GLOBAL PST CONSORTIUM

A Review of the Generic Grid-Forming Model Used by the System Operator in Chile

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The Global Power System Transformation Consortium is an expert and practitioner-driven initiative engaging key power system operators, research and educational institutes, governments, businesses, and stakeholders to overcome common barriers around the globe for enabling clean energy transitions at an unprecedented scale.[1] The authors would also like to thank Liz Breazeale and Isabel McCan for editorial support.

[1] See www.globalpst.org for more details.

List of Acronyms and Abbreviations

AC	alternating current
ABCG	three-phase to ground fault
AEMO	Australian Energy Market Operator
AG	single-phase to ground fault
BC	two-phase fault
BESS	battery energy storage system
EMT	Electromagnetic Transient
EMTP	electromagnetic transient program
EPRI	Electric Power Research Institute
F	frequency
FRT	fault ride-through
GFM	grid-forming
IBR	inverter-Based Resource
ISR	IBR short-term rating
HIL	hardware in the Loop
IEEE	Institute of Electrical and Electronics Engineers
NERC	North American Electric Reliability Corporation
OEM	original equipment manufacturer
P	active power, units MW.
Pu	per unit
POC	point of connection
RMS	root-mean-square
ROCOF	rate of change of frequency
SCR	short-circuit ratio
SCRX	simple excitation system model
S	apparent power, units MVA
SG	synchronous generator
TGOV	turbine-governor model
V	voltage

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1 Introduction

Chile aims to phase out all coal-fired power plants and achieve 80% of its energy supply from inverter-based resources (IBR) by 2030, with a 100% renewable system (wind, solar, concentrated solar power, liquefied natural gas, Carnot battery, and battery energy storage). The penetration of IBR is increasing rapidly; by 2021, the Chilean power system had already reached approximately 22% of annual energy from IBRs and 62% of instantaneous energy at the hour of maximum IBR penetration.

The studies and analyses carried out by the Chilean power system operator, Coordinator Electric de Chile (CEN), as well as the rapid development of new technologies, confirm that the retirement of fossil fuel power plants is a challenging but possible pathway to reach 100% annual operation with renewable energy by 2030. To make this accelerated energy transition scenario feasible, it is necessary to rapidly prepare the electricity grid for the integration of new technologies and to make the necessary investments in renewable energy generation to ensure system stability and meet demand. G-PST is supporting CEN to perform a critical analysis to identify the system impacts of high levels of inverter-based resources and mitigation strategies for any expected system operational risks. This report contributes to this effort by evaluating the performance of a generic model, comparing testing and simulation results for generic models of grid forming resources with those from a manufacture black box model, and finally by describing lessons learned in tuning and adjusting the generic model. It aims to increase CEN confidence in the EMT studies defining the Grid-forming inverter-based resources required in the system to ensure the security, and reliability of the system as they advance in the decarbonization of the system.

Grid-forming inverter-based resources are expected to play a crucial role in transitioning to a 100% renewable energy grid. Since many renewable generators and storage connect to the grid through inverters, it is important to develop and validate IBR models that can accurately represent the behavior of these resources and subsequently help conduct planning studies, allowing for a clearer understanding of the impact of these resources on the power grid before they are integrated.

The objective in this project is to verify the applicability of using generic electro-magnetic transient domain models of GFM technology through a wide range of tests and system conditions proposed by subject matter experts. of GFM technology through a wide range of tests and system conditions proposed by subject matter experts. For this study, we used the generic GFM electro-magnetic transient model available in the EMTP (Electromagnetic Transient Program[2]) software library, and we assessed the model's various GFM capabilities through 12 tests. In this report, we compare the performance of the model with that of an original equipment manufacturer (OEM) GFM model. We also share the key insights and lessons learned from this work.

[2] See https://www.emtp.com

2 GFM Functional Tests

This section details the tests conducted on the generic GFM model available in the EMTP library to verify its various GFM capabilities. In total, we conducted 12 tests, which included a combination of the tests recommended by the voluntary functional specification documents published by the North American Electric Reliability Corporation, the Australian Energy Market Operator, and the Electric Power Research Institute (EPRI) [1]–[3]. The following sections provide a detailed explanation of the model parameters, test setups, success/fail criteria, and any notable observation made during the tests.

2.1 EMTP GFM Model Parameterization

As mentioned above, we used the generic GFM model from the EMTP library in this study. Figure 1 and Figure 2 show the schematic and the collector system configuration of this model, respectively. In this project, this model is configured to represent an average switching model of a battery energy storage system (BESS). The outer control loop configuration is droop-based, with frequency and voltage droop gains of 2%. The control system operates in the decoupled mode, controlling the positive- and negative-sequence currents independently. Figure 3 shows the parameters of the model. The values for the initial active power, reactive power, and AC voltage may vary across different tests, but the rest of the parameters remain unchanged for all tests.

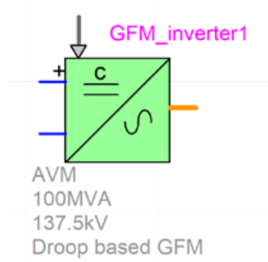

Figure 1. EMTP GFM model schematic

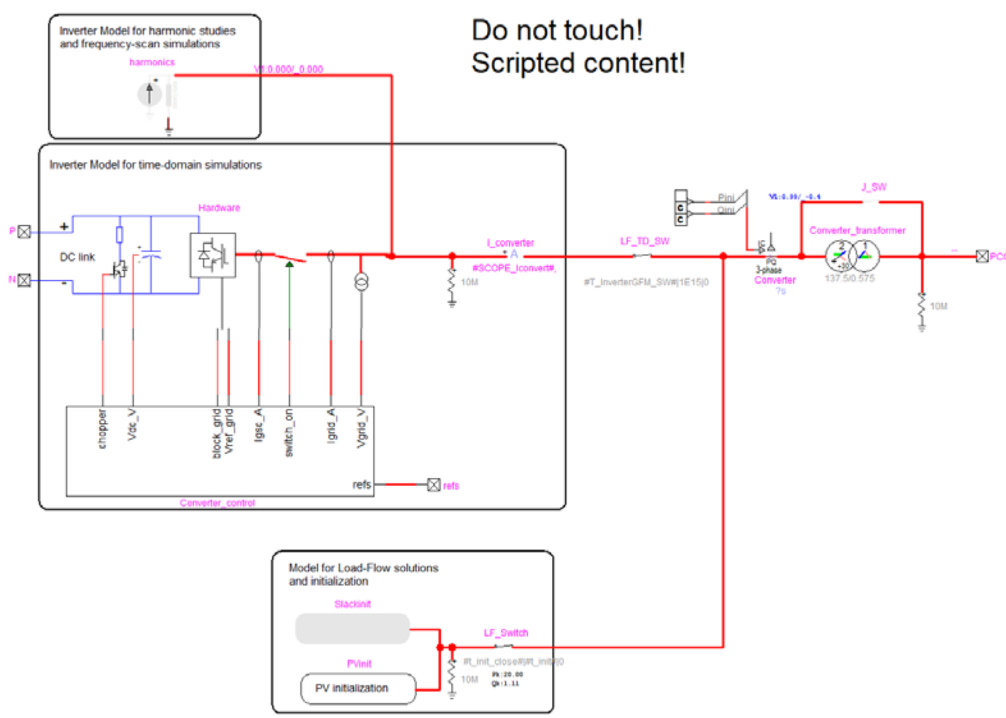

Figure 2. Collector system configuration of the EMTP GFM model

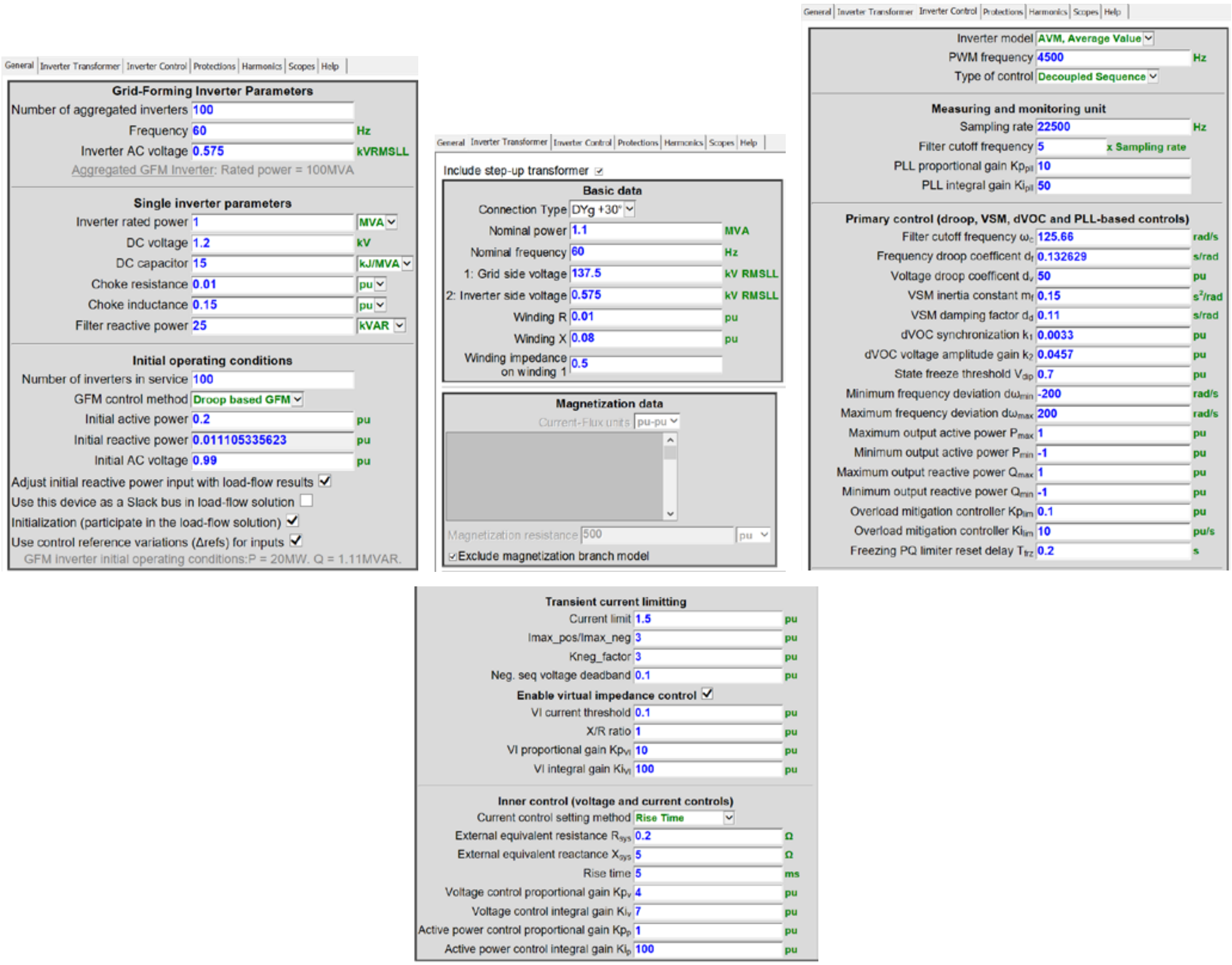

Figure 3. Parameters of the EMTP GFM model

2.2 Test 1: Loss of Synchronous Machine—Discharging

The first test explores the response of the GFM inverters to the loss of the last traditional synchronous generator on the grid. This test, along with the next two tests, are recommended by the North American Electric Reliability Corporation to verify the GFM capability of a model [1].

2.2.1 Test Bench 1

Figure 4 illustrates the test system used for this test, referred to as "Test Bench 1" in this document. This system consists of the following components connected to a single bus without any impedance:

- A synchronous generator (SG) rated at 300 MVA with a simple excitation system model and turbine-governor model, with circuit breaker
- A constant impedance load model with both active and reactive power (inductive) components with a power factor of 0.9
- The project's GFM BESS plant model under test rated at 100 MW
- A duplicate of the project's GFM BESS plant model, rated at half of the model being tested (i.e., 50 MW).

The combined MVA rating of the BESS models must be sufficient to fully supply the load upon disconnection of the SG. The SG MVA rating must be sufficient to simultaneously serve the load and charge both BESS at their rated maximum charge power. Both BESS models should be in voltage control mode with the same voltage and frequency droop settings and set points. The line-to-line voltage level of the system is set to 137.5 kV. Further details about the test system can be found in [1].

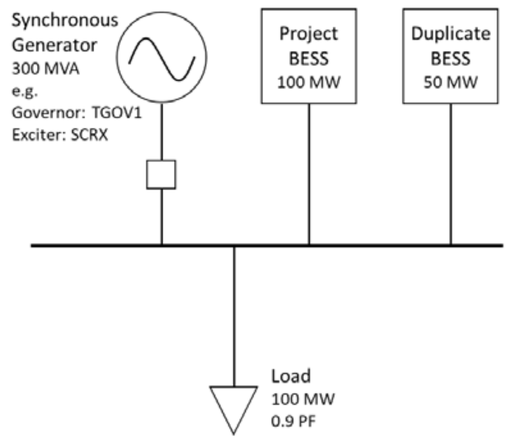

Figure 4. Test Bench 1

Figure 5 shows the implementation of Test Bench 1 in EMTP using the generic GFM model.

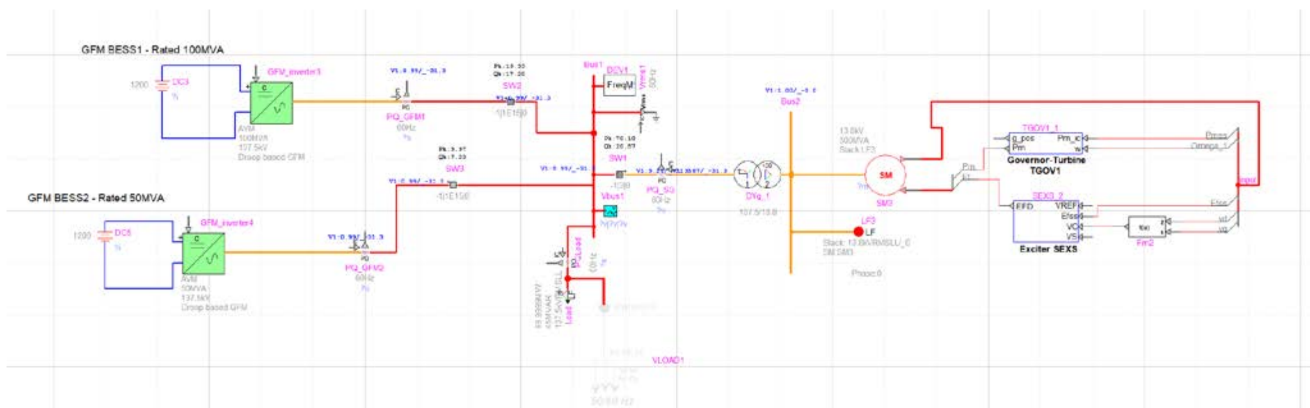

Figure 5 Test Bench 1 in EMTP

2.2.2 Test Description and Success Criteria

Table 1 describes the details of Test 1, including the initial dispatch, test sequence, and pre- and post-trip success criteria. Success criteria are defined as pass/fail conditions in all tests.

Table 1. Test 1 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at 20% of its maximum discharge power limit. • The duplicate BESS is dispatched at 20% of its maximum discharge power limit.	
Test Sequence: • The system is run until it reaches a stable point at the given power flow conditions, without oscillations. • The SG is tripped at $t = 3$ s.	
Success Criteria:	
Pre-Trip:	**Pass/Fail**
1. Each BESS's active power output matches dispatched levels.	
2. SG active power output matches the rest of the load.	
3. Frequency should be 1 pu.	
4. Voltage at Bus 1 should be within 5% of nominal.	
5. Phase voltage and current waveform should not be distorted.	
6. Oscillations should not be present in the root-mean-square (RMS) quantities.	
7. Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
1. Immediately following the trip, BESS 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.	
2. Voltage settles to a stable and acceptable operating point.	
3. The final voltage is as expected based on the droop and deadband settings.	
4. Frequency settles to a stable operating point.	
5. The final frequency is as expected based on the droop and deadband settings.	
6. Any oscillation is settled.	
7. Any distortion observed in phase quantities should dissipate over time.	
8. Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
9. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

2.2.3 Test Results

Results for Test 1 are presented below. Figure 6 depicts the active and reactive power measured at Bus 1 in Figure 5 for GFM 1 (the project BESS in Figure 4), GFM 2 (the duplicate BESS in Figure 4), SG, and the load. Figure 7 shows the frequency and three-phase RMS voltages at Bus 1, while Figure 8 illustrates instantaneous voltages and currents at Bus 1 during this test.

As Figure 6 shows, prior to the trip at $t = 3$ s, GFM 1 and GFM 2 are generating 20 MW and 10 MW, respectively, consistent with the initial 20% dispatch condition in Table 1. The rest of the load power is fed by the SG. Moreover, both the active and reactive power of GFMs remain within the $[-1, 1]$ pu limit range, as indicated in Figure 6, and the frequency and voltage are stable at 60 Hz and 1 pu, without any oscillations, as seen in Figure 7. Additionally, the instantaneous voltages and currents in the system show no distortion before the trip, as shown in Figure 8. Therefore, all pre-trip criteria in Table 1 are successfully passed.

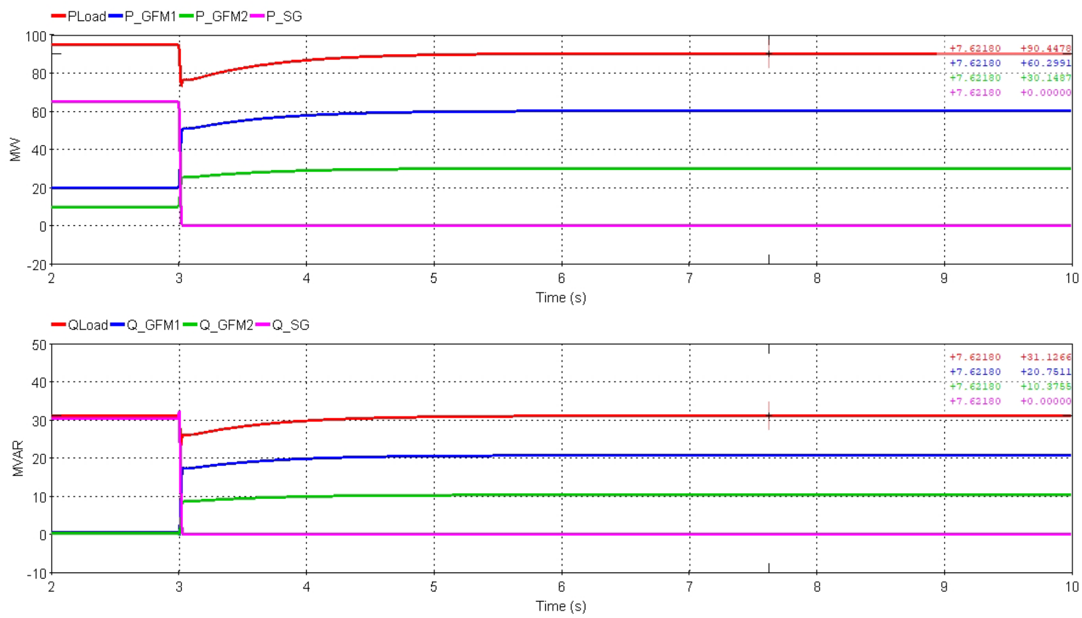

Figure 6. Active and reactive power measured at Bus 1 for Test 1

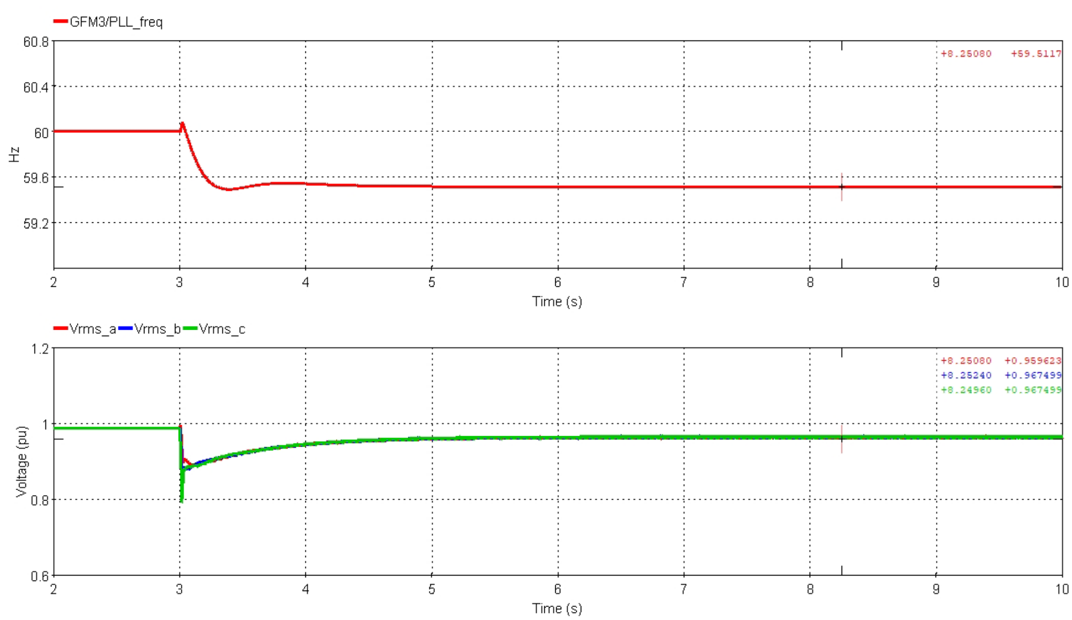

Figure 7. System frequency and three-phase RMS voltages measured at Bus 1 for Test 1

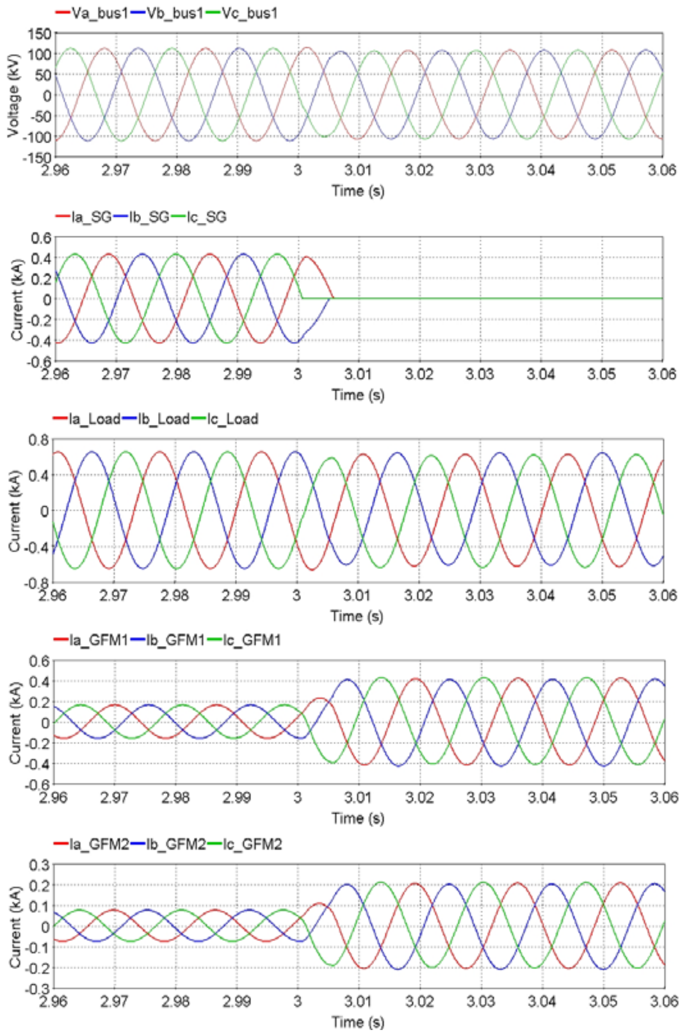

Figure 8. Instantaneous currents and voltages measured at Bus 1 for Test 1

When the SG is tripped at $t = 3$ s, GFM 1 and GFM 2 increase their active and reactive power in a well-controlled manner, as shown in Figure 6, to feed the load and compensate for the power loss of the generator. As a result of this, the frequency and voltage in the system drops to 59.5 Hz and 0.96 pu, respectively, in Figure 7. The 40-MW and 20-MW increase in active power of GFM 1 and GFM 2 aligns with the 2% frequency droop gain and the 0.5 Hz (0.0083 pu) drop in frequency, thereby meeting Success Criterion 8 in Table 1. Similarly, the 20-MVAR and 10-MVAR increase in the reactive power of GFM 1 and GFM 2 in Figure 6 match the expected values for a voltage droop gain of 2% and a voltage drop of $0.989–0.985 = 0.004$ pu at the inverter terminals in Figure 9. Thus, Criterion 9 of the post-trip condition in Table 1 is met too. Moreover, system frequency, three-phase voltages, and currents are stable without any oscillations and settle at the expected values/ranges in Figure 7 and Figure 8, successfully passing the rest of the post-trip metrics in Table 1. As a result, the GFM model with the parameterization of Figure 3 successfully passes all conditions in this test.

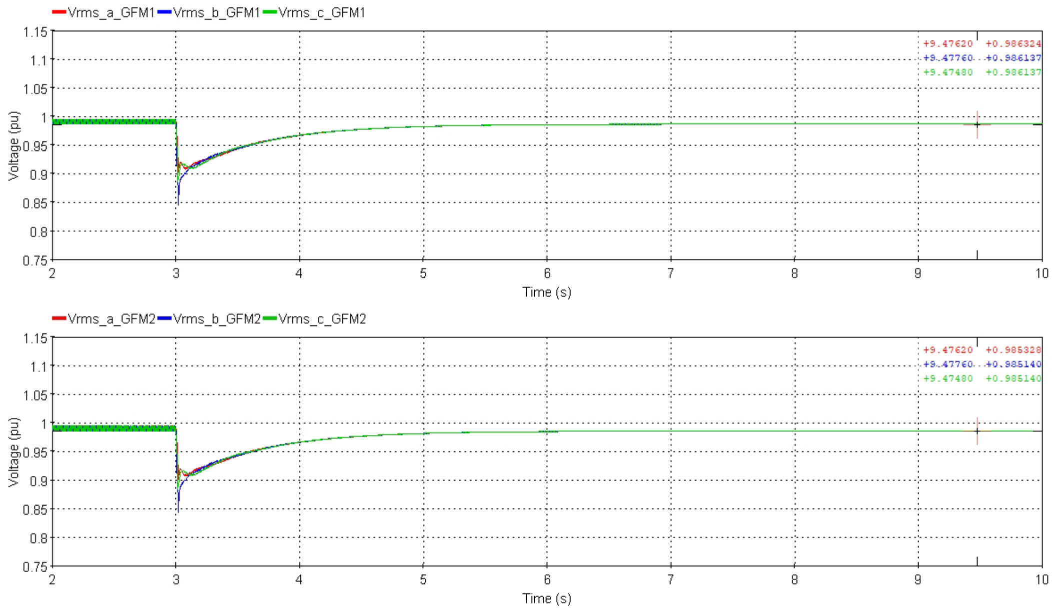

Figure 9. Three-phase RMS voltages at GFM 1 and GFM 2 inverters terminal

2.3 Test 2: Loss of Synchronous Machine—Charging

This test is very similar to Test 1, except the GFMs operate in a charging mode before the SG is tripped. The test system used is Test Bench 1, as shown in Figure 4.

2.3.1 Test Description and Success Criteria

Table 2 explains the details of Test 2.

Table 2. Test 2 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at 50% of its maximum charge power limit. • The duplicate BESS is dispatched at 50% of its maximum charge power limit.	
Test Sequence: • The system is run until it reaches a stable point at the given power flow conditions, without oscillations. • The SG is tripped at $t = 3$ s.	
Success Criteria:	
Pre-Trip:	**Pass/Fail**
1. Each BESS's active power output matches dispatched levels.	
2. SG active power output matches the load and BESS charging.	
3. Frequency should be 1 pu.	
4. Voltage at Bus 1 should be within 5% of nominal.	
5. Phase voltage and current waveform should not be distorted.	
6. Oscillations should not be present in the RMS quantities.	
7. Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
1. Immediately following the trip, BESS 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.	
2. Voltage settles to a stable and acceptable operating point.	
3. The final voltage is as expected based on the droop and deadband settings.	
4. Frequency settles to a stable operating point.	
5. The final frequency is as expected based on the droop and deadband settings.	
6. Any oscillation shall be settled.	
7. Any distortion observed in phase quantities should dissipate over time.	
8. Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
9. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

2.3.2 Test Results

Figure 10, Figure 11, and Figure 12 demonstrate the simulation results for this test. As can be seen in Figure 10, the initial dispatch condition of 50% charging mode is met by both GFMs with active power being equal to −50 MW and −25 MW before the SG is tripped. The active power of SG is also 175 MW to feed both the load and GFMs. The reactive power of GFMs are also within the limits. Figure 11 shows that the frequency and voltage are stable without any oscillations and equal to 60 Hz and 1 pu, respectively, before the trip. Finally, the phase voltages and currents are not distorted in Figure 12, and so all pre-trip conditions in Table 2 are passed.

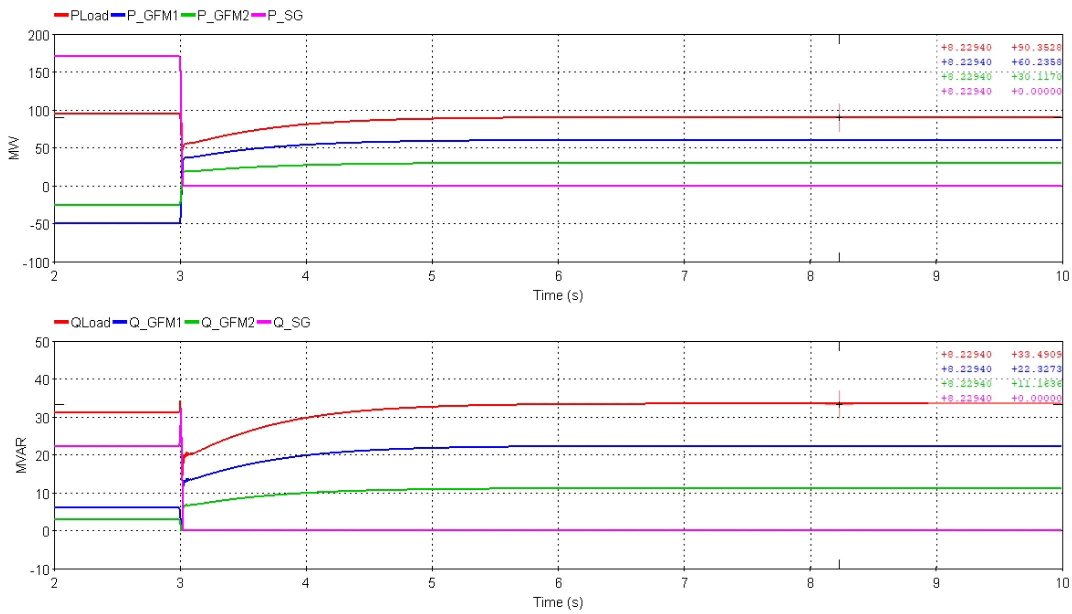

Figure 10. Active and reactive power measured at Bus 1 for Test 2

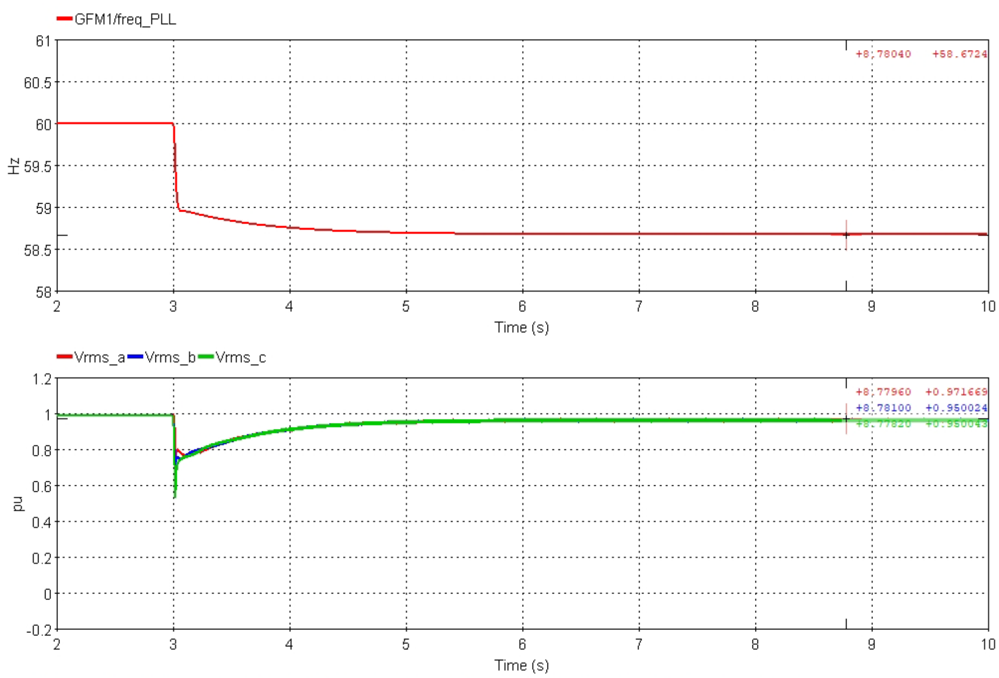

Figure 11. System frequency and three-phase RMS voltages measured at Bus 1 for Test 2

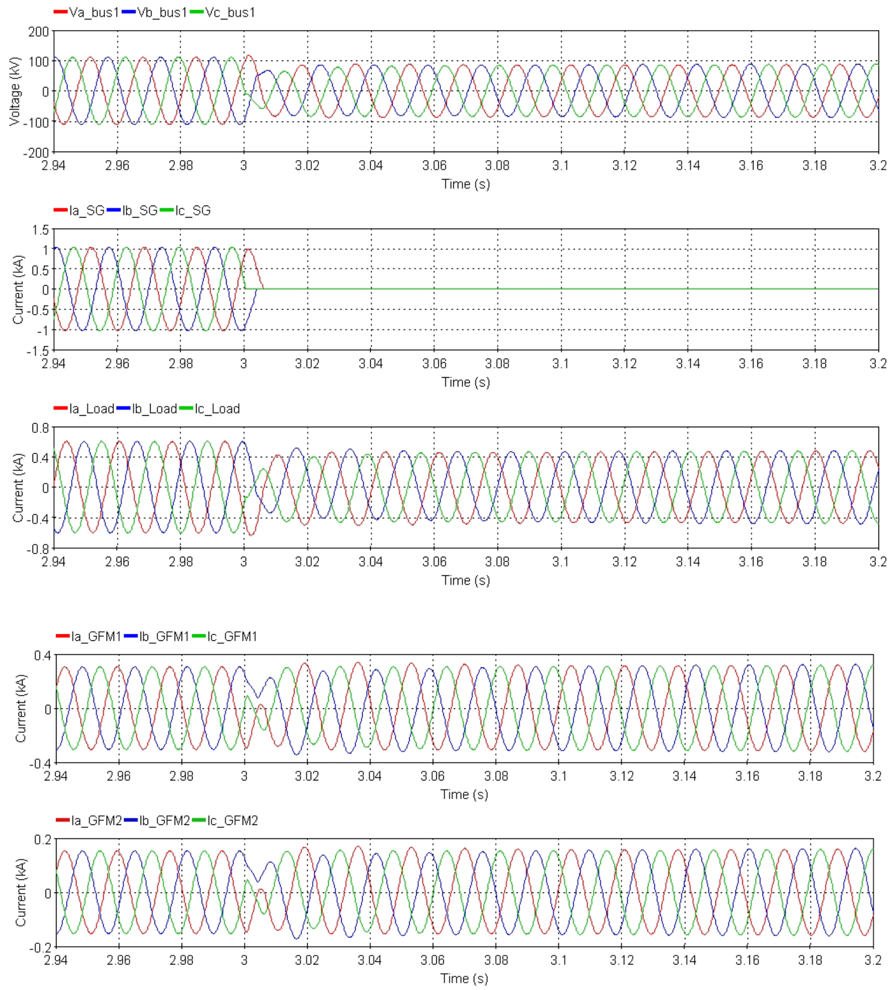

Figure 12. Instantaneous currents and voltages measured at Bus 1 for Test 2

Once the SG is tripped, active and reactive power of SG drop to zero, as shown in Figure 10. The GFMs increase their active power to 60 MW and 30 MW, according to a frequency drop of 2% and a frequency drop of 0.022 pu. The reactive power also increases to 22 MVAR and 11 MVAR (Figure 10) that matches the reactive power voltage droop characteristic. Moreover, Figure 11 illustrates that the frequency and voltage are stable without any oscillations and settle at 58.67 Hz and 0.95 pu, as expected by the droop characteristics. Finally, instantaneous current and voltage waveforms across the system are perfectly sinusoidal without any oscillations in Figure 12. Therefore, all post-fault conditions in Table 2 are successfully passed.

2.4 Test 3: Loss of Synchronous Machine—Limit Test

The objective in this test is to examine the performance of the GFM model when operating close to its limit (1 pu). Like the previous two tests, the test system used for this test is Test Bench 1 from Figure 4.

2.4.1 Test Description and Success Criteria

Table 3 explains the details of Test 3.

Table 3. Test 3 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at 0 MW. • The duplicate BESS is dispatched at its steady-state maximum discharge power limit.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The SG is tripped at $t = 3$ s.	
Success Criteria:	
Pre-Trip:	**Pass/Fail**
1. Each BESS's active power output matches dispatched levels.	
2. SG active power output matches the rest of the load.	
3. Frequency should be 1 pu.	
4. Voltage at Bus 1 should be within 5% of nominal.	
5. Phase voltage and current waveform should not be distorted.	
6. Oscillations should not be present in the RMS quantities.	
7. Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
1. Immediately following the trip, BESS 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.	
2. Voltage settles to a stable and acceptable operating point.	
3. The final voltage is as expected based on the droop and deadband settings.	
4. Frequency settles to a stable operating point.	
5. The final frequency is as expected based on the droop and deadband settings.	
6. Any oscillation should be settled.	
7. Any distortion observed in phase quantities should dissipate over time.	
8. Active power from BESS 1 should move immediately to meet the load requirement and settle according to its frequency droop setting. Active power from BESS 2 should not exceed its maximum discharge power limit at steady-state.	
9. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

2.4.2 Test Results

Figures 13, 14, and 15 depict the simulation results for this test. As can be observed, all pre-trip conditions in Table 3 are met, and GFMs are generating 0 MW and 50 MW before the trip. When the SG is tripped at $t = 3$ s, GFM 1 immediately increases its active power (Figure 13) to maintain the balance between supply and demand in the system, and P_GFM1 rises to 41.2 MW to comply with the frequency droop setting of 2% and the frequency drop of 0.5 Hz (Figure 14). GFM 2, on the other hand, maintains its active power at 50 MW, as it is already operating at the maximum active power capacity. Immediately following the trip, the active power of GFM 2 temporarily increases beyond the 1 pu = 50 MW limit but decreases below the limit in less than half a second. Besides the active power, the GFMs increase their reactive power following the trip in Figure 13 to feed the load and maintain the voltage at the inverter terminal according to the voltage droop setting. As a result, the voltage at Bus 1 remains within 5% of the nominal value and settles at around 0.96 pu in Figure 14. During this test, all phase currents and voltages are perfectly sinusoidal, as shown in Figure 15, and all oscillations in the system are damped. Thus, the GFM model successfully passes all post-trip conditions in Table 3.

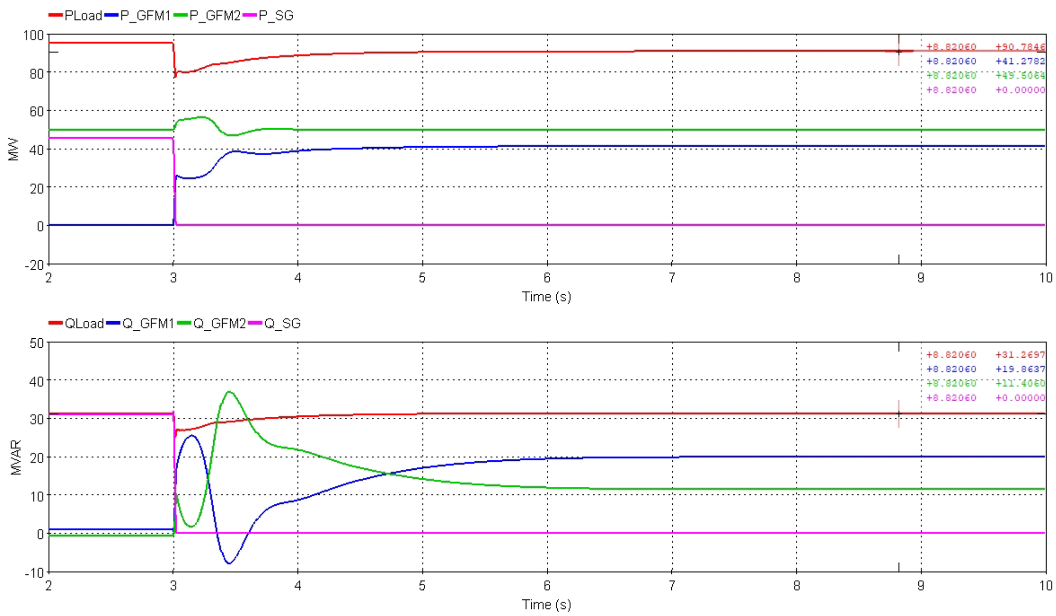

Figure 13. Active and reactive power measured at Bus 1 for Test 3

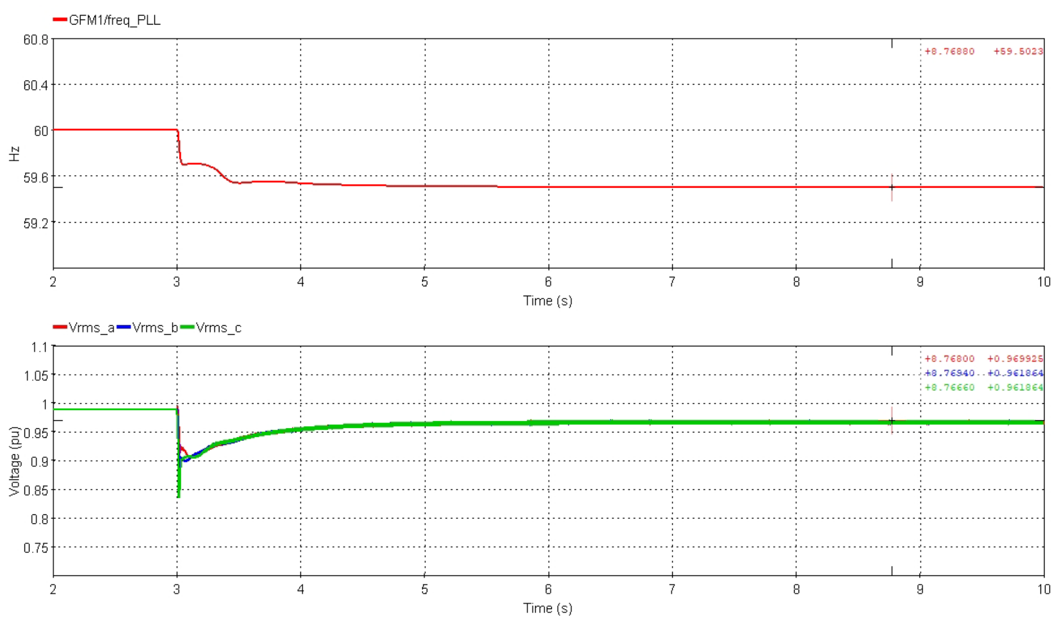

Figure 14. System frequency and three-phase RMS voltages measured at Bus 1 for Test 3

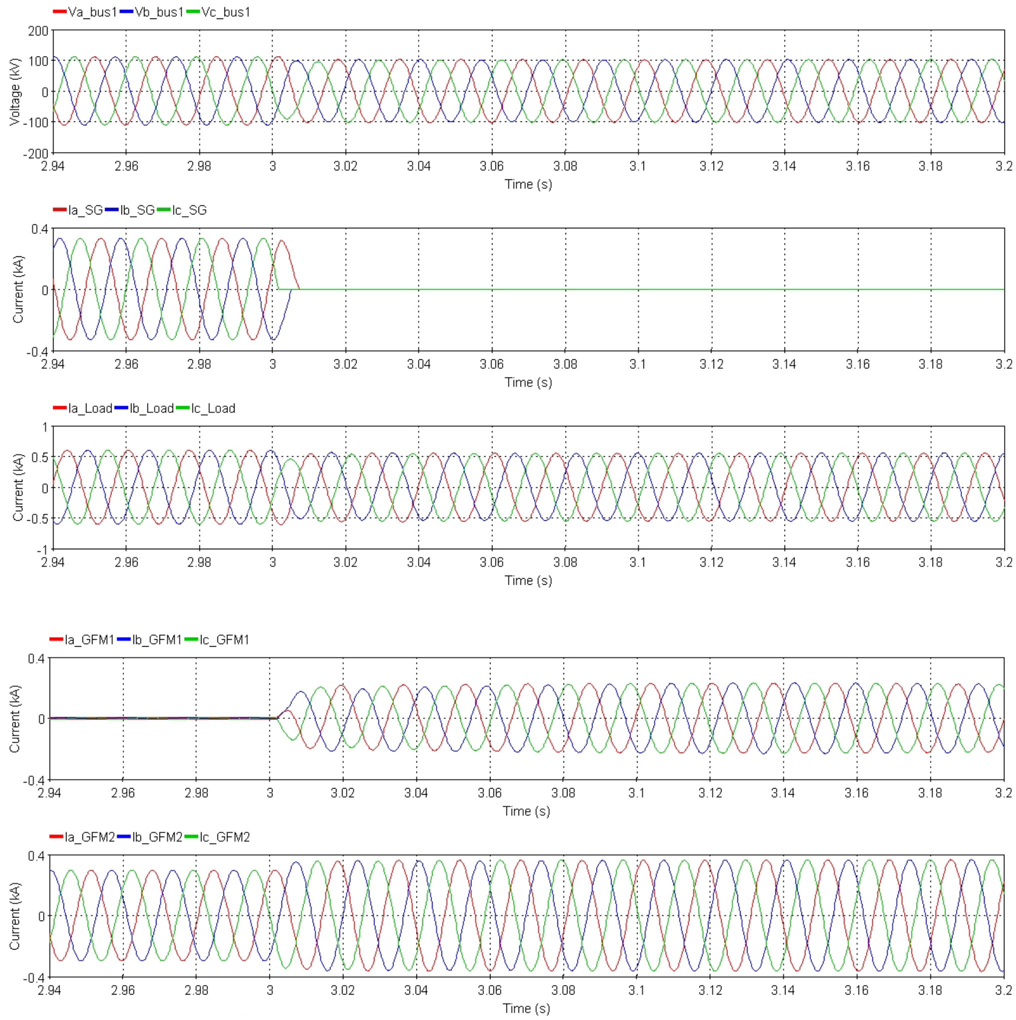

Figure 15. Instantaneous currents and voltages measured at Bus 1 for Test 3

2.5 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 SG, such that the GFM device and the load are balanced. This test is recommended by the Australian Energy Market Operator [2] and is more directed toward GFM devices with very little energy storage or active power margin when compared to Tests 1–3. Test Bench 1 is used for this test as well.

2.5.1 Test Description and Success Criteria

Table 4 explains the details of Test 4. Some of the initial dispatch and post-trip criteria in this test are different from the previous tests.

Table 4. Test 4 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at half of its maximum discharge power limit. • The duplicate BESS is dispatched at half of its maximum discharge power limit. • The load is set to 75% of the project BESS active power limit, with a power factor of 0.95 lagging. • The synchronous machine is supplying 100% of the reactive power to the load.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The SG is tripped at $t = 3$ s.	
Success Criteria:	
Pre-Trip:	**Pass/Fail**
1. Each BESS's active power output matches dispatched levels.	
2. SG active power output is zero or close to zero.	
3. Frequency should be 1 pu.	
4. Voltage at Bus 1 should be within 5% of nominal.	
5. Phase voltage and current waveform should not be distorted.	
6. Oscillations should not be present in the RMS quantities.	
7. Reactive power output from all devices should be within limits.	
Post-Trip:	**Pass/Fail**
1. Immediately following the trip, BESS 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.	
2. Voltage settles to a stable and acceptable operating point.	
3. The final voltage is as expected based on the droop and deadband settings.	
4. Frequency settles at the nominal value.	
5. Any oscillation should be settled.	
6. Any distortion observed in phase quantities should dissipate over time.	
7. Active power from BESS should settle back to pre-trip values.	
8. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	
9. Voltage should not deviate outside of [0.8, 1.1] pu for longer than 0.1 s throughout the test. These voltage bounds and the time threshold are based on preliminary testing and may be adjusted as more experience with this requirement is gained.	

2.5.2 Test Results

The figures below show the measurements for Test 4. As shown in Figure 16, both GFMs are operating at 0.5 pu active power before the SG trip, and the active power of SG is zero. Moreover, GFM reactive power are zero, and the SG is feeding the entire reactive power consumed by the load. Figure 17 and Figure 18 also show that the frequency and voltage are at the nominal values, and three-phase voltage and current waveforms are sinusoidal without any distortion.

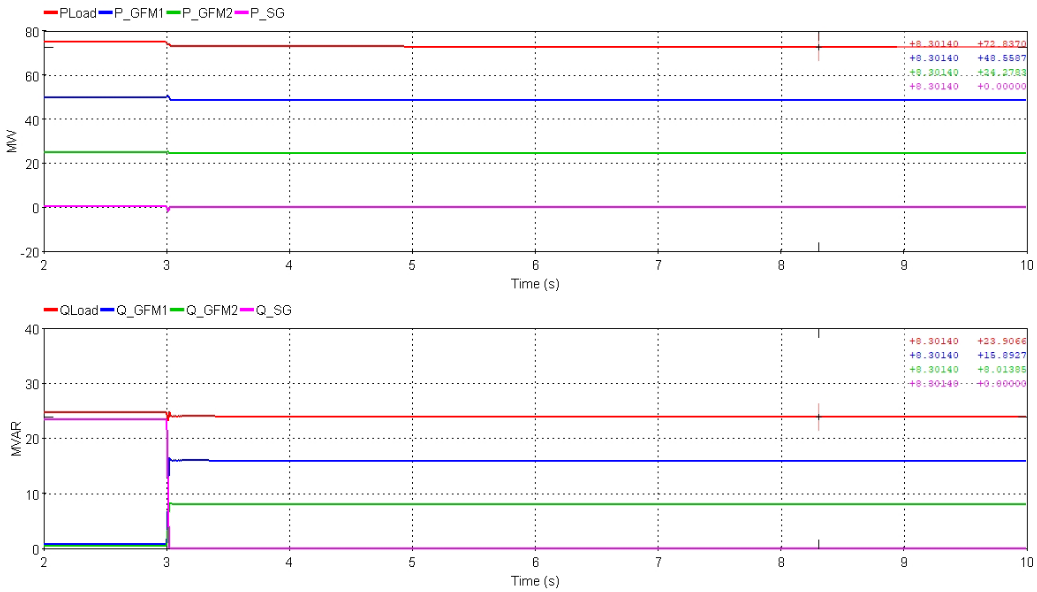

Figure 16. Active and reactive power measured at Bus 1 for Test 4

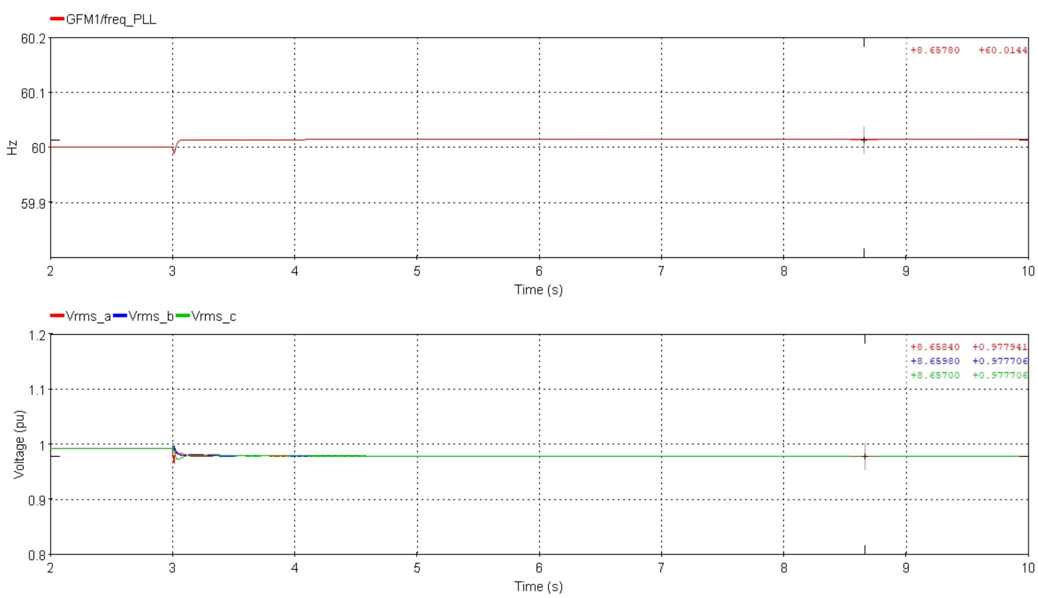

Figure 17. System frequency and three-phase RMS voltages measured at Bus 1 for Test 4

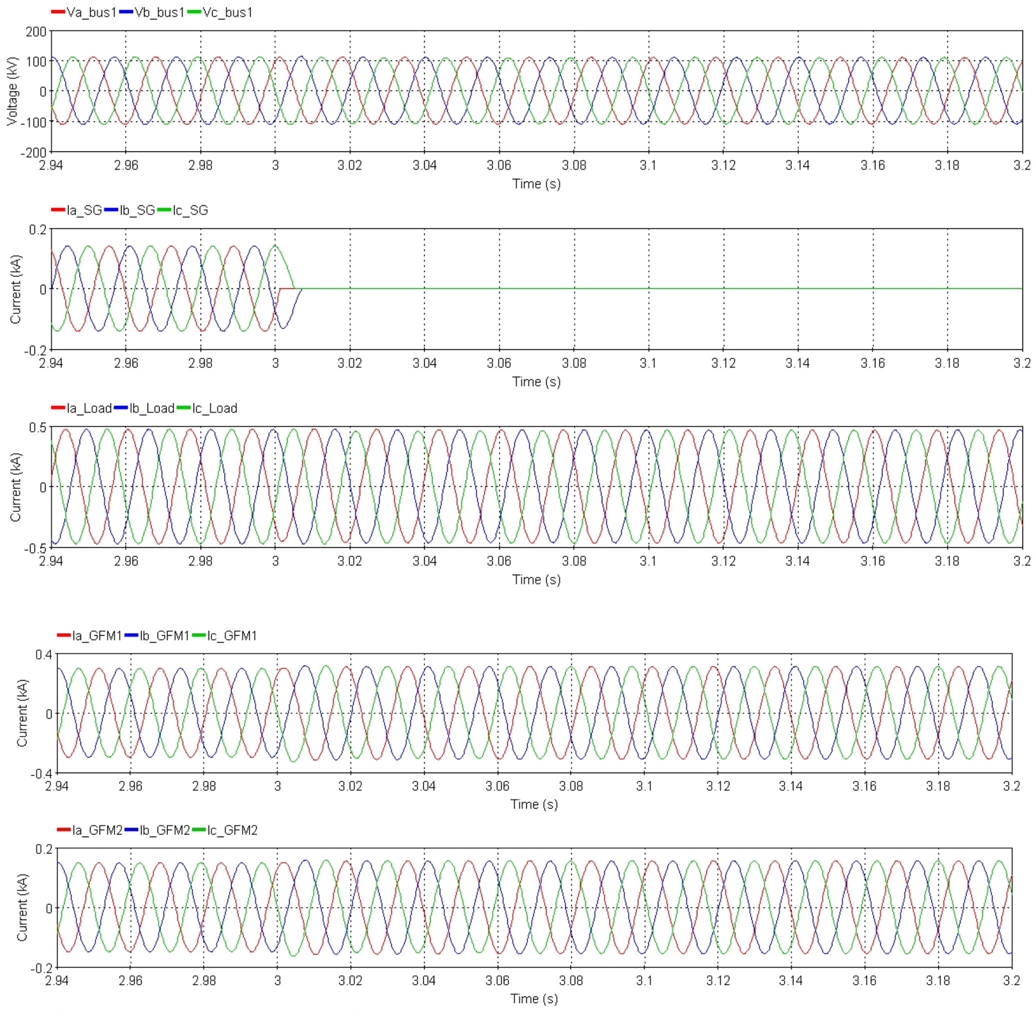

Figure 18. Instantaneous currents and voltages measured at Bus 1 for Test 4

After the SG is tripped, Figure 16 shows that GFMs maintain their active power output close to the pre-trip values, and so the system frequency remains at 60 Hz in Figure 17, matching post-trip Criterion 4 from Table 4. The reactive power, on the other hand, increase to feed the load based on the droop characteristic. Figure 17 also shows that the system voltage remains within the [0.8, 1.1] pu range throughout the test and settles at 0.977 pu in Figure 17, thereby passing post-trip Criterion 9 from Table 4. Furthermore, Figure 18 demonstrates that current and voltage waveforms do not have any distortion and do not change much compared to the pre-trip values. Therefore, the model passes all post-trip criteria in Table 4.

2.6 Test 5: Load Increase—Synchronous Machine in Service

This test evaluates the impact of load increase on the GFM model while the synchronous machine remains in service. This test, along with Test 6, make up a subset of EPRI's tests [3]. Test Bench 1 is used for this test also.

2.6.1 Test Description and Success Criteria

Table 5 provides a detailed explanation of Test 5.

Table 5. Test 5 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at half of its maximum discharge power limit. • The duplicate BESS is dispatched at half of its maximum discharge power limit. • The load is set to 100% of the project BESS active power limit, with a power factor of 0.95 lagging. • The synchronous machine is supplying 100% of the reactive power to the load.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The load is increased by 25% of the initial load at $t = 2$ s. • The load is increased by 100% of the initial load at $t = 10$ s. • All the additional loads are tripped at $t = 18$ s.	
Success Criteria:	
Before Load Increase:	**Pass/Fail**
1. Each BESS's active power output matches dispatched levels.	
2. SG active power output matches the rest of the load.	
3. Frequency should be 1 pu.	
4. Voltage at Bus 1 should be within 5% of nominal.	
5. Phase voltage and current waveform should not be distorted.	
6. Oscillations should not be present in the RMS quantities.	
7. Reactive power output from all devices should be within limits.	
After Load Increase:	**Pass/Fail**
1. Immediately following the load increase, BESS 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.	
2. Voltage settles to a stable and acceptable operating point following load changes.	
3. The final voltage is as expected based on the droop and deadband settings.	
4. Frequency should finally settle at the nominal value after additional loads are disconnected.	
5. Any oscillation should be settled.	
6. Any distortion observed in phase quantities should dissipate over time.	
7. Active power from BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
8. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

2.6.2 Test Results

The figures below show the simulation results for this test. A 25% increase in load happens at $t = 2$ s, which causes the GFM 1 and GFM 2 active power to increase by 8.33 MW and 4.16 MW, respectively, as shown in Figure 19. This matches the frequency droop gain of 2% and the frequency drop of 0.1 Hz shown in Figure 20. Moreover, the reactive power of GFMs increase by 1.4 MVAR and 0.7 MVAR to accommodate the rise in reactive power of the load based on the voltage droop setting of 2% and voltage drop of 0.00028 at the inverter terminal. A similar pattern happens at $t = 10$ s when the load is increased again. Finally, once all the additional loads are disconnected at $t = 18$ s, active and reactive power, frequency, and voltage settle at the values before the load increase $t = 2$ s shown in Figure 19 and Figure 20. Figure 21 also illustrates the lack of undamped oscillation in the system. Voltage and current waveforms do not have any distortion, so all criteria in Table 5 are passed.

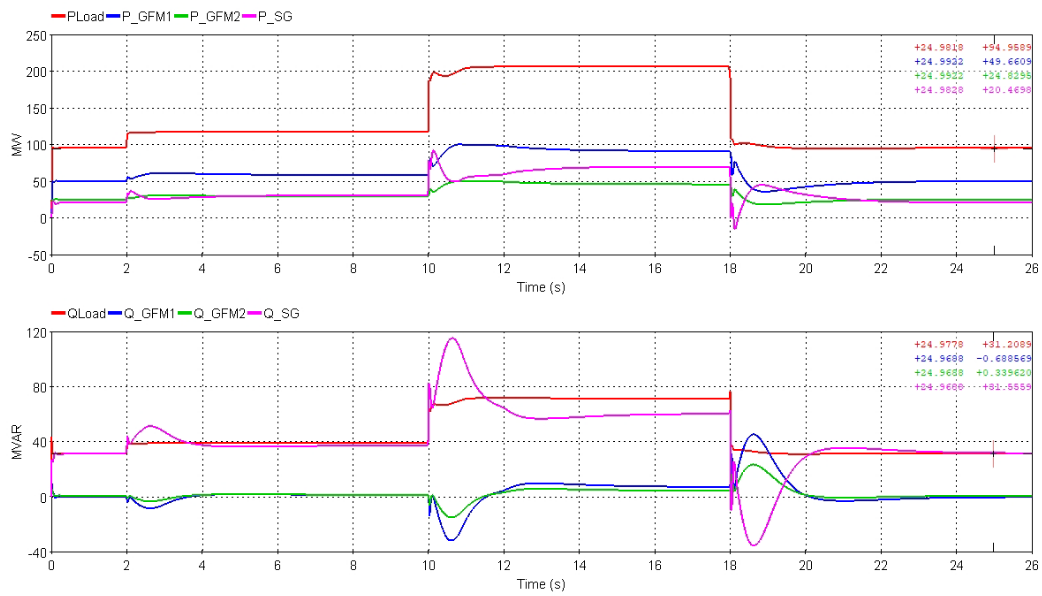

Figure 19. Active and reactive power measured at Bus 1 for Test 5

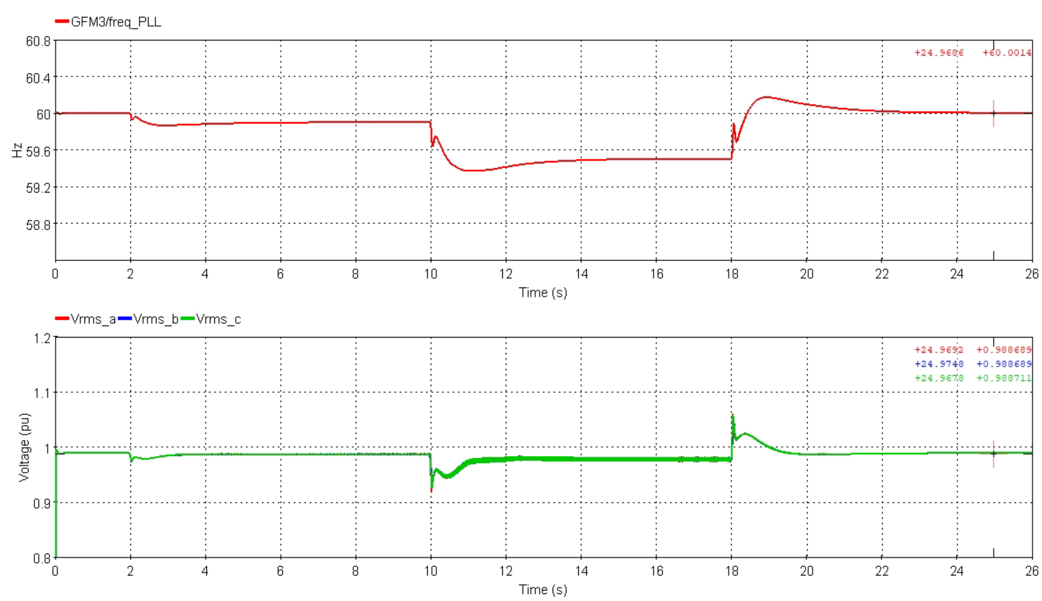

Figure 20. System frequency and three-phase RMS voltages measured at Bus 1 for Test 5

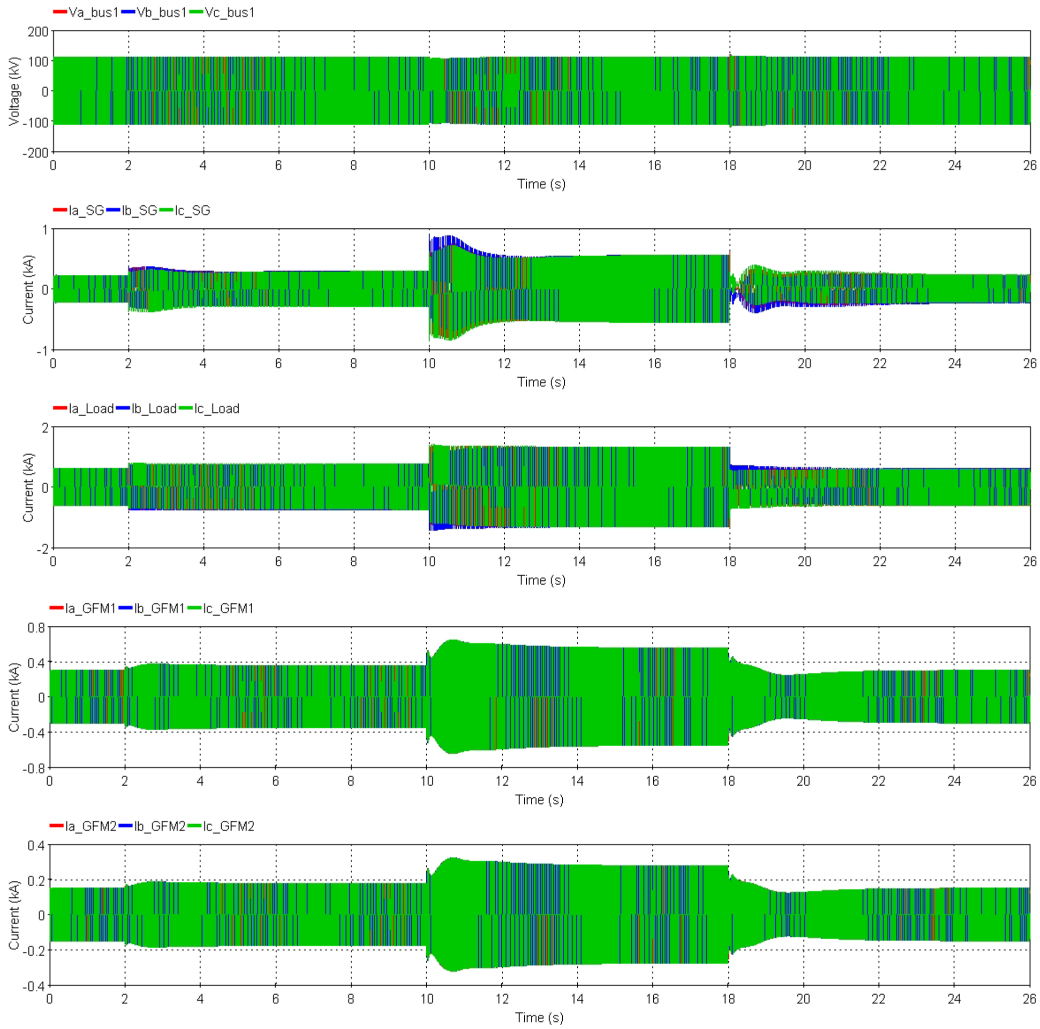

Figure 21. Instantaneous currents and voltages measured at Bus 1 for Test 5

2.7 Test 6: Load Increase—Loss of Synchronous Machine

Test 6 is similar to Test 5, except that the SG is tripped before changing the load, so the response of the GFMs to load change can be observed. Test Bench 1 is used for this test also.

2.7.1 Test Description and Success Criteria

Table 6 explains the steps of Test 6.

Table 6. Test 6 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at half of its maximum discharge power limit. • The duplicate BESS is dispatched at half of its maximum discharge power limit. • The load is set to 100% of the project BESS active power limit, with a power factor of 0.95 lagging. • The synchronous machine is supplying 100% of the reactive power to the load.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The SG is tripped at $t = 2$ s. • The load is increased by 25% of the initial load at $t = 6$ s. • The load is increased by 25% of the initial load at $t = 10$ s. • All additional loads are tripped at $t = 14$ s. • The load is increased by 50% of the initial load at $t = 18$ s.	
Success Criteria:	
Before Load Change:	**Pass/Fail**
1. Each BESS's active power output matches dispatched levels.	
2. SG active power output matches the rest of the load.	
3. Frequency should be 1 pu.	
4. Voltage at Bus 1 should be within 5% of nominal.	
5. Phase voltage and current waveform should not be distorted.	
6. Oscillations should not be present in the RMS quantities.	
7. Reactive power output from all devices should be within limits.	
After Load Change:	**Pass/Fail**
1. Immediately following the trip and load changes, BESS 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.	
2. Voltage settles to a stable and acceptable operating point following the trip and load changes.	
3. The final voltage is as expected based on the droop and deadband settings.	
4. Frequency should finally settle at the expected value based on the load in the system and the frequency droop gain.	
5. Any oscillation should be settled.	
6. Any distortion observed in phase quantities should dissipate over time.	
7. Active power from BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
8. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

2.7.2 Test Results

Figure 22, Figure 23, and Figure 24 show that both GFMs are able to provide sufficient active and reactive power to the changing load in the system in a stable and fast manner, while remaining within the limits of the GFM and following the droop characteristic. The system frequency and voltage are stable as well and settle in the acceptable ranges following each load change. Similar to the previous test, no distortion occurs in instantaneous current and voltages across the system. Therefore, all metrics in Table 6 are successfully passed, and this test showcases the capability of the GFM model in standing an SG trip followed by load increase/decrease in a 100% inverter-based resource system.

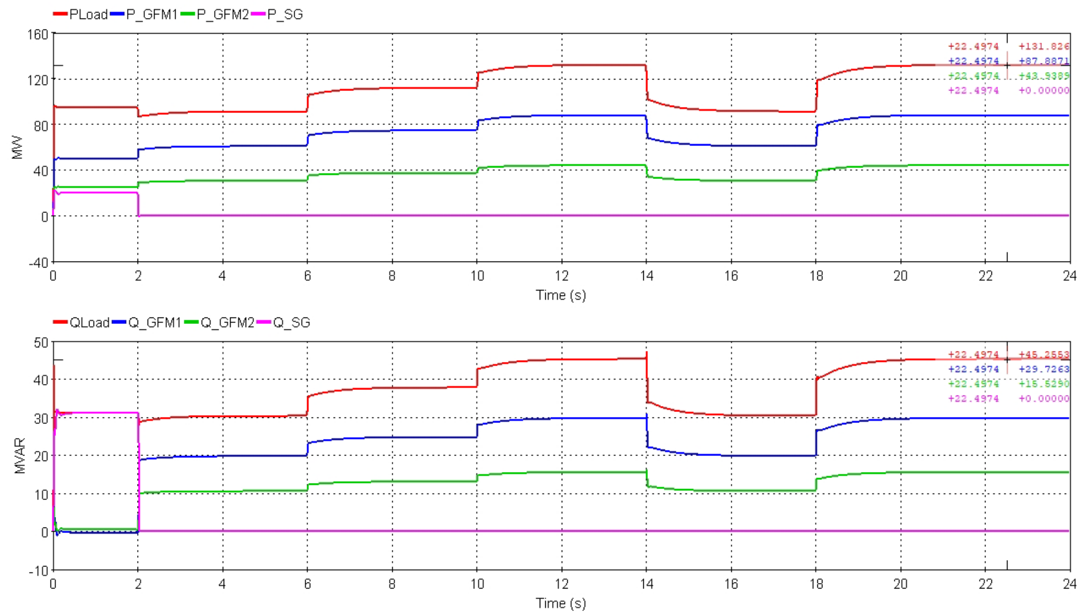

Figure 22. Active and reactive power measured at Bus 1 for Test 6

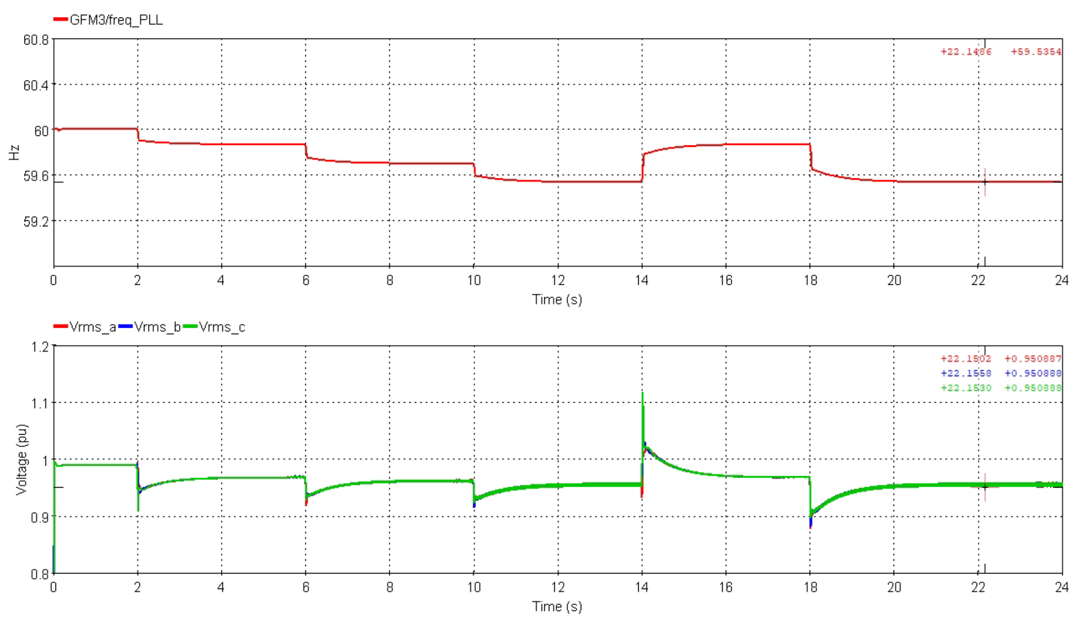

Figure 23. System frequency and three-phase RMS voltages measured at Bus 1 for Test 6

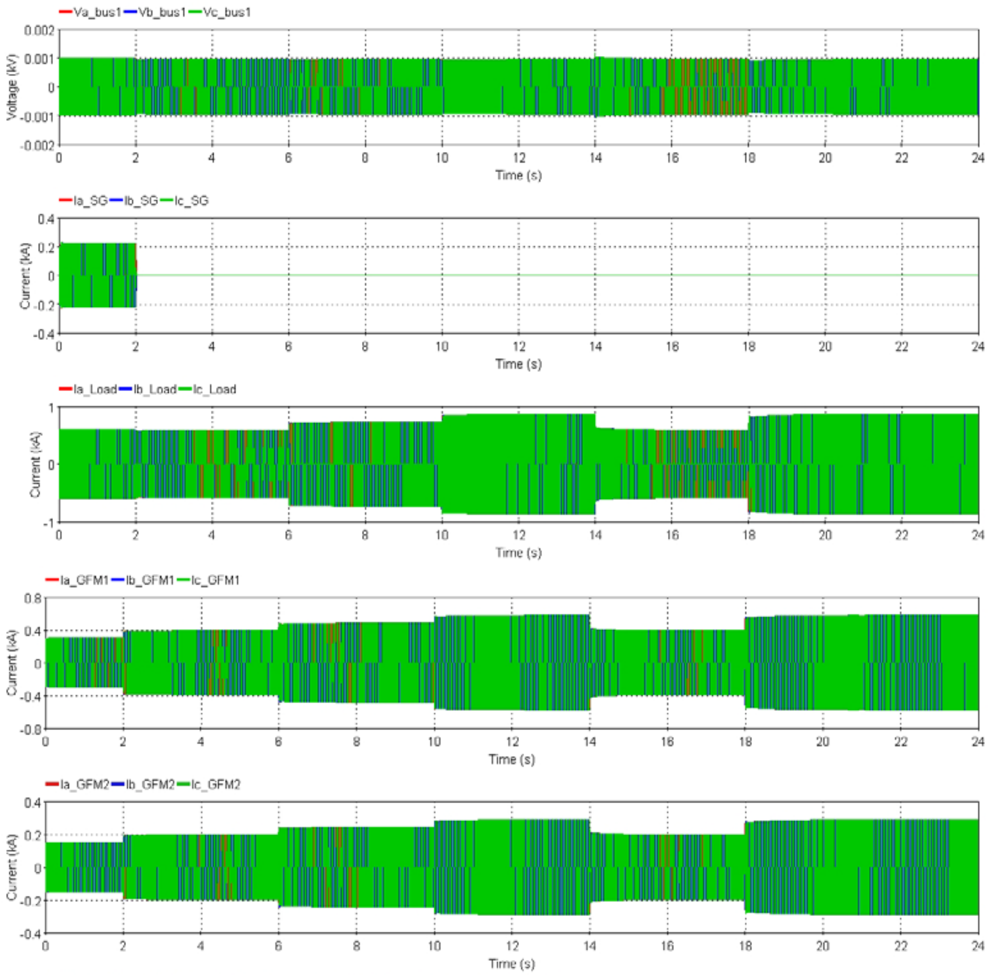

Figure 24. Instantaneous currents and voltages measured at Bus 1 for Test 6

2.8 Test 7: Stability of Plant With Changing Frequency

Test 7, as well as Tests 8 and 9, were recommended by the Australian Energy Market Operator [2]. These tests are performed in a new test bench, explained below. Test 7 is intended to evaluate the stability of the GFM plant in response to frequency changes in both directions (increasing and decreasing frequency).

2.8.1 Test Bench 2

The test system used for Test Bench 2 consists of an ideal voltage source connected to the GFM BESS through a controllable series impedance as well as a variable impedance fault component shown in Figure 25. The source has inputs for voltage (including magnitude, phase, and frequency), and the series impedance is variable such that the connection point strength and voltage may be set. Unlike Test Bench 1, Test Bench 2 includes only the project BESS with no duplicate plant. Depending on the specific requirements of a test, the fault component may be enabled or disabled. For the tests done in this study, the default magnitude, angle, and frequency of the voltage source are 137.5 kV (line-to-line, RMS), 0°, and 60 Hz, respectively. Moreover, the GFM BESS is rated at 100 MW.

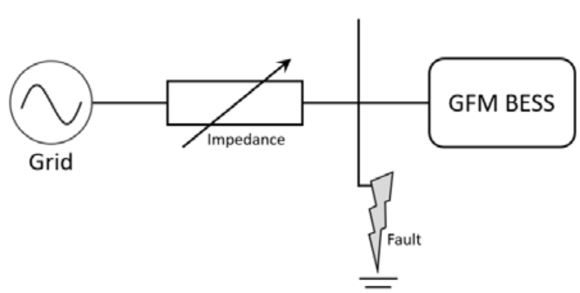

Figure 25. Test Bench 2

2.8.2 Test Description and Success Criteria

Table 7 explains the details of Test 7.

Table 7. Test 7 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at half of its maximum discharge power limit. • The short-circuit ratio (SCR) at the connection point is set to 10. System equivalent X/R is set to 6. • Only the project plant, no duplicate.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The frequency is ramped from 60 Hz to 61 Hz at 4 Hz/s at $t = 3$ s and stays at 61 Hz for 5 seconds. • The frequency is ramped from 61 Hz to 60 Hz at 4 Hz/s at $t = 8.25$ and stays at 61 Hz for 5 seconds. • The frequency is ramped from 60 Hz to 59 Hz at 4 Hz/s at $t = 13.5$ and stays at 59 Hz for 5 seconds. • The frequency is ramped from 59 Hz to 60 Hz at 4 Hz/s at $t = 18.75$ and stays at 60 Hz for 5 seconds.	
Success Criteria:	**Pass/Fail**
1. 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.	
2. Voltage settles to a stable operating point when frequency is not ramping.	
3. Active power should settle according to its frequency droop and deadband settings when frequency is not ramping.	
4. Any oscillation shall be adequately damped in line with definition presented in the National Electricity Rules [4].	

2.8.3 Test Results

Figure 26 and Figure 27 show the results for this test. Prior to ramping the frequency, the GFM is generating 50 MW and −5 MVAR (Figure 26). Following the test sequence in Table 7, the frequency of the voltage source is ramped up at $t = 3$ s (Figure 26). The ramping of the frequency is done uniformly over a time span of 250 ms to achieve a rate of change of frequency of 4 Hz/s, per the test requirement. During this period, active and reactive power of the GFM in Figure 26 oscillate and exceed the 1-pu limit. However, when the frequency settles at 61 Hz, these oscillations disappear, and P_GFM and Q_GFM settle at −33.3 MW and 5.7 MVAR, respectively, both of which are within the limits and match the expected values based the frequency and voltage droop characteristics. Because the total power generated by the GFM has decreased compared to the initial dispatch value, the GFM current magnitude has decreased in Figure 27. A similar pattern of change in active and reactive power of the GFM can be observed for the rest of the frequency changes in Figure 26, which includes oscillations in P and Q once the frequency starts ramping, an overshoot/undershoot beyond the limits during the ramping, and settling within the limits based on the droop once the frequency settles. During the frequency ramping, voltage and current waveforms of the GFM oscillate as well and become distorted. The reason behind these oscillations is that the GFM control system loses synchronism with the grid when the frequency deviates from 60 Hz, and it takes some time for the control system to track the moving frequency setpoint and settle at the new value. Figure 26 also shows that, when the frequency returns to 60 Hz, active and reactive power of the GFM become equal to the values before $t = 3$ s. In addition, Figure 27 shows that the RMS voltage oscillates when the frequency is ramping but settles close to 1 pu when the frequency becomes stable. Finally, Figure 27 demonstrates that the GFM current is stable without any undamped oscillations when the frequency settles. Considering the success criterion 1 in Table 7, the definition of "well controlled" is open to interpretation. It is not clear whether the oscillations in P, Q, and V during the frequency ramping is considered controlled or uncontrolled, given that the oscillations subside once the frequency settles. However, other than Criterion 1, the GFM model passes the remaining criteria in Table 7 successfully. This test was re-simulated for a system frequency of 50 Hz as well, and the results and conclusions are similar to what is observed for the 60-Hz system.

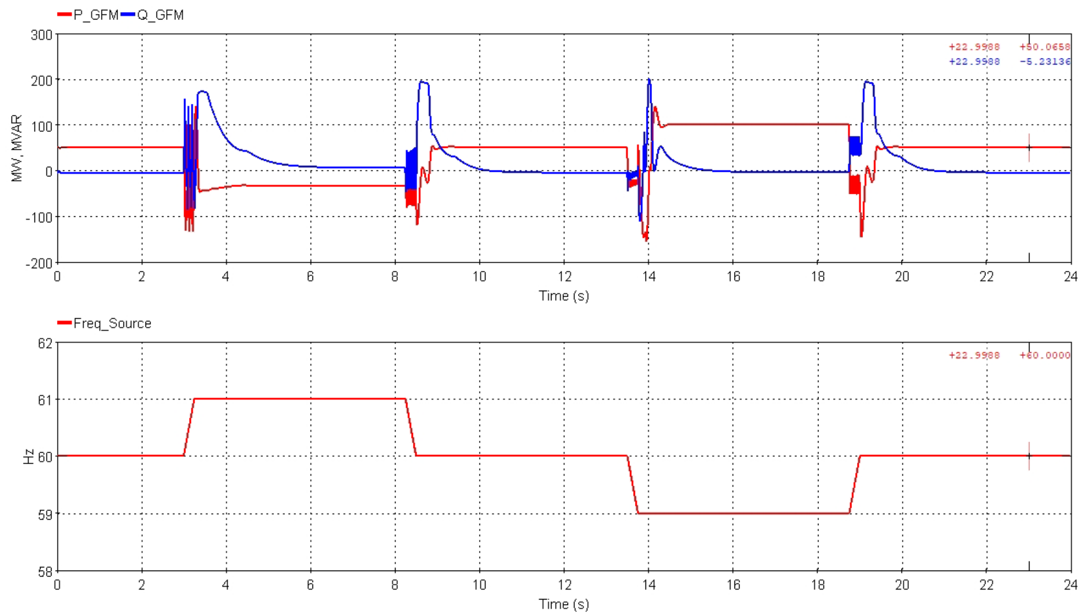

Figure 26. Active and reactive power of the GFM at the bus and the frequency of the voltage source for Test 7

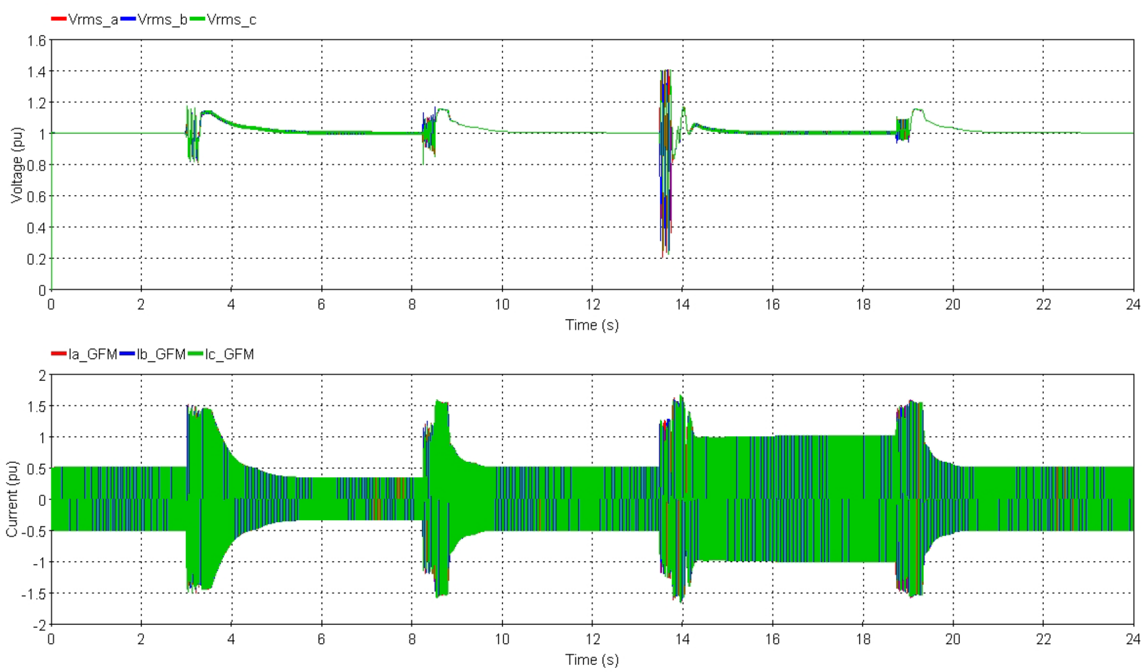

Figure 27. Three-phase RMS voltage and instantaneous currents of the GFM at the bus for Test 7

2.9 Test 8: SCR Step Down With Fault

Test 8 evaluates the stability of the GFM control system in weak system conditions down to an SCR of 1.25. Test Bench 2 is used for this test.

2.9.1 Test Description and Success Criteria

Table 8 explains the details of Test 8.

Table 8. Test 8 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at its maximum discharge power limit. • SCR at the connection point is set to 20. System equivalent X/R is set to 6. • Only the project plant, no duplicate.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • SCR at the connection point is stepped down repeatedly in this progression: 10, 3, 2, 1.5, 1.25. • A six-cycle two-phase-to-ground fault is applied with a minimum fault depth of 0.5 pu just before each SCR transition. The SCR transition occurs at fault clearing time.	
Success Criteria:	**Pass/Fail**
1. 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.	

2.9.2 Test Results

The response of the GFM model in this test is displayed in the figures below. Following the test sequence in Table 8, bolted phase-A-to-phase-B-to-ground faults are applied for 6 cycles (i.e., 100 ms), on the bus in Test Bench 2 (Figure 25). Following the fault clearance, the SCR of the system is decreased to the values specified in . Figure 28 illustrates that the GFM maintains its active power output at 100 MW after clearance of the faults and SCR reductions. The reactive power, on the other hand, increases following each SCR reduction to account for the larger voltage drop across the source impedance, which is reflected at the inverter terminal as well. An interesting observation in this figure is that, the smaller the SCR, the longer the time that it takes for the RMS voltage oscillations to dissipate, showing a less stable voltage due to the larger impedance of the source. Moreover, the frequency of the system remains at 60 Hz before and after the faults in Figure 28, which is the main reason for the GFM active power to remain at 100 MW. Additionally, the GFM current is well controlled and remains below the 1.5-pu limit during both faults and non-fault periods without any undamped oscillations in Figure 29. Thus, all criteria in Table 8 are successfully passed.

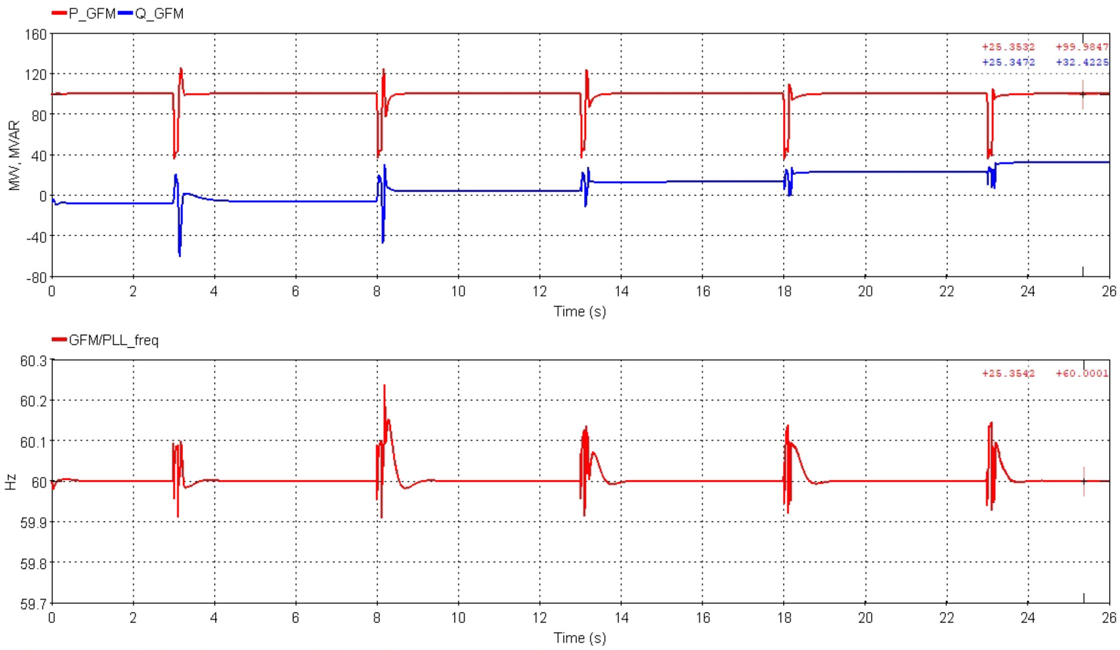

Figure 28. Active and reactive power of the GFM and the system frequency for Test 8

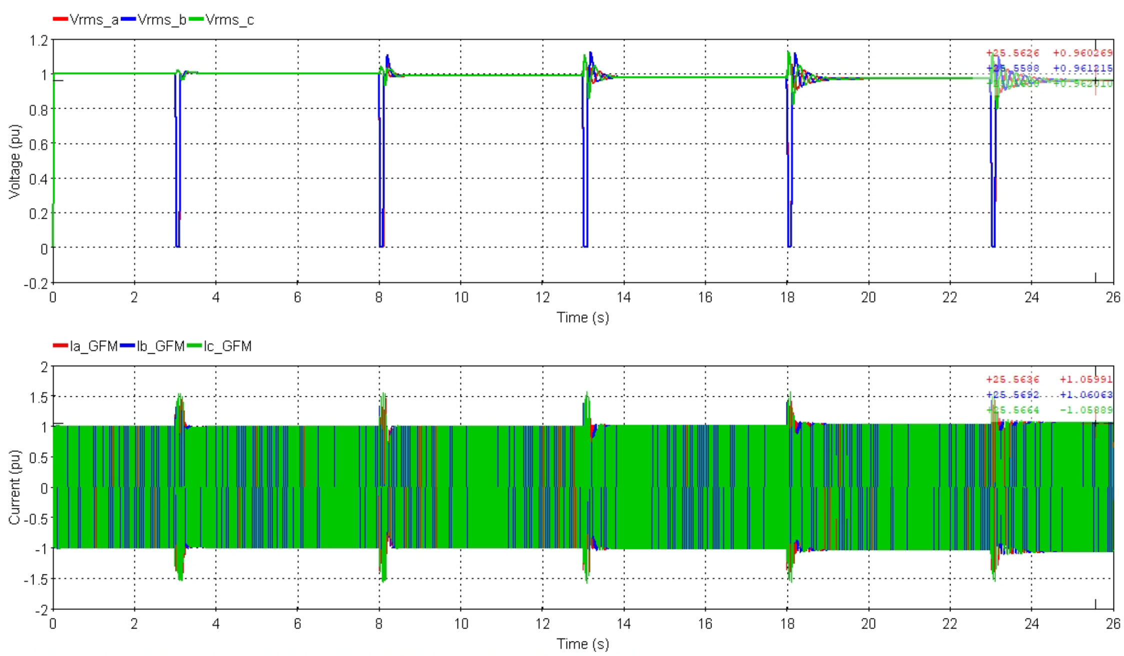

Figure 29. Three-phase RMS voltage at the bus and instantaneous currents of the GFM for Test 8

2.10 Test 9: 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. Test Bench 2 is used for this test also.

2.10.1 Test Description and Success Criteria

Table 9 explains the details of Test 9.

Table 9. Test 9 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at 50% of its maximum discharge power limit. • The SCR at the connection point is set to 3. System equivalent X/R is set to 6. • Only the project plant, no duplicate.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • Angle of the voltage source is decreased instantaneously by 10° at $t = 5$ s. • 5 seconds later, angle of the voltage source is increased by 10°. • 5 seconds later, angle of the voltage source is decreased instantaneously by 30°. • 5 seconds later, angle of the voltage source is increased by 30°. • 5 seconds later, angle of the voltage source is decreased instantaneously by 60°. • 5 seconds later, angle of the voltage source is increased by 60°.	
Success Criteria:	**Pass/Fail**
1. The instantaneous active power output of the plant should quickly respond to oppose the angle change for each of the 10° 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°, and should temporarily decrease active power from 50 to 30 MW or below when voltage source angle is increased by 10°).	
2. For each of the 10° voltage phase angle jumps, response time to 90% of initial change in instantaneous active power should occur within 15 ms.	
3. Active power settles to pre-disturbance level shortly after all phase jumps.	
4. If active power/current reaches limits for the 60° phase change, the plant should return to pre-event power levels in a stable manner.	
5. Any oscillation should be settled.	
6. Any distortion observed in phase quantities should dissipate over time.	

2.10.2 Test Results

The following figures show the results for this test. Active and reactive power of the GFM undergo a transient following each phase angle change but finally settle back at 50 MW and 0 MVAR, respectively, in Figure 30. The most severe transients happen for the phase angle drop of 60°, which even pushes the GFM into the fault ride-through (FRT) mode. As shown in Figure 31, the measured RMS voltage drops below 0.7 pu (i.e., the threshold for FRT activation) immediately following the voltage angle drop, and so the FRT mode gets activated. This contributes to the extreme transients in active and reactive power in this case compared to the other phase angle changes in Figure 30. Nonetheless, the GFM successfully rides through this event and recovers active and reactive power back to 50 MW and 0 MVAR. Although the 60° phase angle change is required to be evaluated in this test, the Australian Energy Market Operator confirmed that a +/− 60° phase angle change is severe and only feasible in a small subset of network locations and that testing should focus around the 20°–30° phase angle jumps. For larger angle steps, the test should still be applied, but the determination of pass/fail should be situational and subject to actual connection point condition [2].

Figure 30 shows that, for all phase angle changes, the GFM active power increases/decreases by more than 20 MW = 0.2 pu. To better illustrate this point, Figure 31 shows a zoomed-in version of the active power during the 10° phase angle drop. Active power of the GFM starts rising at $t = 5$ s, exceeds 70 MW, and reaches a peak of 77.8 MW. Thus, Success Criterion 1 in Table 9 is passed. Figure 31 also demonstrates that it takes about 20 ms for the active power to reach 90% of the peak value (i.e., 70 MW). This is 5 ms longer than the 15-ms requirement in Success Criterion 2 of Table 9, indicating that the model does not pass it. However, the term "initial change" in this criterion is open to interpretation. Assuming that this term is referring to the peak value, the GFM model does not pass this criterion. Making the voltage control loop faster also did not help increasing the speed and put the model on the brink of instability, which resulted in the model failing several criteria of other tests. Therefore, we concluded that the current settings of the model in Figure 3 are the most suitable settings that can pass most of success criteria in different tests.

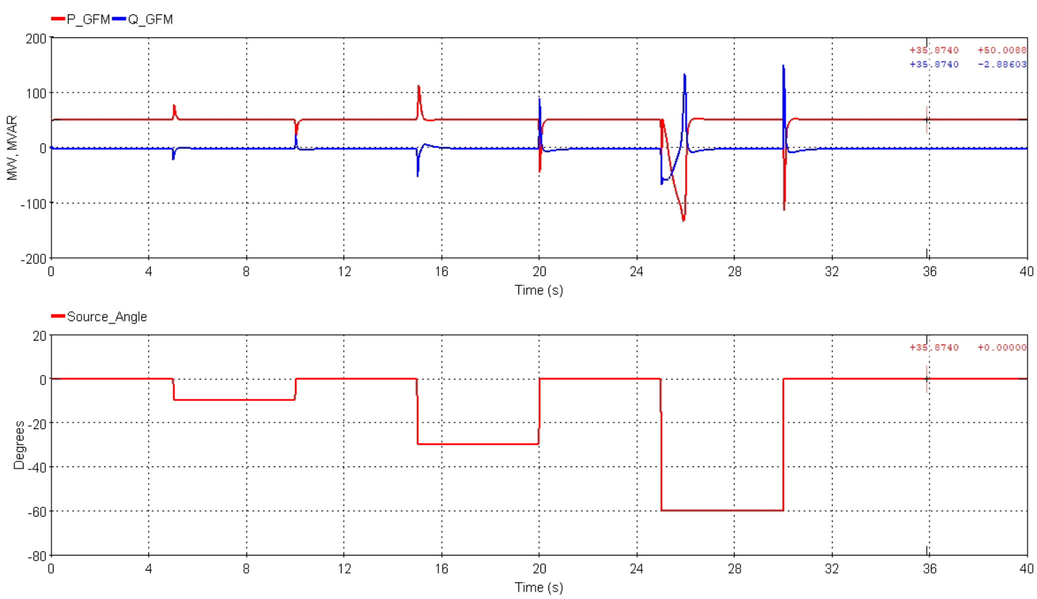

Figure 30. Active and reactive power of the GFM at the bus and the angle of the voltage source for Test 9

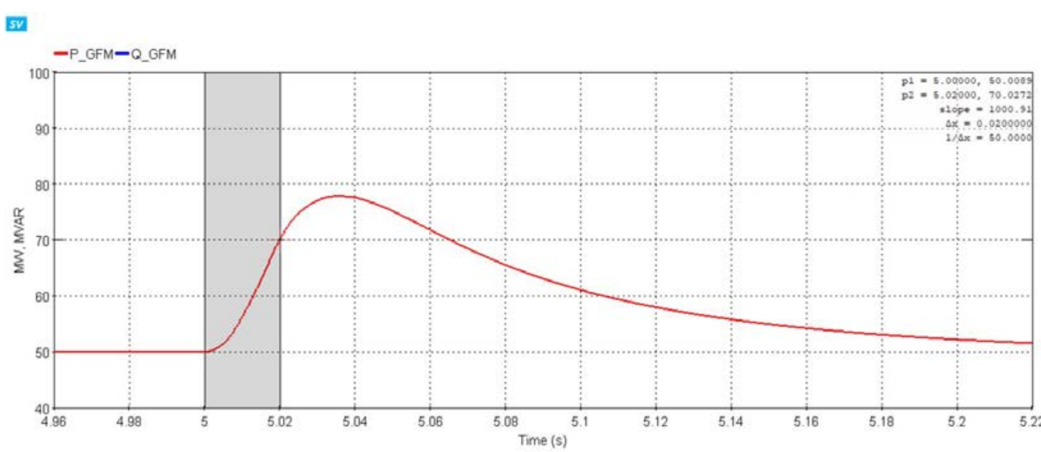

Figure 31. Zoomed-in version of the active power of GFM during the 10° phase angle drop in Test 9

Figure 32 depicts the system frequency and RMS voltages at the bus during this test. Similar to the active and reactive power, the frequency and voltage also experience transients following each voltage angle change but recover back to their rated values shortly after. The largest transients are observed for the 60° phase angle drop, for which the GFM control system frequency gets frozen for a short period of time in Figure 32 due to activation of the FRT mode. Finally, Figure 33 shows that the GFM current response is stable, without any undamped oscillations as well as distortions. Moreover, the peak of the phase currents remains below 1.5 pu = 890 A current limit of the inverter throughout the test. Only during the 60° phase angle drop does the current reach 1.5 pu, which is a characteristic of the FRT strategy of the model that is designed to maximize the inverter current during faults.

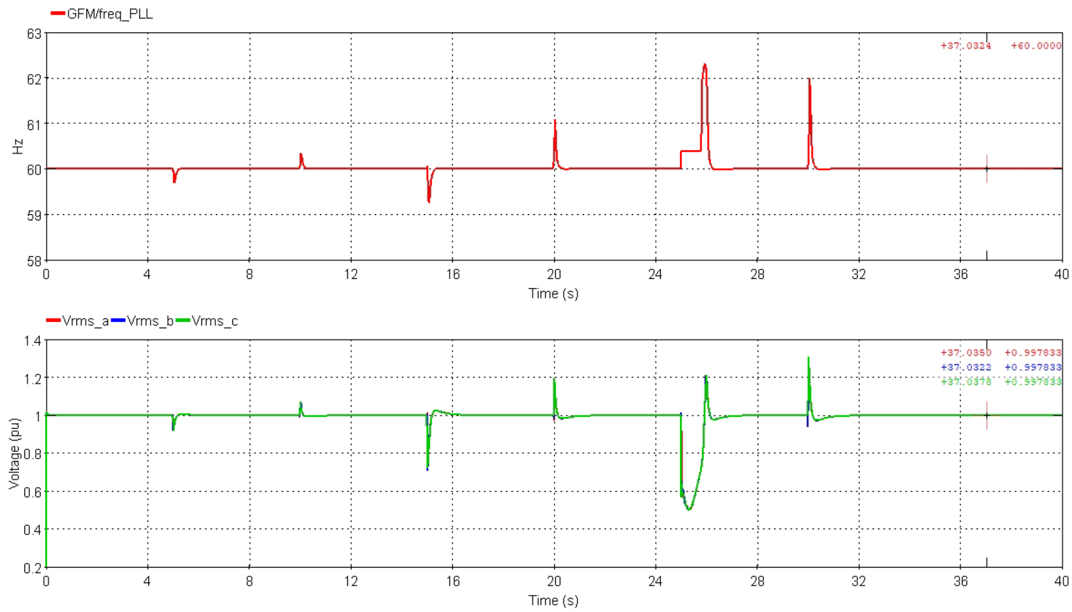

Figure 32. System frequency and three-phase RMS voltages at the bus for Test 9

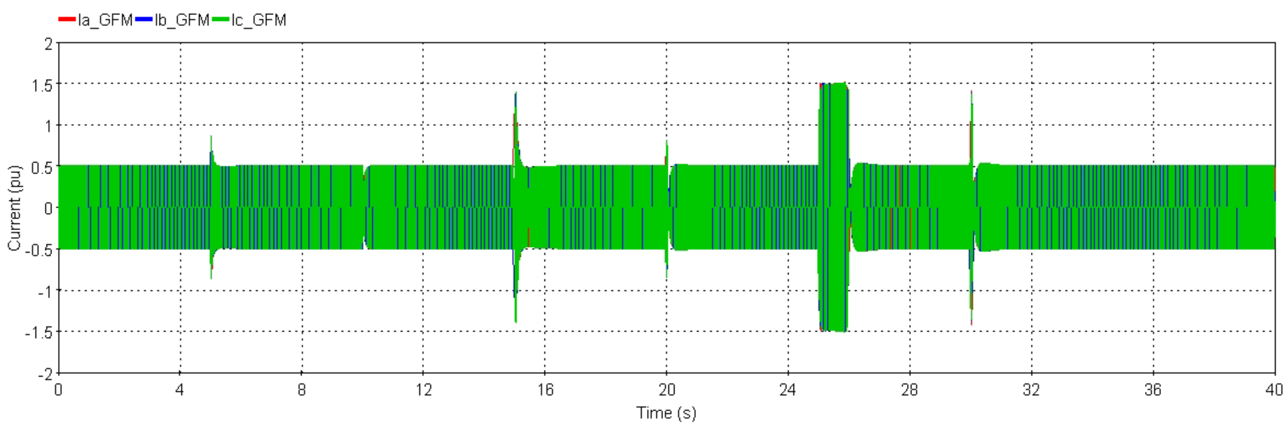

Figure 33. Instantaneous currents of the GFM at the bus for Test 9

2.11 Test 10: Voltage Magnitude Change

The objective in Test 10 is to assess the response of the reactive power voltage droop control of the GFM model. Tests 10 and 11 are from the EPRI test set [3]. Test Bench 2 is used for this test also.

2.11.1 Test Description and Success Criteria

Details of Test 10 are explained in .

Table 10. Test 10 Setup and Success Criteria

Initial Dispatch:

- The project BESS is dispatched at 50% of its maximum discharge power limit.
- SCR at the connection point is set to 20. System equivalent X/R is set to 6.
- Only the project plant, no duplicate.

Test Sequence:

- Run until the system is stable at the given power flow conditions, without oscillations.
- Magnitude of the voltage source is decreased instantaneously by 10% at $t = 5$ s.
- 5 seconds later, magnitude of the voltage source is increased by 10%.
- 5 seconds later, magnitude of the voltage source is increased by 10%.
- 5 seconds later, magnitude of the voltage source is decreased by 10%.

Success Criteria:	Pass/Fail
1. Plant real and reactive power output should be well controlled, and plant should not trip or reduce power for any extended period.	
2. For each voltage magnitude change, reactive power from the BESS should move immediately and settle according to its voltage droop setting.	
3. Active power should remain at 0.5 pu following all voltage magnitude changes.	
4. Reactive power should not oscillate excessively beyond the limits for a significant amount of time.	
5. Any oscillation should be settled.	
6. Any distortion observed in phase quantities should dissipate over time.	

2.11.2 Test Results

For this test, the GFM is dispatched at 50 MW active power and −6.2 MVAR reactive power, as Figure 34 shows. The voltage and frequency are 1 pu in Figure 35. At $t = 5$ s, the magnitude of the voltage source is decreased by 0.1 pu and becomes 0.9 pu. As a result of this, the reactive power of the GFM starts changing immediately in Figure 34 and increases by about 70 MVAR. To examine that if the 70-MVAR change in reactive power (ΔQ) matches the droop characteristic, the reference voltage used by the voltage droop control of the GFM (i.e., voltage at the point of connection [POC]) is shown in Figure 36. When the voltage source magnitude is decreased by 0.1 pu, the voltage at the POC becomes 0.985 pu, so the voltage drop is 0.015 pu. Given that the voltage droop gain is 2%, $\Delta Q = \Delta V / Droop\_gain$ = 0.015/0.02 = 0.75 pu = 75 MVAR. Thus, the GFM increases its reactive power by 75 MVAR, and so 68.8 MVAR reactive power is available at the bus, as Figure 34 shows. A similar pattern is observed for the next voltage magnitude changes in this test. Despite the reactive power, active power of the GFM remains unchanged at steady-state following each voltage magnitude change, which is expected as the system frequency has not changed in Figure 35. Moreover, the GFM current does not exceed the maximum limit (1.5 pu) in Figure 36 and also does not have any distortions or undamped oscillations. Therefore, this test showcases the capability of the GFM model in responding to sudden voltage magnitude changes, and all the criteria for this test (Table 10) are successfully passed.

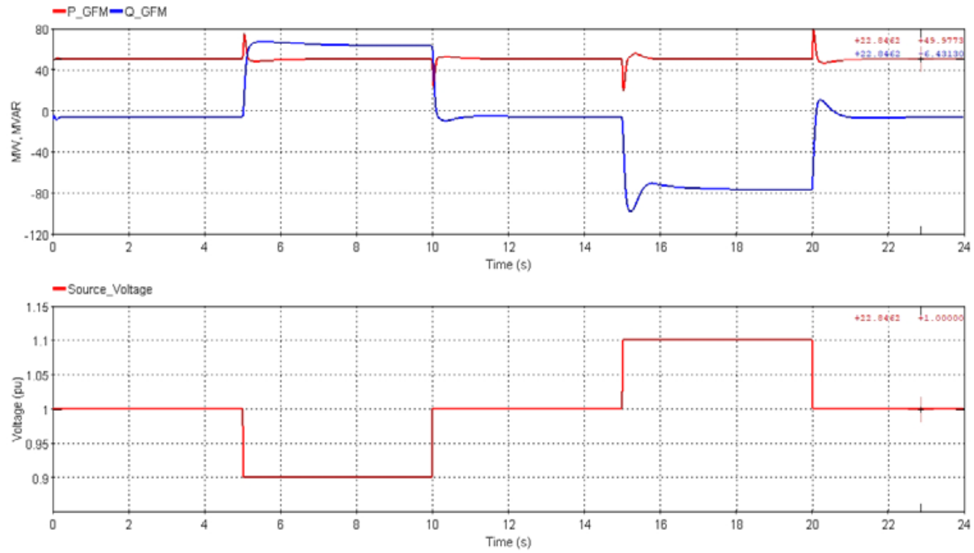

Figure 34. Active and reactive power of the GFM at the bus and the magnitude of the voltage source for Test 10

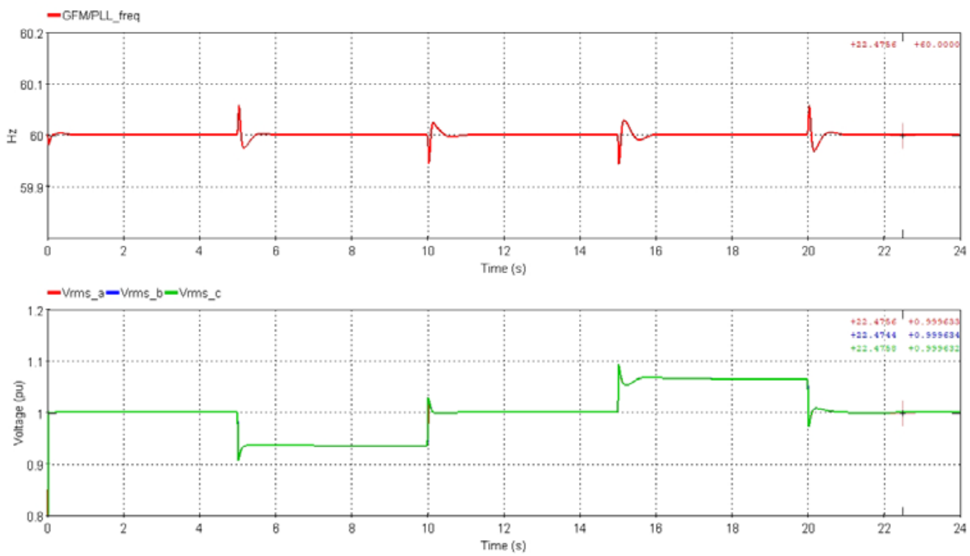

Figure 35. System frequency and three-phase RMS voltages at the bus for Test 10

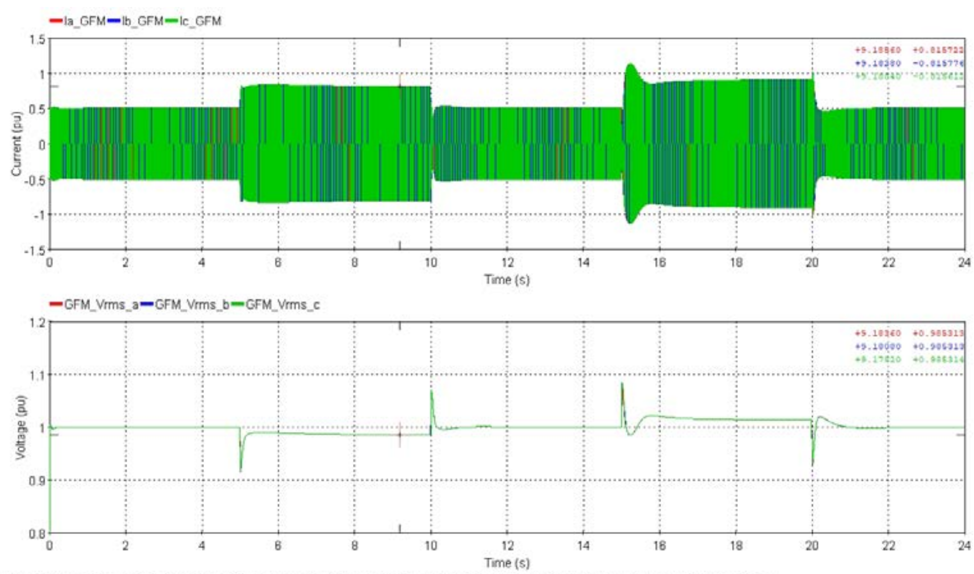

Figure 36. Instantaneous currents of the GFM and three-phase RMS voltages at the POC

2.12 Test 11: FRT

This test assesses the FRT performance of the GFM model in Test Bench 2 for balanced and unbalanced faults. As detailed below the IBR is expected to continue to provide output during and after the faults.

2.12.1 Test Description and Success Criteria

Details of Test 11 are explained in .

Table 11. Test 11 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at 100% of its maximum discharge power limit. • The SCR at the connection point is set to 20. System equivalent X/R is set to 6. • Only the project plant, no duplicate.	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • A bolted single-line-to-ground fault is applied at $t = 3$ s for 6 cycles. • 5 seconds later, a bolted line-to-line fault is applied for 6 cycles. • 5 seconds later, a bolted three-phase-to-ground fault is applied for 6 cycles.	
Success Criteria:	**Pass/Fail**
1. The BESS rides through the faults in a stable manner and does not trip.	
2. Active and reactive power are recovered to the pre-fault values after the fault clearance.	
3. Any oscillation should be settled.	
4. Any distortion observed in phase quantities should dissipate over time.	

2.12.2 Test Results

The simulation results for this test are shown in the figures below. Following the test sequence in Table 11, bolted AG, BC, and ABCG faults are applied on the bus in Test Bench 2 in Figure 25. Figure 37 shows the active and reactive power of the GFM along with the three-phase RMS voltages measured at the bus. During all three faults, the GFM active power drops, but the reactive power rises. After the fault is cleared, the active and reactive power of the GFM recover to the pre-fault values in about a second.

Figure 38 illustrates the instantaneous voltages at the bus and instantaneous currents at the GFM terminal. It can be observed that the GFM stays connected to the system and rides through all three faults in a stable manner. The GFM current increases to 1.5 pu during all three faults and drops back to 1 pu shortly after the fault clearance without any undamped oscillations or distortions. To get a better view of the GFM FRT response, Figure 39, Figure 40, and Figure 41 show a zoomed-in version of the voltages and currents during the faults in Figure 38. The FRT strategy of the EMTP GFM model uses the virtual impedance current limiter and current saturation in the positive-sequence circuit and K-factor control with current saturation in the negative-sequence circuit with the settings in Figure 3. The GFM injects an unbalanced current during the AG and BC faults in Figures 39 and 40. Moreover, for all three faults, the phase currents remain below the 1.5-pu current limit, and so the current limiters operate correctly in both positive- and negative-sequence control loops. Furthermore, the peak of at least one of the phase currents reaches 1.5 pu during all three faults, showing that the inverter utilizes its maximum capacity during the FRT. Therefore, the GFM model successfully passes the criteria of this test.

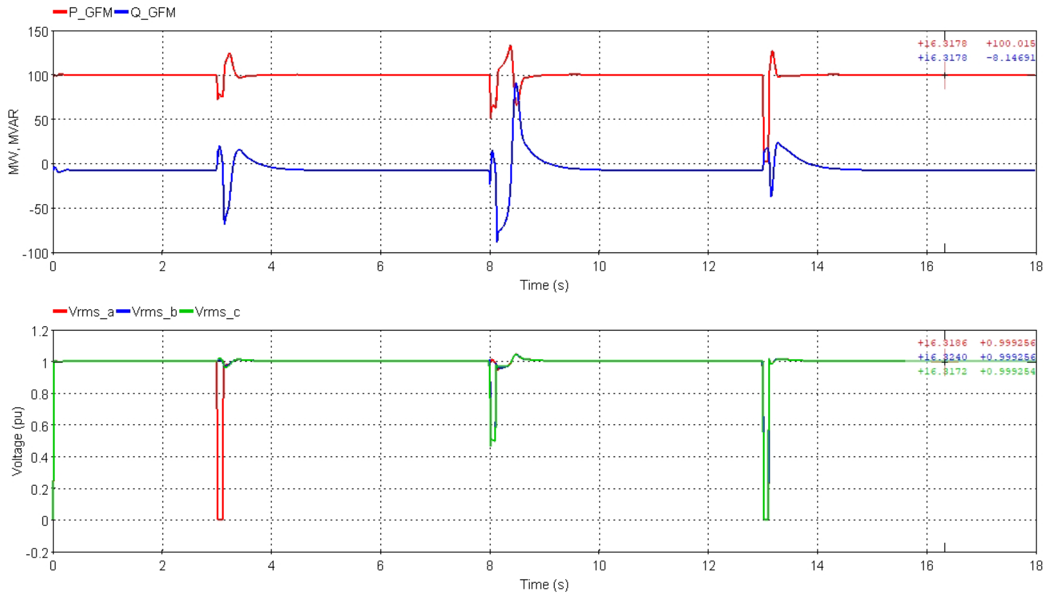

Figure 37. Active and reactive power of the GFM and the three-phase RMS voltages at the bus for Test 11

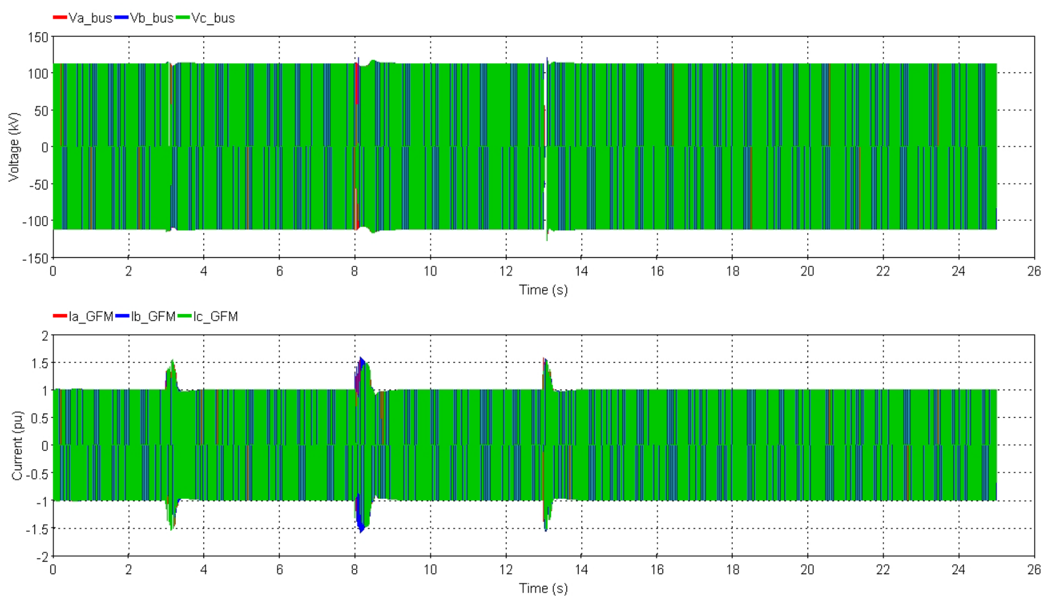

Figure 38. Instantaneous voltages at the bus and instantaneous currents at the GFM terminal for Test 11

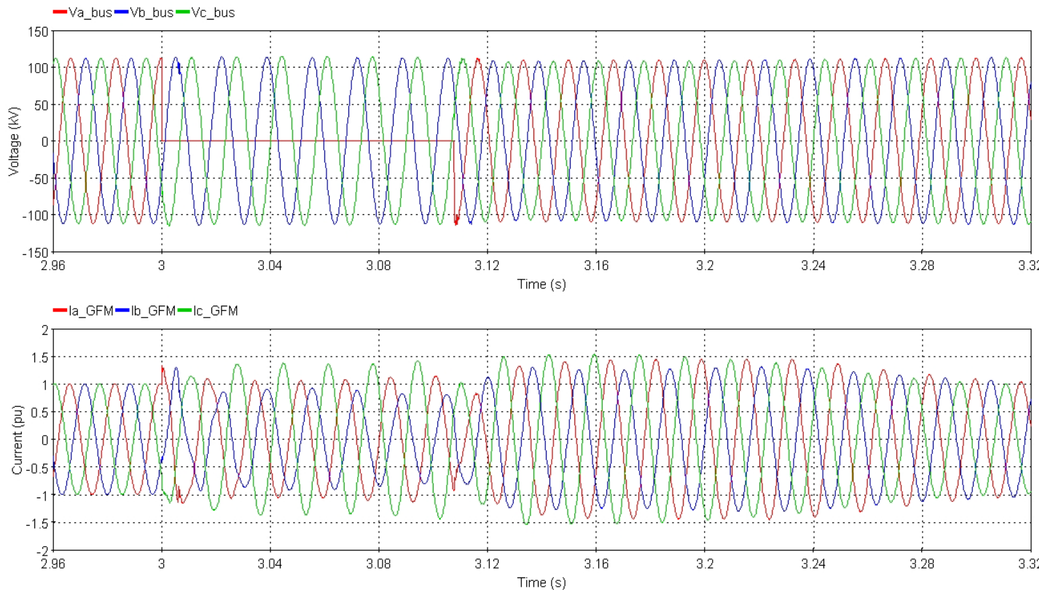

Figure 39. Instantaneous voltages at the bus and instantaneous currents at the GFM terminal during the AG fault in Test 11

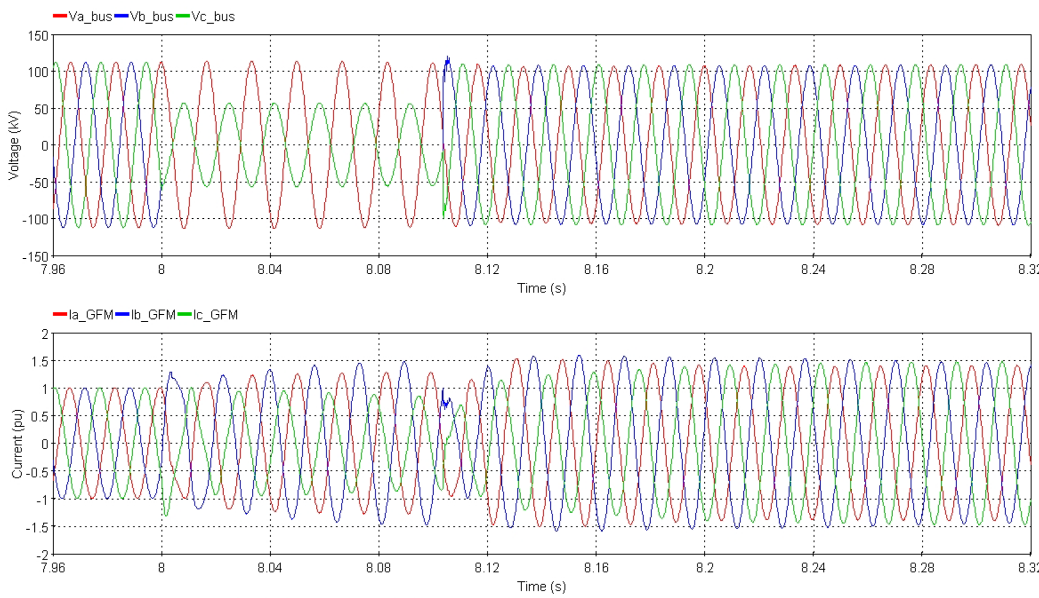

Figure 40. Instantaneous voltages at the bus and instantaneous currents at the GFM terminal during the BC fault in Test 11

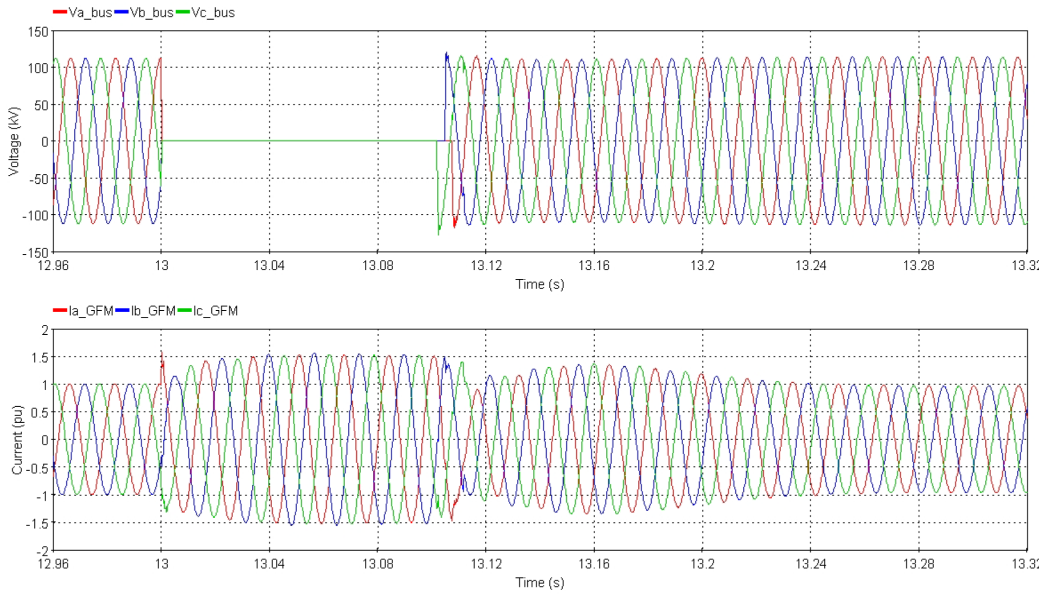

Figure 41. Instantaneous voltages at the bus and instantaneous currents at the GFM terminal during the ABCG fault in Test 11

2.13 Test 12: FRT—Loss of Synchronous Machine

Test 12 further evaluates the FRT performance of the GFM model using a new test bench, which provides a more practical representation of a system that captures the interaction between resources during the loss of a synchronous machine. This test is part of EPRI's recommended testing [3]. The details of the new test bench are provided below.

2.13.1 Test Bench 3

Test Bench 3 is a multisource network, as shown in Figure 42. This system is designed to identify any interactions that may arise between the inverter under test and another inverter-based resource plant that has its performance designed to meet the requirements from Institute of Electrical and Electronics Engineers (IEEE) Std 2800-2022 [5]. Because this study is focused around one model, the IEEE 2800-2022 plant in Figure 42 is replaced with the duplicate of the project BESS, similar to the previous tests. Further, this test system includes a synchronous condenser in addition to the SG, which are connected to the GFM plants through two similar parallel lines. The synchronous condenser and SG are connected to the east bus through delta wye grounded transformers. For Test 12, the project BESS is rated at 100 MVA, and the network voltage level is 137.5 kV.

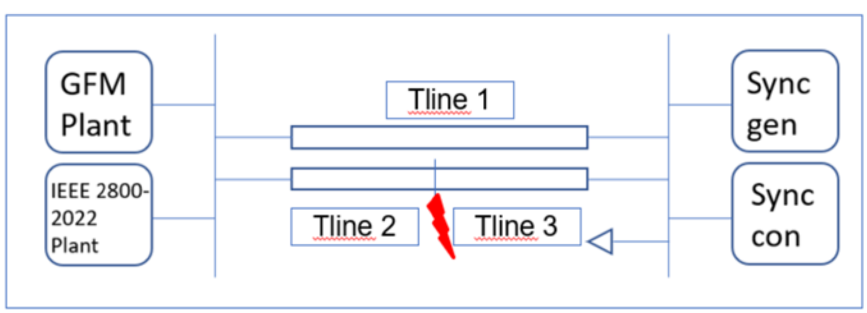

Figure 42. Test Bench 3

2.13.2 Test Description and Success Criteria

Conditions of Test 12 are described in .

Table 12. Test 12 Setup and Success Criteria	
Initial Dispatch: • The project BESS is dispatched at 90% of its maximum discharge power limit. • MVA rating of the duplicate BESS is set to 1.1 times the MVA rating of the project BESS. • MW output of the duplicate BESS is set to 0.9 times the MVA rating of the project BESS. • MVA rating of the SG is set to be approximately 1/3 MW output of the duplicate BESS. • MVA rating of the synchronous condenser is set to be approximately 15% of the MW output of the duplicate BESS. • Load is set to be approximately 10% greater than the total MW output of the project and duplicate BESS, with 0.95 lagging power factor. • The length of the line should be chosen such that the power transfer across the lines is not at the transfer limit. Additionally, the receiving end voltage should be within the continuous operating region (0.95–1.05 pu).	
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The synchronous condenser and SG are tripped at $t = 3$ s. • A bolted single-line-to-ground fault is applied at $t = 3$ s for six cycles in the middle of one of the parallel lines. • 5 seconds later, a bolted line-to-line fault is applied for six cycles in the middle of one of the parallel lines. • 5 seconds later, a bolted three-phase-to-ground fault is applied for six cycles in the middle of one of the parallel lines.	
Success Criteria:	**Pass/Fail**
1. The BESS rides through the faults in a stable manner and does not trip.	
2. Any oscillation should be settled.	
3. Any distortion observed in phase quantities should dissipate over time.	
4. Active and reactive power are recovered to the pre-fault values after the fault clearance.	
5. Following the trip and the single-line-to-ground fault, BESS 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.	
6. Voltage settles to a stable and acceptable operating point after the fault clearance.	
7. The final voltage after the trip is as expected based on the droop and deadband settings.	
8. Frequency settles to a stable operating point.	
9. The final frequency after the trip is as expected based on the droop and deadband settings.	
10. Active power from each BESS should move immediately to meet the load requirement and settle according to its frequency droop setting.	
11. Reactive power from each BESS should move immediately and settle according to its voltage droop setting.	

2.13.3 Test Results

This section goes through the simulation results for Test 12. This test evaluates the FRT response of the model under extreme conditions (i.e., simultaneous loss of synchronous machines and faults). Figure 43 shows that the initial dispatch conditions in Table 12 are met before the trip. When the SG and synchronous condenser are tripped at $t = 3$ s, a bolted AG fault is applied at 50% of the parallel line for 100 ms. Figure 44 shows that Phase A RMS voltage drops to zero during this fault. To get a more comprehensive picture of the FRT response of the model, GFM 1, or the project BESS, is configured to use current saturation during faults, while GFM 2, or the duplicate BESS, uses virtual impedance with the settings in Figure 3. Figure 47 and Figure 48 depict the instantaneous and sequence currents of GFM 1 and GFM 2 at the POC during the AG fault, respectively. These figures show that both GFMs successfully ride through the fault, increase their current close to the maximum limit of 1.5 pu, and inject a negative-sequence current beside the positive-sequence current. The general pattern of the positive-sequence current is similar in both GFMs, indicating a similar performance for the current saturation and virtual impedance methods for this fault. An interesting observation in this test is that it takes more than 100 ms for the negative-sequence current to settle in both GFMs. Consequently, the desired positive- to negative-sequence current magnitude ratio, which is set to 3 in both GFMs, is not achieved during the fault. Moreover, the negative-sequence current does not reach the specified value based on the K-factor diagram for a K of 3, as set in Figure 3. However, this does not impact the model passing the requirements of this test, and the model is able to ride through the fault in a stable manner and recover successfully, as demonstrated in Figure 45 and Figure 46.

When the AG fault is cleared, the active and reactive power of the GFMs increase to compensate for the loss of the SG and synchronous condenser. As a result, the system frequency and voltage drop to 59.96 Hz and 0.986 pu, respectively, in Figure 44, which match the expected values based on the droop settings. 5 seconds after the AG fault, a bolted BC fault is applied in the middle of the line. Figure 49 and Figure 50 illustrate the GFM responses during this fault. The general pattern of the response is quite similar to the response for the AG fault, and both GFMs ride through this fault smoothly and are able to recover active and reactive power to the pre-fault values shortly after the fault clearance. Finally, a bolted ABCG fault is applied at $t = 13$ s. Figure 51 and Figure 52 demonstrate that both GFMs inject a fully positive-sequence current equal to 1.5 pu during this fault. Moreover, the speed of the response is almost similar for the virtual impedance and current saturation methods. This can be attributed to the fact that the GFM model keeps current saturation active while virtual impedance is enabled, which makes the response of these methods very close. Also, these figures show that GFMs can recover smoothly from this fault as well. Therefore, all criteria for this test are passed.

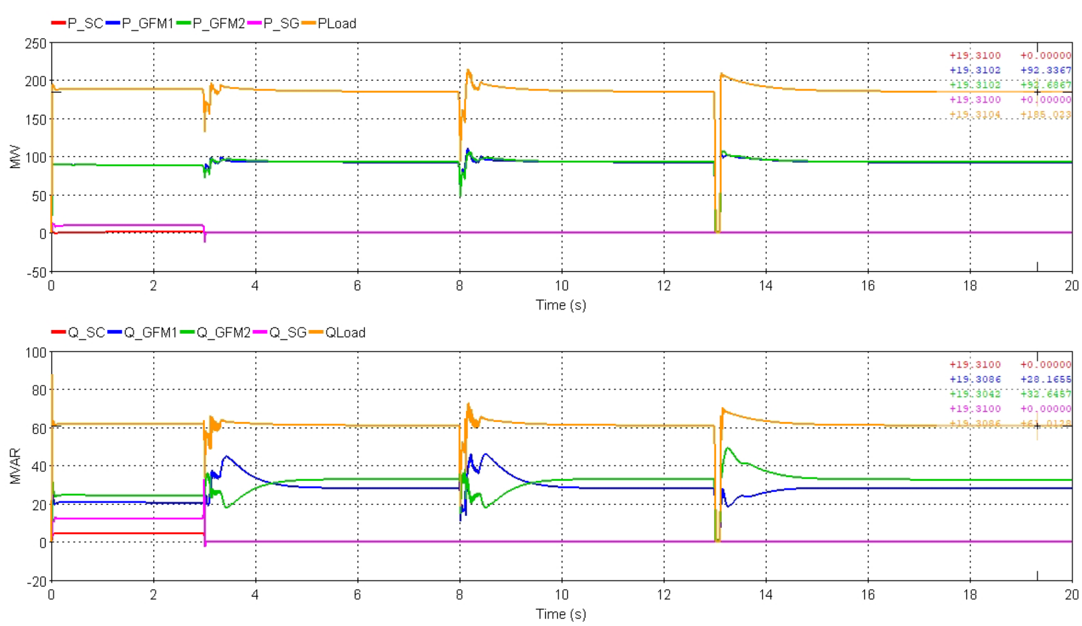

Figure 43. Active and reactive power for Test 12

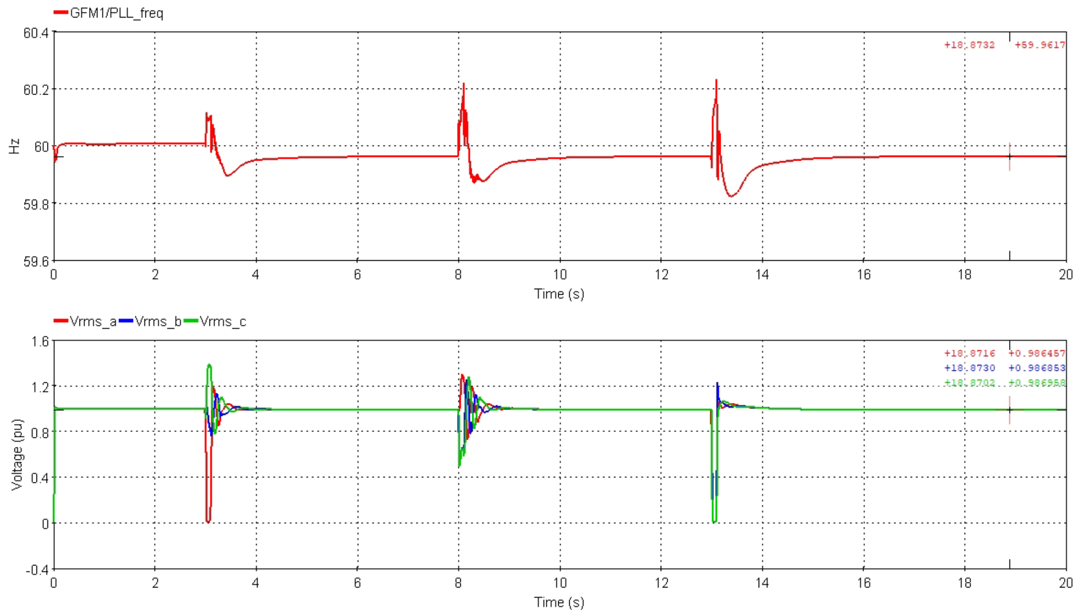

Figure 44. System frequency and three-phase RMS voltages for Test 12

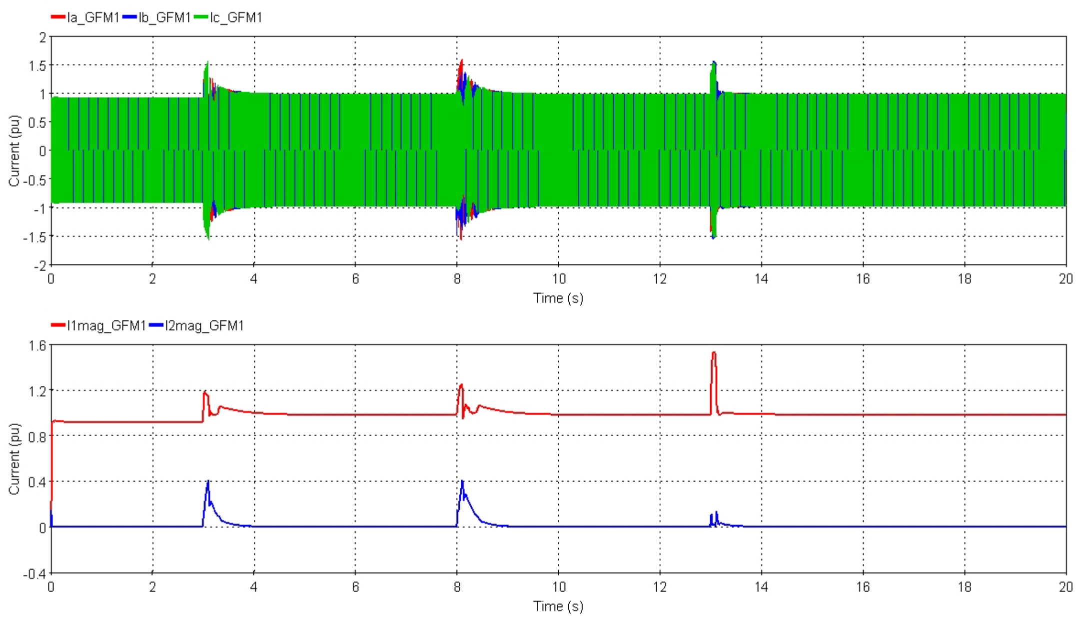

Figure 45. GFM 1 instantaneous and sequence currents at the POC for Test 12

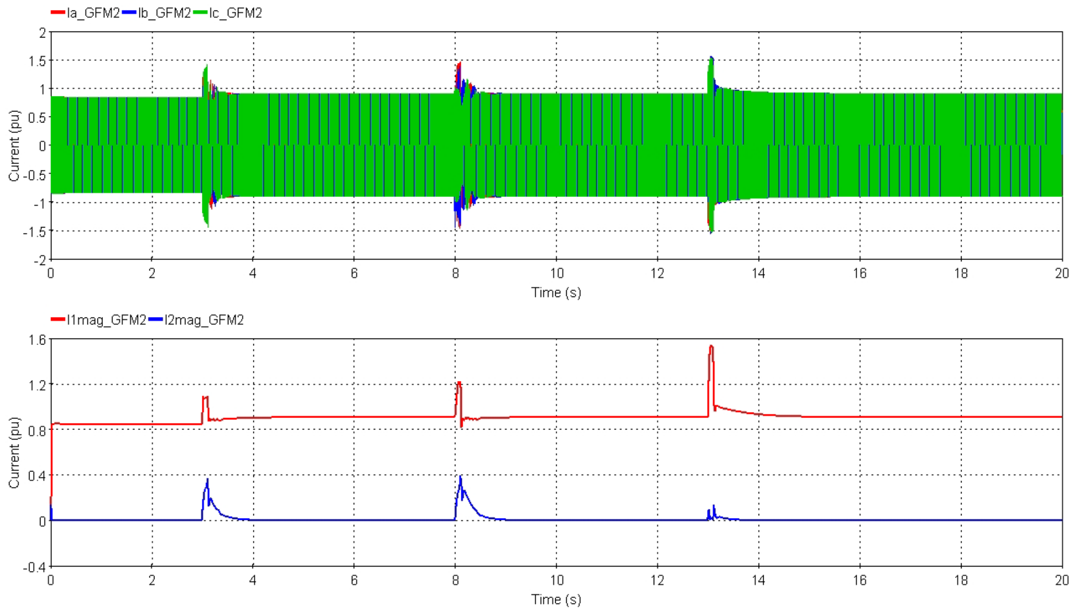

Figure 46. GFM 2 instantaneous and sequence currents at the POC for Test 12

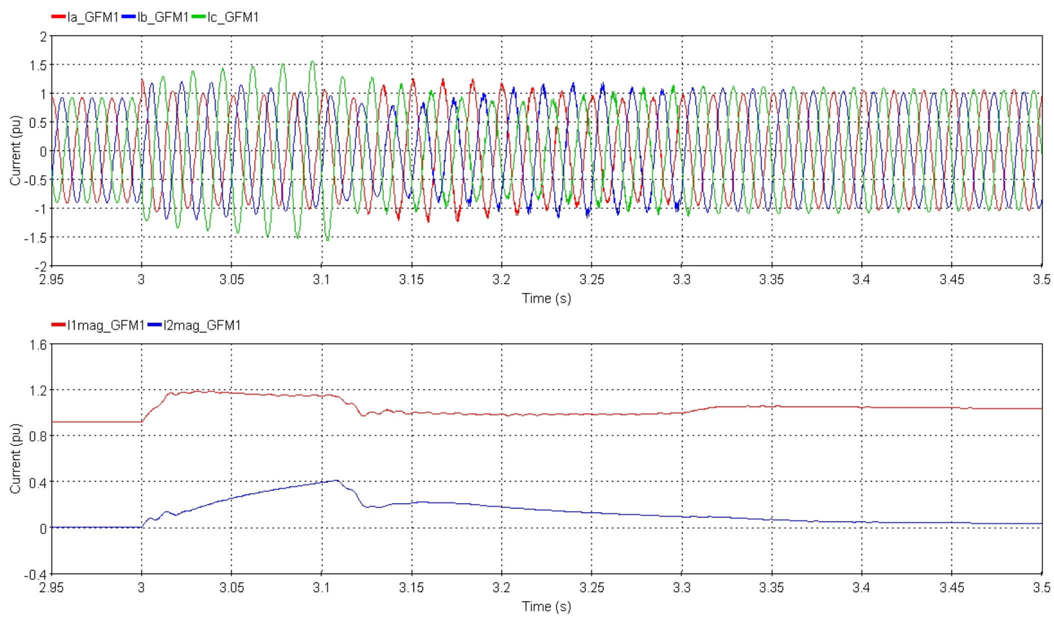

Figure 47. GFM 1 instantaneous and sequence currents at the POC during the AG fault in Test 12

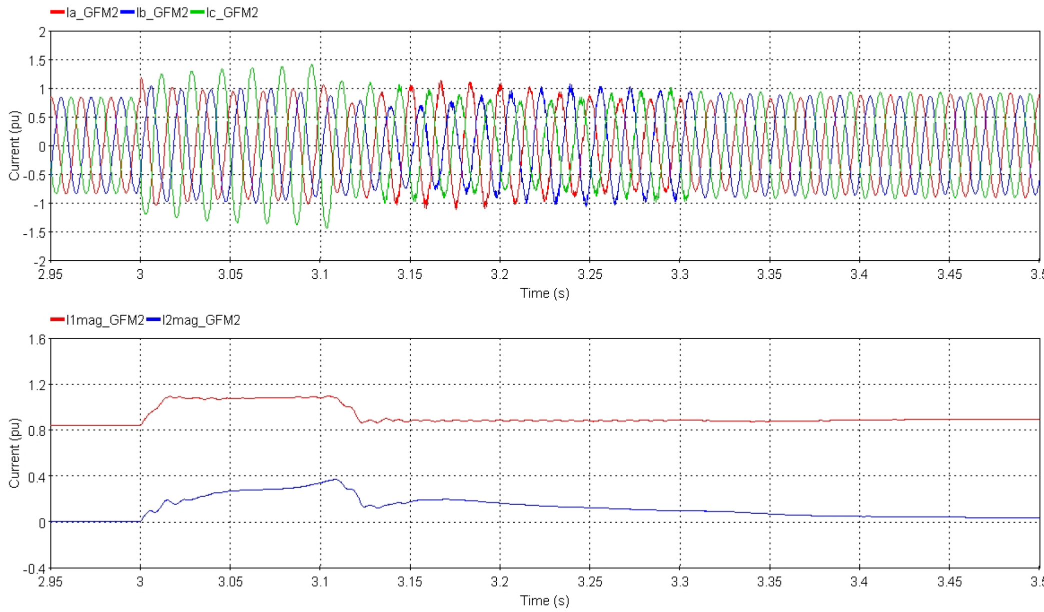

Figure 48. GFM 2 instantaneous and sequence currents at the POC during the AG fault in Test 12

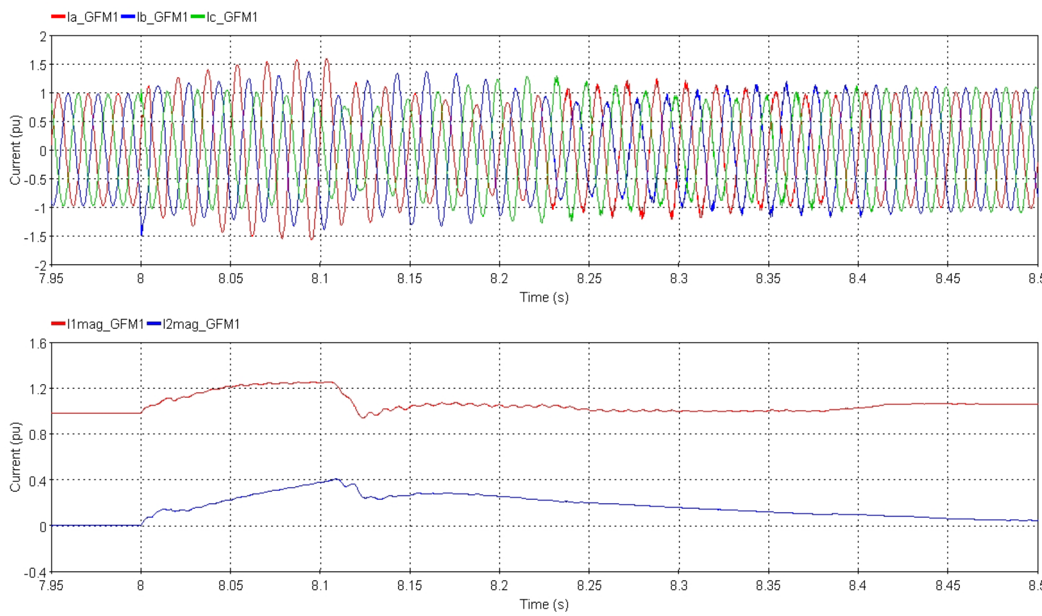

Figure 49. GFM 1 instantaneous and sequence currents at the POC during the BC fault in Test 12

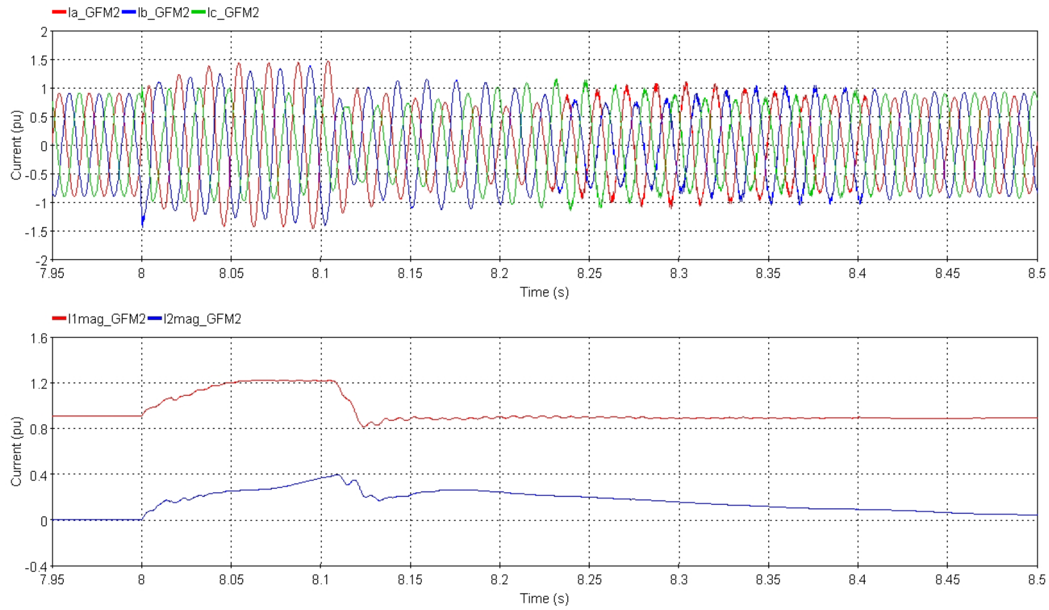

Figure 50. GFM 2 instantaneous and sequence currents at the POC during the BC fault in Test 12

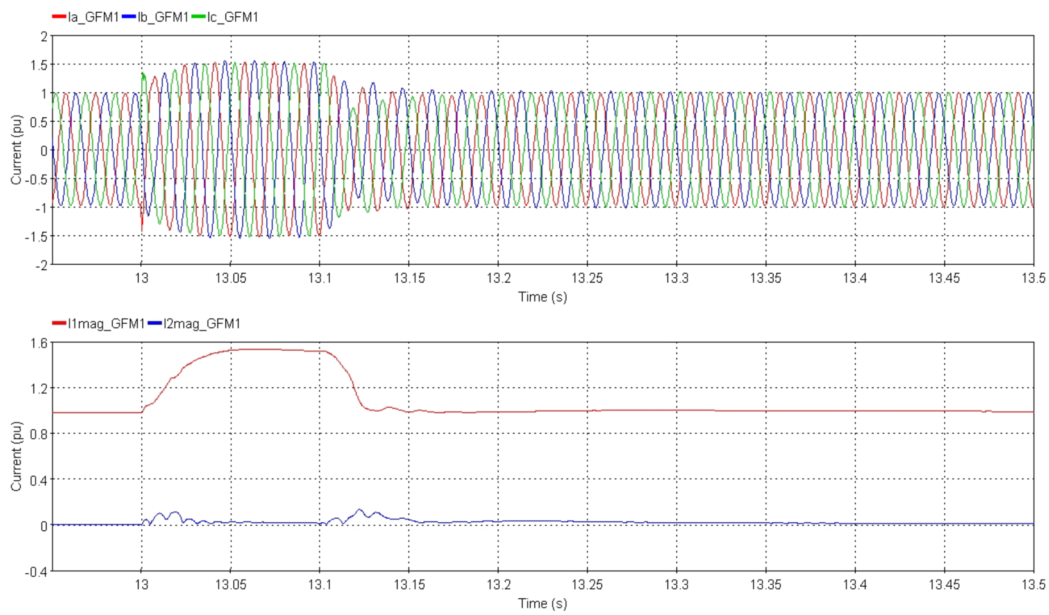

Figure 51. GFM 1 instantaneous and sequence currents at the POC during the ABCG fault in Test 12

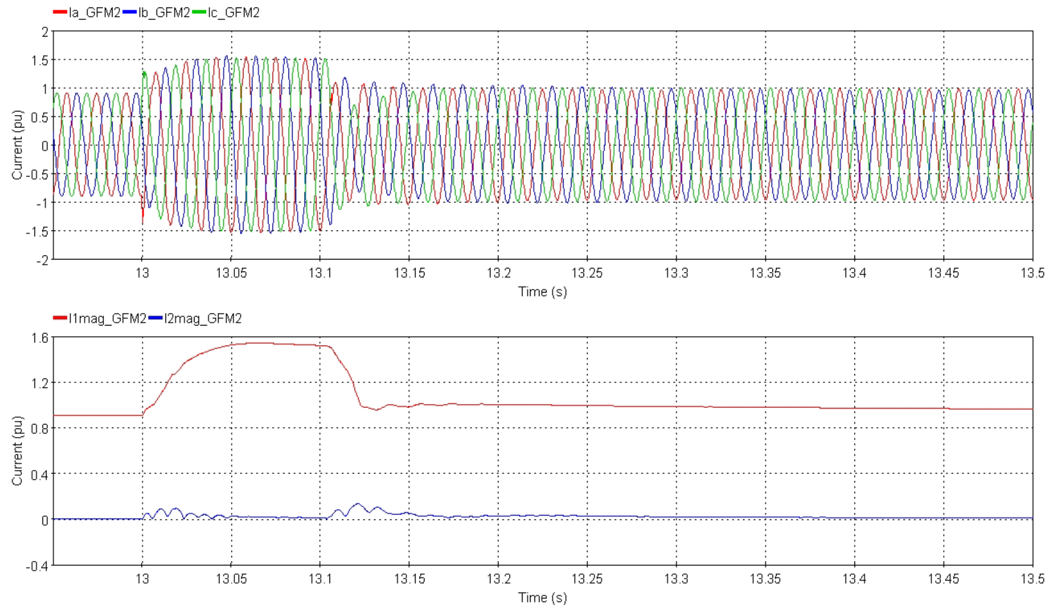

Figure 52. GFM 2 instantaneous and sequence currents at the POC during the ABCG fault in Test 12

3 Performance Comparison of the Generic GFM Model With an OEM Model

This section compares the performance of the EMTP generic GFM model with that of a PSCAD OEM GFM model. The intent of these tests is not to compare results across software. Any mismatches in results are attributed to potential differences in control architecture within the models.

We performed two tests in Test Bench 1. Because the settings of the OEM model cannot be changed, the EMTP model settings were changed to match those of the OEM model to achieve a reasonable comparison. However, it should be noted that the OEM model is a black box model, so it is not possible to make sure that the control systems of both models, as well as their parameters, are the same. The following is a list of the changes made in the generic model based on structure/physical characteristics of the OEM plant:

1. Inverter filter Resistor (R)-Inductor (L)-Capacitor (C) parameters
2. Inverter maximum current magnitude
3. Collector system configuration
4. DC link voltage level
5. Inverter and collector system voltage levels
6. Number of inverters
7. Plant power rating.

The following is a list of changes made to the generic model through trial and error:

1. K-factor
2. Voltage control loop gains
3. Voltage and frequency droop gains.

Besides the GFM model parameters above, the parameters for the rest of the devices in the network, including the load and SG, were selected to match in the PSCAD and EMTP platforms.

3.1 Test 1 Response to Synchronous Generator Trip

This test compares the performance of the generic model with a manufacturers black box model during a simulated synchronous generator trip. Table 13 explains the details of Test 1.

Unlike the previous tests, this one does not include any pass/fail criteria, as the primary objective is to gain insights into the compatibility of the performance between the generic GFM model and an OEM model. Again, the intent of these tests is not to compare individual simulation software. Importantly, because the rated power of the OEM model cannot be changed, as mentioned earlier, both the project and duplicate BESS were rated at 100 MW during both Tests 1 and 2.

Table 13. Test 1 Setup
• The project BESS is dispatched at 20% of its maximum discharge power limit. • The duplicate BESS is dispatched at 20% of its maximum discharge power limit.
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The SG is tripped at $t = 5$ s.

3.1.1 Test 1 Results

The figures below show the simulation results for this test. Because the project and duplicate GFMs are exactly the same in this test, the figures only show the measurements for one GFM plant. Figure 53 illustrates the RMS voltage at the bus in Test Bench 1 with the EMTP generic GFM model and OEM GFM model. Before the trip at $t = 5$ s, the voltage is almost 1 in both systems. Following the trip, both voltages go through a transient and drop to 0.99 pu for the generic EMTP model and 0.97 for the OEM model. The interesting observation here is that it takes a much longer time for the voltage to reach steady state in the system with the EMTP model, while the voltage changes almost instantly with the OEM black box model. Nonetheless, the final value of the voltage is close in both models.

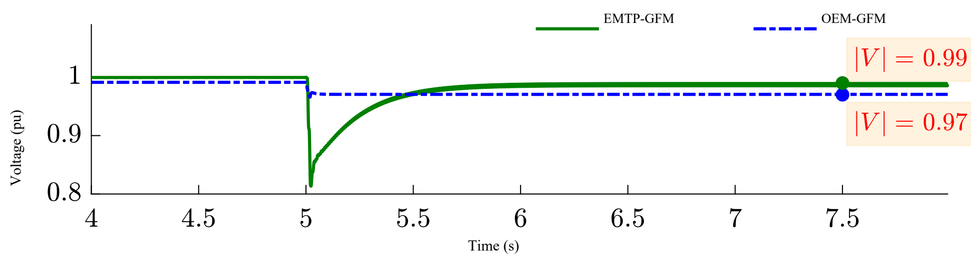

Figure 53. RMS voltage at the bus in Test Bench 1 for Test 1

Figure 54 shows the system frequency during this test. The steady-state value of the frequency is the same with both models and equal to 59.75 Hz. However, similar to the voltage, the frequency trajectory is different between the two models. This pattern can be observed in active and reactive power of the GFMs, SGs, and loads in the rest of the figures as well. Therefore, it can be concluded that the steady-state response of the EMTP generic GFM model and the OEM GFM model are close, but the transients are different.

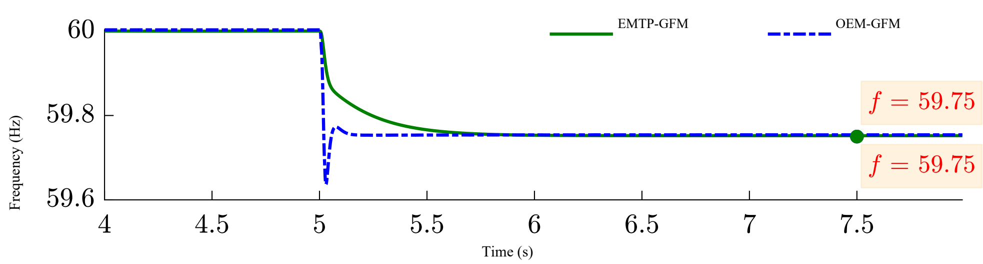

Figure 54. System frequency for Test 1

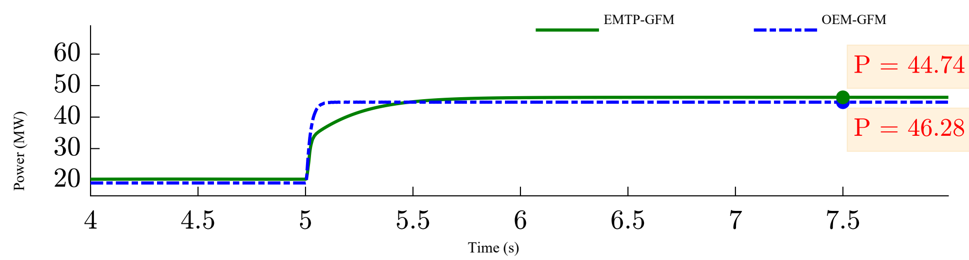

Figure 55. Active power of GFMs for Test 1

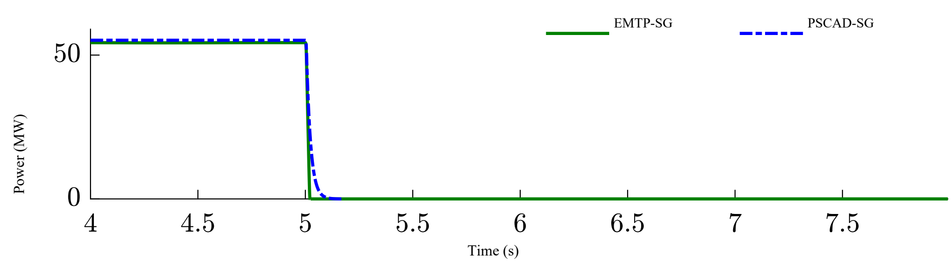

Figure 56. Active power of SGs for Test 1

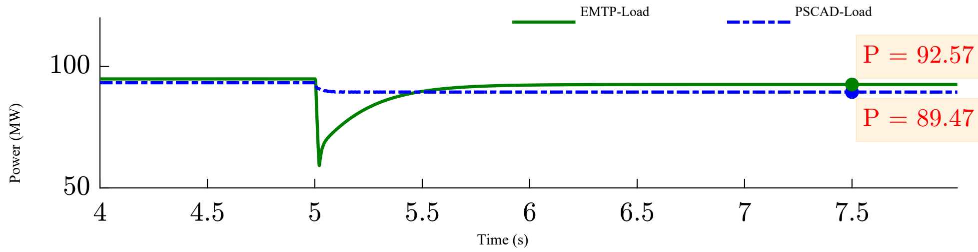

Figure 57. Active power of the loads for Test 1

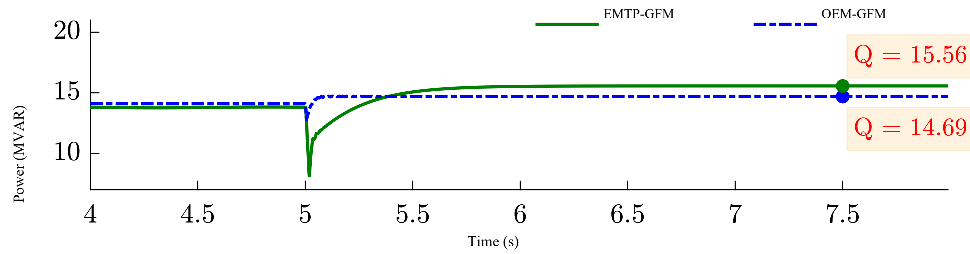

Figure 58. Reactive power of GFMs for Test 1

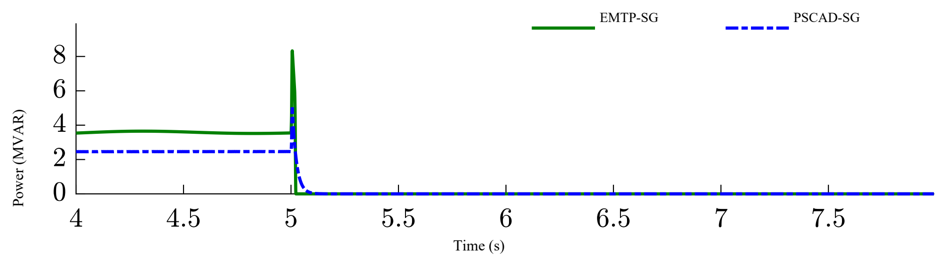

Figure 59. Reactive power of SGs for Test 1

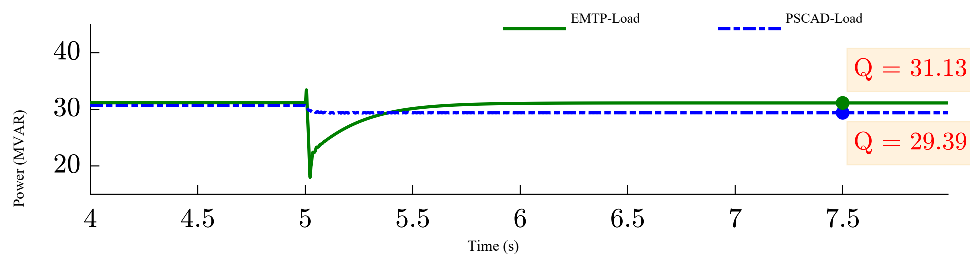

Figure 60. Reactive power of the loads for Test 1

3.2 Test 2 FRT response

This test compares the performance of the generic model with a manufacturers black box model on the FRT response. Table 14 goes through the details of Test 2. This test is designed to compare the FRT response of the models.

Table 14. Test 2 Setup
• The project BESS is dispatched at 20% of its maximum discharge power limit. • The duplicate BESS is dispatched at 20% of its maximum discharge power limit.
Test Sequence: • Run until the system is stable at the given power flow conditions, without oscillations. • The SG is tripped at $t = 5$ s. • A bolted ABCG fault is applied on the bus at $t = 8$ s for about 10 cycles. • A bolted BC fault is applied on the bus at $t = 12$ s for about five cycles.

3.2.1 Test 2 Results

Because the focus in this test is on the FRT response of the models, the figures below show the response of the GFM models during faults only. Unlike the previous test, as Figures 61 to 68 show, the FRT response of the generic model is different from that of the OEM model from different aspects, including current limiting and magnitudes of positive- and negative-sequence currents. Figure 61, Figure 62, Figure 65, and Figure 66 illustrate that the inverter phase currents are limited below the 1-pu maximum limit with a higher speed in the generic model compared to the OEM for both the ABCG and BC faults. In other words, the current limiter of the OEM model operates slower than that of the generic model. In the generic model, a virtual impedance with current saturation is implemented. The current limiter algorithm of the OEM model is unknown due to the black box nature of the model. In addition, the OEM model allows an overcurrent beyond 1-pu limit that lasts about 60 ms, while the generic model does not allow any overcurrent. The difference in the current limiters of the models results in a difference in the magnitude of the positive-sequence current, as Figure 63 and Figure 67 demonstrate. The positive-sequence current of the OEM model goes through an overshoot and settles in about 70 to 100 ms, but the positive-sequence current of the generic model does not have any overshoot and settles in less than 50 ms. Similarly, the negative-sequence current of the models are different during both faults in Figure 64 and Figure 68. Considering these differences, it can be concluded that the FRT strategy of the OEM model is probably different from that of the generic model.

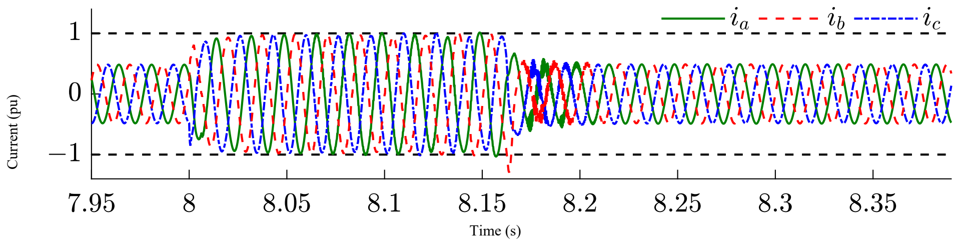

Figure 61. Instantaneous currents of the generic GFM model during the ABCG fault in Test 2

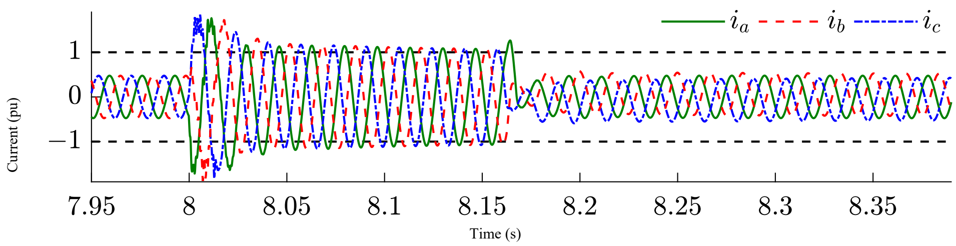

Figure 62. Instantaneous currents of the OEM GFM model during the ABCG fault in Test 2

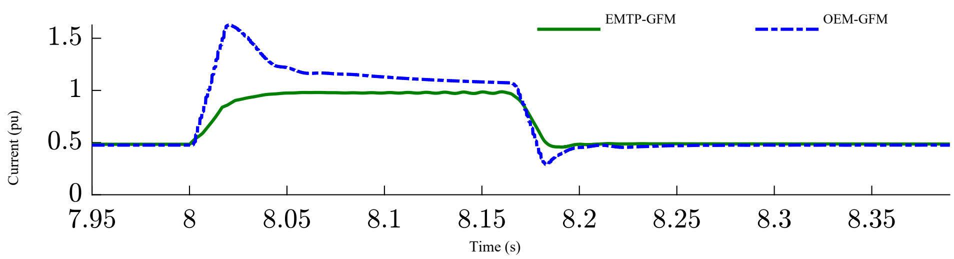

Figure 63. Positive-sequence current during the ABCG fault in Test 2

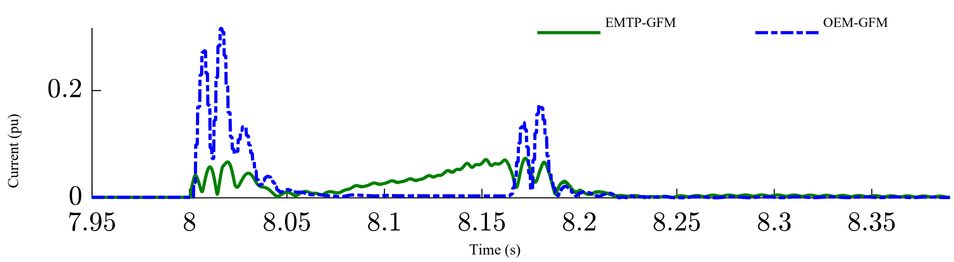

Figure 64. Negative-sequence current during the ABCG fault in Test 2

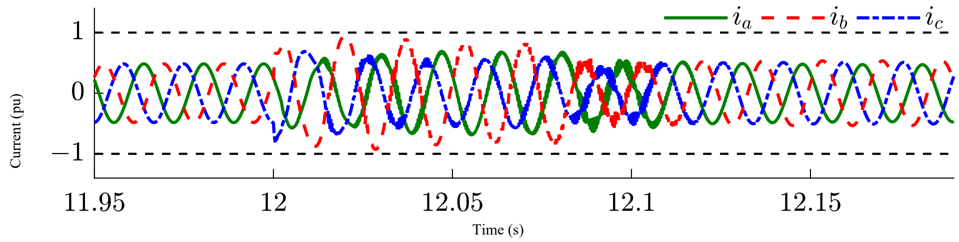

Figure 65. Instantaneous currents of the generic GFM model during the BC fault in Test 2

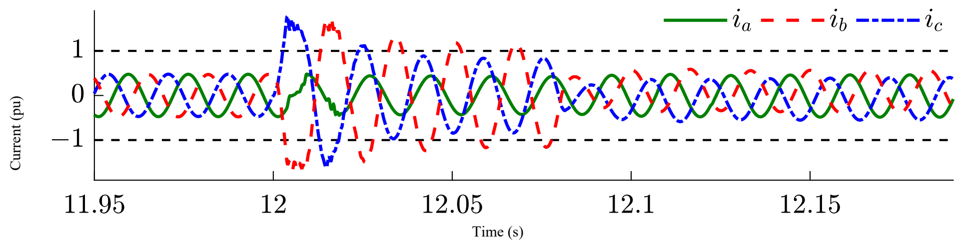

Figure 66. Instantaneous currents of the OEM GFM model during the BC fault in Test 2

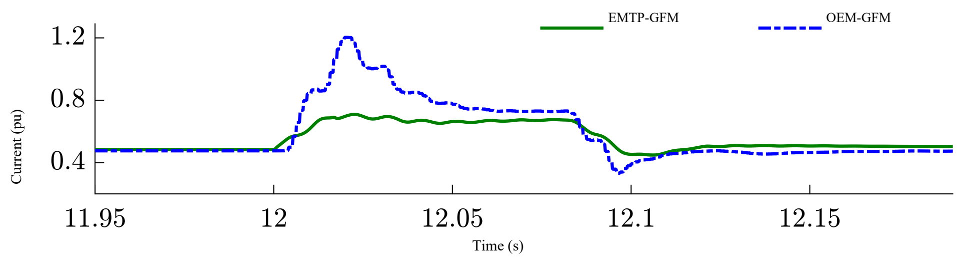

Figure 67. Positive-sequence current during the BC fault in Test 2

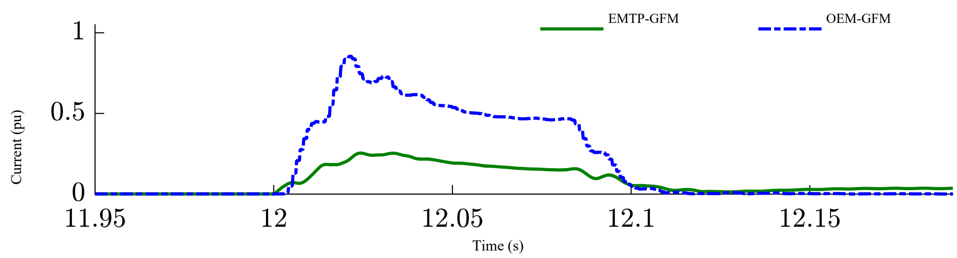

Figure 68. Negative-sequence current during the BC fault in Test 2

4 Lessons Learned

This section provides insights into the findings and learnings from performing different tests on the generic GFM model in this project. This includes but is not limited to the sensitivity analysis done on different parameters of the model and the impact each parameter had on the model performance during various tests.

4.1 Impact of State Freeze Threshold

State freeze threshold is a settable parameter between 0 and 1 in the mask of the EMTP GFM model, as shown in Figure 3. The value of this parameter is used as the threshold for the model to enter the FRT mode, which activates current limiters and negative-sequence current control loop, and freezes the frequency output of the droop as well as the integrators of the voltage control loop. If the magnitude of the positive-sequence voltage at the POC of the inverter drops below this threshold, the FRT flag is raised. In this study, we found that the value selected for this parameter can directly impact voltage recovery of the GFM during non-fault events.

Figure 69 shows a screenshot of the voltage control loop in the EMTP GFM model. The FRT flag, denoted by Voltage dip in this figure, is wired to the PI controllers of the voltage control loop. When this flag becomes one, that is, $\sqrt{V_d^2 + V_q^2}$ drops below the state freeze threshold setting, the integrators of the PI controllers are frozen. This mechanism prevents the integrators from winding up during faults when the voltage control loop enters the saturation state. However, this operation can potentially disrupt the proper functionality of the voltage control loop during non-fault events, in which fast tracking of reference voltages is critical. In other words, if the model enters the FRT mode when the voltage temporarily drops below the threshold during a non-fault event, the voltage control loop integrators are frozen, and so the voltage references are no longer being followed at the GFM terminal. This not only disrupts proper droop implementation but also can hinder voltage recovery.

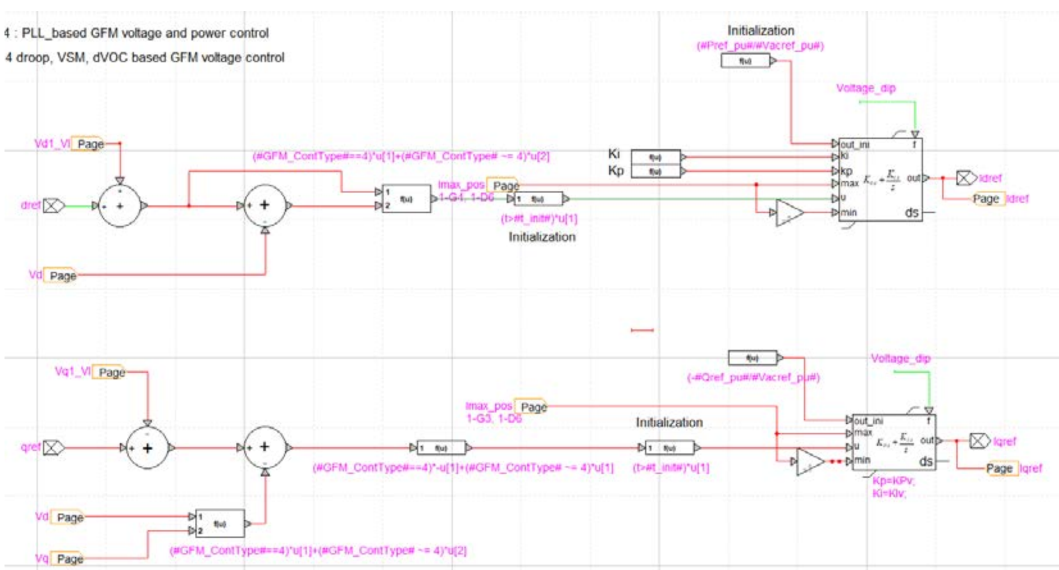

Figure 69. Voltage control loop structure of the EMTP GFM model

To better illustrate the impact of the state freeze threshold setting on the voltage recovery of the GFM, consider Test 2 in Section 82.3. Figure 70 and Figure 71 show the dq voltage control loop signals of the GFM when the state freeze threshold, denoted by V_{dip}, is set to 0.8 pu and 0.2 pu, respectively. Figure 70 shows that after the SG is tripped at $t = 3$ s, the magnitude of the positive-sequence voltage, or $\sqrt{V_d^2 + V_q^2}$, drops below 0.8 pu, so the FRT mode is activated and the voltage control loop integrators are frozen. As a result of this, the PI controllers of the voltage control loop are no longer able to make the error between V_{dref} and V_d as well as V_{qref} and V_q zero. Thus, the reference signals are not followed by V_d and V_q in Figure 70. Consequently, the voltage at the GFM terminal does not recover to above 0.8 pu after the trip, and so the GFM fails this test.

Decreasing V_{dip} from 0.8 pu to 0.2 pu solves this problem. Figure 71 shows that the voltage references are properly followed when $V_{dip} = 0.2$ pu, and so the voltage recovers successfully after the SG trip. Although it may seem that the easy solution here is to choose a small V_{dip}, as mentioned earlier, the value of V_{dip} is used as the threshold for the GFM to detect faults and enter the FRT mode. A smaller V_{dip} means that the GFM will not detect a larger number of faults, and so the FRT mode will be activated only for a small subset of faults (mostly severe faults). This can jeopardize the stability of the grid as well as overcurrent protection of the inverter switches. Therefore, it is important to meticulously select the value of state freeze threshold based on exhaustive testing of the model. In this study, this parameter is set to 0.7 pu, as shown in Figure 3. It was found that this value establishes a good balance between voltage recovery and fault detection and also helps the model perform well during all tests, as demonstrated in the previous sections.

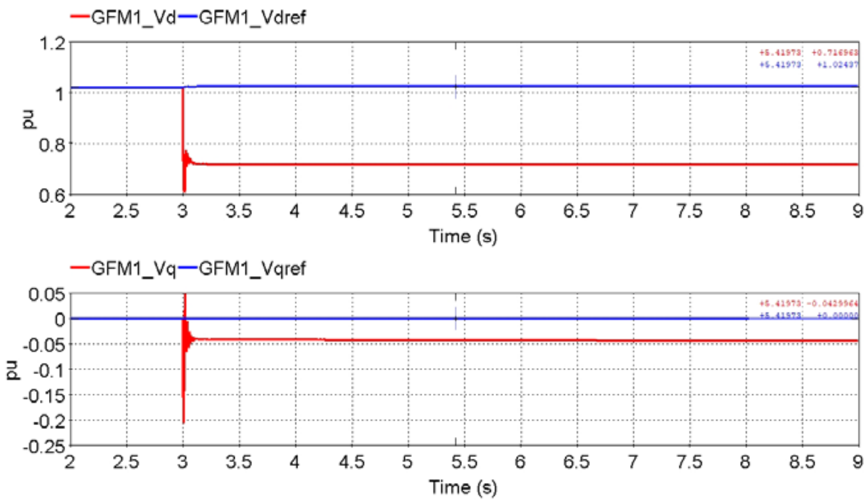

Figure 70. Voltage control loop signals of the GFM model with $V_{dip} = 0.8$ pu during Test 2

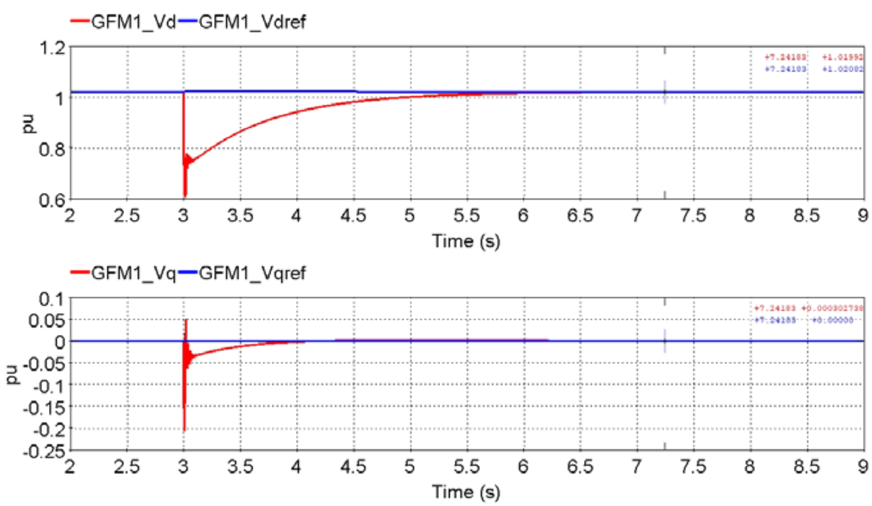

Figure 71. Voltage control loop signals of the GFM model with $V_{dip} = 0.2$ pu during Test 2

4.2 Impact of Voltage Control Loop Gains

In several of the tests in the previous sections, performance of the generic GFM model was heavily impacted by the gains of the PI controllers in the voltage control loop. If the proportional and integral gains of this controller are not properly selected, the stability as well as the ability of the GFM to recover voltage after a disturbance can be adversely impacted.

As an example, we evaluated the performance of the GFM model for different proportional, Kp_v, and integral, Ki_v, gains of the voltage control loop in Figure 3 during Test 2 in Section 82.3. Figure 72 illustrates the dq voltage control loop signals of the GFM for $Kp_v = 3$ and $Ki_v = 20$. After the SG is tripped at $t = 3$ s, V_d and V_q properly track the reference signals and settle in about 0.6 s. This response is desirably fast, but it causes control instability. As Figure 72 shows, V_d and V_q start oscillating at $t = 5.5$ s, and the oscillations grow larger to the point that the control system becomes unstable. Figure 73 shows that if Ki_v is decreased to 5, which reduces the speed of the voltage control loop, control system stability is maintained throughout the test. This shows that the voltage control loop should not be tuned with a high bandwidth just to obtain a fast response. The bandwidth of the voltage control loop should be small enough to ensure stability and minimum interference with the inner current control loop. This interference is applicable with respect to the control structure under evaluation.

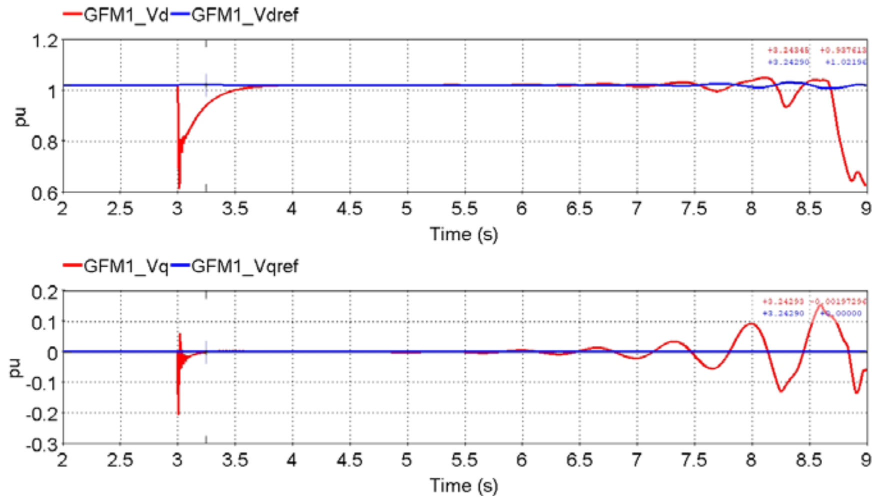

Figure 72. Voltage control loop signals of the GFM model with $Kp_v = 3$ and $Ki_v = 20$ during Test 2

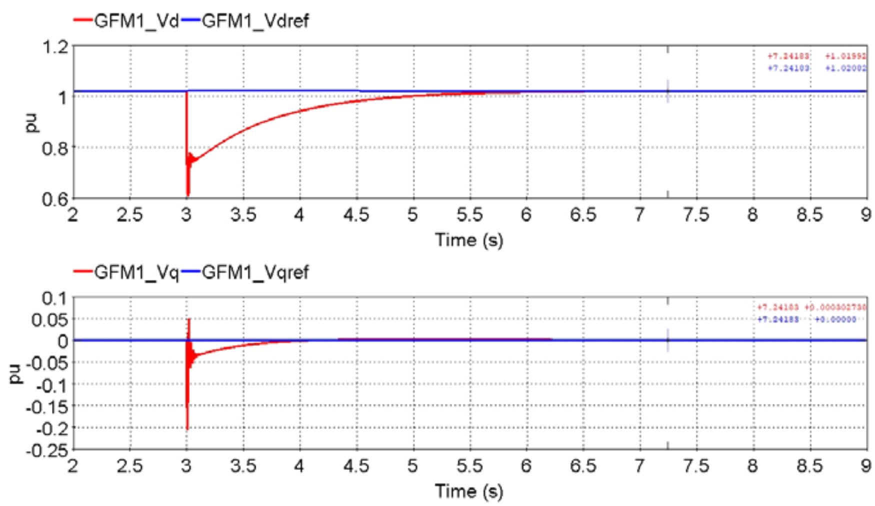

Figure 73. Voltage control loop signals of the GFM model with $Kp_v = 3$ and $Ki_v = 5$ during Test 2

4.3 Impact of Overload Mitigation Controller Gains

The EMTP generic GFM model is equipped with an overload mitigation controller to ensure that the active and reactive power of the GFM do not exceed the specified limits during steady state. Details of this controller can be found in the help document of the model in EMTP. In this project, it was observed that the proportional gain, Kp_{lim}, and integral gain, Ki_{lim}, of this controller in Figure 3 can impact the trajectory of active and reactive power of the model, especially in cases where the GFM is operating close to the limit. For instance, consider Test 3. Active and reactive power of the GFMs for this test were previously shown in Figure 13 and are reshown below in Figure 74. In this case, Kp_{lim} is 0.1 and Ki_{lim} is 10, and the active and reactive power of the GFMs remain within the limits for most of the test duration. If Ki_{lim} is decreased to 1, Figure 75 illustrates that the trajectory of active and reactive power of GFMs changes significantly. Both P and Q oscillate excessively beyond the −1-pu and 1-pu limits and settle down slower than Figure 74. To demonstrate the impact of Kp_{lim}, Figure 75 shows the active and reactive power response of GFMs for the same test when Kp_{lim} is 1 and Ki_{lim} is 10. This figure shows that increasing Kp_{lim} also changes the trajectory of P and Q. The peak of the oscillations has reduced for both P and Q compared to Figure 74, but the settling time has not changed much. Therefore, this sensitivity analysis confirms that the P and Q response of the GFM model can be impacted by the gains of the overload mitigation controller. Therefore, it is important to tune this controller properly to ensure a reliable operation within the limits during all conditions. Notably, the operation of this controller can impact the inferences obtained for a frequency response event. For example, if a grid frequency event results in the GFM active power output to tend toward its limit, and if the active power limit controller is set to be slower, it can result in the portrayal of a superior frequency response, as the model will show the GFM as injecting (or absorbing) a greater amount of energy into (or from) the grid.

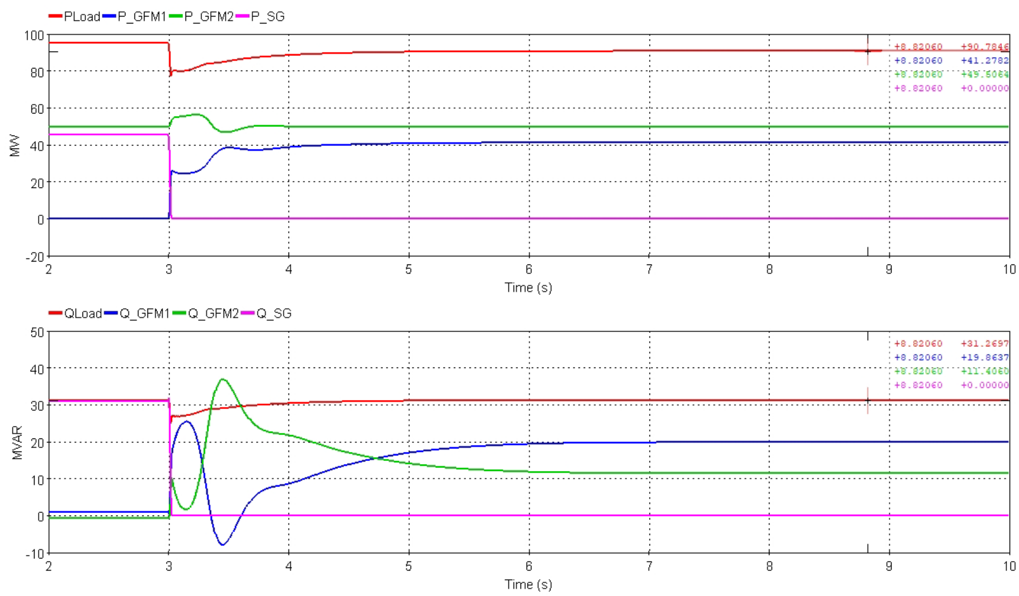

Figure 74. Active and reactive power of the GFM with Kp_{lim} = 0.1 and Ki_{lim} = 10

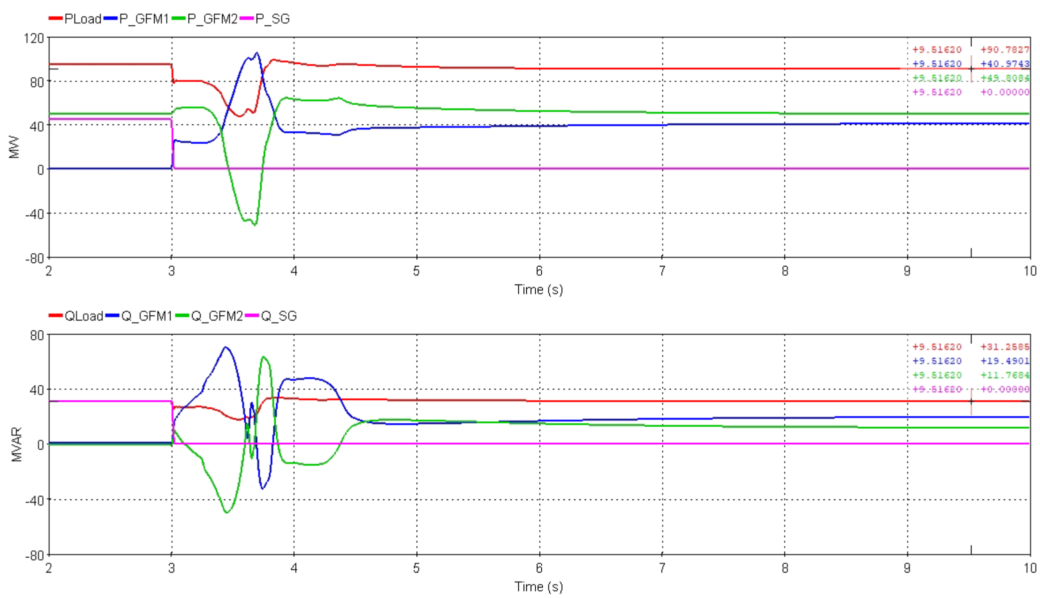

Figure 75. Active and reactive power of the GFM with Kp_{lim} = 0.1 and Ki_{lim} = 1

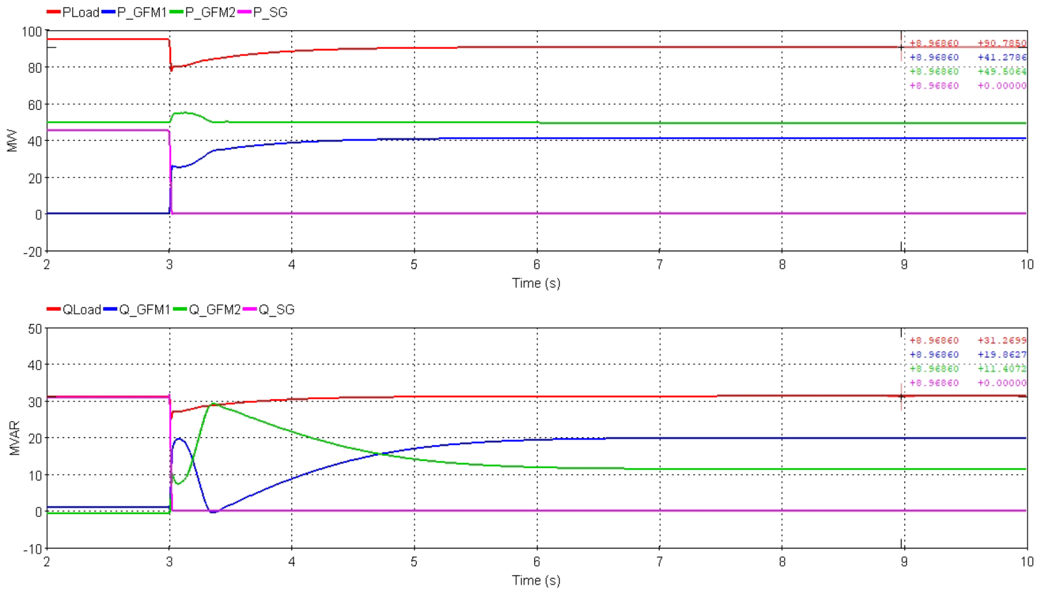

Figure 76. Active and reactive power of the GFM with $Kp_{lim} = 1$ and $Ki_{lim} = 10$

4.4 Other Influential Parameters

Aside from the parameters mentioned in the previous sections, we also identified other parameters that could influence the response of the GFM model for different tests. These parameters are listed below, along with a brief explanation on how they can potentially affect GFM performance.

1. **Current limit of the inverter, I_{max}**: Can play a role when the GFM is operating close to the power limit. As can be seen in Figure 3, this parameter is set to 1.5 pu for all tests.
2. **P_{max}, P_{min}, Q_{max}, and Q_{min}**: Can impact the final values and trajectory of active/reactive power and are set to 1 pu in all tests.
3. **Frequency/voltage droop coefficients**: Can impact the frequency and voltage responses.
4. **Inverter transformer impedance**: May necessitate retuning the controller gains.
5. **Inverter filter inductance**: Can impact the voltage setpoints and may require retuning the controller gains.

5 Summary

Through a series of detailed simulations, the EMT generic model utilized by CEN parameterization in accordance with Figure 3 has been demonstrated to successfully pass the tests recommended by NERC for the verification of GFM capability in a model [1], in addition to the set of tests recommended by AEMO [2] and the testing recommended by EPRI [3].

Furthermore, the parameters that could potentially impact the GFM model's response to varying tests were identified (State freeze threshold, voltage control loop gains, overload mitigation controller, Current limit of the inverter, Frequency/voltage droop coefficients, Inverter transformer impedance and Inverter filter inductance).

Additionally, a comparison was conducted between the generic EMT model and the OEM GFM model. During steady-state conditions, the results were found to be similar; however, during transients, differences emerged.

Following the completion of the aforementioned tests, CEN is now better positioned to utilize the generic EMTP model in instances where OEM EMT models are not available, with a clear understanding of their respective capabilities and limitations.

Development and improvement of generic models are a continuous process and the project team and the software developers would continue to collaborate in order to improve the robustness and features available in the generic model.

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[1] NERC (North American Reliability Corporation). 2023. *White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage.* Atlanta, GA: NERC. https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf.

[2] AEMO (Australian Energy Market Operator). 2024. *Voluntary Specification for Grid-forming Inverters.* https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf?la=en&hash=7778A2249D8C29A95A2FADCD9AAA509D

[3] EPRI. 2023. *Generalized Procedures to Identify and Verify Grid Forming Property in Inverter-Based Devices Simulation Models: Specific to Simulation Platforms*. Palo Alto, CA: EPRI. 3002027121. https://www.epri.com/research/products/000000003002027121.

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