Testing the Performance of Grid-Forming Resources

TEST METHODS AND PERFORMANCE METRICS FOR EVALUATING THE VOLTAGE SOURCE BEHAVIOR OF GRID-FORMING RESOURCES

A Report by the
Energy Systems Integration Group's
GFM Testing Project Team

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Testing the Performance of Grid-Forming Resources: Test Methods and Performance Metrics for Evaluating the Voltage Source Behavior of Grid-Forming Resources

A Report by the Energy Systems Integration Group's GFM Testing Project Team

Prepared by

Shahil Shah, National Renewable Energy Laboratory

Deepak Ramasubramanian, EPRI

Project Team Members

Dustin Howard, GE Vernova

Julia Matevosyan, Energy Systems Integration Group

Przemyslaw Koralewicz, National Renewable Energy Laboratory

Ignacio Vieto, GE Vernova

Shruti Rao, GE Vernova

Nilesh Modi, Australian Energy Market Operator

Babak Badrzadeh, Etik Energy

Jason MacDowell, GE Vernova

Anderson Hoke, National Renewable Energy Laboratory

Vahan Gevorgian, National Renewable Energy Laboratory

Pengxiang Huang, National Renewable Energy Laboratory

Andrew Isaacs, Electranix

Ling Xu, GE Vernova

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Abbreviations

BESS	Battery energy storage system
EMT	Electromagnetic transient
ERCOT	Electric Reliability Council of Texas
GFL	Grid-following
GFM	Grid-forming
IBR	Inverter-based resource
MISO	Midcontinent Independent System Operator
NERC	North American Electric Reliability Corporation
PDT	Phasor-domain transient
POI	Point of interconnection
PPC	Power plant controller
RoCoF	Rate of change of frequency
SCR	Short-circuit ratio

Executive Summary

Power system operators around the world are pushing the limits of integrating inverter-interfaced generation from wind, solar, and batteries to very high levels, identifying grid-forming (GFM) technology as a key enabler to support this transition. A number of systems have integrated several GFM battery energy storage systems to ensure stable operation of their grids, and they are the front runners in developing preliminary and non-mandatory specifications for GFM resources.* On the other end of this spectrum are large power system operators with moderate but ever-increasing levels of inverter-based resources (IBRs) that are still able to maintain grid reliability using synchronous generators present in their systems at this time. However, early proactive deployment of GFM resources can mitigate reliability challenges that could otherwise require significant transmission infrastructure investment.

The value of proactive deployment of GFM resources is especially true for the hundreds of gigawatts of battery storage capacity in interconnection queues for which the GFM capability can be enabled relatively easily through software changes. A common refrain from large power system operators is, what is GFM control and how can we specify its requirements? This report is an effort to answer that question.

Early, proactive deployment of GFM resources can mitigate reliability challenges that could otherwise require significant transmission infrastructure investment.

The report's primary objective is to provide clarity around quantifying the performance of GFM resources to meet functional requirements that are defined in various guidelines and standards on GFM resources' performance.

Voltage Source Behavior—the Essence of GFM Resources

The report's primary objective is to provide clarity to the industry on evaluating the core voltage source behavior of GFM resources, which is important for improving grid strength and support stability of bulk power systems.

* See listings on the Energy Systems Integration Group's website of installed GFM projects (https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/projects/) and GFM specifications in various systems around the world (https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/specifications-and-requirements/).

The report documents tests for quantifying the voltage source behavior from GFM resources by benchmarking their performance against an ideal voltage source with a reactor. These tests are designed to help quantify the functional requirements that are defined in various guidelines and standards on GFM resources' performance. This is achieved by documenting the principles, procedures, and performance metrics for various test methods for evaluating the performance of GFM resources.

Specifically, this report provides guidance to practitioners for evaluating the extent of voltage source–like behavior exhibited by IBRs during a short time frame, as the voltage source behavior forms one of the core performance metrics for GFM resources. The report includes test methods that are well accepted by industry as well as new methods that are still evolving and not yet widely used. It also provides example specifications and performance metrics for test methods that can be tailored depending on the system characteristics.

Time-Domain and Frequency-Domain Test Methods

This report documents time-domain and frequency-domain test methods for evaluating the voltage source behavior from GFM resources. Performance metrics are defined for each of the test methods to quantify the voltage source behavior. The test methods and associated performance metrics are applicable to any type of resource including inverter-based resources (battery/wind/solar power plants, high-voltage DC converter stations, STATCOM, etc.) as well as rotating machine–based resources (conventional generators, synchronous condensers, etc.). The performance metrics are demonstrated for several GFM resources using vendor-supplied electromagnetic transient (EMT) models as well as experimental results on the actual hardware.

Time-domain tests in this report for quantifying the voltage source behavior of GFM resources include a phase-jump test and voltage-jump test. Performance metrics for these time-domain tests are defined to capture the speed, magnitude, and duration of the response from GFM resources during either a phase jump or voltage jump disturbance. Performance metrics also define the system condition in terms of grid strength for performing either of these two tests.

Example specifications are provided to explain how the voltage source behavior can be required of GFM resources during procurement—to be adapted based on the characteristics of the system where a GFM resource will be installed and on quantifiable objectives for improving system strength and stability.

Frequency-domain tests in this report for quantifying the voltage source behavior of GFM resources include a Q/V frequency scan, P/θ frequency scan, and V/I or impedance frequency scan. Performance metrics for these frequency-domain tests are defined to capture the magnitude and phase response of a frequency scan withing a particular frequency range.

Example Specifications Provided

Example specifications are provided to explain how the voltage source behavior can be required of GFM resources during procurement. The example specifications are intentionally kept less demanding in this report with higher room for error tolerance in order to not make them too restrictive for various GFM technologies if they are adopted as-is. Specifications based on the test methods and performance metrics presented in the report should be adapted based on the characteristics of the system where a GFM resource is going to be installed and on quantifiable objectives for improving system strength and stability.

Sizing of GFM Resources for Grid Strength

The stability boundary of IBRs is generally defined in terms of their ability to operate under low system strength conditions. Specifically, the stability boundary of an IBR is specified as the minimum strength or the short-circuit ratio (SCR) that it needs from the grid at its point of interconnection for a stable operation. The tests and performance metrics presented in this report quantify the amount of grid strength provided by GFM resources. Hence, they can be used for sizing GFM resources to meet specific grid strength improvement targets to enable stable operation of IBRs under low system strength conditions.

Introduction

Power system operators around the world are pushing the limits of integrating inverter-interfaced generation from wind, solar, and batteries to very high levels, including in Australia, Ireland, the Hawaiian Islands, and Great Britain. These and several other system operators have identified the value of grid-forming (GFM) technology as a key enabler to support this transition. They have integrated several GFM battery energy storage systems to ensure stable operation of their grids, and they are also the front runners in developing preliminary and non-mandatory specifications for GFM resources.[1] On the other end of this spectrum are large power system operators with moderate but ever-increasing levels of inverter-based resources (IBRs) that are still able to maintain grid reliability using synchronous generators present in their systems at this time.

There is an ongoing discussion on the cost of inaction and missed opportunity by these large operators toward the deployment of GFM resources. Early, proactive action can mitigate reliability challenges that could otherwise require significant transmission infrastructure investment. This is especially true for the hundreds of gigawatts of battery storage capacity in interconnection queues for which the GFM capability can be enabled relatively easily through software changes. A common refrain from large power system operators is, what is GFM control and how can we specify its requirements? This report is an effort to answer that question.

The report's primary objective is to provide clarity to the industry on evaluating the core voltage source behavior of GFM resources—important for improving grid strength—with tests to help quantify the qualitative functional requirements that are defined in various guidelines and standards on GFM resources' performance.

The report's primary objective is to provide clarity to the industry on evaluating the core voltage source behavior of GFM resources, which is important for improving grid strength. These tests are designed to help quantify the qualitative functional requirements that are defined in various guidelines and standards on GFM resources' performance. This is achieved by documenting the principles, procedures, and performance metrics for various test methods for evaluating the performance of GFM resources. Specifically, this report provides guidance to practitioners for evaluating the extent of voltage source–like behavior exhibited by IBRs during a short time frame, as the voltage source behavior forms one of the core performance metrics for GFM resources. The report includes test methods that are well accepted by industry as well as new methods that are still evolving and not yet widely used. It also provides example specifications and performance metrics for test methods that can be tailored depending on the system characteristics.

It is important to emphasize that this report:

- Does not recommend that all of the tests and associated performance metrics discussed be adopted by all users. Rather, the selection of specific tests and

1 See listings on the Energy Systems Integration Group's website of installed GFM projects (https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/projects/) and GFM specifications in various systems around the world (https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/specifications-and-requirements/).

expected performance metrics should be determined by the system characteristics and needs, which must be evaluated by conducting appropriate system stability studies.

- Does not recommend that users test for identical performance as demonstrated by some GFM resources used as examples in this report.
- Does not include tests for GFM resources for evaluating performance that does not form a core requirement of voltage source behavior as typically seen in performance standards. For example, it does not include tests for evaluating response to rate of change of frequency (RoCoF), power balancing performance, short-circuit current contribution, islanded operation or loss of last synchronous machine, or blackstart capability.

The test methods presented here can be applied to both unit-level and plant-level testing for evaluating the performance of GFM resources.

What Is Grid-Forming?

The North American Electric Reliability Corporation (NERC) has defined the GFM control of IBRs as "controls with the primary objective of maintaining an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame" (NERC, 2021). The Australian Energy Market Operator has adopted a similar definition: "a GFM inverter maintains a constant internal voltage phasor in a short time frame, with magnitude and frequency set locally by the inverter, thereby allowing immediate response to a change in the external grid" (AEMO, 2023). The National Energy System Operator for Great Britain has defined non-mandatory specifications requiring GFM plants to comprise an internal voltage source with a physical reactor and appropriate response to various grid disturbances within 5 ms of the disturbance (National Grid ESO, 2023).

Despite our having several definitions, the lack of consensus on "what is GFM?" comes about because GFM is often described as a type of IBR that can offer a suite of services, rather than as a single capability or a service. For example, services associated with GFM range from fast active and reactive power response for grid stabilization, droop-like primary frequency control, and oscillation-damping control to quasi-steady-state capabilities such as blackstart and fault current contribution. But some of the capabilities that have been associated with GFM IBRs—such as droop response, positive

It is important to identify minimum core capabilities that can constitute GFM behavior. Others can be deemed advanced, but they should be optional when a GFM resource is procured, depending on system needs.

damping, and fault current contribution—can also be provided by grid-following (GFL) IBRs, though potentially over a longer time duration. (The terms GFL and non-GFM are used interchangeably in this report.) Conversely, some capabilities that are sometimes used to identify characteristics of GFM technology, such as droop response and blackstart, cannot be provided even by some conventional power plants with synchronous generators. For example, nuclear units and synchronous condensers do not provide droop-like primary frequency control, and some conventional power plants are not blackstart-capable, but they could still be classified as GFM resources, albeit those that may not provide all services required by a future power system. It is hence important to identify minimum core capabilities that can constitute GFM behavior; other capabilities can be deemed advanced, but they should be optional when a GFM resource is procured, depending on the system needs.

It is also important to clarify the meaning of phrases such as "sub-transient to transient time frame" or "short time frame" in these definitions. While GFM resources behave as a voltage source behind a reactance, it is important to note that, when operating within equipment limits, they have closed-loop controls that continuously adjust the voltage magnitude and angle to meet various control objectives. These controls act continuously, but generally do not result in rapid changes in the voltage magnitude or angle in the sub-transient to transient or the short time frame unless equipment limits are reached. In this context, the term "short time frame" is used to define the time period during which the response of a GFM resource is evaluated just following a grid disturbance. This is generally around 5 to 15 cycles of the fundamental frequency.

Lastly, we wish to clarify that although certain GFM definitions use the phrase "internal voltage source," a GFM unit does not always need to have a physical voltage source. Rather, GFM units need to *behave* as a voltage source during a short time frame following a disturbance. Hence, the term "voltage source behavior" is better suited to describe the GFM capability.

Voltage Source Behavior—the Essence of a GFM Resource

The above discussion shows that the unique characteristics of a GFM resource are the fast voltage- and frequency-stabilizing response during the short time frame following a grid disturbance, and the ability to act as a near ideal voltage source with an internal impedance in these fast timescales—essentially, to allow a change of current being injected into the grid such that the change in current aids in the maintenance of voltage and frequency at the terminals of the device and such that the change in current does not impact the value of voltage of the source. The power system industry has identified the value of these two core functional requirements expected from GFM resources for managing high shares of IBRs in power systems (ENTSO-E, 2021; NERC, 2023; National Grid ESO, 2021; AEMO, 2023). Note that a change in active and reactive power injection from a GFM resource that aids in improving stability of a network during the short time frame is a manifestation of its ability to behave as a voltage source with internal impedance during these timescales (AEMO, 2023). Hence, the voltage source behavior during the short time frame is the essence of a GFM resource. It should be noted that the consequence of voltage source behavior is the near instantaneous change in injected current that aids voltage and frequency control; this voltage source behavior should not be confused with an actual voltage source. It should also be noted that this voltage source behavior does not guarantee stability and interoperability of various sources in a grid with a high percentage of IBRs.

The unique characteristics of a GFM resource are the fast voltage- and frequency-stabilizing response during the short time frame following a grid disturbance, and the ability to act as a near ideal voltage source with an internal impedance in these fast timescales.

Testing Methods for Quantifying the Performance of GFM Resources

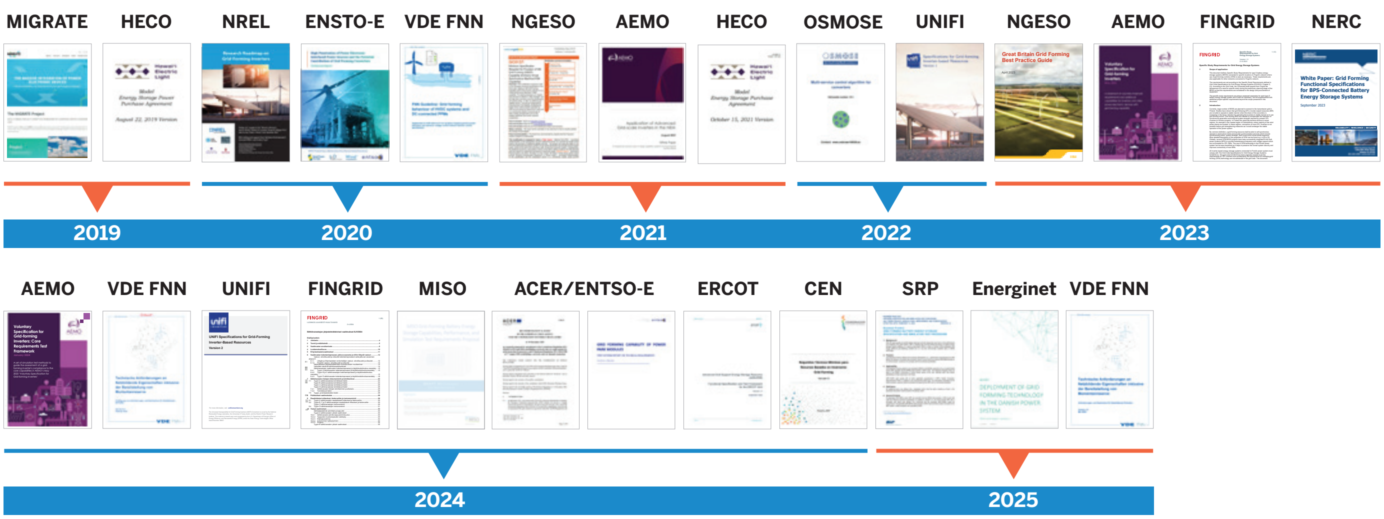
Testing methods for quantifying the performance of GFM resources can be classified based on the functional requirements expected from them: (1) test methods for core functional requirements, and (2) test methods for additional functional requirements. Testing methods for core functional requirements should focus on evaluating the performance of the voltage source behavior, given that all core functional requirements from a GFM resource are manifestations of its ability to hold its internal voltage phasor relatively constant in the short time frame following a grid disturbance, or, in other words, to behave as a voltage source behind an internal impedance during the short time frame.

Because the core functional requirement of a voltage source behavior is a new capability specific to GFM control, which was not demanded from IBRs with GFL control, new methods are required for quantifying such behavior. The additional capabilities demanded from GFM resources, however, are easier to test because many of them can also be provided by state-of-the-art GFL IBRs (e.g., droop response or power balancing, and fault current contribution), and some are also provided by synchronous generators (e.g., blackstart); therefore, existing test methods can be adopted for quantifying additional capabilities of GFM resources.

GFM Specifications Landscape

Over the past five years, specifications for GFM IBRs have begun to emerge, as seen in Figure 1.[2] The specifications were first developed as high-level functionality descriptions by research consortia (e.g., MIGRATE,[3] UNIFI Consortium[4]) and regulators (e.g., the European Network of Transmission System Operators for Electricity (ENTSO-E)). This was followed by system operators in areas seeing large shares of IBRs, e.g., the Hawaiian Electric Company, National Energy System Operator for Great Britain, Australian Energy Market Operator, and others.

FIGURE 1
Grid-Forming Specification Landscape, 2019–2025



Shown are the covers of GFM specifications published globally over the past six years.

Source: Energy Systems Integration Group. Links to the publications can be found at https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/specifications-and-requirements/

2 https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/

3 https://cordis.europa.eu/project/id/691800

4 https://unificonsortium.org/

Notably, NERC has developed a white paper with recommended specifications for GFM battery energy storage systems (BESS) (NERC, 2023). Not only has this document been widely referenced internationally, it also served as a springboard for the Electric Reliability Council of Texas (ERCOT) and Midcontinent Independent System Operator (MISO) for development of their GFM BESS specifications. MISO's specification has already gone through a stakeholder process and will apply to all future transmission-connected BESS, while ERCOT's specification is currently in the stakeholder process but is seeking to require GFM capabilities from all future transmission-connected BESS (with signed interconnection agreements after April 1, 2026).

Specifications developed to date vary in their level of detail. Some specifications contain only functional requirements, while others are test-based or contain both types of requirements.[5] Some specifications are split into (1) core capabilities, i.e., where only software changes are required to achieve grid-forming functionality, and (2) advanced capabilities, i.e., where inverter oversizing or an additional energy buffer is required. Some requirements are voluntary while others are mandatory and apply to all future GFM IBRs. Some requirements apply to all resources while others only specify GFM capability for BESS, recognizing that GFM capability in battery storage is relatively easy to achieve—the low-hanging fruit (ESIG, 2023).

While details of the specifications vary widely in different documents, there is relative agreement on overall high-level capabilities that are required, listed here. Resources with GFM capabilities would be able to:

- Respond to voltage phase angle or magnitude change
- Limit the RoCoF after a large generation loss or load loss event
- Share active power with other GFM IBRs | and synchronous generators
- Demonstrate certain behavior at the current limit
- Counter imbalances
- Counter harmonics
- Provide damping
- Not cause control interactions, and have interoperability with other power electronic devices
- Operate at low system strength
- Support islanded operation and re-synchronization back with the main grid
- Survive the loss of the last synchronous machine
- Have blackstart capability (in some requirements, requires special hardware design considerations)

5 A functional requirement or specification describes what a GFM IBR is supposed to do in certain situations or system conditions—how it is expected to perform to be classified as GFM. A test-based requirement (1) is a description of the tests (usually simulation-based) that an IBR will be a subject to, to demonstrate its GFM capability, and (2) has accompanying pass/fail criteria for each of the tests.

Framework for Testing Grid-Forming Resources

The test methods for evaluating core capabilities of GFM resources focus either on certain performance metrics that quantify the core capabilities or on pass/fail transient tests that mimic certain abnormal grid conditions in which GFM IBRs are expected to operate in a stable manner or support grid stability. The performance metrics can be defined as time-domain or frequency-domain specifications. The pass/fail transient tests for GFM resources, in contrast, focus on certain abnormal grid conditions such as the operation of a GFM resource during the loss of the last synchronous generator in the system or under extremely weak grid conditions.

The abnormal grid conditions under which a GFM resource should be tested using a pass/fail transient test can be different for different applications. For example, the loss-of-last-synchronous-machine test might emulate a reasonably extreme scenario in special applications such as microgrids and small island systems; however, for bulk power systems, it is unlikely that the "loss of last synchronous machine" means the "the loss of other GFM resources within the interconnected system." Hence, requiring that all GFM IBRs for bulk power systems be capable of maintaining a grid during the loss of last synchronous machine and without any other GFM resource in the system might make the equipment overly expensive, and it is likely not necessary for bulk power systems. For bulk power systems, a reasonable abnormal extreme scenario might be a GFM IBR that supplies additional system load in a short time frame within its rating during a plausible contingency.

This section describes two types of methods for testing the performance of GFM resources: through time-domain and frequency-domain testing. The test methods and associated performance metrics can be used to evaluate GFM performance of either an IBR plant (a BESS power plant, wind power plant, PV power plant, etc.) or an IBR unit (inverter, wind turbine, etc.). If the test methods are applied to an IBR plant, the performance is evaluated at the point of interconnection (POI) of the plant with the bulk transmission system. If they are applied to an IBR unit, the performance is evaluated at the point of coupling (POC). The definition of POI and POC are based on the IEEE 2800-2022 standard (IEEE, 2022).

The tests described here can be performed on a real hardware IBR unit (e.g., inverter, wind turbine, etc.) or in simulation using validated and verified simulation models of adequate detail as appropriate for the software domain being used and the test specifications/criteria. Validation of the performance of a simulation model (electromagnetic transient (EMT), phasor-domain transient (PDT), or real-time simulator) against hardware is not in the scope of this report.

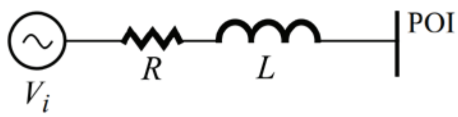
Voltage Source with a Reactor

Because we want a GFM resource to behave as a voltage source with a reactor during the short time frame following a grid disturbance, here we define the time-domain and frequency-domain behavior of an ideal voltage source with a reactor, such as the one shown in Figure 2 (p. 7), in a desired short time frame after a disturbance, as seen from the POI.

Many of the tests used in the industry for evaluating the GFM behavior of a resource such as a phase-jump test, voltage-jump test, RoCoF test, etc. evaluate the ability of the resource to behave as a voltage source. The voltage source behavior of a GFM resource can be quantified by evaluating its time-domain behavior and by evaluating

FIGURE 2

Ideal Voltage Source, V_i, with a Reactor with Inductance L and Resistance R



Source: National Renewable Energy Laboratory.

its frequency-domain behavior. Specific tests for such evaluation can be classified as:

- Time-Domain Testing
  - **Active power:** Evaluate the active power output of a GFM resource in response to a step change in the phase of the three-phase grid voltages at the POI.

    The active power response of a GFM resource can also be evaluated using the RoCoF test, which evaluates the speed and magnitude of the primary frequency or droop-type response of the resource.
  - **Reactive power:** Evaluate the reactive power output of a GFM resource in response to a step change in the magnitude of the three-phase grid voltages at the POI.
- Frequency-Domain Testing
  - **Active power:** Evaluate the transfer function from the phase of the three-phase grid voltages at the POI to the active power output of a GFM resource.
  - **Reactive power:** Evaluate the transfer function from the magnitude of the three-phase grid voltages at the POI to the reactive power output of a GFM resource.
  - **Impedance:** Evaluate the Thevenin impedance of a GFM resource.

Time- and Frequency-Domain Specifications for Voltage Source Behavior

Reactive Power Response

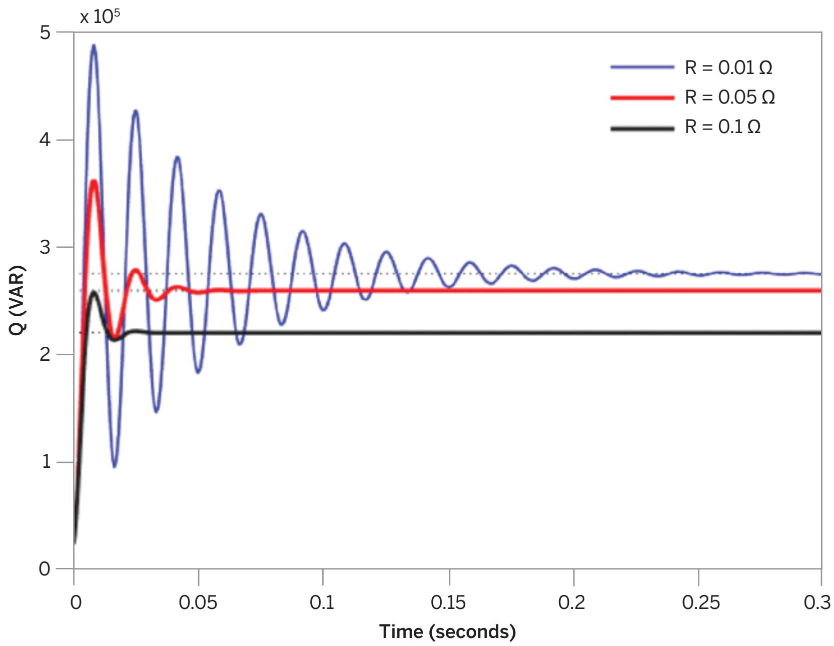
As an example of the second time-domain test defined above, Figure 3 (p. 8) shows the simulated response of the reactive power output at the POI of the voltage source with a reactor as shown in Figure 2 when the magnitude of the three-phase grid voltages at the POI is reduced by a 10% step change. The value of resistance of the reactor for the three plots is different. As can be seen from the results, the voltage source with a reactor naturally dispatches positive reactive power output in response to a reduction in the voltage magnitude at the POI. The reactive power output is delivered quickly, within a few tens of milliseconds, which is equivalent to a few cycles of the fundamental frequency. Moreover, for a small step change in the grid voltage, the reactive power output response is proportional to the magnitude of the step change. This indicates that the relationship between the change in the reactive power output of a voltage source with a reactor and the magnitude of the voltages at the POI can be approximated by a negative constant gain. Finally, Figure 3 shows that the reactive power response of the voltage source with a reactor is oscillatory when the resistance of the reactor is low, indicating low damping characteristics; the frequency of oscillation is closer to the fundamental frequency, which is 60 Hz for the simulations shown here.

The above discussion shows that the voltage source behavior of a GFM resource can be specified in the time domain using the response of its reactive power output during a step change in the magnitude of the three-phase voltages at the POI of the GFM resource. The parameters that can be used to define the reactive power response include:

- **Rise time:** The time required to achieve 90% of the steady-state reactive power output.
- **Gain:** The gain from the magnitude of the voltage disturbance to the additional steady-state reactive power output dispatched by the GFM resource. This might be a difficult performance metric to estimate if the reactive power output of the GFM resource does not remain almost constant during the short time frame after the disturbance.
- **Damping:** The damping ratio of oscillations in the reactive power output. This might be a difficult performance metric to estimate if the reactive power output of the GFM resource exhibits oscillations of varying characteristics during the short time frame after the disturbance.

FIGURE 3

Reactive Power Response from an Ideal Voltage Source with a Reactor During a Step Reduction in the Magnitude of the Three-Phase Grid Voltages by 10% at the POI



The internal voltage source magnitude is 0.69 kV line-line root-mean-square, and the inductance (L) of the reactor is 0.5 mH. The response is shown for three values of resistance (R) of the reactor.

Source: National Renewable Energy Laboratory.

- **Reactive energy:** The integral of the change in reactive power from an initial operating point over the short time frame after the disturbance. This performance metric can be useful in comparing the reactive power response of different GFM resources with a different shape of the response.

The reactive power response of an ideal voltage source with a reactor can also be described in the frequency domain by a transfer function from the magnitude of the three-phase voltages at the POI, V_m, to the reactive power output of the voltage source with a reactor, Q. The analytical expression for this Q/V transfer function for an ideal voltage source with a reactor is (Shah et al., 2023):

$$\left.\frac{Q(s)}{V_m(s)}\right|_{\theta(s)=0} = \frac{Q_0}{V_1} - \frac{3}{2}V_1 \cdot \frac{\omega_1 L}{(R+sL)^2+(\omega_1 L)^2} \quad (1)$$

where Q_0 is the reactive power output of the ideal voltage source at the POI before the disturbance; V_1 is the peak of the phase-to-neutral voltages of the ideal voltage source; R and L are the resistance and inductance of the reactor, respectively; and ω_1 is the fundamental frequency in radians per second. The subscript '$\theta(s) = 0$' on the left-hand side indicates that the phase angles of the three-phase voltages at the POI are kept unperturbed while obtaining this transfer function. For convenience, Q_0 is assumed to be zero in (1), but the concept holds at other values of initial operating value of the reactive power output. Hence, the transfer function in (1) becomes a second-order low-pass filter with a negative gain and with the corner frequency being the same as the fundamental frequency. Moreover, the steady-state gain of the transfer function at $s = 0$ can be approximated as:

$$\frac{Q}{V_m} = -\frac{3}{2}\frac{V_1}{\omega_1 L} \quad \text{VAR/Volt} \quad (2)$$

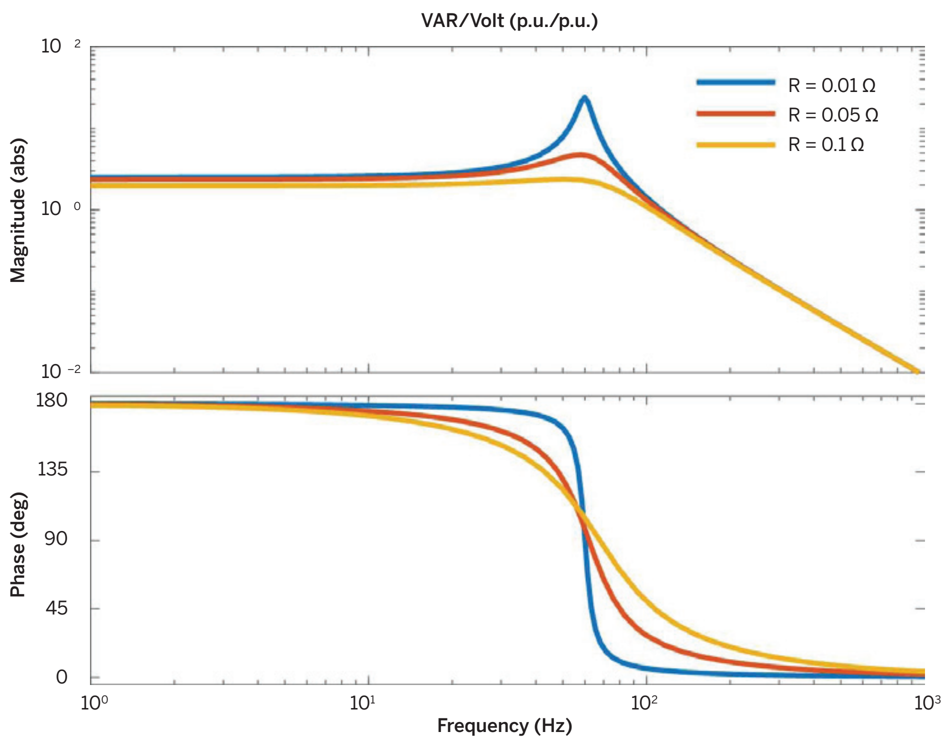
If the steady state VAR/Volt gain in (2) is expressed in p.u./p.u., it will be exactly equal to the value of short-circuit ratio (SCR) that the ideal voltage source with a reactor represents for the base values used for obtaining the gain in p.u./p.u.

Figure 4 shows the response of the transfer function Q/V of the ideal voltage source with a reactor shown in Figure 2 (p. 7). The figure and (1) show that the Q/V transfer function of an ideal voltage source with a reactor exhibits the behavior of a low-pass second-order filter with a negative DC gain. Moreover, the damping of the low-pass second-order filter increases with the resistance of the reactor.

The response of the transfer function Q/V exhibiting a constant negative gain below the fundamental frequency shows that the ideal voltage source with a reactor will dispatch positive reactive power during a voltage disturbance that is proportional to the drop in the magnitude of voltages at its terminal. This response is similar to that presented in Figure 3 (p. 8). Hence, for the operation of a resource within its limits, its response in the reactive power output during a step change in the magnitude of voltages at its terminal provides similar information as the response of the transfer function Q/V. However, it can be easier to define the reactive power response of a GFM resource from the frequency-domain transfer function Q/V because: (1) the short time frame in the time domain is easier to visualize and characterize in the frequency domain, and (2) the frequency-domain response of the transfer function Q/V can be measured independently of the strength of the grid at the terminal of the GFM resource. The

FIGURE 4

Response of the Transfer Function from the Magnitude of Three-Phase Voltages at the POI to the Reactive Power Output of an Ideal Voltage Source with a Reactor



The internal voltage source magnitude is 0.69 kV line-line rms, and the inductance (L) of the reactor is 0.5 mH. This value corresponds to an SCR of 2.5 for power and voltage base values of 1 MW and 0.69 kV, respectively. The response is shown for three values of resistance (R) of the reactor. Note that the response is plotted in p.u./p.u. and the DC gain of the response is the same as the SCR value used for sizing the reactor, i.e., 2.5.

Source: National Renewable Energy Laboratory.

advantages and complementarity of the frequency-domain characterization of GFM resources will become evident from the test results of GFM resources presented in the subsequent sections of this report.

The above discussion shows that one way the voltage source behavior of a GFM resource can be specified in the frequency domain is by its response of the Q/V transfer function. The parameters that can be used to define the transfer function characteristic include:

- **Gain:** The gain of Q/V transfer function of an ideal voltage source with a reactor is constant or flat at frequencies below the fundamental frequency. Because we expect a GFM resource to behave like an ideal voltage source with a reactor only during the short time frame following a grid disturbance, the flatness of the gain of the Q/V frequency scan of a GFM resource can be evaluated over a smaller frequency range, say, 4 to 40 Hz; this range covers the short time frame where the voltage source behavior is expected. Again, the gain of the Q/V transfer function of a GFM resource should be almost constant within this specified frequency range. Moreover, the average gain over this frequency range provides the measure of the magnitude of the reactive power response from a GFM resource in response to a specific change in the magnitude of voltages at the POI.
- **Phase:** The phase of Q/V transfer function of an ideal voltage source with a reactor is around 180° at frequencies below the fundamental frequency. Following the same argument as above, the phase of the Q/V transfer function of a GFM resource should be around 180° within a specified frequency range such as 4 to 40 Hz.

Based on the above discussion, a pass-fail criterion is proposed for GFM resources based on the Q/V frequency scans. It prescribes that the resource is grid-forming only if the Q/V frequency scan has almost constant (or almost flat) magnitude and phase responses between 4 to 40 Hz, and the phase response in this frequency range is closer to 180° (see Shah et al. (2023)).

Active Power Response

Time-domain and frequency-domain specifications of active power response for the voltage source behavior expected from a GFM resource can be defined in a similar way as the specification for the reactive power response. The principal difference is that the active power response is obtained in response to a disturbance in the phase of the three-phase voltages at the POI. Hence, for time-domain specifications, the active power response is obtained for a phase jump in the three-phase voltages at the POI. Similarly, the transfer function from the phase of the three-phase voltages at the POI of a GFM resource to the active power output of the GFM resource, that is, P/θ, is used for defining frequency-domain specifications.

The analytical expression for the P/θ transfer function for an ideal voltage source with a reactor is (Shah et al., 2023):

$$\left.\frac{P(s)}{\theta(s)}\right|_{V_m(s)=0} = -Q_0 - \frac{3}{2}V_1^2 \cdot \frac{\omega_1 L}{(R+sL)^2+(\omega_1 L)^2} \quad (3)$$

where P_0 is the active power output of the ideal voltage source at the POI before the disturbance. The subscript "$V_m(s) = 0$" on the left-hand side indicates that the magnitude of the three-phase voltages at the POI is kept unperturbed. For convenience, Q_0 is assumed to be zero in (3), but the concept holds at other values of initial operating value of the reactive power. Hence, the transfer function in (3) becomes a second-order low-pass filter with a negative gain and with the corner frequency being the same as the fundamental frequency. Moreover, the steady-state gain of the transfer function at $s = 0$ can be approximated as:

$$\frac{P}{\theta} = -\frac{3}{2}\frac{V_1^2}{\omega_1 L} \text{ Watts/Radian} \quad (4)$$

Eq. (4) shows that the transfer function P/θ of an ideal voltage source with a reactor exhibits the behavior of a low-pass second-order filter with a negative DC gain. Moreover, the damping of the low-pass second-order filter increases with the resistance of the reactor. Hence, similar to the reactive power response, the voltage source behavior of a GFM resource can be specified in the frequency domain by its response of the P/θ transfer function, with the similar performance parameters as the Q/V transfer function.

Based on the above discussion, a pass-fail criterion is proposed for GFM resources based on the P/θ frequency scans. It prescribes that the resource is grid-forming only if the P/θ frequency scan has almost constant (or almost flat) magnitude and phase responses between 4 to 40 Hz, and the phase response in this frequency range is closer to 180° (see Shah et al. (2023)).

It is important to recognize the practical equipment limits of existing IBRs in providing an active power response that resembles that of an ideal voltage source with a reactor. Unlike for the reactive power response, the demand for the fast active power response similar to that of an ideal voltage source with a reactor might require additional short-term storage and/or induce additional stresses (for example, mechanical stress in wind turbines) in GFM resources as compared to their operation without GFM control. Considering these aspects in the development of specifications for active power response from GFM resource will help to avoid unnecessarily increasing equipment costs for future equipment or preventing existing assets from potentially contributing to grid stability. These aspects are discussed later in the report.

Impedance Response

Because the impedance of an ideal voltage source with a reactor is the same as that of an R-L branch, the voltage source behavior of a GFM resource can also be quantified using its frequency-domain positive-sequence impedance response. If the impedance response of a resource resembles that of an inductor (reactor) in the frequency range of interest, then the resource can be exhibiting voltage source behavior. Following the same argument as the Q/V frequency scan, the frequency range of interest for checking the impedance response would be (f_1 ± 40) Hz, except for a narrow band around the fundamental frequency, f_1 . Note that the 4 to 40 Hz frequency range in the Q/V and P/θ scans would translate to (f_1 ± 40) Hz frequency range minus the (f_1 ± 4) Hz band in the positive-sequence impedance scan.

Based on the above discussion, a pass-fail criterion is proposed for GFM resources based on the impedance or V/I frequency scans. It prescribes that the resource is grid-forming only if the impedance or V/I frequency scan resembles that of a reactor (i.e., an R-L branch) within f_1 ***± 40 Hz frequency range, while ignoring a response in a narrow band around the fundamental frequency (see Shah et al. (2023)).***

Testing Setup

Figure 5 shows a testbench setup for testing the core capabilities of GFM resources. A GFM resource such as a GFM BESS is connected to an ideal voltage source through an inductive impedance. The ideal voltage source should be capable of controlling its magnitude, phase, and frequency to create various transient events such as phase jump, magnitude jump, and RoCoF events. The inductive impedance should be capable of emulating various grid strengths in terms of SCR and X/R ratio; hence, it basically includes series-connected variable inductors and resistors.

The test setup described above can be easily implemented in a simulation environment for testing of GFM resources using their EMT or PDT models. For laboratory testing of the actual hardware, the ideal voltage source can be realized using a grid simulator, and the inductive impedance can be realized using an impedance network with high-power reactors that can be switched in and out for emulating different grid strength conditions. The grid simulator should be able to control the magnitude, phase, and frequency of its output three-phase voltages with fast control bandwidth to be able to emulate magnitude jump, phase jump, and RoCoF events. The impedance network should be able to emulate different SCR values ranging from a high value of 5 to a low value of 1. Such an impedance network for emulating different weak grid conditions was recently commissioned at the Flatirons Campus of the National Renewable Energy Laboratory, which can simulate a grid with SCR down to 1 for devices with up to 7 MVA rating (Figure 6).

Certain tests require bypassing the impedance network to evaluate the performance of the GFM resources during extremely strong grid conditions. Such testing is particularly important if the POI of a GFM resource is located closer to the transmission backbone of the system and the SCR is significantly higher than 5.

FIGURE 6

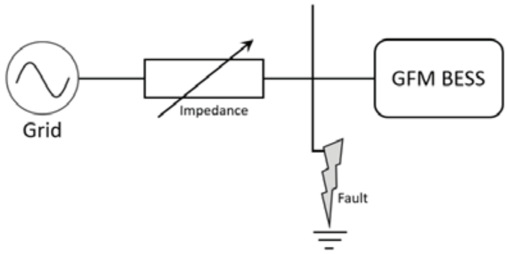
Medium-Voltage Impedance Network Capable of Emulating Weak-Grid Conditions

This medium-voltage impedance network at the Flatirons Campus of National Renewable Energy Laboratory is capable of emulating weak grid conditions with an SCR down to 1 for up to 7 MVA test articles. The impedance network can also emulate series compensation of up to 50%.

Source: Shahil Shah, National Renewable Energy Laboratory.

FIGURE 5

Setup for Testing GFM Resources



Source: Australian Energy Market Operator's *Voluntary Specification for Grid-forming Inverters (2023)*.

Time-Domain Tests

This section presents results from various GFM resources during time-domain tests including the phase-jump test and voltage-jump test.

Phase-Jump Test

Certain questions commonly come up when defining specifications for the active power response of a GFM resource based on the response during a phase-jump test. These questions are articulated and responded to here using the response of different GFM resources in the following tests.

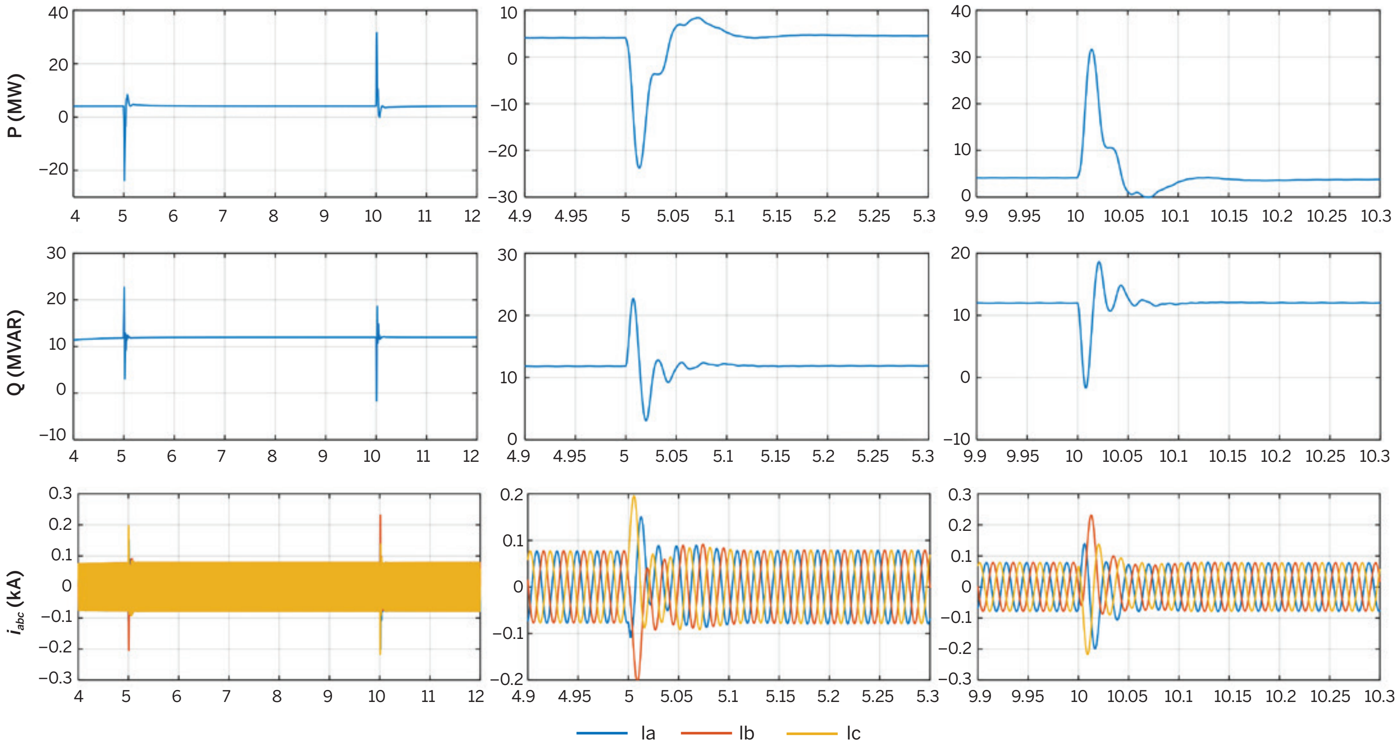
GFM BESS #1

Figure 7 (p. 14) shows the response of GFM BESS #1 obtained using its vendor-supplied EMT model during a phase-jump test. The BESS is connected to an ideal voltage source for this particular test. A positive 10 degree phase jump is applied at t = 5 s, and a negative 10 degree phase jump is applied at t = 10 s to the three-phase voltages at the POI. As shown in the figure, GFM BESS #1 immediately reduces its power output by around 25 MW during the positive phase jump and increases power output by around 25 MW during the negative phase jump. In both cases, however, the active power response is pulled back within around 50 ms after the disturbance.

> **Question 1:** Should the performance metric for the magnitude of the phase jump active power response be specified as the initial change in the active power output (25 MW in Figure 7) or the average active power response during a specified duration?

FIGURE 7

Response of a GFM BESS #1 During a Phase-Jump Test When Connected to an Ideal Voltage Source with Zero Internal Impedance



A positive 10 degree phase jump is applied to voltages at t = 5 s, and a negative 10 degree phase jump is applied to voltages at t = 10 s.

Source: National Renewable Energy Laboratory.

This question is addressed by defining a specification for active power response with performance parameters including rise time, minimum active power response for a particular duration, and area under the active power response.

Figure 8 (p.15) shows the response of GFM BESS #1 for the same phase-jump test as previously, but when it is connected to an ideal voltage source with an inductive impedance sized to represent a grid with an SCR of 5. As can be seen from the figure, the initial phase jump active power has slightly reduced because of the finite grid impedance.

Figure 9 (p. 16) shows the response of GFM BESS #1 for the same phase-jump test as previously, but when it is connected to an ideal voltage source with an inductive impedance sized to represent a grid with an SCR of 1.25. The phase-jump response of the BESS is quite oscillatory in this case because of its operation with a significantly weaker grid. Moreover, as can be seen from the figure, the initial phase jump active power has significantly reduced because of the large impedance in the grid.

Question 2: Under what grid SCR should the active power response of a GFM resource be tested?

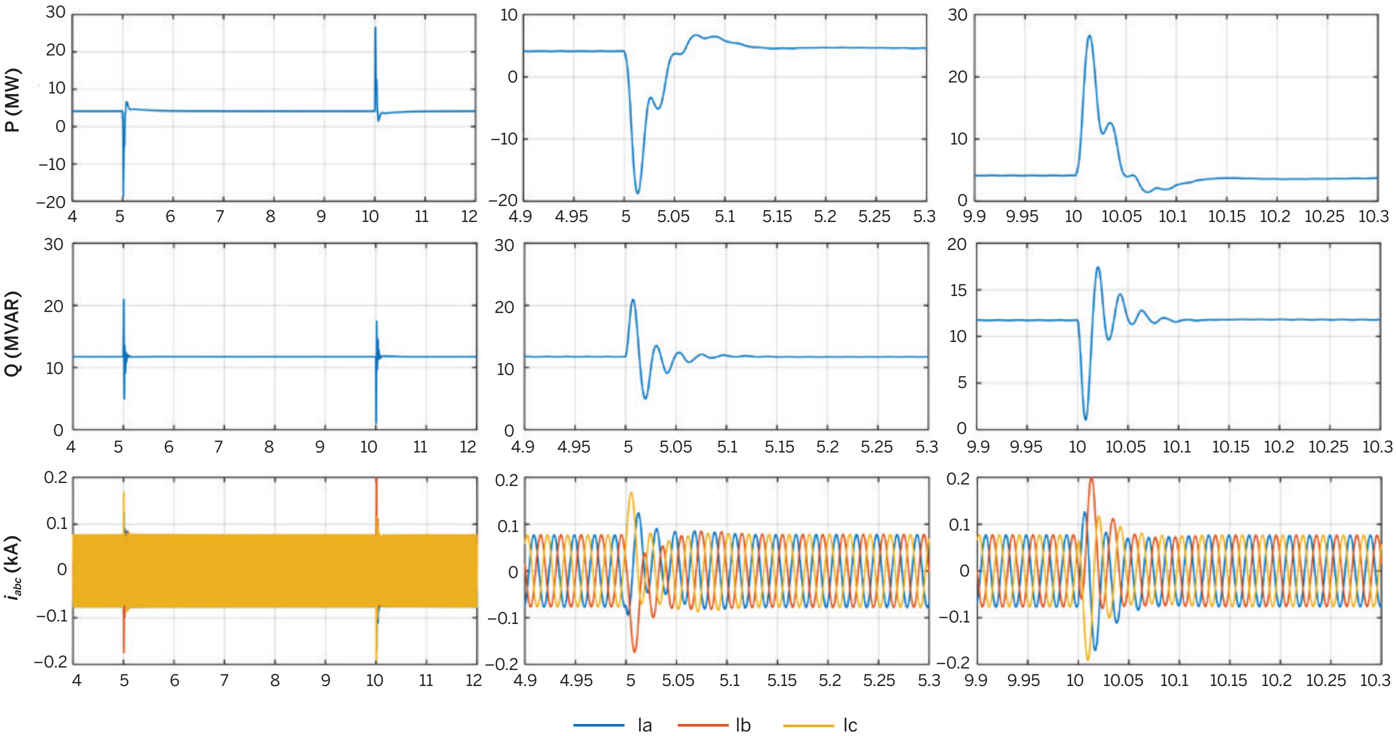
This question is addressed by defining a specification that includes the grid SCR and X/R ratio that should be used for performing the phase-jump test.

Question 3: Should one specify the damping of the active power response of a GFM resource as a performance metric?

This question is addressed by defining a specification that requires the active power response to be properly damped without giving any particular range for the damping factor.

FIGURE 8

Response of a GFM BESS #1 During a Phase-Jump Test When Connected to an Ideal Voltage Source with Inductive Impedance Representing an SCR of 5



A positive 10 degree phase jump is applied to voltages at t = 5 s, and a negative 10 degree phase jump is applied to voltages at t = 10 s.

Source: National Renewable Energy Laboratory.

GFM BESS #2

Different GFM resources might have a completely different type of active power response during a phase-jump test. For example, Figures 10 and 11 (p. 17) show the response of another GFM resource, GFM BESS #2, obtained using its vendor-supplied EMT model during a phase-jump test using the same setup as described above for GFM BESS #1. GFM BESS #2 instantaneously dispatches active power in response to a phase jump, similar to GFM BESS #1. However, unlike GFM BESS #1, where the active power stayed at a particular level for a duration of around 50 ms, the active power response of GFM BESS #2 following the phase-jump event starts reducing slowly to the pre-disturbance level. This raises the following set of questions regarding defining specifications for the active power response of a GFM resource during a phase-jump test.

Question 4: Should one specify a particular shape for the active power response from a GFM resource during a phase-jump event? If so, should it be square-ish, should it be triangular, or should it be something else?

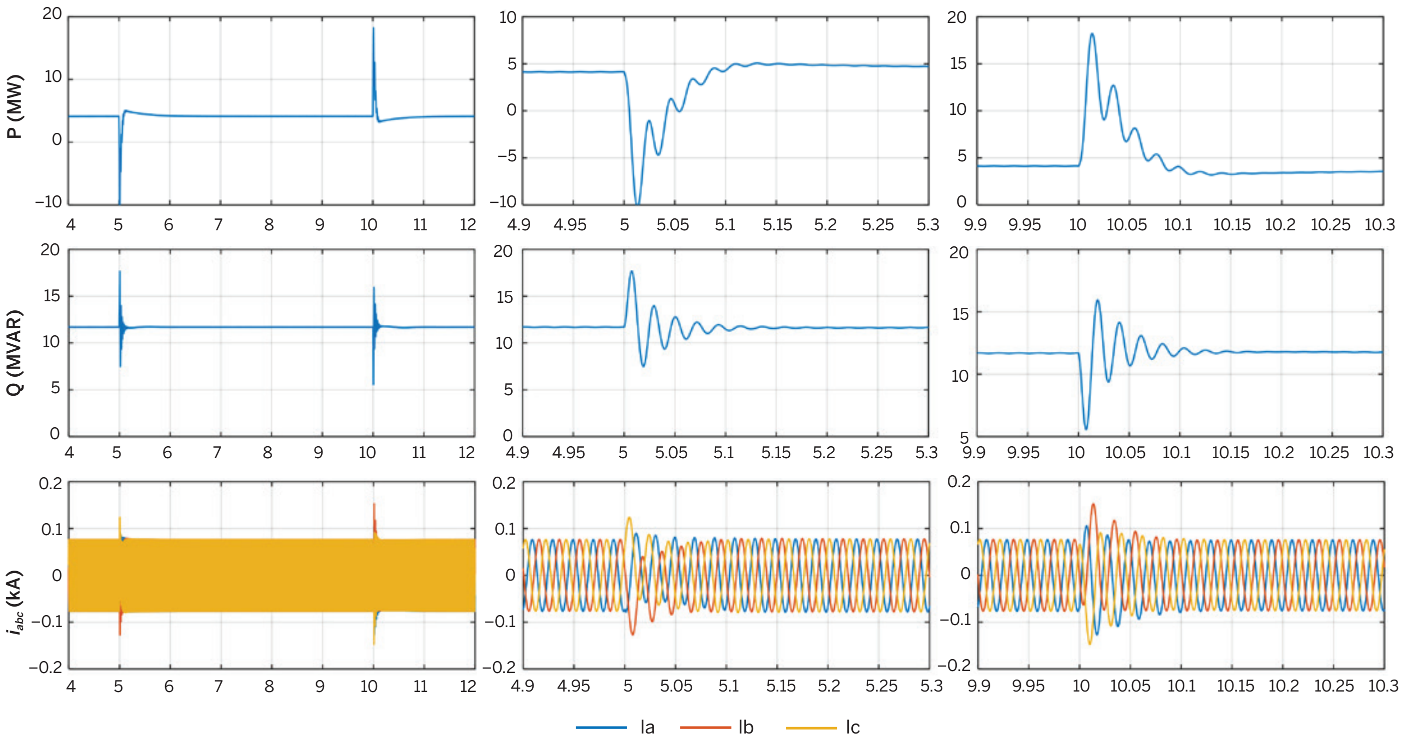
This question is addressed by defining a specification for active power response with performance parameters including rise time, minimum active power response for a particular duration, and area under the active power response.

Comparison of GFM and GFL Resources

To further highlight the performance of a GFM resource during a phase-jump test compared to a non-GFM resource we compared the response of an IBR during the phase-jump test for GFM and non-GFM

FIGURE 9

Response of a GFM BESS #1 During a Phase-Jump Test When Connected to an Ideal Voltage Source with Inductive Impedance Representing an SCR of 1.25



A positive 10 degree phase jump is applied to voltages at t = 5 s, and a negative 10 degree phase jump is applied to voltages at t = 10 s.

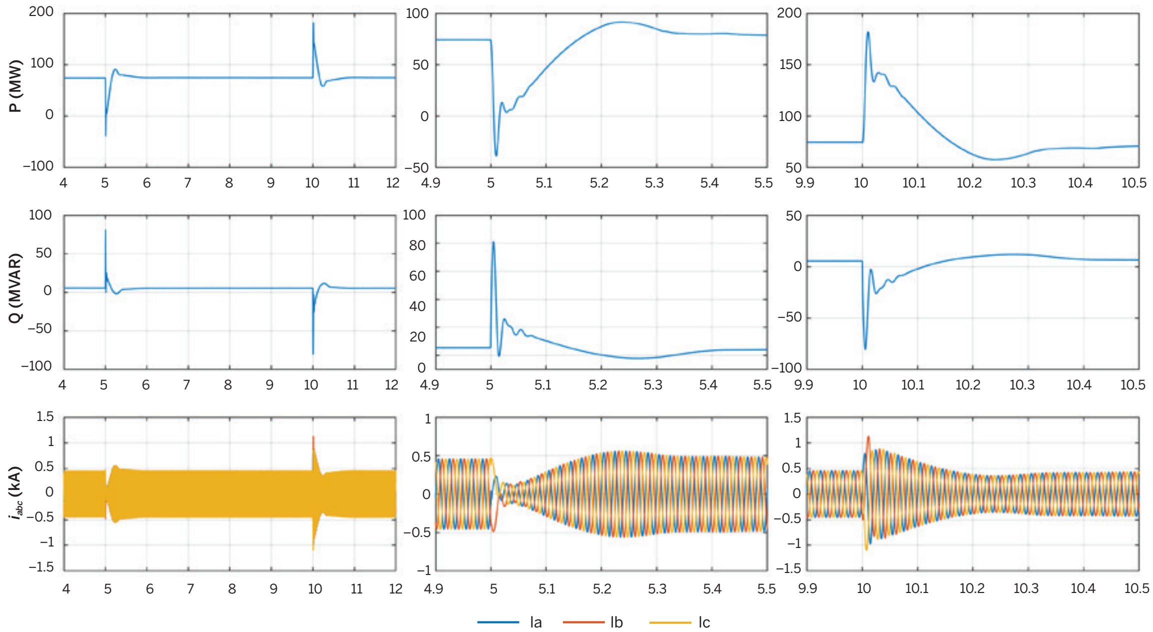
Source: National Renewable Energy Laboratory.

control modes (Figure 12, p. 18). The responses for both modes are obtained from the blackbox EMT model of the IBR that is capable of being configured in GFM and non-GFM modes. The test was carried out at an SCR of 1.2 with an X/R ratio of 10 and without a power plant controller (PPC). First, a relative phase increase of 30 degrees is applied at t = 9 s followed by a relative phase decrease of 30 degrees applied at t = 13 s. Care was taken to ensure that the pre-event operating point is far away from the current limit.

In both operating modes—GFM and non-GFM—there is an appropriate change in current injection in the sub-transient time frame. However, the GFM configuration provides more current injection to the network. Further, in the non-GFM mode there is a controller operating at a higher bandwidth (low rise and settling time) to bring P and Q back to the pre-event values. In contrast, in the GFM mode this controller is of much lower bandwidth (large rise and settling time); therefore, there are more degrees of freedom and flexibility in operation. The response of the instantaneous current from the device shown in Figure 13 (p. 19), observed at the measurement node described in the test setup, also showcases the initial sub-cycle appropriate response of current from the non-GFM configuration. Equally observable is the subsequent response of the power control loops, along with the effect of their high (low) bandwidth respectively in non-GFM (GFM) modes of operation.

FIGURE 10

Response of a GFM BESS #2 During a Phase-Jump Test When Connected to an Ideal Voltage Source with Zero Internal Impedance

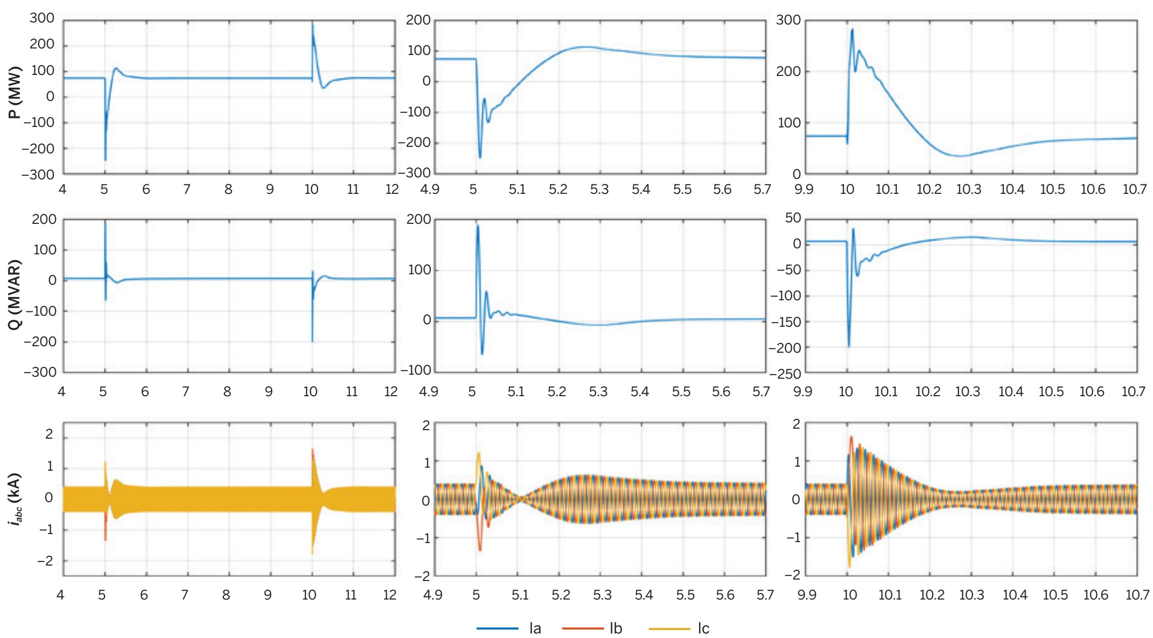


A positive 10 degree phase jump is applied to voltages at t = 5 s, and a negative 10 degree phase jump is applied to voltages at t = 10 s.

Source: National Renewable Energy Laboratory.

FIGURE 11

Response of a GFM BESS #2 During a Phase-Jump Test When Connected to an Ideal Voltage Source with Inductive Impedance Representing an SCR of 5

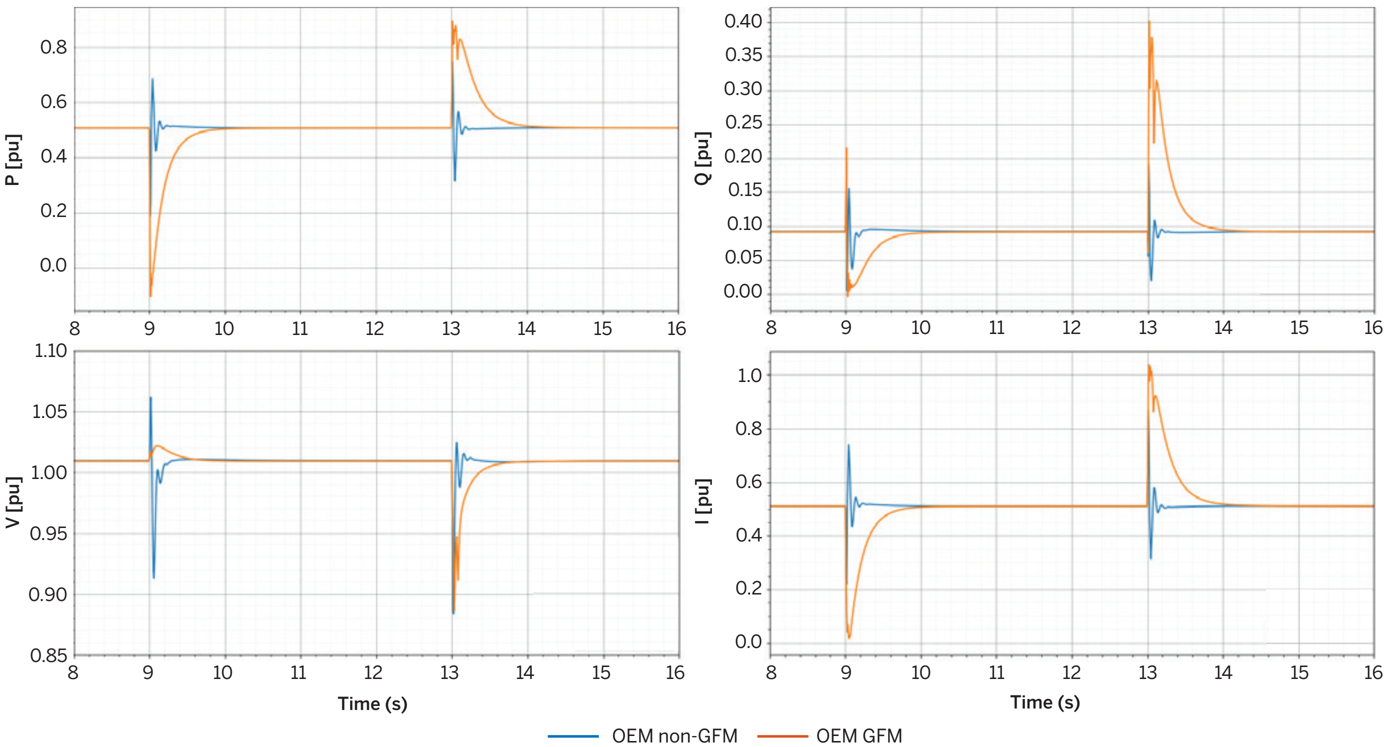


A positive 10 degree phase jump is applied to voltages at t = 5 s, and a negative 10 degree phase jump is applied to voltages at t = 10 s.

Source: National Renewable Energy Laboratory.

FIGURE 12

Response of an IBR in GFM and non-GFM Modes for a Phase-Jump Test



This plot shows the response from a blackbox EMT model of an IBR in GFM and non-GFM control modes to phase change disturbances. At t = 9 s, a phase jump (increase) of 30 degrees is applied to the voltages, followed by a phase jump (decrease) of negative 30 degrees applied to the voltages at t = 13 s.

Source: EPRI (2024).

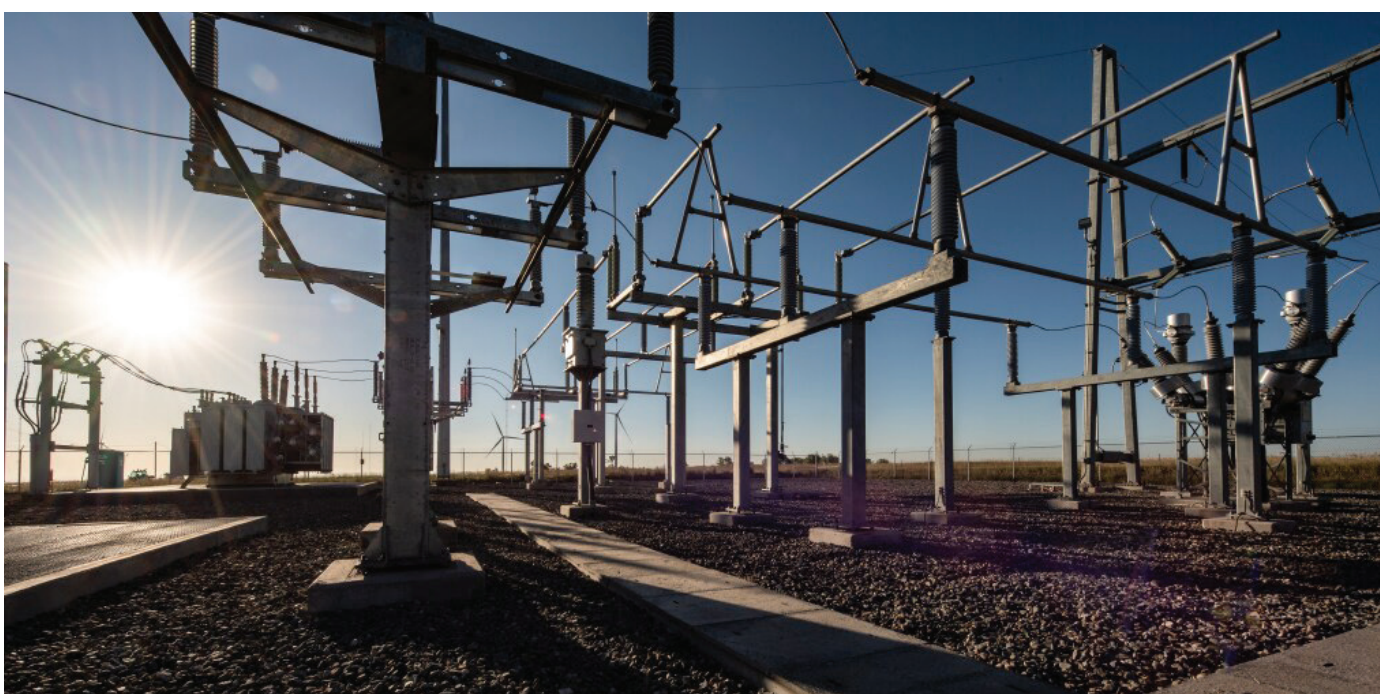
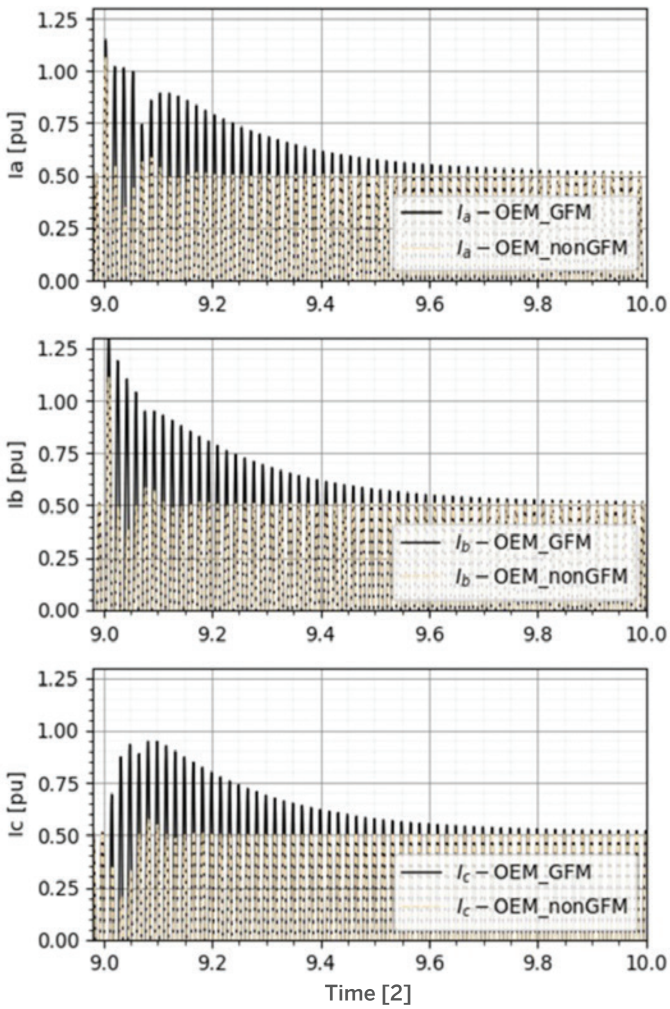


FIGURE 13

Instantaneous Response of Current from an IBR in GFM and Non-GFM Modes During a Phase-Jump Test



The plot shows the initial sub-cycle response from a blackbox EMT model of an IBR in GFM and non-GFM control modes after applying a phase change disturbance. At t = 9 s, a phase jump of 30 degrees is applied to the voltages, and the figure plots the individual phase currents at the measurement node.

Source: EPRI.

TABLE 1

Performance Metrics for Phase-Jump Test

Performance Metric	Suggested Specification
Phase jump active power	A GFM resource should increase its active power output by at least **0.05 per unit** (p.u.) when a negative phase jump of **10 degrees** is applied to the three-phase voltages of source behind the impedance used for testing. To meet this performance metric, the increase in the active power output from the GFM resource should remain higher than **0.05 p.u.** for at least **100 ms** during any part of the first **250 ms** following the phase-jump event.
Phase jump rise time	A GFM resource should increase its active power output by more than **0.05 p.u.** when a negative phase jump of **10 degrees** is applied to the three-phase voltages at its POI within the first **40 ms** after the phase-jump event. The additional active power response can fall below **0.05 p.u.** after reaching that level as long as it does not violate other performance metrics.
Phase jump active energy	The total additional active energy (that is, the integral of the additional active power output over time) delivered by the GFM response during the first **200 ms** after a negative phase jump of **10 degrees** is applied to the three-phase voltages at its POI should be higher than **10 p.u.-ms**. For example, if a GFM resource dispatches additional phase-jump power that is constant and equal to 0.05 p.u. for the first 200 ms after a negative 10 degree phase-jump event, its phase jump active energy will be equal to 0.05 x 200 = 10 p.u.-ms.
Grid strength and damping	The phase-jump test should be performed at a grid strength with an **SCR of 3** and **X/R ratio of 10** at the POI of the GFM resource. Any oscillations observed in the active power output of the GFM resource during the phase-jump test must be properly damped.

Note: The performance parameters highlighted in bold should be changed based on the system requirements.

Source: Energy Systems Integration Group.

Performance Metrics for Phase-Jump Test

Based on the above discussion of various aspects of performance and setting for the phase-jump test on GFM resources, the performance metrics in Table 1 are suggested. However, as noted at the beginning of this report, the user must select performance metrics recommended from this list depending on the system requirements. The performance parameters highlighted in bold should also be changed based on the system requirements.

The performance parameters for a positive phase jump should be similarly defined. Note that for a positive phase-jump event, a GFM resource is expected to reduce its active power output. The performance parameters for positive and negative phase-jump events need not be the same.

Voltage-Jump Test

GFM BESS #1

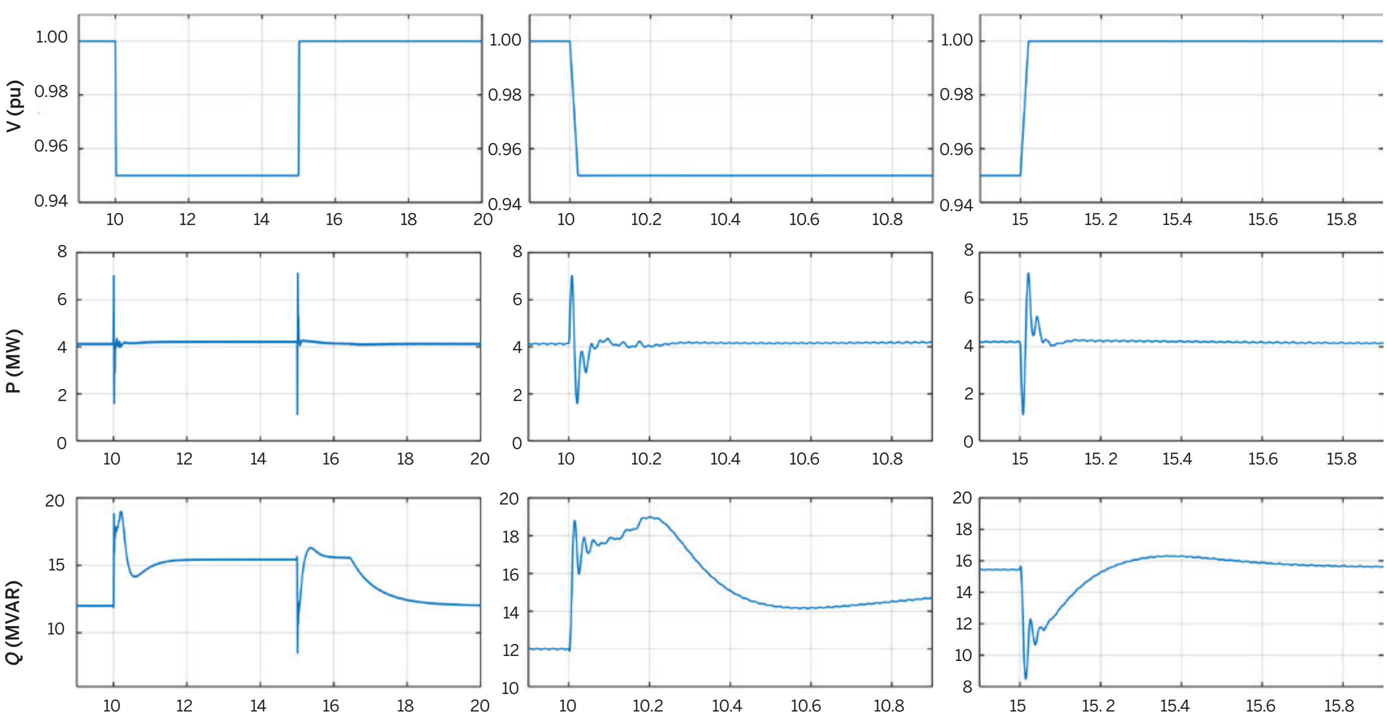
Figure 14 shows the response of GFM BESS #1 obtained using its vendor-supplied EMT model during a voltage-jump test. The BESS is connected to an ideal voltage source for this particular test. The magnitude of voltages at the POI of the BESS is reduced from 1 p.u. by 5% at t = 10 s, and it is increased back to 1 p.u. at t = 15 s. GFM BESS immediately increases its reactive power output by around 5 MVAR when the voltage is reduced from 1 p.u. to 0.95 p.u. The reactive power is sustained at this level for about 200 ms (see the zoomed-in plot in the middle) before it settles to a lower level; the latter is still higher than the pre-disturbance level of the reactive power output. The additional reactive power output over the longer time frame is because of the droop gain in the BESS. On the other hand, the instantaneous reactive power response that persisted for 200 ms is due to the GFM control. It is important to differentiate the fast reactive power response during the short time frame because of the GFM control from the slow reactive power response during the longer time frame because of the droop settings. The zoomed-in plot on the right side of the figure shows reversed behavior when the magnitude of the voltages at the POI is increased back to 1 p.u. at t = 15 s.

GFM BESS #2

Figure 15 (p. 21) shows the response of GFM BESS #2 during a voltage-jump test when it is connected to an ideal voltage source. The magnitude of voltages at the POI is reduced from 1 to 0.95 p.u. at t = 5 s. Just as is seen with GFM BESS #1, GFM BESS #2 dispatches additional reactive power within 20 to 30 ms after the voltage at the POI drops from 1 to 0.95 p.u., and it

FIGURE 14

Response of a GFM BESS #1 During a Voltage Magnitude Jump Test When It Is Connected to an Ideal Voltage Source with Zero Internal Impedance

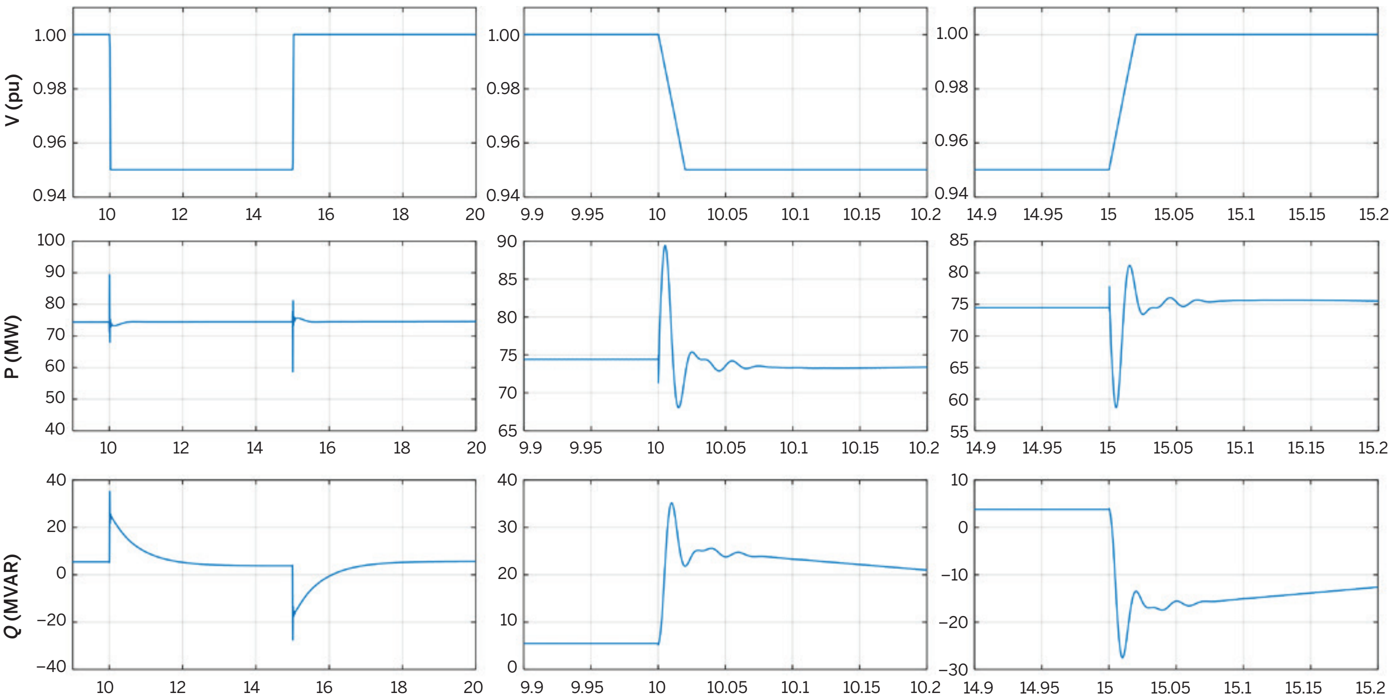


Left: Response of the GFM BESS when the voltage magnitude is reduced by 5% at t = 10 s, and it is restored back to the pre-disturbance level in the step change at t = 15 s. Middle: zoomed-in response during the voltage step-down near t = 10 s. Right: zoomed-in response during the voltage step-up near t = 15 s.

Source: National Renewable Energy Laboratory.

FIGURE 15

GFM BESS #2's Response to a 5% Voltage Drop When It Is Connected Directly to an Ideal Voltage Source



Left: Response of the GFM BESS when the voltage magnitude is reduced by 5% at t = 10 s, and it is restored back to the pre-disturbance level in the step change at t = 15 s. Middle: zoomed-in response during the voltage step-down near t = 10 s. Right: zoomed-in response during the voltage step-up near t = 15 s.

Source: National Renewable Energy Laboratory.

maintains that higher level for about 200 ms. However, unlike GFM BESS #1, GFM BESS #2 withdraws additional reactive power more gradually. It is also worth noting that while GFM BESS #1 dispatches about 5 MVAR of additional reactive power during the voltage drop event, GFM BESS #2 dispatches 25 MVAR of additional reactive power for the same voltage drop event. This indicates that the voltage jump reactive power response from GFM BESS #2 is five times higher than that from GFM BESS #1.

Comparison of GFM and GFL Resources

For a voltage-jump test, again a comparison of performance between GFM and non-GFM mode of an IBR was carried out at an SCR of 1.2 and X/R of 10 (Figure 16, p. 22). Both configurations' initial reactive power change in response to a voltage jump are quite similar, until around 3 to 4 cycles. Following this, the operation of the high-bandwidth power control loops in the non-GFM configuration are observable, thereby bringing the reactive power back to the pre-event value. A point to note here is that the non-GFM mode results in a greater injection of current into the network, but since reactive power is held at the pre-event value, this greater injection of current does not aid or support the grid. As a result, the voltage at the measurement node falls by a larger value than in the GFM mode.

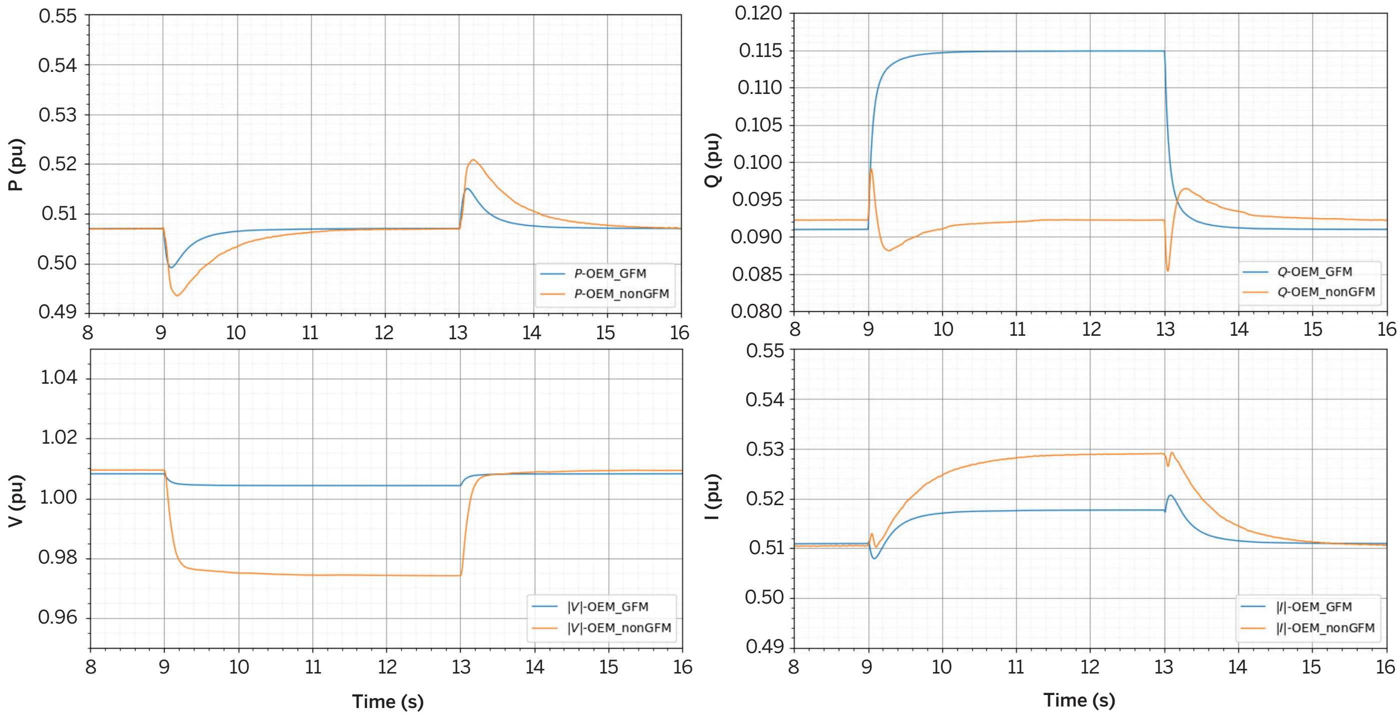
Performance Metrics for Voltage-Jump Test

Based on the above discussion, the following performance metrics are suggested. However, as noted at the beginning of this report, the user must select performance metrics recommended from this list depending on the system requirements. The performance parameters highlighted in bold should also be changed based on the system requirements.

- **Voltage jump reactive power:** A GFM resource should increase its reactive power output by at least

FIGURE 16

Response of an IBR in GFM and Non-GFM Mode to a Voltage Jump



The plot shows the active power, reactive power, and voltage and current at the measurement node for a voltage-jump disturbance applied at t = 9 s. At t = 13 s, the voltage jumps back to its pre-disturbance value.

Source: EPRI (2024).

0.05 p.u. when a **5% drop** is applied to the magnitude of three-phase voltages at its POI. To meet this performance metric, the increase in the reactive power output from the GFM resource should remain higher than **0.05 p.u.** for at least **100 ms** during any part of the first **250 ms** following the voltage-jump event.

- **Voltage jump rise time:** A GFM resource should increase its reactive power output by more than **0.05 p.u.** when a **5% drop** is applied to the magnitude of three-phase voltages at its POI within first **40 ms** after the voltage-jump event. The additional reactive power response can fall below **0.05 p.u.** after reaching that level as long as it does not violate other performance metrics.
- **Voltage jump reactive energy:** The total additional reactive energy—that is, the integral of the additional reactive power output over time—delivered by the GFM resource during the first **200 ms** after a **5% drop** is applied to the magnitude of three-phase voltages at its POI should be higher than **10 p.u.-milliseconds.** For example, if a GFM resource dispatches additional reactive power that is constant and equal to 0.05 p.u. for the first 200 ms after a -5% voltage-jump event, its voltage jump reactive energy will be equal to 0.05 x 200 = 10 p.u.-ms.
- **Grid strength and damping:** The voltage-jump test should be performed at grid strength with an **SCR of 3** and **X/R ratio of 10** at the POI of the GFM resource. Any oscillations observed in the reactive power output of the GFM resource during the voltage-jump test must be properly damped.

The performance parameters for a positive voltage jump—when the voltage magnitude is increased by a step change—should be similarly defined; note that for a positive phase-jump event, a GFM resource is expected to reduce its active power output. The performance parameters for positive and negative voltage-jump events need not be the same.

Frequency-Domain Tests

This section presents results from various GFM resources during frequency-domain tests including the impedance scan, Q/V scan, and P/θ scan. The frequency scans performed for conducting these tests use the same test setup as shown in Figure 5 (p. 12). The ideal voltage source in the test setup is used to inject perturbations at different frequencies for performing frequency scans. Different types of perturbations are injected depending on the type of frequency scan being conducted. For example, for the positive-sequence impedance scan—the V/I scan—positive-sequence perturbations are injected in the instantaneous three-phase voltages; for the Q/V scan, perturbations are injected in the magnitude of the three-phase voltages; and for the P/θ scan, perturbations are injected in the phase angle of the three-phase voltages. Three-phase voltages and currents are measured at the POI of the GFM resource for obtaining the desired frequency-domain transfer function. As mentioned above, the ideal voltage source in the test setup can be realized by a grid simulator for the hardware testing of GFM resources. The procedure and practical aspects for performing frequency scan testing are reported in Shah et al. (2022).

Note that the frequency-domain characteristics of a GFM resource obtained using frequency scans are independent of the grid strength or SCR used during the test; this is assuming that any coupling through the grid, if present, is properly mitigated in the frequency scan process. The ability of the frequency-domain characteristics to capture the dynamic behavior of GFM resources independently from the grid condition makes them attractive for evaluating the performance of GFM resources (see Shah et al. (2024)).

It is worth mentioning that one can derive different types of frequency scan responses directly from sequence impedance/admittance measurement if the full sequence impedance/admittance matrix measured considers frequency coupling between the positive- and negative-sequence impedance/admittance responses.

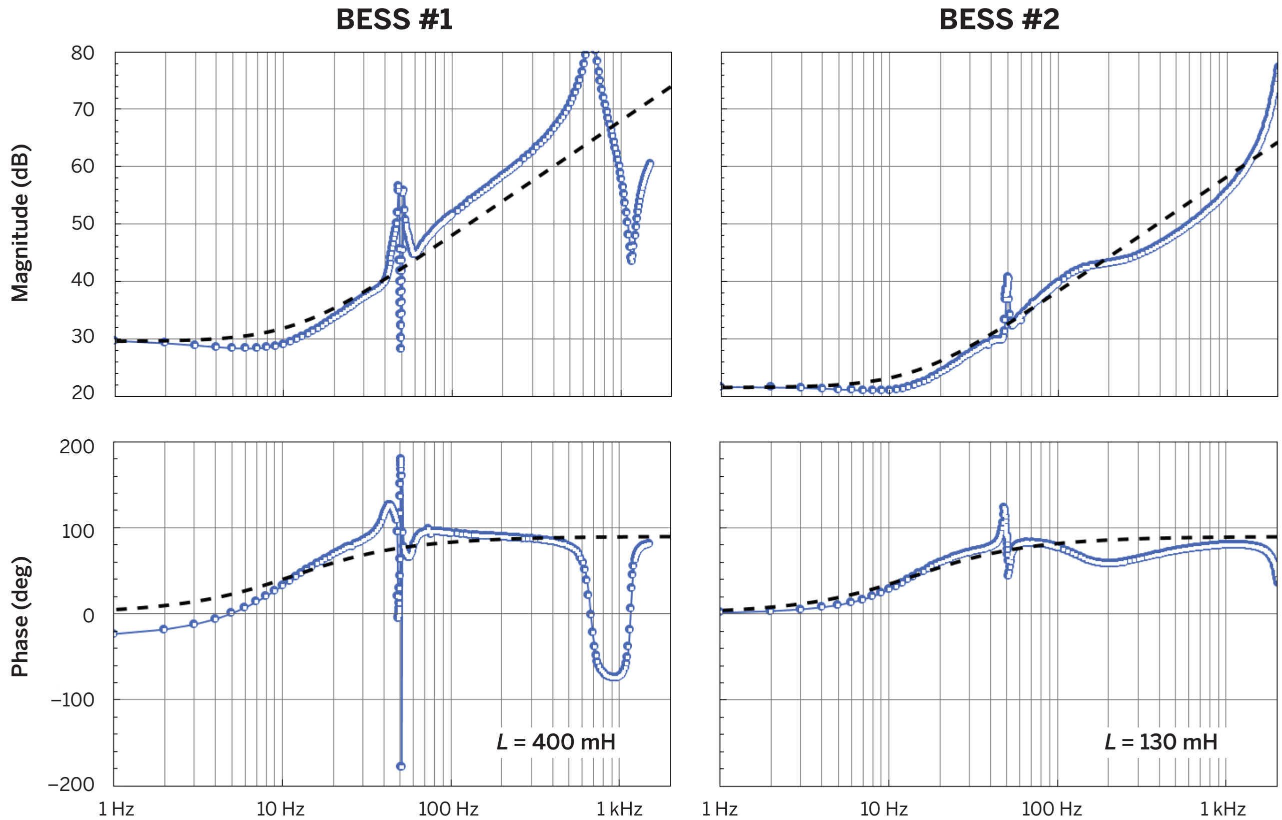
Impedance Scan

Figure 17 (p. 24) shows the positive-sequence impedance response of GFM BESS #1 and #2 obtained from their vendor-supplied EMT models. The impedance responses are compared with the impedance response of a reactor (i.e., an R-L branch) with appropriate parameters. The comparison shows that the impedance response of both GFM resources resembles that of a reactor within f_1 ± 40 Hz frequency range except for a narrow band around the fundamental frequency. Hence, according to the impedance scan-based pass/fail criteria described above, both BESS are GFM resources.

The comparison of the impedance responses of both BESS with that of a reactor in Figure 17 shows that BESS #1 is acting like an ideal voltage source in series with an inductor of 400 mH, whereas BESS #2 is acting like an ideal voltage source in series with an inductor of 130 mH. The equivalent inductance of a GFM resource can be correlated with the amount of voltage stiffness or grid strength it contributes to the grid at its POI. Hence, from Figure 17 it can be interpreted that BESS #2 provides a higher level of voltage stiffness or grid strength than BESS #1 because BESS #2 has significantly lower equivalent inductance. Note that the impedance responses of both BESS are measured after a step-up transformer from the same voltage level, which allows direct comparison of their equivalent inductance values.

FIGURE 17

Positive-Sequence Impedance Response of Two Different GFM BESS Obtained from Their Vendor-Supplied Blackbox EMT Models



Blue lines: impedance response obtained from EMT models. Black lines: approximation of the impedance response using the impedance response of an R-L branch with appropriate parameters.

Source: National Renewable Energy Laboratory.

The following points summarize this discussion:

- The positive-sequence impedance of a GFM resource is similar to that of an R-L branch around the fundamental frequency (except for a narrow band around the fundamental frequency), as the resource is expected to behave as a voltage source behind a reactor.
- The "strength" of the voltage source behavior of a GFM resource can be quantified using its positive-sequence impedance response within a frequency range.
- The magnitude of the impedance (reactance) can be used to quantify the relative strength of the voltage source behavior.

Performance Metrics for the Impedance Scan Test

Based on the above discussion of various aspects of performance for the impedance scan test on GFM resources, the performance metrics in Table 2 (p. 25) are suggested. However, as noted at the beginning of this report, the user must select performance metrics recommended from this list depending on the system requirements. The performance parameters highlighted in bold should also be changed based on the system requirements.

TABLE 2

Performance Metric for a GFM Resource Based on an Impedance Scan Test

Performance Metric	Suggested Specification
Equivalent inductance	A GFM resource should have a positive-sequence impedance response similar to that of an R-L branch within f_1 ± **40 Hz** frequency range except for a narrow band around the fundamental frequency (e.g., f_1 ± **4 Hz**). In addition, the equivalent inductance of the GFM resource obtained from the impedance scan response should not be higher than **0.75 p.u.** This is equivalent to the grid strength contribution during the short time frame as provided by a grid with an SCR of **1.33**. Resonance or mechanical considerations might require deviation from this specification around certain narrow frequency ranges.

Note: The performance parameters highlighted in bold should be changed based on the system requirements.

Source: Energy Systems Integration Group.

Q/V Scan

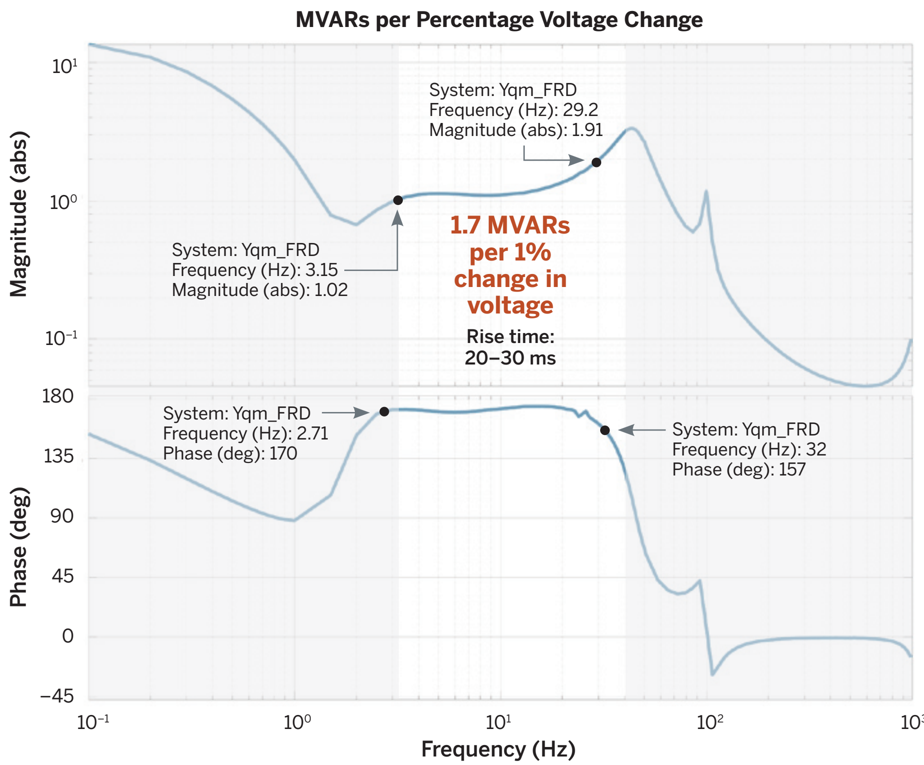
GFM BESS #1

Figure 18 shows the Q/V frequency scan of GFM BESS #1 obtained from its vendor-supplied EMT model. It shows that the BESS passes the pass-fail criterion for GFM resources described above based on the Q/V frequency scan—the magnitude response within 4 to 40 Hz is almost constant, and the phase response within the same frequency range is around 180 degrees.

Note that the magnitude of the Q/V frequency scan in Figure 18 varies from around 1.0 MVAR/1% voltage magnitude change at 4 Hz to around 1.9 MVAR/1% voltage magnitude change at 30 Hz. This shows that the BESS would quickly supply additional reactive power of around 5x1.9 = 9.5 MVAR within 30 ms during a sudden 5% drop in voltage magnitude at its POI. Moreover, it will sustain additional reactive power of around 5x1 = 5 MVAR for around 200 ms following the 5%

FIGURE 18

Q/V Frequency Scan of GFM BESS #1 Obtained from the Vendor-Supplied Blackbox EMT Model



The figure shows that the GFM BESS provides around 1.7 MVAR of additional reactive power during the short time frame in response to 1% change in the voltage magnitude at its terminal.

Source: National Renewable Energy Laboratory.

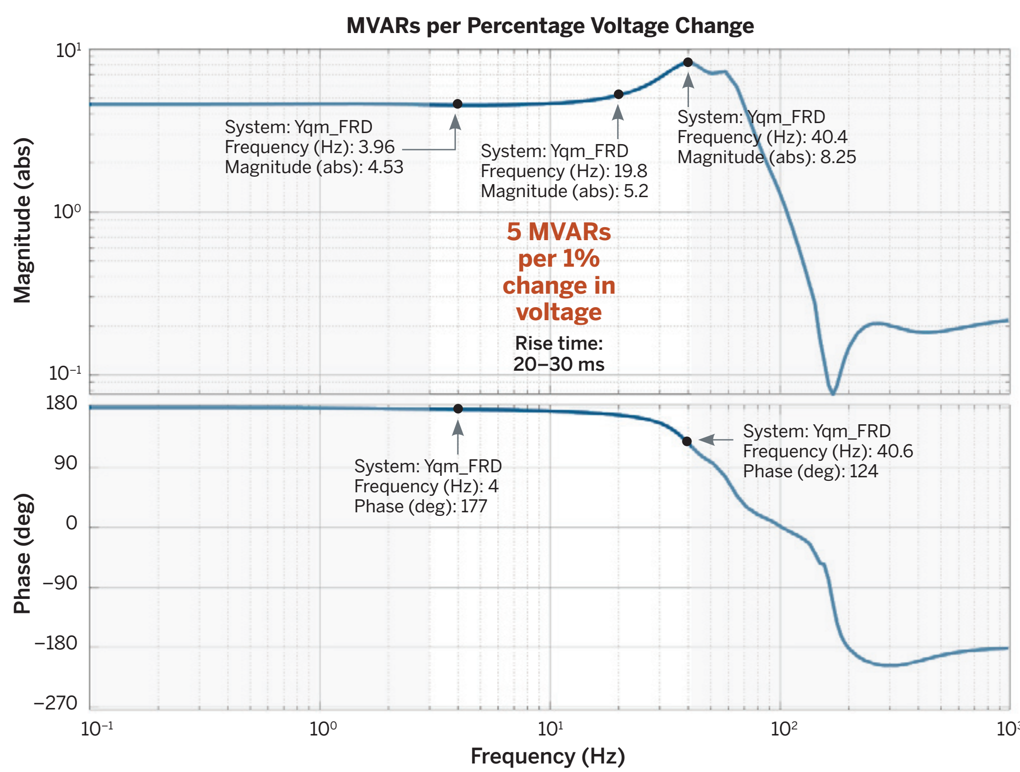
voltage drop event at its POI. These inferences from the Q/V frequency scan align well with observations from the time-domain voltage-jump test results shown in Figure 14 (p. 20); those results showed that GFM BESS #1 dispatched around 7 MVAR within 30 ms and sustained the additional reactive power of around 5.5 MVAR following a sudden 5% drop in the voltage magnitude at its POI.

GFM BESS #2

Figure 19 shows the Q/V frequency scan of GFM BESS #2 obtained from its vendor-supplied EMT model. It shows that the BESS passes the pass-fail criterion for GFM resources described above based on the Q/V frequency scan—the magnitude response within 4 to 40 Hz is almost constant, and the phase response within the same frequency range is around 180 degrees.

Note that the magnitude of the Q/V frequency scan in Figure 19 varies from around 5 MVAR/1% voltage magnitude change at 4 Hz to around 8 MVAR/1% voltage magnitude change at 40 Hz. This shows that the BESS would quickly supply additional reactive power of around 5x8 = 40 MVAR within 20 ms during a sudden 5% drop in voltage magnitude at its POI. Moreover, it will sustain additional reactive power of around 5x5 = 25 MVAR for around 200 ms following the 5% voltage drop event at its POI. These inferences from the Q/V frequency scan align well with observations from the time-domain voltage-jump test results shown in Figure 15 (p. 21); those results showed that GFM BESS #2 dispatched around 35 MVAR within 30 ms and sustained the additional reactive power of around 25 MVAR following a sudden 5% drop in the voltage magnitude at its POI.

FIGURE 19
Q/V Frequency Scan of BESS #2 Obtained from the Vendor-Supplied Blackbox EMT Model



The figure shows that the GFM BESS provides around 5 MVAR of additional reactive power during a short time frame in response to 1% change in the voltage magnitude at its terminal.

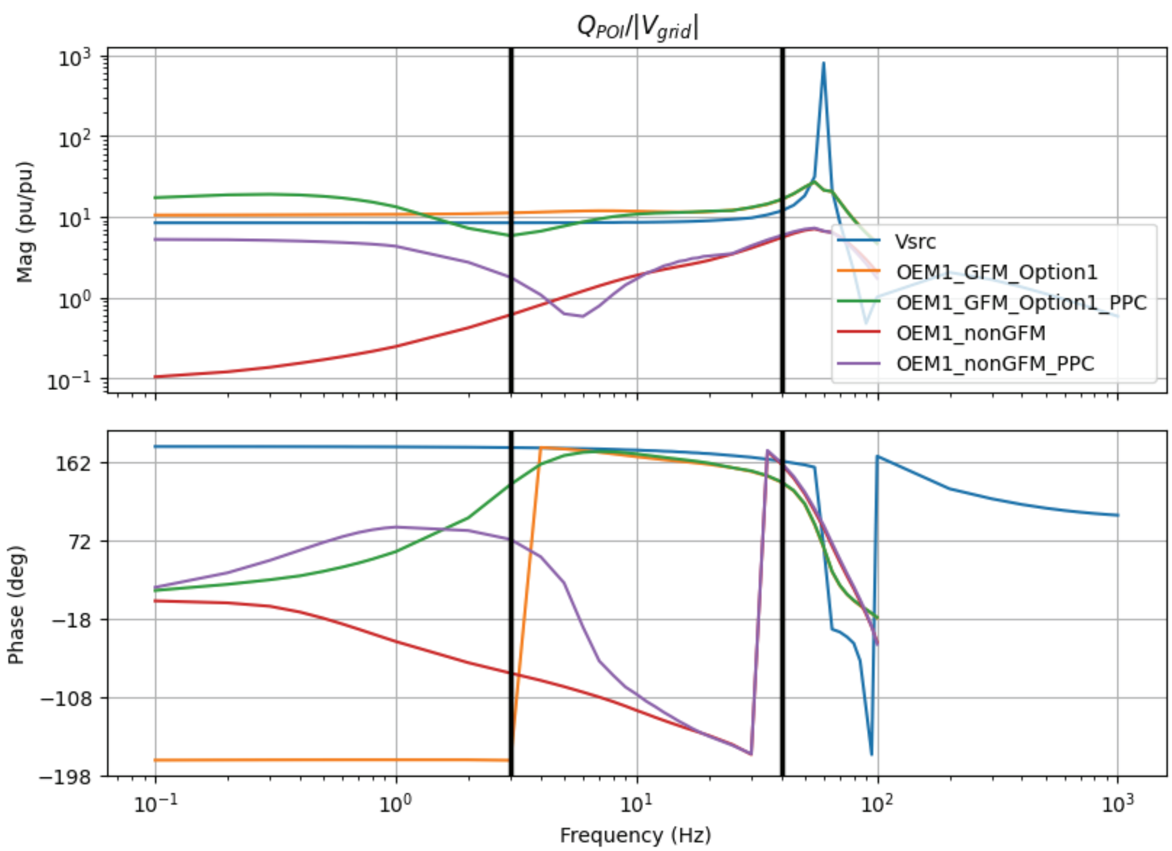
Source: National Renewable Energy Laboratory.

The above comparison of the reactive power response of GFM BESS #1 and #2 using time-domain and frequency-domain testing confirms that either of them can be used for quantifying the reactive power response of a GFM resource. However, the time-domain test results can change with the grid condition. Moreover, the behavior of a GFM resource during the short time frame might be difficult to differentiate from high-frequency oscillations and longer time frame response due to slow-acting controls from time-domain test results. Both issues associated with using time-domain testing for characterizing the voltage source behavior of GFM resources are addressed by frequency-domain testing, as the frequency-domain responses are independent of the grid condition, and they allow separation of responses over different time frames. On the other hand, the frequency-domain characterization evaluates small-signal behavior and might not be able to accurately capture the behavior of GFM resources during large transients, particularly when a resource is operating at or near its rating limits. In summary, time-domain and frequency-domain test methods complement each other, and both are recommended for evaluating the voltage source behavior of GFM resources.

Time-domain and frequency-domain test methods complement each other, and both are recommended for evaluating the voltage source behavior of GFM resources.

FIGURE 20

Impact of the Power Plant Controller on the Q/V Scan of IBRs



Q/V scans of an IBR obtained from its blackbox EMT model with GFM and non-GFM control modes. Scans are obtained for both control modes with and without enabling the PPC in the model.

Source: EPRI.

Power Plant Controller and GFM Behavior

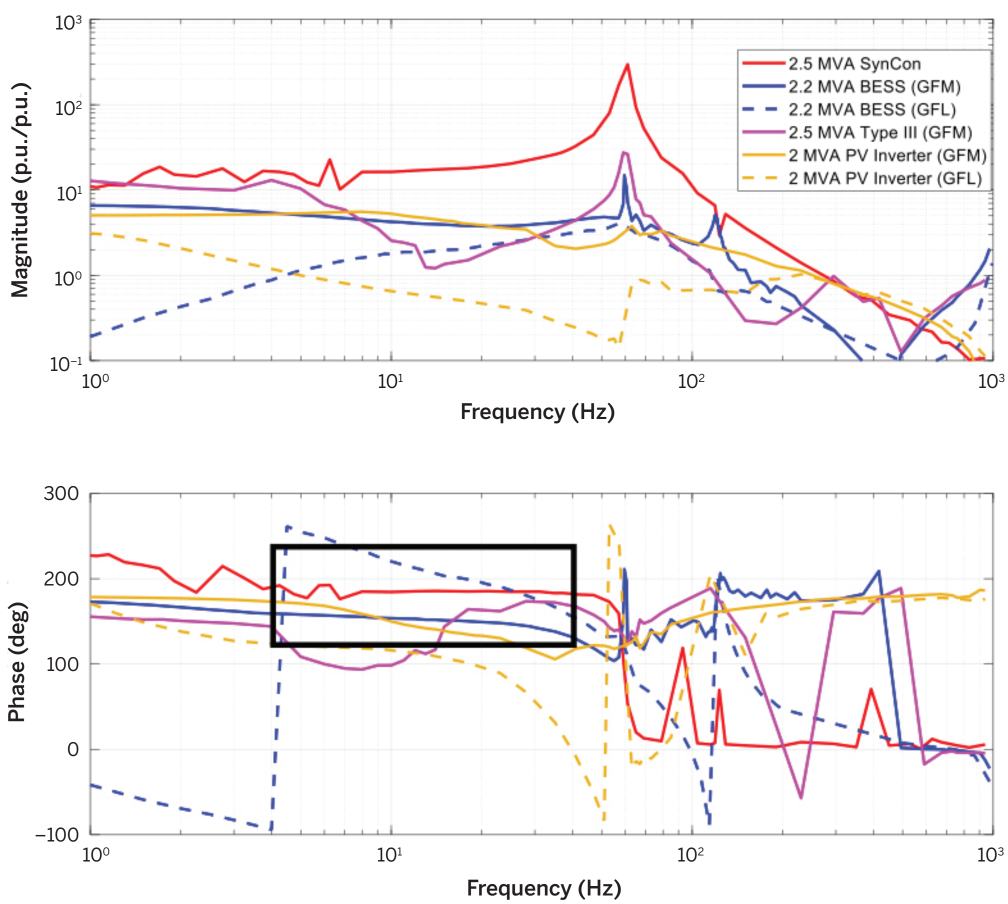
Figure 20 (p. 27) compares the Q/V scan of an IBR device obtained from its blackbox EMT model for operation in GFM and non-GFM control modes with and without the PPC. The Q/V scan of an an ideal voltage source (Vsrc) with a reactor is also shown for comparison. The inclusion of a PPC in both GFM and non-GFM configurations brings about interesting characteristics. First, in the lower frequency range, the characteristics of the PPC dominate over those of the inverter. This is observable in both GFM and non-GFM modes. As the frequency increases, the PPC is no longer dominant as the frequencies are filtered out and the inverter or unit-level characteristics dominate. This shows that the desired response over a longer time frame from an IBR plant can be obtained through the proper tuning of the PPC. However, the voltage source behavior over the short time frame expected from GFM resources is difficult to achieve just through tuning of the PPC; the unit-level characteristics (e.g., control of inverters and wind turbines) is significantly more important for achieving the voltage source behavior over the short time frame at a plant level.

Comparison of Q/V Scans of GFM and GFL Resources

To demonstrate the effectiveness of the pass-fail criterion based on the Q/V frequency scan in identifying the

FIGURE 21

Q/V Frequency Scans of GFM and GFL Devices Obtained from Experimental Measurements



Responses for GFM devices are plotted using solid lines, and responses for GFL devices are plotted using dash-dot lines. The synchronous condenser is treated as a GFM device for plotting convention. The magnitude of the response is plotted in p.u./p.u. for appropriate comparison of VAR/Volt response of different devices.

Source: National Renewable Energy Laboratory.

GFM behavior, we experimentally measured the Q/V frequency scans at NREL of several megawatt-scale resources including (i) a 2.5 MVA synchronous condenser (SynCon), (ii) a 2.2 MVA BESS inverter that can be operated in both GFM and GFL control modes, (iii) a 1 MVA BESS inverter with GFM control mode, (iv) a 2.5 MVA Type III wind turbine with GFM control mode, and (v) a 2 MVA PV inverter that can be operated in both GFM and GFL control modes. Figure 21 (p. 28) shows the experimentally measured responses of the Q/V transfer functions for these devices.

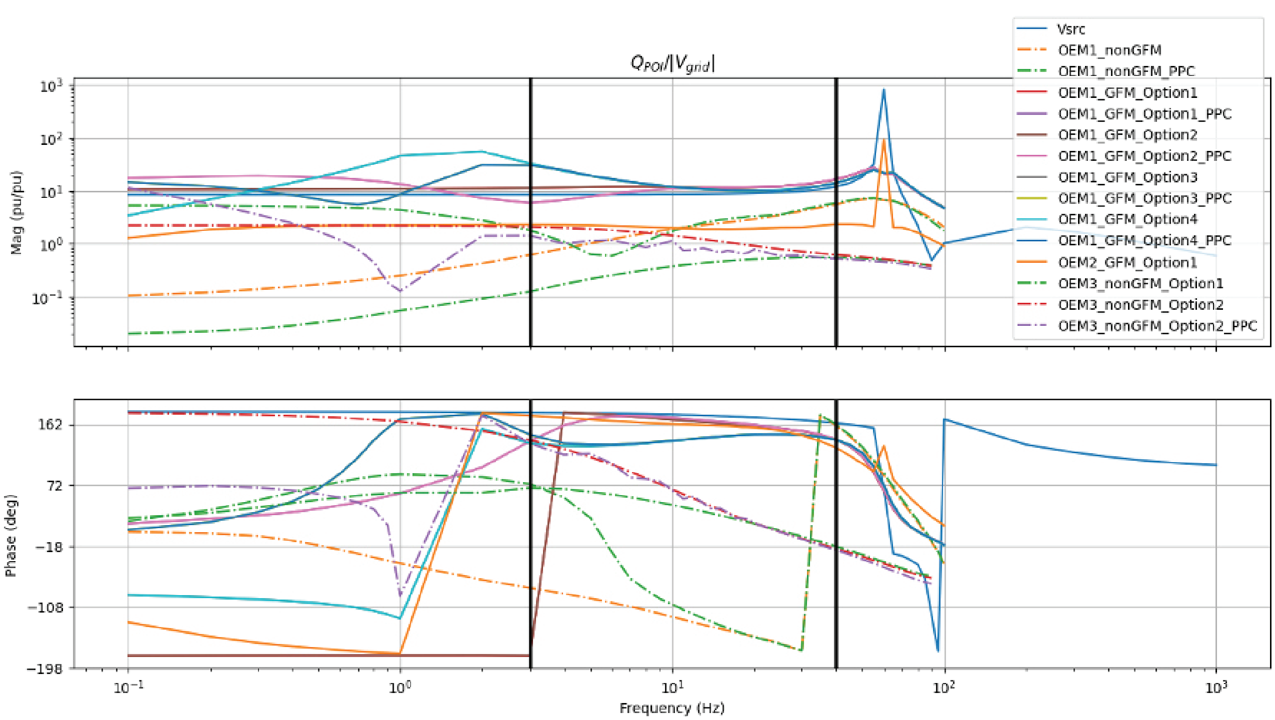
The figure shows that the Q/V frequency scan effectively differentiates GFM resources from non-GFM resources. All GFM resources exhibit almost constant or flat magnitude and phase responses within 4 to 40 Hz with phase being closer to 180 degrees in this frequency range, indicating that they pass the Q/V frequency scan–based pass-fail criterion for GFM resources. In contrast, non-GFM or GFL devices do not pass the pass-fail criterion.

Similar to the experimental results, Q/V scans of various devices obtained from the EMT blackbox models are shown in Figure 22. The label of GFM or non-GFM is based on how the manufacturer chose to label its product/function. One aspect to consider here is that a variety of conventional IBR controls can have deadbands within them to prevent operation for continuous perturbations around nominal grid frequency and voltage. When conducting frequency scans to obtain the relationship of the transfer functions, it is important to consider the effect of these deadbands.

Performance Metrics Based on Q/V Scan Test

Based on the above discussion of various aspects of performance and settings for the Q/V frequency scan test on GFM resources, the performance metrics in Table 3 (p. 30) are suggested.

FIGURE 22
Q/V Frequency Scans of GFM and GFL Devices Obtained from Vendor-Supplied Blackbox EMT Models



Responses for GFM devices are plotted using solid lines, and responses for GFL devices are plotted using dash-dot lines. These responses are obtained from vendor-supplied blackbox EMT models of the devices. The responses are labeled GFM or non-GFM based on how the manufacturer identified the particular product.

Source: EPRI.

TABLE 3

Performance Metrics for a GFM Resource Based on a Q/V Scan Test

Performance Metric	Suggested Specification
Magnitude response	The magnitude of the Q/V frequency scan should be higher than **0.5 p.u./p.u.** (p.u. reactive power output per p.u. change in the voltage magnitude) within the frequency range of **4 to 40 Hz**. Resonance or mechanical considerations might require deviation from this specification around certain narrow frequency ranges.
Phase response	The phase of the Q/V frequency scan should be ±180 degrees within the frequency range of **4 to 40 Hz**. The error between the actual phase angle ±180 degrees within the pre-scribed frequency range should be smaller than **60 degrees**. This tolerance band is intentionally kept wider to keep the example specification less restrictive than what might be desired in field installations.

Note: The performance parameters highlighted in bold should be changed based on the system requirements.

Source: Energy Systems Integration Group.

P/θ Scan

GFM BESS #1 and #2

Figure 23 (p. 31) shows the P/θ frequency scan of GFM BESS #1 and #2 obtained from their vendor-supplied EMT models. It shows that GFM BESS #2 passes the pass-fail criterion for GFM resources described above based on the P/θ frequency scan—the magnitude response within 4 to 40 Hz is almost constant, and the phase response within the same frequency range is around 180 degrees. However, GFM BESS #1 exhibits a constant magnitude and phase response around 180 degrees only above 10 Hz; hence, it marginally fails the pass-fail criterion for GFM resources based on the P/θ frequency scan.

Impacts of Power/Energy Limits

As the emphasis on IBR performance shifts toward exhibiting voltage source rather than current source characteristics, it is important to recognize practical equipment limits of existing IBRs in providing this type of performance. An important limitation of an IBR's ability to act as a voltage source behind a reactance involves the active power/energy response, and IBR technology types vary greatly in their capabilities and limitations for this aspect. For example, most solar and wind resources without storage will not have the means to provide a similar active power response as voltage source behind reactance over a wide bandwidth and over a wide range of possible operating conditions. Recognizing this fact, together with the other important grid-stabilizing aspects that can be provided without storage, will help to avoid establishing requirements that unnecessarily increase future equipment costs.

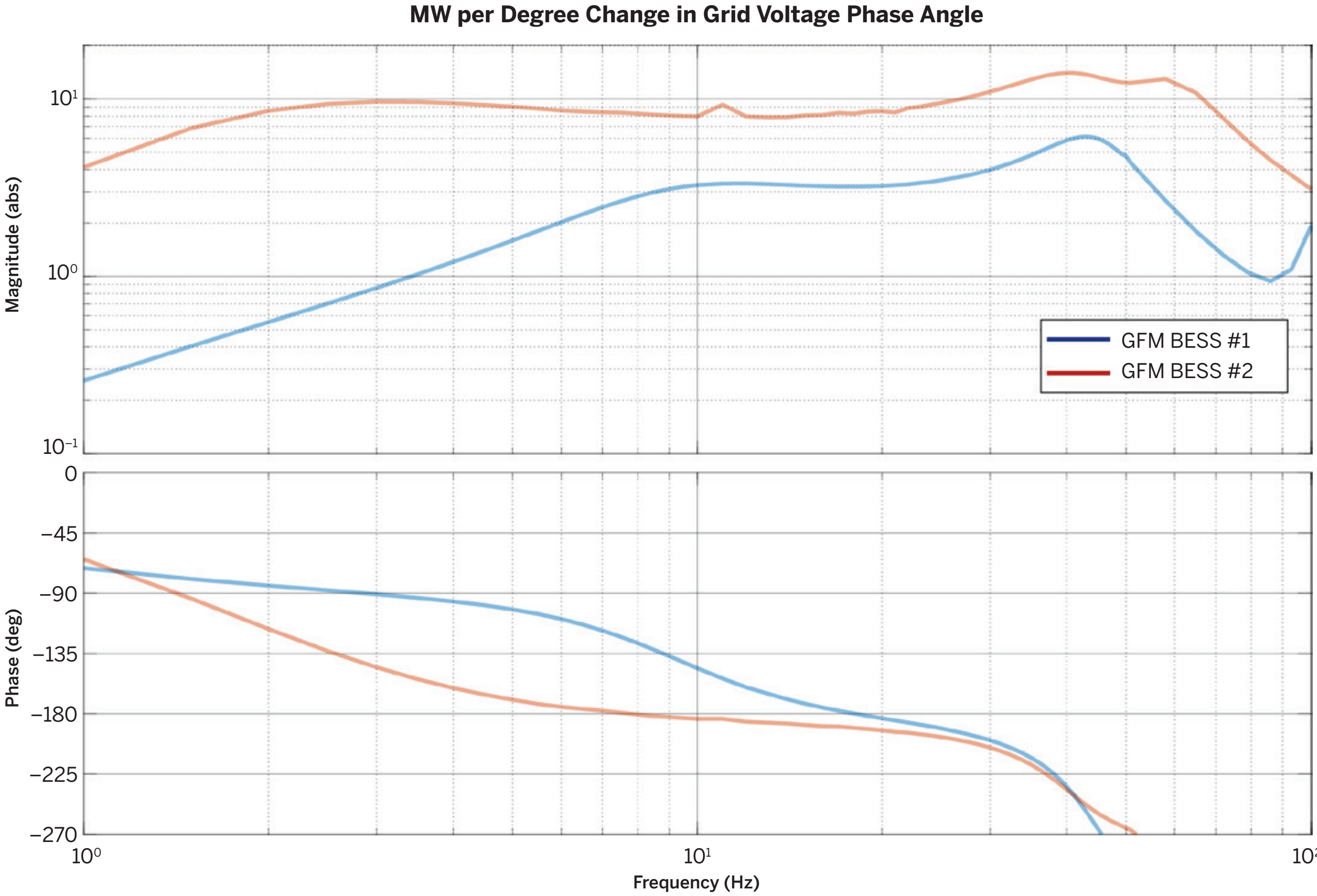
The transfer function between the energy extracted (E) from an IBR for grid angle perturbations is given by

$$\frac{\Delta E(j\omega)}{\Delta\theta(j\omega)} = \frac{1}{s} \cdot \frac{\Delta P(j\omega)}{\Delta\theta(j\omega)} \qquad (5)$$

where ω is the perturbation frequency in rad/sec and s is the Laplace operator. The frequency response for energy extracted is shown in Figure 24 (p. 32) for an ideal voltage source behind reactance, and it illustrates that the amount of energy needed to exhibit voltage source characteristics significantly increases as frequency decreases. Most IBRs do not have batteries, so this energy must either be taken from stored kinetic energy (such as from a rotating electro-mechanical system as in a wind turbine) or other electrical storage (like inductive or capacitive energy storage assuming the resource has no available headroom). Two key limitations in providing this response in power/energy are DC storage limitations and mechanical resonances (associated with GFM IBRs with rotating drivetrains) (Howard, Vieto, and Rao, 2024).

FIGURE 23

P/θ Frequency Scan of GFM BESS #1 and #2 Obtained from Vendor-Supplied Blackbox EMT Models



This figure shows that GFM BESS #1 provides around 3 MW of additional active power during the short time frame per 1-degree sudden change in the phase angle of the three-phase voltages at its terminal. In contrast, GFM BESS #2 provides around 8 MW of additional active power for the same disturbance. The figure also shows that the P/θ scan of GFM BESS #2 remains flat in the magnitude and phase response (the latter being closer to ±180 degrees) up to frequencies as low as 4 Hz as compared to GFM BESS #1, whose gain starts rolling down at frequencies below 10 Hz. Hence, it can be inferred that GFM BESS #2 would sustain the additional active power for significantly longer than GFM BESS #1 would for a similar voltage phase-jump event.

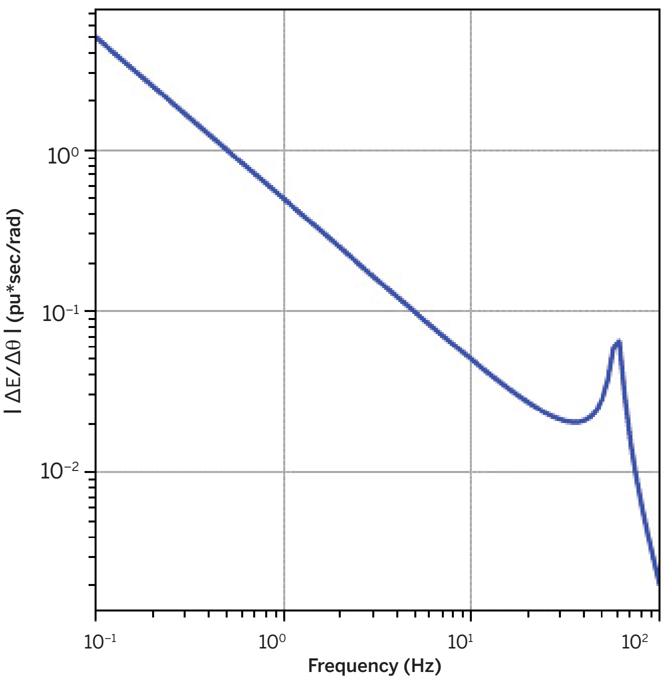
Source: National Renewable Energy Laboratory.

Unlike battery energy storage systems, most types of IBRs based on conventional hardware designs, such as solar and wind resources, have very little stored energy on the DC bus that can have a meaningful impact on grid stability. The relatively small amount of energy is a consequence of the design philosophy, where the DC capacitance is primarily designed to limit DC voltage ripple due to device switching.

Some types of IBRs are not constrained by DC-side stored energy because they have stored kinetic energy in a rotating machine and could potentially offer/exhibit some voltage source behavior. For example, a Type 3 wind turbine (or doubly fed induction generator (DFIG)) is not limited by DC storage constraints because the power/energy is supplied directly from the rotating machine connected to the grid. However, IBRs with rotating machinery are subject to mechanical resonances. These resonance constraints are more complex than DC storage constraints, as the specific resonant frequency is technology dependent. This mechanical resonance phenomenon is similar to conventional steam

FIGURE 24

Gain of Transfer Functions from Change in Grid Angle to Change in Energy of an Ideal Voltage Source Behind an Impedance



Source: Howard, Vieto, and Rao (2024). https://doi.org/10.1049/icp.2024.3857. Published with permission from the Institution of Engineering and Technology (IET).

TABLE 4

Performance Metrics for a GFM Resource Based on a P/θ Scan Test

Performance Metric	Suggested Specification
Magnitude response	The magnitude of the P/θ frequency scan should be higher than **0.05 p.u./10 degrees** (p.u. active power output per 10 degree phase jump) within the frequency range of **4 to 40 Hz**. Resonance or mechanical considerations might require deviation from this specification around certain narrow frequency ranges..
Phase response	The phase of the P/θ frequency scan should be ±180 degrees within the frequency range of **4 to 40 Hz**. The error between the actual phase angle ±180 degrees within the prescribed frequency range should be smaller than **60 degrees**. This tolerance band is intentionally kept wider to keep the example specification less restrictive that what might be desired in field installations.

Note: The performance parameters highlighted in bold should be changed based on the system requirements.

Source: Energy Systems Integration Group.

or gas-turbine generators which have mechanical resonance modes that fall in the vicinity of 10 to 40 Hz. But despite the resonance limitation, the power/energy required to behave as a voltage source behind reactance for small-signal changes in voltage may be realized by IBRs with mechanical resonance constraints provided the resources are operating in appropriate conditions, for example, with a wind turbine when the wind is available and the operating speed is not too close to its upper/lower limits (Vieto and Howard, 2023). Therefore, these resource types may exhibit the desired voltage source characteristics except in special "exclusion zones" around these mechanical resonances (where the IBR is likely to deviate substantially from the desired voltage source behavior in order to prioritize protecting mechanical equipment).

Performance Metrics Based on P/θ Scan Test

Based on the above discussion of various aspects of performance and setting for the P/θ frequency scan test on GFM resources, the performance metrics in Table 4 are suggested.

Summary

Voltage source behavior is the core function expected from GFM resources to improve grid strength and support stability of bulk power systems. This report has documented time-domain and frequency-domain test methods for evaluating the voltage source behavior from GFM resources. Performance metrics are defined for each of the test methods to quantify the voltage source behavior. The test methods and associated performance metrics are applicable to any type of resource including inverter-based resources (battery/wind/solar power plants, high-voltage DC converter stations, STATCOM, etc.) as well as rotating machine–based resources (conventional generators, synchronous condensers, etc.). Example specifications are provided to explain how the voltage source behavior can be demanded from GFM resources during procurement. The example specifications are intentionally kept less demanding with higher room for error tolerance to not make them too restrictive for various GFM technologies if they are adopted as-is. These test methods could be used in specifications that are being developed for GFM resources such as the *UNIFI Specifications for Grid-Forming Inverter-Based Resources* (UNIFI Consortium, 2024). However, specifications based on the test methods and performance metrics presented in this report should be adapted based on the system characteristics where a GFM resource is going to be installed and on quantifiable objectives for improving system strength and stability.

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Testing the Performance of Grid-Forming Resources: Test Methods and Performance Metrics for Evaluating the Voltage Source Behavior of Grid-Forming Resources

A Report by the Energy Systems Integration Group's GFM Testing Project Team

This report is available at https://www.esig.energy/gfm-performance-testing/.

To learn more about ESIG's work on this topic, please send an email to info@esig.energy.

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