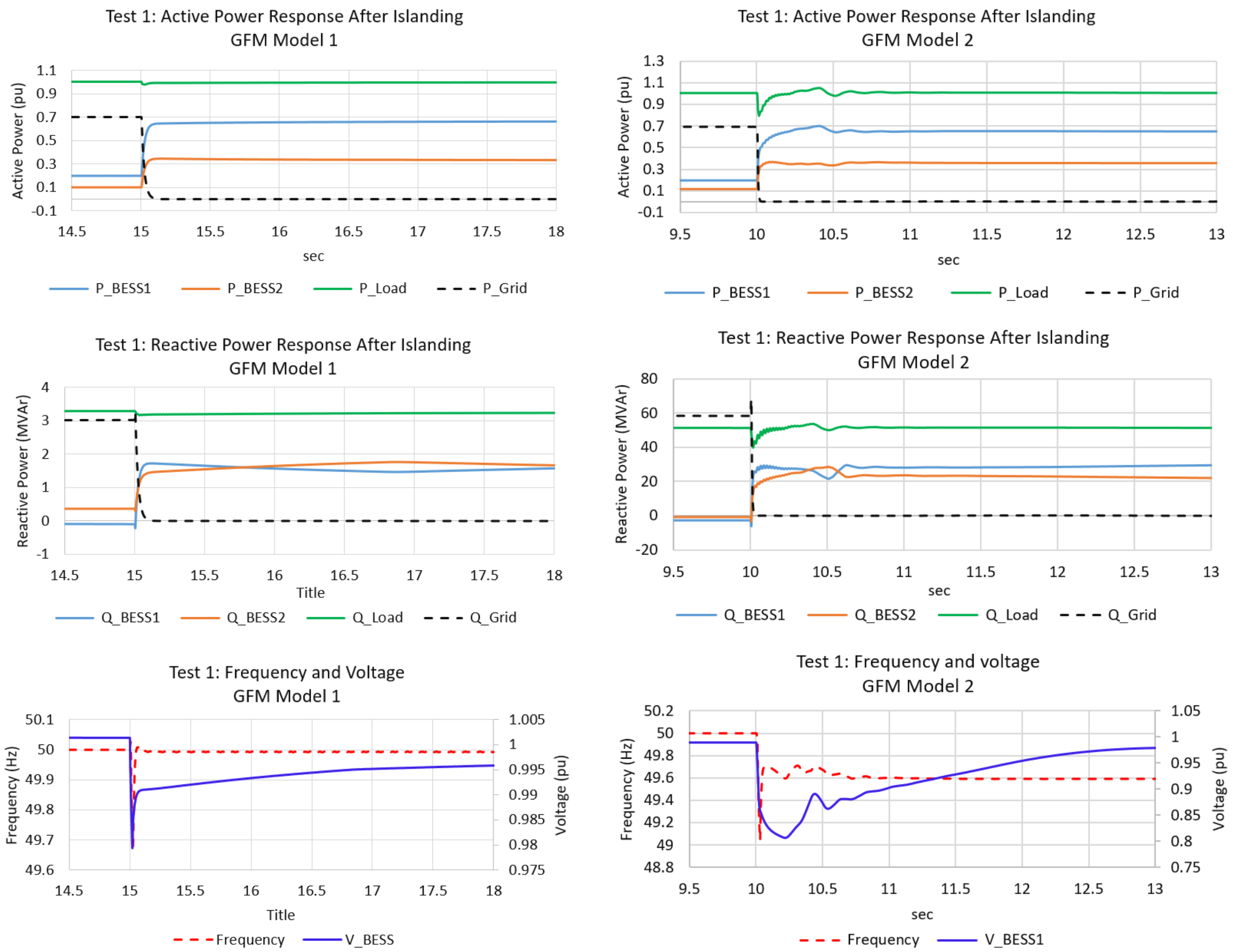
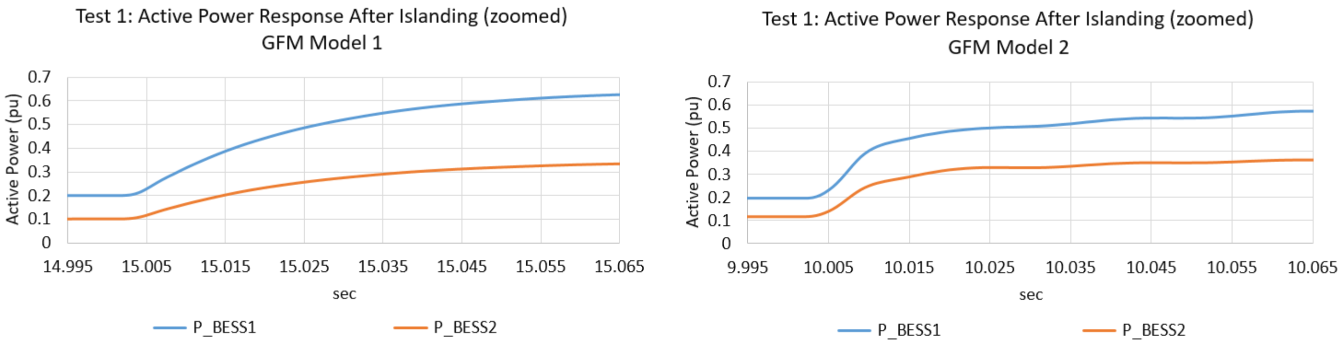


Figure 22 Example results of test 1 for two GFM BESS models (zoomed)



Test 2 – Loss of Synchronous Machine – Charging

Figure 23 Example results of Test 2 for two GFM BESS models

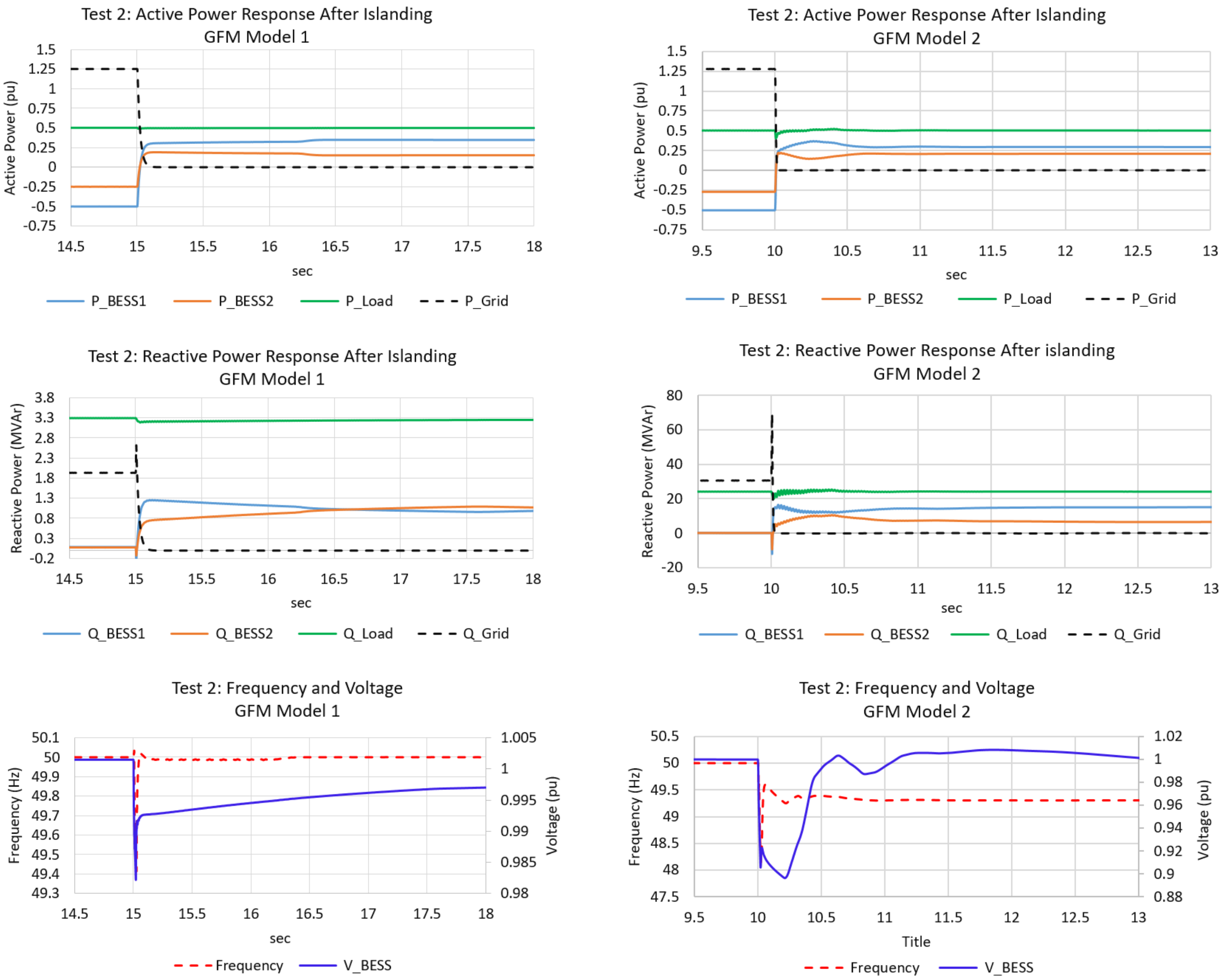
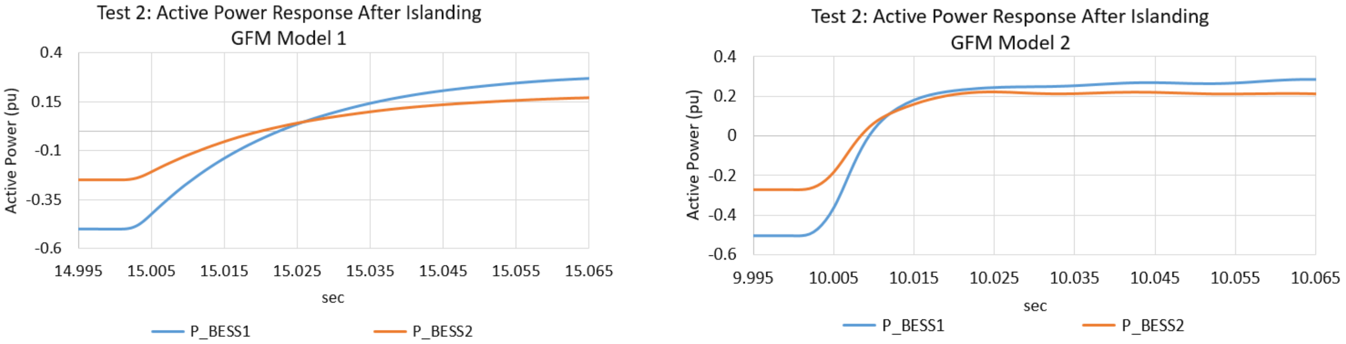


Figure 24 Example results of test 2 for two GFM BESS models (zoomed)



Test 3 – Loss of Synchronous Machine – Limit Test

Figure 25 Example results of test 3 for two GFM BESS models

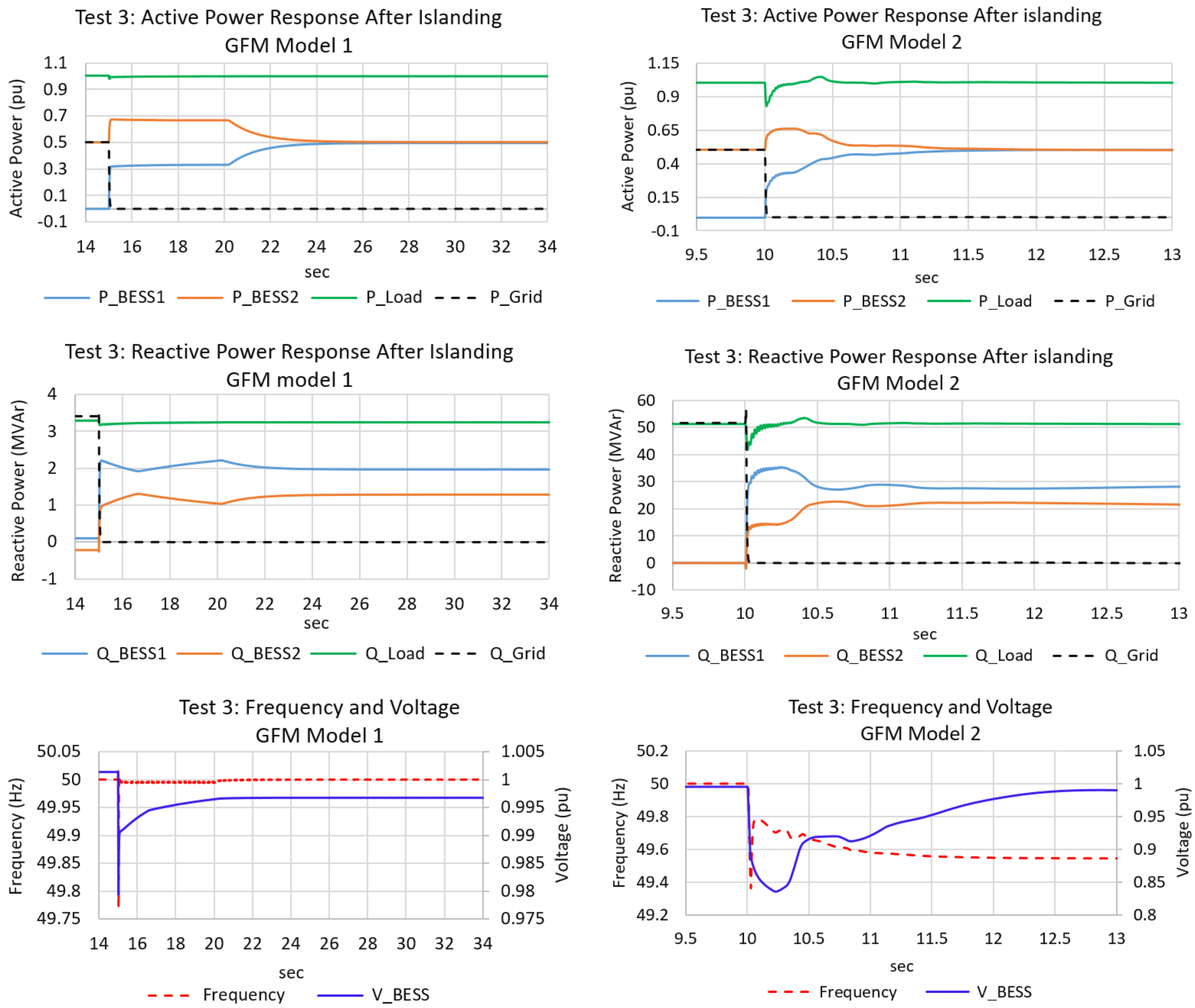
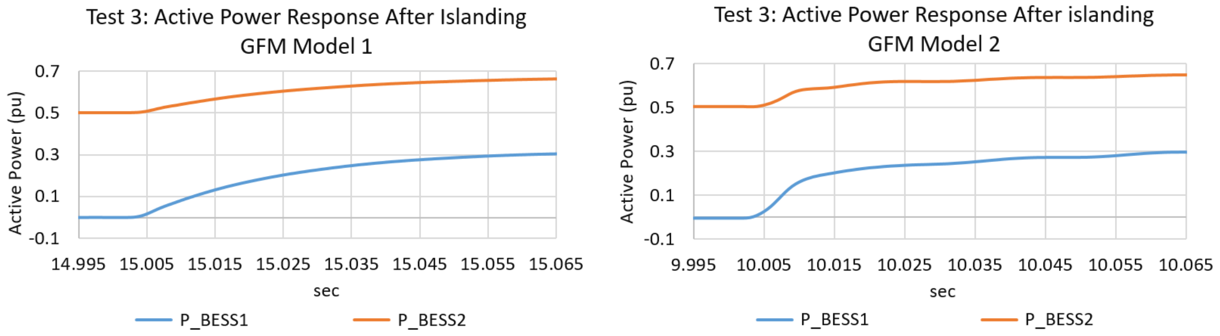
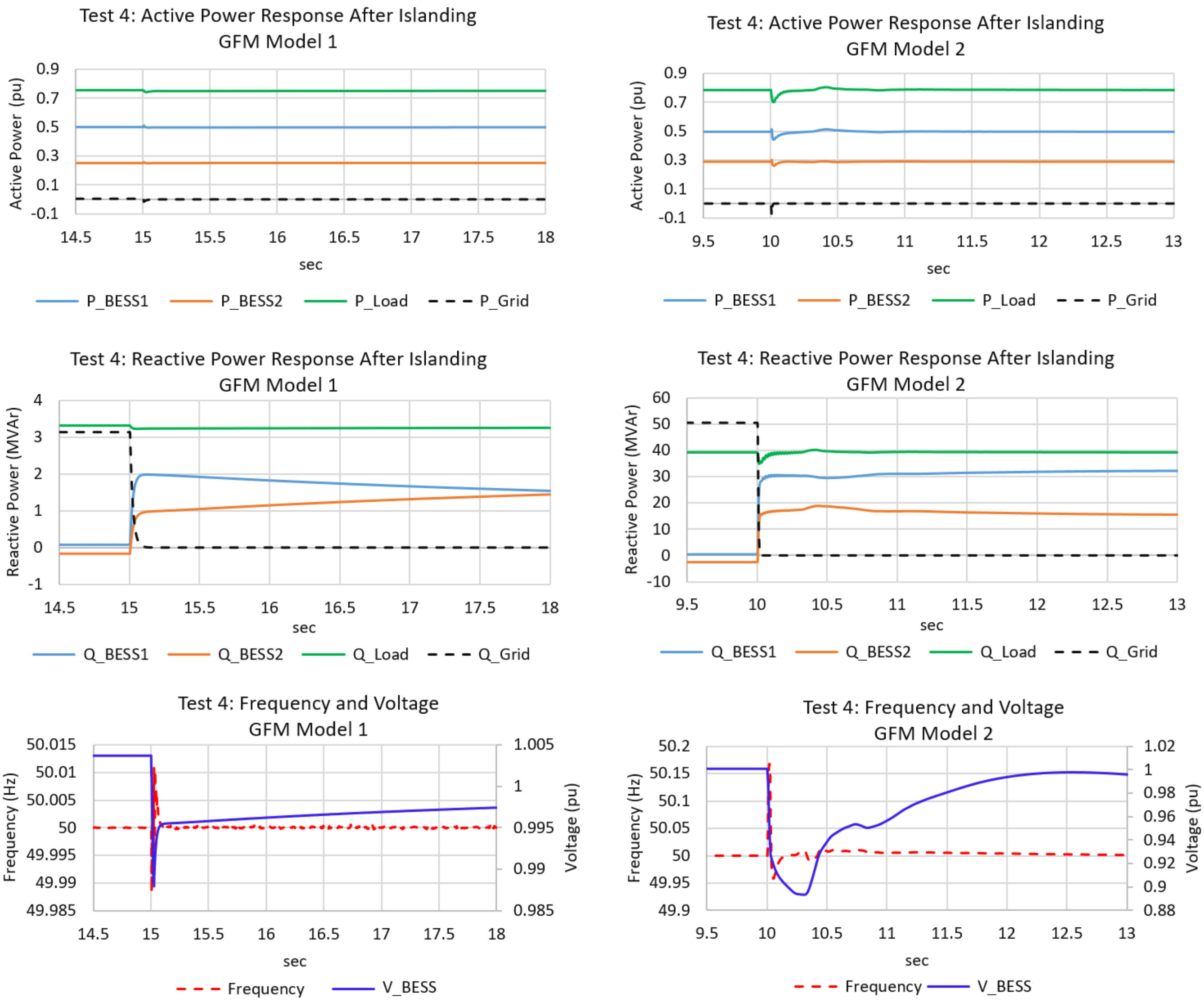


Figure 26 Example results of test 3 for two GFM BESS models (zoomed)



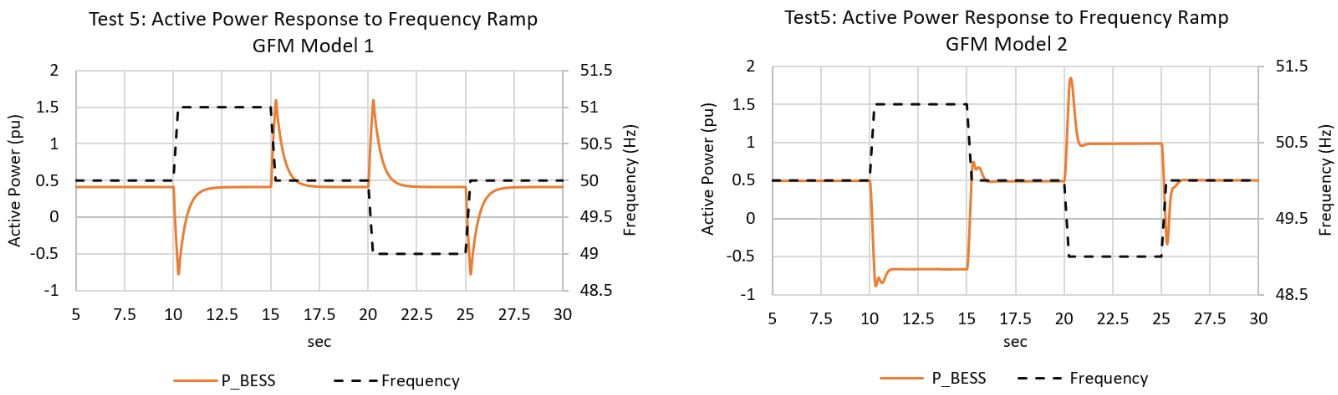
Test 4 – Loss of Synchronous Machine – Power Balance

Figure 27 Example results of test 4 for two GFM BESS models



Test 5 – Stability of Plant with Changing Frequency

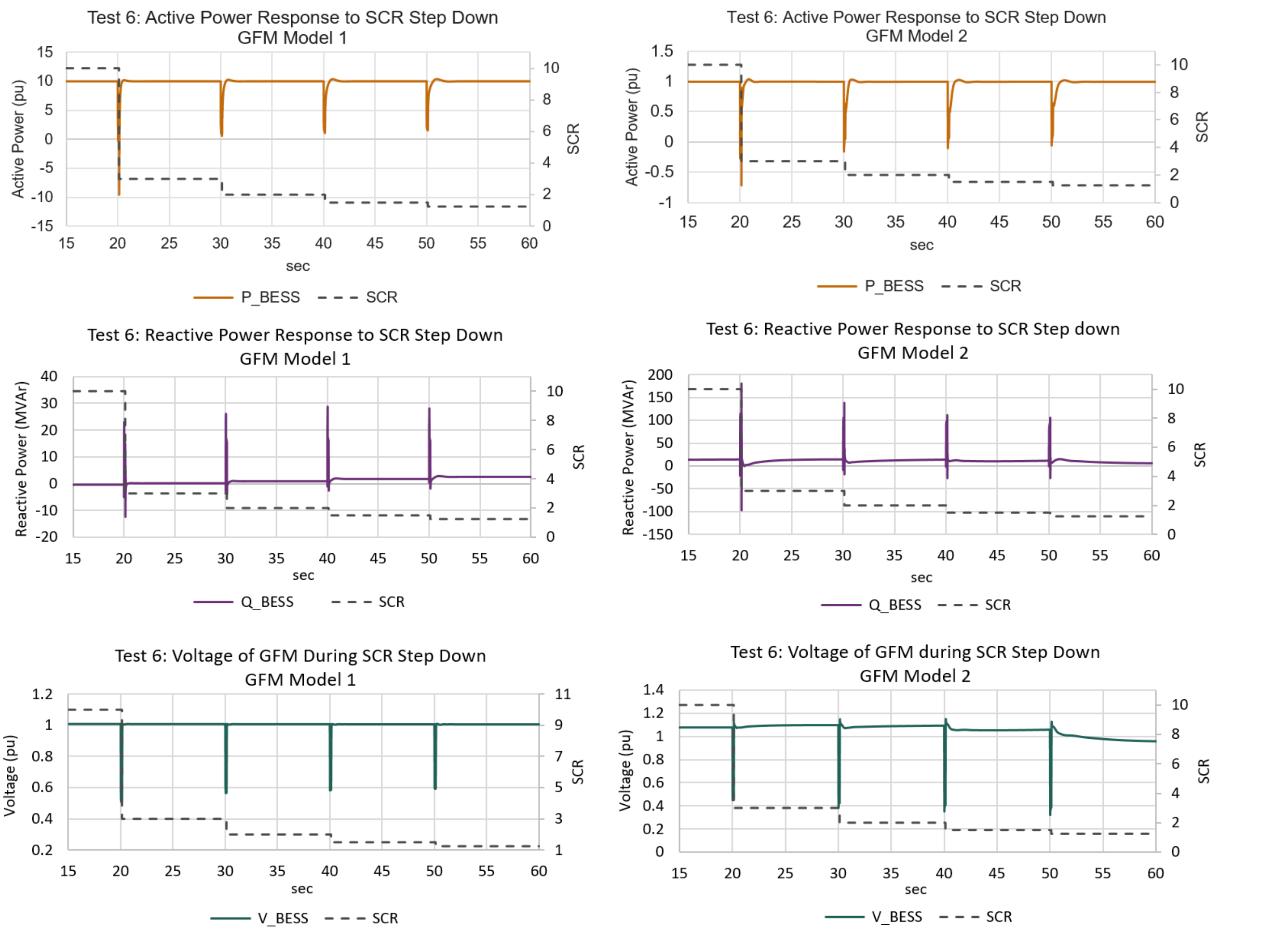
Figure 28 Example results of test 5 for two GFM BESS models



The 'GFM Model 1' plant has primary frequency response disabled. The 'GFM Model 2' plant has frequency response enabled to illustrate different scenarios on the frequency step-up and step-down.

Test 6 – SCR Step Down with Fault

Figure 29 Example results of test 6 for two GFM BESS models



For the example above, a 2ph-ground fault was applied with a fault resistance of 0.01 ohm.

Test 7 – Angle Step Change – Speed of Response

Figure 30 Example results of test 7 for two GFM BESS models

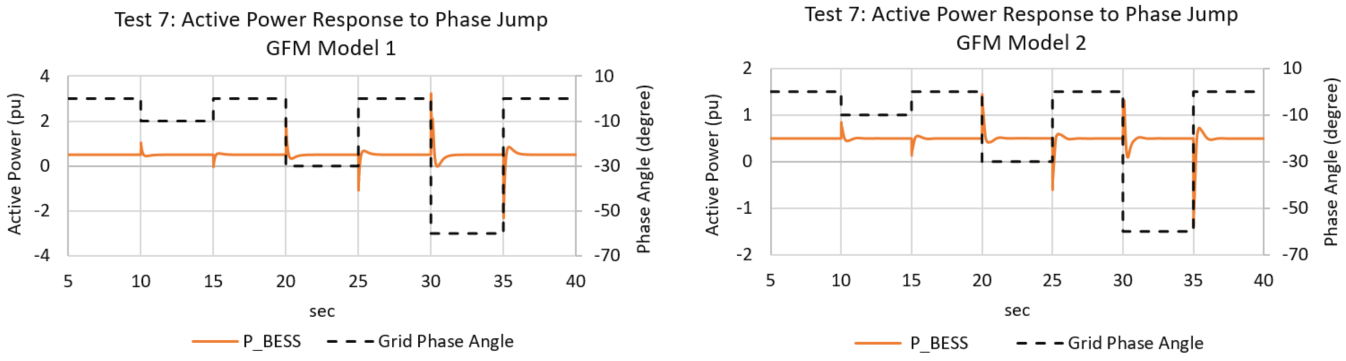
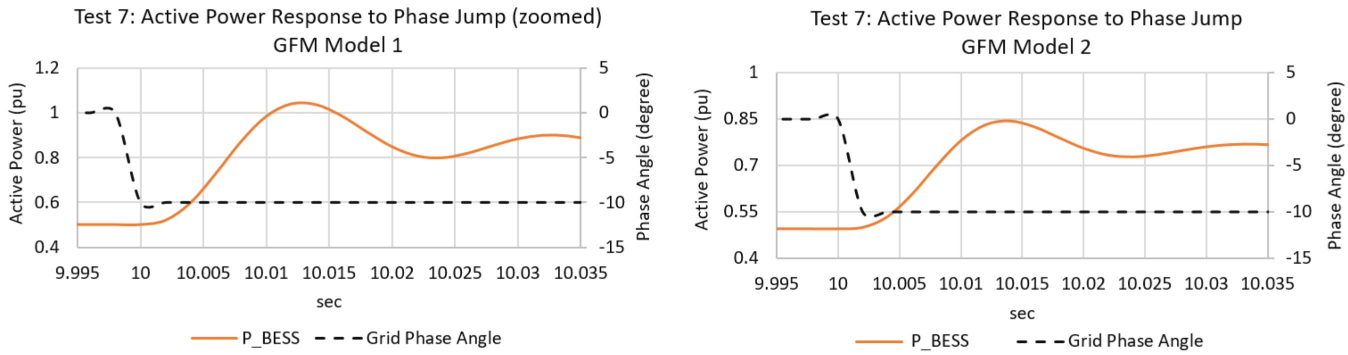


Figure 31 Example results of test 7 for two GFM BESS models (zoomed)



Informational impedance scan

Figure 32 Example results of Impedance Scan for two GFM BESS models

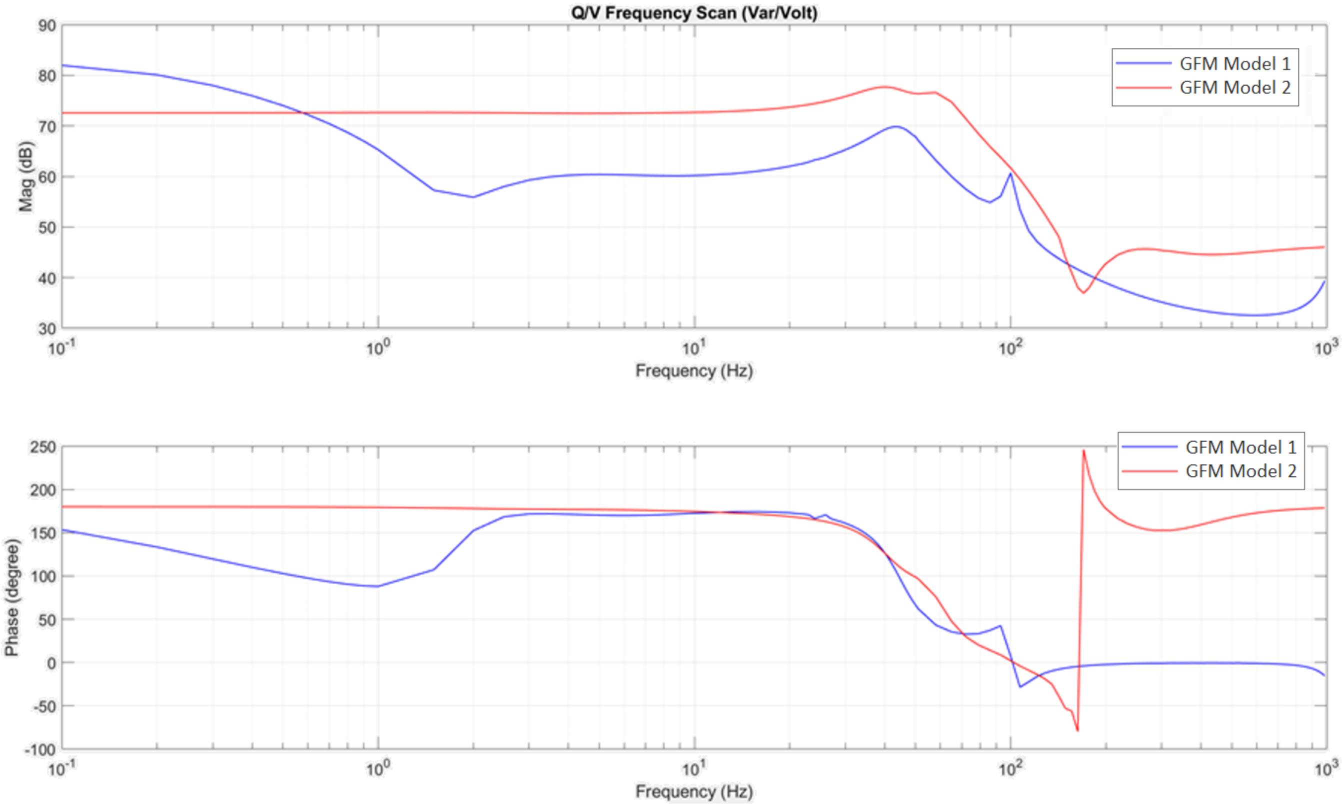
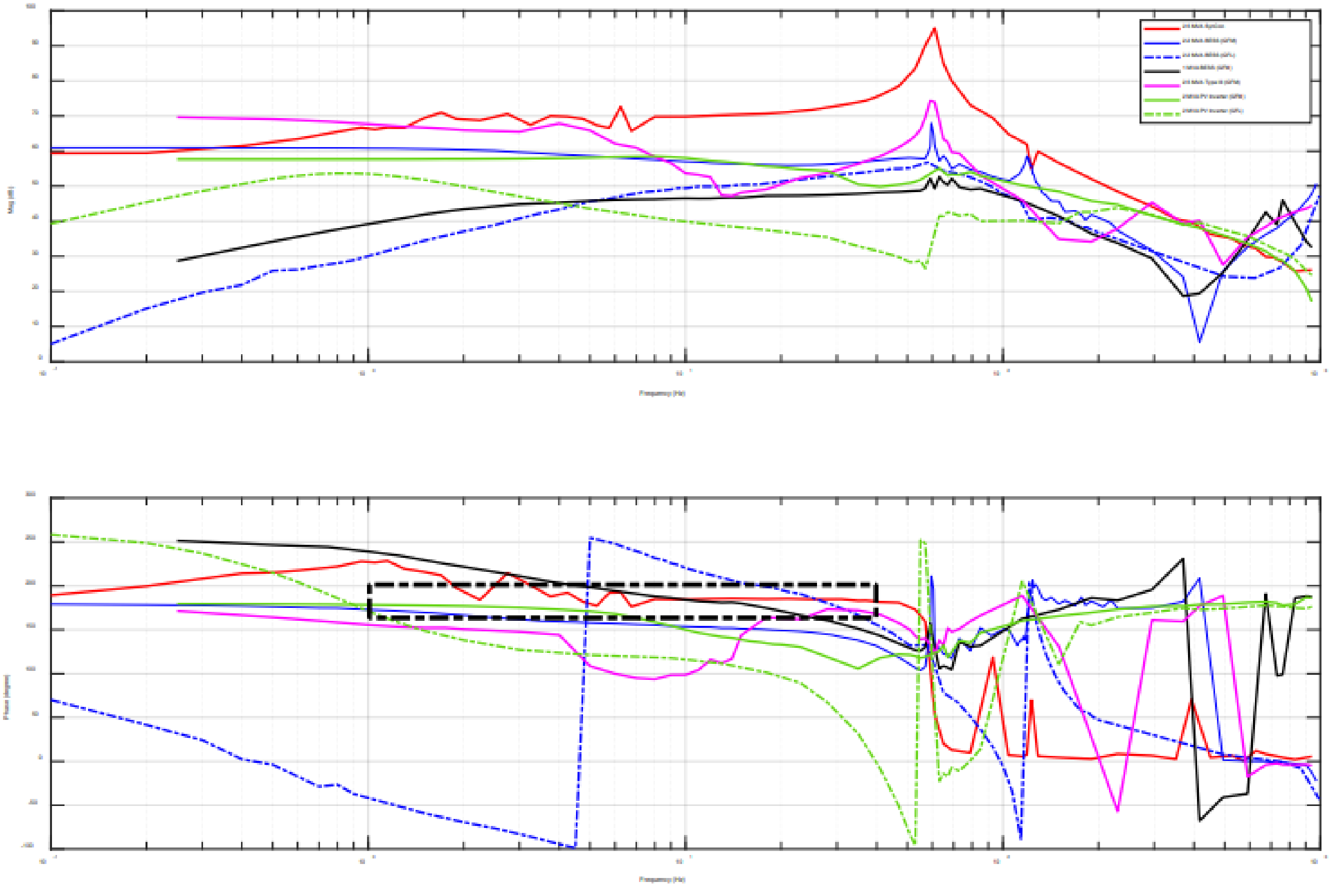


Figure 33 Q/V Impedance Scan - Experimental Scans[28]



[28] At https://www.nrel.gov/docs/fy23osti/87061.pdf.