MISO Grid-Forming Battery Energy Storage Capabilities, Performance, and Simulation Test Requirements Proposal

DRAFT Whitepaper

July~~ne~~ 2024 (Version 0.2~~1~~)

Highlights

- The evolving energy landscape requires MISO and the industry to adopt available grid-forming control technologies to support MISO's Reliability Imperative and grid stability as the fleet transitions.

- MISO proposes an initial draft framework of capability and performance requirements with supporting simulations tests to determine conformity.

- MISO's current effort aligns with the general direction of industry to anticipate advancements in grid-forming inverter technology capabilities and standard maturity.

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Executive summary

MISO and stakeholders have an opportunity to adopt new resource capabilities that bring needed system attributes. The opportunity arises from a combination of current control technology availability and increasing level of energy storage interconnection requests within MISO.

Given the industry landscape, in 2023, NERC recommended all newly interconnecting battery energy storage systems (BESS) have "grid-forming" (GFM) controls. GFM inverters can contribute to stability in weak grid areas, while traditional "grid-following" (GFL) inverters may become unstable under weak grid conditions, due to their reliance on tracking grid voltage set by other resources.

While action is warranted now, and energy storage plants with advanced capabilities are operational today, MISO acknowledges that standards for GFM inverter-based resources (IBRs) are in early stages of development. Considering this evolving landscape, MISO's workplan and approach are intended to be flexible, to accommodate continued industry advancements. MISO is setting a deliberate pace with regular opportunities for stakeholder input, aligning industry readiness with the creation of IBR requirements. Further, it includes targeted outreach to original equipment manufacturers (OEMs) supplying GFM controls.

MISO is proposing a framework of GFM IBR requirements for stand-alone energy storage systems. This framework has two parts: 1) several functional capability and performance requirements defining voltage source characteristics; and 2) required simulation tests to demonstrate GFM characteristics and stable control responses.

After review of readily available industry GFM practices and standards, MISO proposes performance requirements limited to inverter software changes. The proposed requirements aim to have no significant impact on plant hardware needs. These requirements are a subset of currently available GFM BESS performance capabilities and are collectively referred to as "core capabilities" by the Australian grid operator. Some specific core capabilities (e.g., oscillation damping) and associated performance characteristics are more complex to define or may introduce downstream study complexity. MISO declined to propose these types of requirements now and instead shares guidance on recommended performance.

Recognizing a need to integrate proposed GFM requirements with existing and planned requirements applicable to all IBRs under MISO's IEEE 2800-2022 adoption, MISO proposes exemptions or modifications for GFM BESS to specific IEEE 2800-2022 subclauses intended to foster compatibility between requirements sets.

MISO's requirements and tests borrow heavily from NERC guidance and international work, with minor changes to simplify requirements or adjust to the context of the North American grid (e.g., 60 Hz system). The simulation tests are performed in an electro-magnetic transient (EMT) software package called PSCAD, which is the EMT model format MISO currently requires through BPM-015.

Four PSCAD simulation test procedures and success criteria are described, which include the loss of last synchronous machine test, phase jump test, rate of change of frequency test, and short circuit ratio ramp down with fault test. These tests rely on two simple PSCAD test-setups which are also specified. To support MISO's simulation test requirements, MISO is proposes guidance for model quality, data exchange, and process elements.

MISO views this proposal as an initial step on the pathway to deliver needed attributes by enabling GFM, which does not preclude further development of advanced performance requirements from traditional IBR controls (i.e., "grid following").

Scope and Background

INTRODUCTION

MISO's resource fleet is expected to have an influx of inverter-based resources (IBRs) given the volume of IBR interconnection requests in MISO's Definitive Planning Phase (DPP) process (Figure 1~~Figure 1~~). Stand-alone battery energy storage systems (BESS) interconnection requests recently emerged as a significant portion of overall requests, coming in at roughly 28.9 GW or 23% of the overall DPP-2023 queue cycle submissions. DPP-2022 queue cycle also had high levels of storage proposed, coming in at 32 GW. The proposed level of storage in DPP-2021 was only 1/3 the level of DPP-2022 at 10.8 GW.

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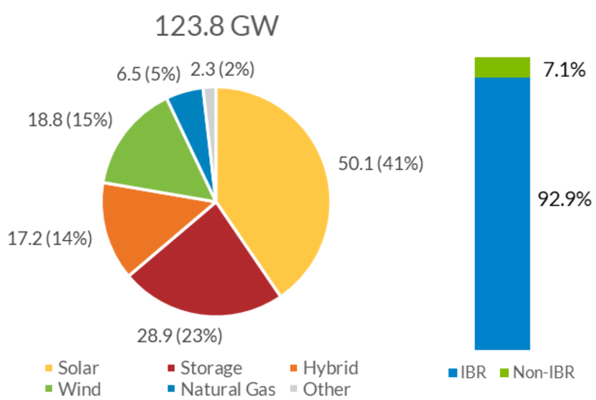

Figure 1. 2023 Interconnection Queue by resource type

Energy storage, like wind and solar, uses inverters for converting direct current to alternating current to interface with the grid. Industry has ~~historically~~ recently classified inverter control technology as "grid-following" (GFL) or "grid-forming" (GFM) to represent the bookends of control characteristics, capabilities, and performance. While this has been useful to broadly communicate fundamental control differences – namely GFM inverters act as an independent voltage source whereas GFL inverters act as a current source dependent on system voltage – this simplification masks advanced capabilities GFL can provide if designed and configured to do so.

Commented [PD1]: Rev 0.2: suggested change from industry expert review

A Department of Energy (DOE) funded consortium, called Universal Interoperability for Grid-Forming Inverters or "unifi", recently updated *Specifications for Grid-Forming Inverter Based Resources* to include four categories of IBRs with increasing capabilities (Figure

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2~~Figure 2~~).[1] MISO sees value in this distinction and plans on exploring advanced GFL IBR performance (e.g. unifi Category 3) in a future phase of IEEE 2800-2022 adoption, with plans to assess benefits and risks of inverter-level fast frequency response and voltage controls. However, for the purposes of MISO's GFM IBR adoption, only IBRs that are capable of surviving grid disturbances are in scope (i.e., unifi Category 4), namely the loss of last synchronous machine. While Category 3 IBR can significantly contribute to dynamic stability support, this technology still relies on a grid voltage source.

Commented [PD2]: Rev 0.2: change suggested by industry expert review.

"The narrative and the figure can provide an unintended impression that only Category 4 can survive grid disturbances. However, category 3 inverters can also help the system survive large systems.

Further, it is mentioned that category 3 falls under GFL category.
Please provide clarifications regarding background for identifying category 3 as GFL. Is it because it may not be able to provide blackstart? If so, suggest to add this note."

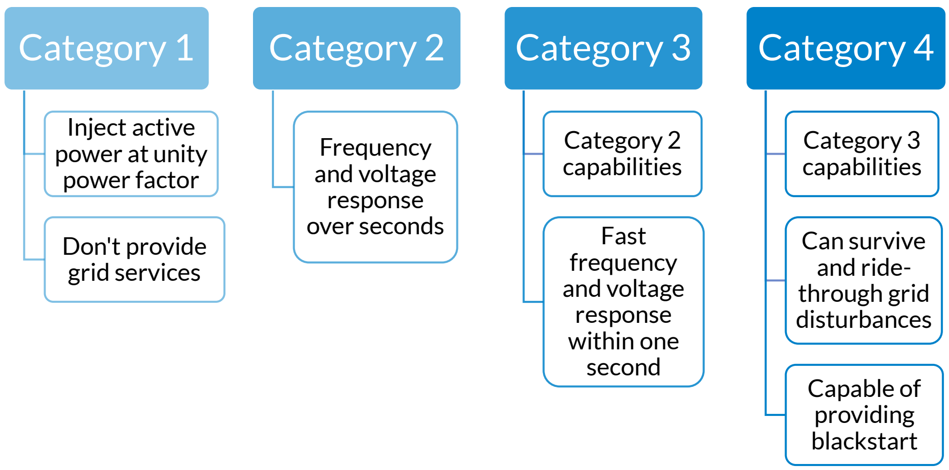

Figure 2. Unifi IBR Categories

This document will use the term "GFM IBR" generically. However, only BESS GFM (i.e., stand-alone BESS systems) are proposed to be in scope for the initial requirements.

Industry research has indicated system stability can be achieved at very high levels of instantaneous IBR penetration if dynamic stability constraints are addressed. For instance, EIRGRID in Ireland currently operates up to 75% instantaneous penetration of IBRs and is evaluating a path to 95% by 2030 which could include GFM control solutions to support system strength and stability.[2, 3] While large systems offer additional challenges, community microgrids served by 100% IBRs, including grid-forming energy

[1] Available at: https://unificonsortium.org/wp-content/uploads/UNIFI-Specs-for-GFM-IBR-Version-2.pdf
[2] EIRGRID, Operational Policy Roadmap 2023-2030. December 2022. Available at: https://cms.eirgrid.ie/sites/default/files/publications/Operational-Policy-Roadmap-2023-to-2030.pdf
[3] EIRGRID, Potential Solutions of Mitigating Technical Challenges Arising from High RES-E Penetration on the Island of Ireland. A Technical Assessment of 2030 Study Outcomes.

storage, are in operation today, demonstrating GFM as a solution in a real-world application.[4]

While the proportion of GFM IBRs needed in a given resource fleet varies depending on the details of the system and resources, studies of IBR dominant systems reviewed in NERC's 2023 whitepaper indicate the level of GFM needed may be anywhere from 11% to 37% of the overall IBR fleet. [5] The lower end of this range (11%) is achieved by enabling advanced GFL features commercially available today. Higher values (e.g., 37%) often assume less capable IBRs (e.g., unifi Category 1), aside from potentially more challenging system conditions.

Regardless of the precise amount of GFM that could be needed, NERC's recent whitepaper points out the opportunity to act now, given commercial availability of technology and the potential cost of inaction. Increased costs could stem from congestion resulting from stability constraints, growing levels of solar and wind curtailment, and additional costs of capital assets to mitigate stability constraints (e.g., synchronous condensors). Given the opportunity available today, and the potential cost of inaction, MISO is proposing GFM capability, performance, and testing requirements for stand-alone BESS systems.

SCOPE

The requirements in this document apply to stand-alone BESS GFM systems (i.e., not applicable to hybrid plants) and will be applied on a go-forward basis[6].

MISO is targeting core capabilities, which are features typically enacted through inverter software changes. MISO is <u>not</u> proposing additional requirements that would require hardware oversizing in the initial development of MISO GFM specifications.[7]

In the future, MISO may propose expanding the requirements to cover the BESS portion of hybrid plants. However, potential complexity associated with demonstrating

[4] California Energy Commission. Energy R&D Division. Borrego Springs: California's First Renewable Energy-Based Community Microgrid. February 2019. Available at: https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2019-013.pdf
[5] NERC. White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems. September 2023. Available at: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf
[6] MISO intends to share an implementation plan at the July IPWG that will describe applying the requirements on a "go-forward basis".
[7] Examples of capabilities expected to result in hardware oversizing include short circuit current, black start, power quality support, and specified amounts of inertia, among other capabilities.

compatibility of hybrid plants with MISO's proposed GFM IBR requirements is the reason for limiting the current proposal to stand-alone BESS systems.

Similarly, IBR plants using other primary energy sources, such as wind and solar, face technical complexities for which research and development is underway.[8] MISO is not proposing requirements for these types of plants at this time. Instead, MISO is looking to implement commercially available controls today to support system stability, which is the reason for limiting the initial proposal to BESS. MISO views this as a technology neutral approach that utilizes available resource characteristics, similar to how the current system utilizes inherent synchronous machine responses such as inertia and high fault current injection.

DRIVERS AND INDUSTRY LANDSCAPE

In 2021, MISO's Renewable Integration Impact Assessment (RIIA) described a range of localized and regional grid stability challenges that could materialize as renewable penetration levels increase, absent solutions to support stability.[9] RIIA indicated that transient voltage stability in weak grid areas may be the first stability issue encountered (30% energy served by renewables milestone). Further, RIIA projected that voltage stability issues could represent the largest capital cost to mitigate, when considering the range of potential stability issues. The RIIA analysis was a multi-year effort, largely performed before GFM IBR models were widely available and therefore the technology was not considered as a solution.

Given the potential for current technology solutions to address stability challenges, NERC issued a 2023 whitepaper encouraging utilities and system operators to consider the benefits and integration needs associated with GFM BESS.

[8] U.S. Department of Energy, Solar Energy Technologies Office, Solar and Wind Grid Services and Reliability Demonstration Funding program. Information available at: https://www.energy.gov/eere/solar/solar-and-wind-grid-services-and-reliability-demonstration-funding-program

[9] MISO, Renewable Integration Impact Assessment, Summary Report. Feburary 2021. Available at: https://cdn.misoenergy.org/RIIA%20Summary%20Report520051.pdf

NERC GFM recommendations are consistent with the direction of the industry internationally. For instance, the Australian grid operator AEMO included the NERC simulation tests when developing voluntary GFM BESS simulation test specifications in 2024.[10] Based on the NERC whitepaper findings on industry readiness and need, coupled with international field experience (e.g., AEMO), MISO's 2023 Attributes recommendations pointed to GFM controls as a key near-term solution for improving system strength and voltage stability in weak grid areas.[11]

NERC whitepaper takeaways and recommendations:

- GFM technology has been shown to operate reliably and provide stabilizing characteristics in transmission systems with high IBR.
- GFM technology is commercially available and field proven.
- All newly interconnecting BPS-connected BESS should consider GFM controls.
- Now is the time to begin the process of establishing GFM functional specifications for BESS in interconnection requirements, using NERC's functional specifications.
- Testing and validation of GFM performance is still needed before broad deployment.

While MISO's proposed GFM IBR framework is largely modeled after the NERC guidance and AEMO's method, due to similarities with the MISO need, MISO also reviewed and considered GFM specification development work by other grid operators including Finland (Fingrid)[12], the United Kingdom (ESO)[13], and Hawaii (HECO)[14].

The Department of Energy funded Universal Interoperability for Grid-Forming Inverters (unifi) Consortium, a multi-year effort underway to advance GFM technology, produced the second version of GFM specifications in March 2024. MISO reviewed and adopted several aspects of this work in requirements and guidance as well.

[10] AEMO, Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework. January 2024. Available at: https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf?la=en

[11] MISO, Attributes Roadmap. December 2023. Available at: https://cdn.misoenergy.org/2023%20Attributes%20Roadmap631174.pdf

[12] Fingrid, Specific Study Requirements for Grid Energy Storage Systems. June 2023. Available at: https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/specific-study-requirements-for-grid-energy-storage-systems-en.pdf

[13] National Grid ESO, Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability. November 2021. Available at: https://www.nationalgrideso.com/industry-information/codes/gc/modifications/gc0137-minimum-specification-required-provision-gb-grid-forming-gbgf-capability-formerly-virtual-synchronous-machinevsm-capability

[14] HECO, Hawaiian Electric Facility Technical Model Requirements and Review Process. August 2021. Available at: https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20210901_cbre_rfp/20210825_redline_lmi_appxb_att3.pdf

While each effort has taken slightly different approaches to specifying GFM capabilities and performance, several common themes have emerged, as characterized by the Global Power System Transition (G-PST). [15]

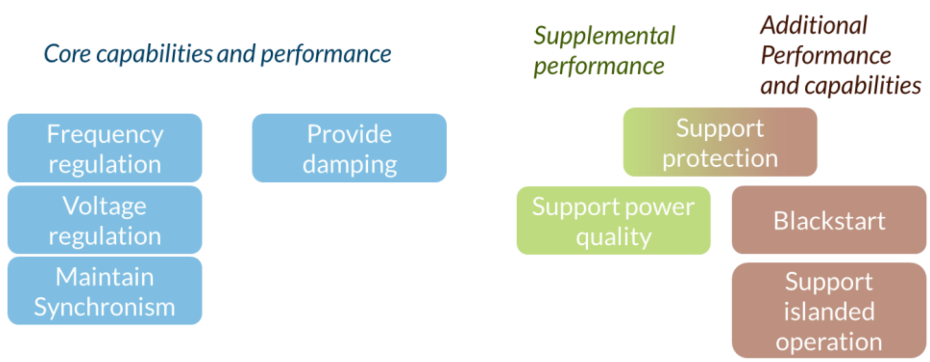

Figure 3. Categorization of common grid forming control capabilities and performance , adapted from G-PST summary of capability and performance

International efforts have also sought to characterize how different types of capabilities impact GFM IBR hardware sizing requirements. For instance, AEMO generally considers "core" capabilities as those that require only software changes (i.e., no hardware oversizing) and which differ from "additional" capabilities that may require additional hardware (Figure 4~~Figure 4~~).[16] Similarly, OSMOSE describes four types of GFM, depending on the services they provide, which has the potential to impact energy buffer (i.e., hardware) requirements.[17]

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[15] Global PST Consortium, Draft summary of GFM Capability and Performance Requirements Driven by System Needs. L. Ramirez, H. Ross, J Matevosyan, J. Macdowell. Available at: https://globalpst.org/wp-content/uploads/202405GFM-draft.pdf

[16] AEMO. Voluntary Specification for Grid-forming Inverters. May 2023. Available at: https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf

[17] OSMOSE, Final Report. March 2022. Available at: https://www.osmose-h2020.eu/wp-content/uploads/2022/03/OSMOSE-Final-Brochure-Full-version.pdf

Core capabilities:

- Voltage source behavior
- Frequency domain response
- Inertial response
- Surviving the last synchronous connection
- Weak grid operation and system strength support
- Oscillation damping

Additional capabilities:

- Headroom and energy buffer
- Current capacity above continuous rating
- Black start capability
- Power quality improvement

Figure 4. Classification of core capabilities versus additional capabilities, adapted from AEMO

Even without comprehensive technical standards available, NERC's whitepaper points out that numerous GFM IBR plants are deployed or under construction today (Table 1~~Table 1~~).

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Project Name	Location	Size (MW)	Time
Project #1	Kauai, USA	13	2018
Kauai PMRF	Kauai, USA	14	2022
Kapolei Energy Storage	Hawaii, USA	185	2023
Hornsdale Power Reserve	Australia	150	2022
Wallgrove	Australia	50	2022
Broken Hill BESS	Australia	50	2023
Riverina and Darlington Point	Australia	150	2023
New England BESS	Australia	50	2023
Dalrymple	Australia	30	2018
Blackhillock[19]	Great Britain	300	2024
Bordesholm[20]	Germany	15	2019

Table 1. GFM BESS Projects Deployed or Under Construction (Source: NERC)

Information presented publicly at unifi's March 18th, 2024, technical seminar suggests at least eight unique original equipment manufacturers (OEMs) currently offer some form of GFM IBR controls, with differences in control architecture, model availability, capabilities, and performance.[18] To date, MISO has contacted seven of the OEMs with GFM controls to make them aware of MISO's GFM requirement development effort and to request models for simulation testing.

In terms of activities in the continental United States to advance GFM IBR specifications, ERCOT recently presented on an intention to propose requirements in 2024.[19]

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[18] Unifi Seminar Series, March 18, 2024. Babak Badrzadeh: Grid-forming BESS under medium system strength conditions. Recording available at: https://www.youtube.com/watch?v=t6TK9aS3kNU

[19] ERCOT. IBRWG Meeting, April 12, 2024. Agenda item #4. Agenda and select presentations available at: https://www.ercot.com/calendar/04122024-IBRWG-Meeting-_-Webex

MISO'S GFM IBR REQUIREMENT DEVELOPMENT

MISO's 2023 Attributes effort led to submission of a tracked MISO Issue (PAC-2024-2) to advance IBR performance requirements, including GFM controls for BESS. The Attributes work contemplated GFM control capabilities to improve dynamic stability, more specifically voltage stability. As MISO reviewed GFM control natural responses, MISO decided to include frequency stability support capabilities in the proposal (Figure 5Figure 5).

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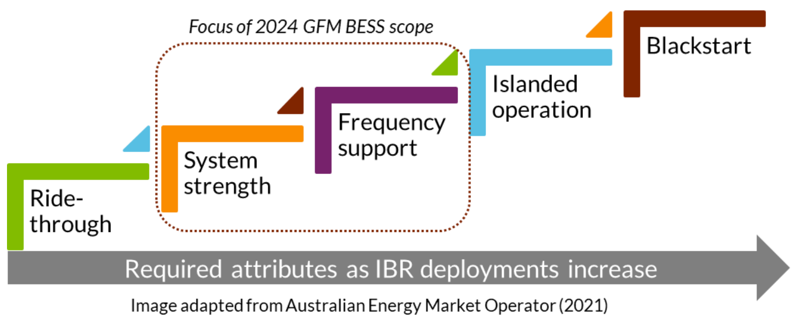

Figure 5. Illustration of capability progression underway at MISO

In January 2024, MISO initiated a stakeholder process through the Interconnection Process Working Group (IPWG) to develop requirements, notifying stakeholders that MISO was beginning internal efforts (see schedule in Appendix). At the May 2024 IPWG, MISO proposed a conceptual framework (Figure 6~~Figure 6~~) along with GFM BESS requirements. The framework takes inspiration from standards such as IEEE 2800-2022 with companion standard IEEE P2800.2, which is similar to IEEE 1547-2018 and companion IEEE 1547.1-2020. In this framework, the requirements language is intentionally separate from the test and verification procedures that demonstrate conformity. MISO recognizes the proposed GFM BESS conformity procedures cover only a portion of more extensive conformity requirements sets, like what is being developed in IEEE P2800.2. While more mature technologies (e.g., GFL IBR) may warrant more comprehensive evaluation frameworks, MISO aims for a simple and effective set of criteria at this early stage of adoption for GFM IBR.

Principles MISO introduced in IPWG for GFM IBR development:

- Supporting system reliability is primary aim of requirements.
- Consider Original Equipment Manufacturer (OEM) equipment and plant design capabilities as a key input, in addition to the system reliability need.
- Keep requirements as simple as possible.
- Avoid conflicts with IEEE 2800-2022, which applies to all IBR (including BESS).
- Focus new process and data exchange requirements on crucial features.
- Choose flexibility over delay if needed, given the urgency and opportunity to act now.
- Avoid material impacts on storage operations (e.g., power dispatch and state of charge management) in developing "core capability" requirements.
- Position requirements for extensibility as future needs emerge.

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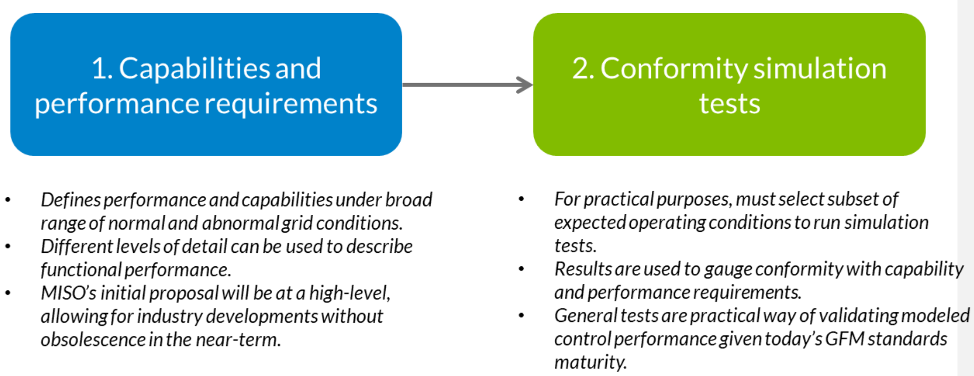

Figure 6. Framework of proposed capabilities, performance, and conformity requirements

After evaluation of the GFM IBR core capabilities described above, MISO selected a set of performance requirements and conformity simulation tests that closely mirror the "core capabilities" outlined by the Australian grid operator AEMO. These capabilities and performance are enacted largely by software changes and are anticipated to have minimal impact on the design and operation of the IBR.

MISO's core proposed capability and performance requirements center around voltage source characteristics, as described in *Capability and performance requirements and recommended practices*~~*Capability and performance requirements and recommended practices*~~. Within the capabilities and performance described in the *Scope and Background*~~*Scope and Background*~~ section, MISO selected requirements that encompass voltage regulation, frequency regulation, and synchronism (Figure 7~~Figure 7~~). While MISO views oscillation damping as a core capability, and a resource attribute that supports stability, MISO declined to propose inclusion of this performance due to potential complexities introduced into the interconnection study process.[20]

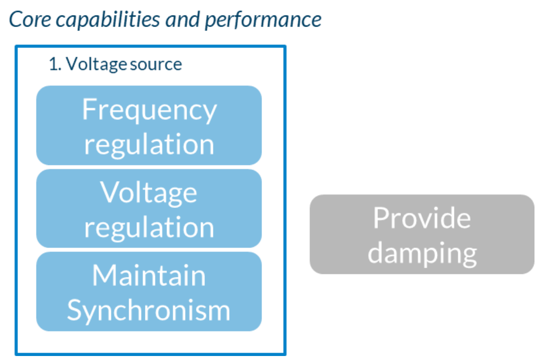

Figure 7. Subset of potential GFM IBR capability and performance requirements proposed by MISO (damping excluded)

At the time of this paper's drafting, MISO plans a minimum of three stakeholder IPWG feedback requests and at least one feedback request at the Planning Advisory Committee. MISO will share an implementation plan proposal at the July 2024 IPWG. MISO currently intends to finalize GFM BESS requirements in November 2024, with an implementation applicable to future projects.

[20] MISO's initial assessment was that inclusion of oscillation damping requirements could increase the potential need for detailed EMT studies across GFM IBR interconnection study processes. While MISO recognizes that need may be increasing anyways due to IBR integration, MISO aims to reduce process implications for this GFM IBR requirements adoption.

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Concurrently with public stakeholder interactions, MISO has been reaching out to OEM vendors that are known to furnish GFM IBR controls. MISO has contacted seven OEMs to date to share information about MISO's effort and request GFM IBR models. These models are proprietary and require non-disclosure agreements. MISO will test the proposed requirements on as many OEM models as is practical, considering availability and other constraints, but does not plan to publicaly share vendor-specific results. However, MISO will use the testing to provide anonymized benchmark responses to clarify MISO's conformity expectations.

Capability and performance requirements and recommended practices

GENERAL

The performance and capability requirements in Appendix G of MISO's pro forma tariff generator interconnection agreement shall apply, in addition to the requirements listed here, unless noted in the exceptions in the section titled *IEEE 2800 compatability and integration*~~IEEE 2800 compatability and integration~~. The simulation tests in the section titled Conformance assessment procedures~~Conformance assessment procedures~~ shall be used to demonstrate GFM IBR plant conformity with MISO's requirements. To contrast requirements from guidance, requirements language generally uses **bold font** whereas guidance uses *italicized font.*

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VOLTAGE SOURCE CAPABILITY REQUIREMENTS

GFM IBR shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame, within the inverter's current limits and the resource's energy limitations.[21]

The voltage phasor of a GFM IBR shall be controlled to maintain synchronism with other generation and electric storage resources on the power system.

The GFM IBR should start to naturally ~~respond~~ react in a few milliseconds[22], achieving full response in ~~around 10 to~~less than 50 milliseconds depending on the nature of the event.[23]

The GFM IBR should improve system strength by resisting voltage magnitude changes in the sub-transient time frame by modulating appropriate levels of reactive and/or active power, enhancing stable operation during and following power system disturbances. The GFM IBR should resist sudden changes in positive sequence voltage phase angle by modulating appropriate levels of reactive and/or active power.

The GFM IBR should provide frequency support in the sub-transient timeframe by appropriately modulating active power in response to frequency excursions.

[21] MISO's GFM requirements do not impose requirements for fault current capability extending beyond equipment ratings. All requirements and recommendations within this document assume that current limits are not exceeded. For readability, this limitation is not repeated for each requirement.
[22] The term "react" used here is considered synonymous with the IEEE 2800-2022 definition of *reaction time*, which points to a measurable change in the direction of the control effort.
[23] "Full response" is viewed by MISO as analogous to IEEE 2800-2022 *step response* defined term.

The GFM IBR should operate stably under a very low short circuit ratio, as defined by the system operator, both under normal operating conditions and when exposed to power system disturbances. The conformity test will assess simulated performance with an SCR as low as 1.25.

Background on voltage source capability requirements

The NERC whitepaper definition provides a foundation for defining required controls capabilities. Unifi's Version 2 of Specification for Grid-Forming Inverter-Based Resources adopts the NERC definition. MISO directly adopted the NERC and unifi language in the voltage source requirement. To define the required synchronization capabilities, a combination of the NERC and AEMO definition is used. AEMO's language provides the basis for the wording on synchronization, but NERC's wording of "controlled to maintain synchronism" was used instead of AEMO's more passive directive to be "capable of synchronizing".

Given the evolving nature of control technology, MISO suggests providing response times as guidance rather than normative requirements. The response time guidance is consistent with FINGRID and NGESO. For phase angle step changes specifically, AEMO requires a response time within 15 ms. For loss of last synchronous machine, AEMO states response time should be within 50 ms. FINGRID requires an initial response within few milliseconds with full response in under 10 ms as indicative response times, without differentiating the time based on type of disturbance.

Finally, MISO is addressing system strength improvements as a natural outcome of specifying voltage source behavior rather than developing specific system strength requirements. For this reason, the system strength is addressed with informative language rather than normative requirements.

REQUIREMENTS TO INTEGRATE IBR GFM WITH IEEE 2800-2022

As discussed in the section titled *IEEE 2800 compatability and integration discussion*~~IEEE 2800 compatability and integration discussion~~, MISO is proposing modifications or exemptions to certain IEEE 2800-2022 subclauses for GFM IBR. The below requirements serve this purpose.[24] MISO acknowledges this is an area where further industry evaluation is needed and provides this information to start the discussion. MISO is open to other solutions for addressing requirements compatibility.

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[24] As a matter of clarity, MISO is removing the 7.2.2.3.3 reference to 7.2.2.3.4. Similarly, the 7.2.2.3.4 reference to 7.2.2.3.5 is removed. Finally, the 7.3.2.1 references to 7.3.2.3.2 and 7.3.2.3.4 are removed

GFM IBR shall be exempt from the following IEEE 2800-2022 subclauses: 4.7 (prioritization of IBR responses), 7.2.2.3.4 (current injection during voltage ride-through mode), and 7.2.2.3.5 (performance specifications).

In the case of the *permissive operation region* mentioned in IEEE 2800-2022 subclauses 7.2.2.1 (general requirements and exceptions, voltage disturbance ridethrough), 7.2.2.3.3 (low and high-voltage ride-through performance), and 7.3.2.1 (general requirements and exceptions, frequency disturbance ridethrough), the GFM IBR shall only implement current blocking for the purpose of equipment protection.[25] Otherwise, the IBR GFM shall operate as if it were in the *mandatory operation region.*

GFM IBR shall be exempt from only Table 13 (voltage ride-through performance requirements), and associated normative language, within subclause 7.2.2.3.2 (low-and high-voltage ride-through capability). Further, the GFM shall not alter voltage source characteristics to meet reactive current priority mode requirements within this subclause and is exempted from this subclause should that be the implication of conformity.[26]

For IEEE 2800-2022 subclause 7.2.2.6, for requirements applicable upon the applicable voltage returning to the continuous operating region after IBR performing ride-through, the GFM active power recover shall occur immediately with the rate of recovery not control-constrained by a default active power recovery rate of 1 second.[27]

MISO RECOMMENDED PRACTICES

Oscillation Damping: *A GFM IBR should be capable of providing positive damping for oscillations in the power system. In addition, the GFM IBR should provide adequate damping of active power and reactive power responses following a disturbance on the power system. The GFM IBR should present positive resistance to the grid within a frequency range of common grid electrical resonances and system disturbances, including from 0-300 Hz.*

The GFM IBR should be designed and configured so as not to interact and affect the operation, performance, or capability of other facilities or equipment connected to the electrical system.

[25] MISO adopts the IEEE 2800-2022 defined term for *current blocking*. The term is synonymous with "momentary cessation".
[26] Reactive current priority is generally preferred performance during voltage ride-through, however, this requirement states that strict reactive current priority is not required if it alters basic GFM operation.
[27] IEEE 2800-2022 subclause 7.2.2.6 sets default active power recover time and rate capability and notes rates may need to be slowed in weak grid conditions. MISO views the stability consideration as mostly related to GFL control responses and understands faster GFM active power recovery to contribute to stability. The term "not control-constrained" indicates natural response should be used instead of 100% recovery in 1 second default rate.

In particular, the GFM IBR should add damping to the system for known oscillatory phenomena, including but not limited to:

- *Sub-synchronous oscillations associated with inverter-to-inverter interactions.*
- *Rotor angle modes of oscillation.*
- *Oscillations at harmonic frequencies resulting from interactions of electrical and control resonances.*

***Prioritization of responses**: The GFM IBR should be allowed to prioritize self-protection, preventing exceedances of capability limits, above other responses. When the GFM IBR is not constrained by capability limits, it should retain the required voltage source characteristics to support system stability.*

***Mode switching**: When connected to the network and operating within current limits, the GFM IBR should operate in GFM mode and not switchover to acting as a non-GFM inverter ~~voltage controlled current source (e.g., grid-following inverter)~~. Whenever a GFM IBR must temporarily cease to operate as a voltage source (e.g., operating at short-duration current rating limits during voltage ride-through), the GFM IBR should be designed to ensure a smooth transition between the operating states.*

***Negative sequence current**: GFM IBR should provide negative sequence current when in the continuous operation region.*

***Voltage balancing**: GFM IBR's voltage source behavior should act to reduce the level of unbalanced voltage conditions caused by disturbances[28], which could be achieved by the inverter emulating a balanced voltage source which naturally injects positive and negative sequence currents depending upon the nature of the voltage disturbance applied. The GFM resource should also ensure its internally generated voltage remains balanced during all near-nominal operating conditions (e.g., 0.9–1.1. p.u. voltage range). The GFM IBR should not actively oppose or prevent the flow of negative sequence current for small levels of voltage unbalance.*

***Configurability for controls tuning:** The GFM IBR should have tunable frequency controls[29], including response time, droop gain, and deadband. Similarly, The GFM IBR should have tunable voltage controls, including fast reactive current response times, droop gain, and deadband. The GFM IBR should be capable of being tuned so that following a disturbance its output is*

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[28] The voltage unbalance factor (VUF) may be used to evaluate level of voltage imbalance as described by R. C. Dugan, M. F. McGranaghan, and H. W. Beaty, Electrical Power Systems Quality. New York: McGraw-Hill, 1996.

[29] Current HECO requirements specify that the frequency dead band should be settable from +/- 0.01 Hz to +/-1.0 Hz and the frequency droop shall be settable in the range of 0.1% to 10% with a typical value of 4%. Requirements available at: https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20210901_cbre_rfp/20210825_redline_lmi_appxb_att3.pdf

adequately damped. Actual damping characteristics for GFM IBRs will need to be determined and tuned based on network characteristics, and to enhance overall system stability.

***Transient overvoltage**: The GFM IBR should be designed to reduce the risk of transient over voltage levels arising following clearance of the fault ~~to mitigate the risk of any form of instability which could result~~.*

Commented [PD3]: Rev 0.2: Not necissary. Industry review suggested removal.

***Power sharing:** The GFM IBR should autonomously share power with other generation and storage resources.*[30]

IEEE 2800 COMPATABILITY AND INTEGRATION DISCUSSION

Unless otherwise noted by exception in the requirements above, MISO intends to apply IEEE 2800-2022 requirements in MISO's Generator Interconnection Agreement to all IBRs, including GFM IBRs. MISO acknowledges industry understanding of compatability of GFM IBR with IEEE 2800-2022 is still evolving and expects changes as industry gains more experience. This section provides rationale for MISO's initial proposal.

MISO began developing IBR-specific performance requirements around 2019 to address risks highlighted in NERC disturbance reports and alerts. In 2023, MISO revised IBR performance requirements through adoption of specific clauses within standard IEEE 2800-2022[31] to foster needed capabilities and performance. MISO's adoption of IEEE 2800-2022 is still underway, with a second phase of requirements currently proposed to stakeholder through the Interconnection Process Working Group (IPWG) and Planning Advisory Committee (PAC). Future phases of IBR requirements adoption may be considered, as noted by MISO's Attributes work.[32] See the Appendix for additional information on MISO's ongoing IEEE 2800-2022 adoption.

MISO intends to apply as much of the IEEE 2800-2022 requirements framework to GFM IBR as practical. However, the standard's specificity and speed of certain control responses poses challenges to how GFM IBR respond when prioritizing voltage responses. The result may be slower control of power when compared to traditional grid-following (GFL) inverter control technologies. A gap analysis of IEEE 2800 standard towards GFM technology was performed under the unifi consortium.[33]

[30] Droop principles are typically used to achieve autonomous power sharing in power systems.
[31] IEEE, "IEEE 2800-2022: IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems". April 2022. Available at: https://standards.ieee.org/ieee/2800/10453/
[32] MISO, Attributes Roadmap. December 2023. Available at: https://cdn.misoenergy.org/2023%20Attributes%20Roadmap631174.pdf
[33] Ramasubramanian, D., et al. 2022. Preliminary Gap Analysis of Existing IEEE 1547 and IEEE 2800 Standards Towards GFM Technology. UNIFI-2022-3-1.

Given fundamental differences in GFL and GFM controls, MISO is exempting or modifying specific IEEE 2800-2022 requirements for GFM BESS application. The requirements considered for exemption or modification are those either enacted through MISO's current Generator Interconnection Agreement Appendix 6 Attachment G or currently proposed. In other words, discussion in this section is limited to consideration of IEEE 2800-2022 Clauses MISO has adopted or is currently contemplating for adoption as indicated by the MISO Attributes roadmap Phase 1 (2023) and Phase 2 (2024)[34]. Table 2~~Table 2~~ lists the IEEE 2800-2022 clauses and subclauses that are modified or exempted for GFM IBR under MISO's adoption of GFM performance requirements.

IEEE 2800	Subclause name	Potential issue	Recommended action
4.7	Prioritization of IBR responses	Incompatibility with GFM fundamental operation (e.g., prioritization between ridethrough and current responses).	GFM exemption
7.2.2.1	Voltage ride-through – General	Definition of permissive operation region in Table 11 and Table 12	Only allow current blocking or tripping for self-protection in permissive operation region.
7.2.2.3.2	Low and high voltage ride-through capability	Refers to performance in Table 13. Defaults to reactive current priority mode.	Exempt Table 13. Exempt reactive current priority, if affecting GFM operation
7.2.2.3.3	Low and high voltage ride-through performance	Permissive operation region allows current blocking	Only allow current blocking or tripping for self-protection in permissive operation region.
7.2.2.3.4	Current injection during voltage ride-through	Specifies type and amount of current injection. References 7.2.2.3.5 performance. Mentions "automatic voltage control"	GFM exemption
7.2.2.3.5	Performance specification [during voltage ridethrough]	Specific step response time	GFM exemption

[34] Clauses not currently contemplated include: power quality (Clause 8), protection (Clause 9). ~~MISO contemplated measurement data for performance monitoring (Clause 11) and instead is looking to the PRC-028 revision.~~ See Appendix for current proposed sequencing of MISO's IEEE 2800-2022 adoption.

Commented [PD4]: Rev 0.2: MISO is addressing the changes to PRC-028 and implication on MISO's IEEE 2800 adoption in a different IPWG item on IEEE 2800 adoption.

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7.2.2.6	Restore output after ride-through	Specific active power recovery time and rate	GFM clarification that rate should not constrain natural response
7.3.2.1	Frequency disturbance ride-through requirements – general	References 7.3.2.3.2 and 7.3.2.3.4	Only allow current blocking or tripping for self-protection in permissive operation region.

Table 2. Summary of IEEE 2800-2022 exemptions or modification for IBR GFM

Considering MISO's IEEE 2800-2022 Clause 4 adoption (General), GFM IBRs are exempted only from the prioritization of responses (4.7) due to potential incompatibilities with voltage source characteristics. All other subclauses would apply, including the reference of applicability (RPA), applicable voltages and frequency, measurement accuracy, operational measurement and communication capability, and control capability.

MISO found no reason to modify or except GFM IBR from any of Clause 5 (Reactive power – voltage control). MISO sees value in applying the reactive power capability requirements. Further, the GFM IBRs are expected to be capable of meeting the reaction time and maximum step response time requirements for voltage control. The damping ratio performance of 0.3 or higher may be a challenge in weak grid areas. However, the IEEE standard states that the system operator shall define a range of transmission system equivalent impedance at the point of measurement, which is being defined in IPWG 2024 activities. MISO suggests this be the method for managing expectations on oscillation damping performance for weak grid applications as needed.

IEEE 2800-2022 Clause 6.1 (Primary frequency response) is proposed for adoption without exemption or modification. Primary frequency response is necessary and is currently required for all resources.

MISO's initial assessment indicates Clause 7 (Response to abnormal conditions) has elements that may need to be addressed for the standard to be fully compatible with desired GFM IBR performance. IEEE 2800-2022 ride-through requirements contains a *permissive operation region* in which current-blocking (i.e., momentary cessation) is allowed. MISO proposes allowing current-blocking only for equipment protection purposes. Further, language under Clause 7 requires specific active power recovery times, step response times, and amounts of current injection, all which may be challenging to meet for GFM controls given the priority for controlling the voltage phasor.

Modeling and data exchange

MODEL QUALITY FUNDAMENTALS

Model quality is important given the model-based performance verification method proposed for adoption. The model must be accurate, verified, and properly parameterized for simulation results useful for demonstrating conformity with required performance. PSCAD models should conform with the latest version of Electranix's PSCAD Requirements consistent with BPM-015 r28 requirements.[35, 36] The model quality recommendations outlined in NERC's EMT Reliability Guideline may also be reviewed as an additional reference.[37]

At minimum, the following conditions should be met to ensure model quality:

- OEM validated models and validation testing with minimum tests including the basic performance verification included in Electranix's PSCAD model requirements.
- Verification from inverter OEM(s) and/or Interconnection Customer that provided models match planned configuration and settings.
- Verification from plant controller OEM(s) and/or Interconnection Customer that models provided match planned configuration and settings.
- Verification from the Interconnection Customer, or third-party technical services provider, that the aggregate model representation of the IBR plant is accurate and matches planned configuration and settings.

MISO recognizes that general IBR data and model validation is a topic NERC is addressing in response to FERC Order 901, with a filing required by November 4, 2025. As potential business needs may emerge before then, MISO anticipates revisiting IBR model quality practices in the future.[38] In the meantime, MISO may request that an Interconnection

[35] Electranix, Latest version at publication is Technical Memo – PSCAD Requirements v12. September 19, 2022. Available at: https://www.electranix.com/wp-content/uploads/2022/09/PSCAD-Model-Requirements-Rev.-12-Sept-2022.pdf

[36] MISO, Business Practice Manual 015 (BPM-015) – Generator Interconnection. Available at: https://www.misoenergy.org/legal/rules-manuals-and-agreements/business-practice-manuals/

[37] NERC, Reliability Guideline Electromagnetic Transient Modeling for BPS-Connected Inverter-Based Resources – Recommended Model Requirements and Verification Practices. March 2023. Available at: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf

[38] NERC filing in FERC Docket No. RM22-12-000. INFORMATIONAL FILING OF THE NORTH AMERICAN RELIABILITY CORPORATION REGARDING THE DEVELOPMENT OF RELIABILITY STANDARDS RESPONSIVE TO ORDER NO. 901. January 18, 2024. Available at:

Customer voluntarily provide model quality procedures and results should MISO have a business purpose in understanding GFM BESS simulation inputs and/or results.

DATA REQUIREMENTS AND DOCUMENTATION

Given MISO's current EMT tool is PSCAD, the GFM IBR model and conformity tests shall be performed using PSCAD Version 5.

To facilitate MISO's review of the GFM IBR capabilities, the Interconnection Customer shall submit the following information:

- A completed test procedure check list using MISO-provided template.
- Simulation test result plots (voltage and reactive power; frequency and active power) for each test in the MISO-provided template.
- The PSCAD test set-ups (e.g., .pscx files, library files) with OEM model included and parametrization as configured during tests.
- Model documentation for both inverter and power plant control -describing functionality and operation of resource and model.[39]

Commented [PD5]: Rev 0.2: Revisions proposed to clarify language in response to Stakholder question.

"On the data requirements and documentation section on page 23, AES requests more information on the test procedure check list to be able to review and provide additional feedback on. AES also requests further clarity on the 4th bullet, "Model documentation describing functionality and operation of resource and model", whether customers need to provide plant-level documentation?"

Conformance assessment procedures

GENERAL

The simulation tests described below are MISO's proposed method of demonstrating conformity with MISO's GFM BESS capability and performance requirements. MISO business practices may change as control technologies, industry practices, and standards evolve. Table 3Table 3 summarizes the purpose for each of the four tests.

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Test	Purpose
Loss of Last Synchronous Machine (LLSM)	Assess general grid-forming capabilities and performance following the loss of the last synchronous generator on the test system given various initial BESS dispatch conditions, including charging and discharging
Rate of Change of Frequency (ROCOF)	Assess control stability and active power responses for increases and decreases in frequency
Phase Jump	Assess active power responses for voltage phase angle changes

https://www.nerc.com/FilingsOrders/us/NERC%20Filings%20to%20FERC%20DL/NERC%20Compliance%20Filing%20Order%20No%20901%20Work%20Plan_packaged%20-%20public%20label.pdf

[39] OEM documentation is typcially required to understand and parameterize the "black box" inverter and plant controller model. MISO is not proposing additional plant-level documentation outside of standard business practices.

Short Circuit Ratio (SCR)	Assess control stability in weak grid conditions before and after faults are applied

Table 3. Summary of the four conformance tests and their purpose

While the tests are expected to definitively determine GFM IBR capability, they are not intended to validate control stability performance under all potential grid conditions. Since the stability of control responses can in part be dependent on electrical system characteristics (e.g., weak grid) and interactions with other system components, the tests have substantial but not full coverage in evaluating GFM IBR control performance under a reasonable set of system conditions. In addition, the tests contain extreme conditions not anticipated on the grid for the purpose of exercising and understanding GFM IBR responses.

As is the case for all bulk system resources, interconnection studies are still required to evaluate steady state and dynamic impacts of the GFM IBR plant for the selected point of interconnection, given the system characteristics and conditions in that area.

MISO is not proposing additional interconnection study EMT simulations as part of the GFM requirements proposal. However, MISO notes that industry is recognizing a growing need for EMT simulations to accurately model impacts of higher levels of IBR.[40]

PROCESS

While MISO anticipates further process details to accompany development of the implementation plan, MISO is sharing an initial perspective of the process for the purposes of understanding MISO's proposed requirements. The implementation plan will clarify how the conformity simulations fit with MISO's definitive planning phase (DPP) process.

1. MISO furnishes test procedures, test sets, and example benchmark test results for conforming and non-conforming plants.
2. Interconnection Customer provides quality-checked OEM-specific PSCAD model, runs simulation tests, supplies completed checklist and other applicable results as outlined in the Data requirements and documentation~~Data requirements and documentation~~ section.

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[40] AEMO. Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high-penetration of inverter connected generation. Available at: https://www.nerc.com/comm/PC/Documents/EMT_simulation_models_for%20large-scale_system_impacts.pdf

3. MISO reviews test results and either: 1) accepts results as demonstrating conformity; or 2) requests additional information necessary to interpret test results.
4. Interconnection Customer provides additional information, as applicable (e.g., paramaterization modifications, model usage guidance).
5. Process iterates on step #3 as needed.

FUNCTIONAL TEST SYSTEMS

Two functional test set-ups within PSCAD are needed to demonstrate stable grid forming control responses across a range of simulated system disturbances. Table 4~~Table 4~~ shows the application of the test set-ups across the required simulations.

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Test set-up	Simulations
A – Loss of last Synchronous Machine	1. Loss of last synchronous machine (Cases 1 – 34)
B – Variable source and impedance	2. Rate of change of frequency
	3. Phase jump
	4. Low SCR with fault

Table 4. Summary of test set-up mapping to simulations

The GFM IBR shall be in voltage control mode with identical voltage and frequency control settings and set points.

The GFM IBR voltage and frequency protection settings shall be set as wide as possible within equipment capabilities and ratings (i.e., self-protection). These settings shall be consistent with the intended field application.

Commented [PD6]: Rev 0.2: Stakeholder asked for more specificity. This is aligned with NERC Level 2 report from which MISO is drawing justification for this requirement. NERC Alert IBR Performance

Test set-up A: Loss of last synchronous machine

Test set-up A (loss of last synchronous machine) is from NERC's 2023 guideline. It is a simplified power system consisting of a synchronous machine, constant impedance load, and two GFM BESS (Figure 8~~Figure 8~~).

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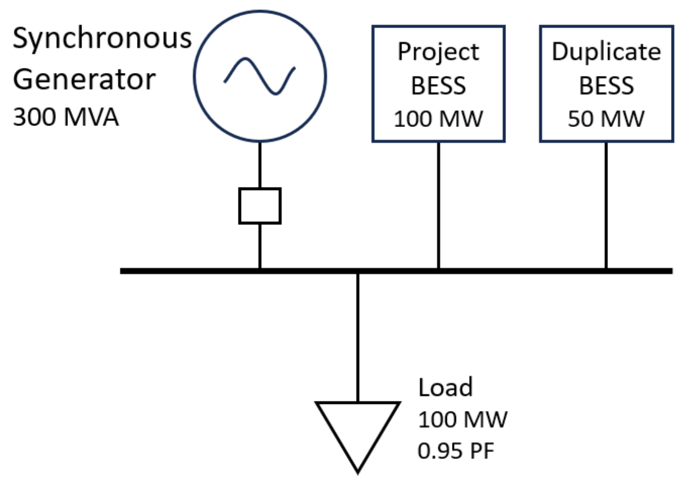

Figure 8. Test set-up A configured for 100 MW GFM IBR (source: NERC)

The synchronous generator ~~has a simple excitation system model (e.g., SCRX) and turbine-governor model (e.g., TGOV1), with a circuit breaker to disconnect the generator~~is approximated by using a simple voltage source rather than a synchronous generator model. The test results are unaffected by representing the synchronous generator as a simple voltage source because GFM IBR dynamic responses occurs only after the generator or source is disconnected, leaving no potential for interaction between simulated GFM dynamic response and these other modeled components.

~~The constant impedance load has a minimum power factor of 0.9.~~

The set-up includes the GFM IBR plant under test and a duplicate, half-rated GFM IBR plant. The fully rated GFM IBR is the plant under test while the half-rated duplicate is used to demonstrate compatibility among GFM controls, as well as to allow the fully rated GFM IBR to be dispatched at its limit during testing. The half-rated unit could be represented by a separate model or by scaling the original model.

Test set-up B: Variable source and impedance

Test set-up B (variable source and impedance) consists of an ideal, controllable voltage source connected to the GFM IBR through a controllable impedance (Figure 9~~Figure 9~~).

Commented [PD7]: Rev 0.2: Image replaced to remove references to modeling generator excitor and governor.

Commented [PD8]: Rev 0.2: discussions with industry technical experts with extensive PSCAD and GFM requirements experience indicates that synchronous machines introduce modeling complexity that does not serve a purpose for these particular simulations. MISO simulations are consistent with this experience.

Commented [PD9]: Rev 0.2: The constant impedance load maintains a power factor of 0.95.

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Additionally, a variable impedance fault component is required for one of the three tests that uses this test set-up, the low SCR with fault test.

The voltage source magnitude, phase, and frequency shall be user configurable. Similarly, the series impedance shall be configurable such that the simulated GFM IBR connection point strength (i.e., impedance and X/R ratio) and voltage is configurable.

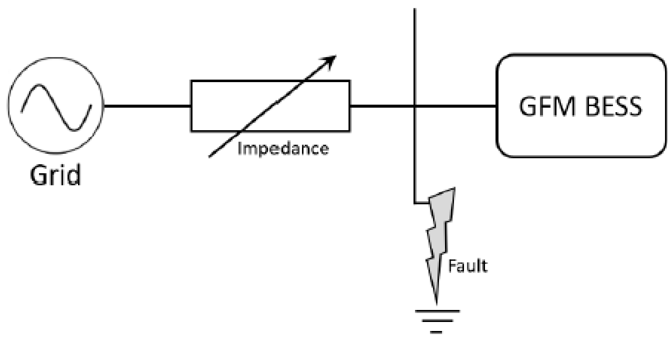

Figure 9. Test set-up B: variable source and impedance (source: AEMO)

TEST DESCRIPTIONS AND SUCCESS CRITERIA

Loss of last synchronous machine test

The loss of last synchronous machine (LLSM) test consists of ~~four~~ three cases on test set-up A, using different pre-disturbance conditions to test different aspects of the GFM IBR control response. Table 5~~Table 5~~ summarizes the conditions for each case, with detailed descriptions of the test sequences and success criteria below the table.

Case	Description	Project Plant[1]	Duplicate Plant[1]	Load[2] (% of project plant rating)
~~1~~	~~BESS Discharging~~	~~20% discharge~~	~~20% discharge~~	~~100%~~
1~~2~~	BESS Charging	50% charge	50% charge	50%
2~~3~~	Limit Test	0% exchange	100% discharge	100%

Commented [PD10]: Rev 0.2: removed a previous Case 1 based on Stakeholder feedback, industry input, and MISO simulation results.

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Commented [PD11]: Rev 0.2: previous Case 1 removed because response is covered by other cases. For instance, old Case 4 (new Case 3) is similar and more severe.

34	**Power Balance**	50% discharge	50% discharge	75%

Notes: (1) values are as a percentage of the IBR continuous active power rating. (2) load values are expressed as a percentage of the project plant active power continuous rating.
Table 5. Summary of cases associated with loss of last synchronous machine simulations

In all ~~four~~ three cases, the synchronous machine is supplying all the load's reactive power prior to the simulated disturbance (i.e., opening of breaker). The load is configured with a power factor of 0.95 lagging in each case.

LLSM test sequence

The following test sequence is consistent across all ~~four~~ three loss of last synchronous machine cases:

1. Initiate simulation and run until system is stable at the given power flow conditions, without oscillations.[41]
2. Trip the synchronous generator by opening the breaker (no fault).

LLSM success criteria

The following success criteria are consistent across all ~~four~~ three cases, with minor clarifications made for case 34 in footnotes.[42] Refer to Table 5~~Table 5~~ for required initial conditions of resources and load prior to the synchronous generator tripping. All pre-trip and post-trip conditions shall be met for the test to be considered "pass".

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Pre-trip:

a. Both BESS plants active power outputs match dispatched levels.
b. Synchronous generator active power output matches the rest of the load.
c. Frequency is 1 p.u.
d. Voltage at bus 1 is within 5% of nominal (i.e., 0.95 to 1.05 p.u.).
e. Phase voltage and current waveforms are not distorted.
f. Oscillations are not present in RMS quantities.
g. Reactive power output from all devices should be within limits.

The synchronous generator breaker is opened after pre-trip conditions are met.

Post-trip:

a. Plant output is well controlled with no significant frequency/voltage oscillations.

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[41] ~~In future versions of this whitepaper, MISO intends to provide example simulations that would be considered to not meet pre-trip or post-trip criteria related to oscillation, damping, and settling. MISO recommends against defining specific pass/fail technical criteria in these areas currently~~Refer to the Example Test Results section for guidance on acceptable results.

[42] Case 34 differs from the previous three cases' criteria because the synchronous generator is not serving any of the load's active power.

b. Voltage settles to a stable operating point.
c. Final voltage is expected based on droop and deadband settings.
d. Frequency settles to a stable operating point.[43]
e. Final frequency is expected based on droop and deadband settings.
f. Oscillations is adequately damped.
g. Distortion observed in phase quantities dissipates over time.
h. Active power immediately moves to meet load requirement and settle according to its frequency droop setting. [44]
i. Reactive power response is immediate and settles according to voltage droop setting.[45]
    a. *Voltage should not deviate beyond 0.8 pu or 1.1 pu for longer than 0.1s throughout the test.*

Rate of change of frequency response test

The rate of change of frequency test (ROCOF) tests the stability of GFM IBR in response to changing frequency. The test procedure includes both frequency increases and decreases. Test set-up B is used for the ROCOF test, with the following conditions:

- The short circuit ratio (SCR) at the GFM IBR connection point shall be set to 10.
- The system equivalent X/R shall be set to 6.
- The BESS is dispatched to 50% of continuous rating.

ROCOF test sequence

1. Ramp frequency from 60 to 61 Hz at 4 Hz/s. Remain at 61 Hz for 5 seconds.
2. Ramp frequency from 61 to 60 Hz at 4 Hz/s. Remain at 60 Hz for 5 seconds.
3. Ramp frequency from 60 to 59 Hz at 4 Hz/s. Remain at 59 Hz for 5 seconds.
4. Ramp frequency from 59 to 60 Hz at 4 Hz/s.

ROCOF success criteria

a. Plant output is well controlled with no significant frequency/voltage oscillations.[46]
b. Voltage settles to stable operating point when frequency is not ramping.
c. Active power should settle based on frequency droop and deadband settings when frequency is not ramping.
d. Oscillations should be adequately damped.

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[43] For Case 34, frequency should settle to nominal frequency.
[44] For Cases 1, 2, and 3, the response time to 90% should occur within 50 ms. For Case 4, the active power should settle back to pre-trip levels. Site specific response may need to be slower to ensure system security. Intent is to ensure inherent initiation of active power response.
[45] The NERC whitepaper recommends a performance target reaction time of less than 16 milliseconds for large disturbance voltage step changes.
[46] MISO intends to provide benchmark responses to clarify intent.

Phase Jump test

The phase jump test evaluates the speed and magnitude of simulated active power responses under different phase angle changes. Test set-up B is used for the phase jump test, with the following conditions:

- The short circuit ratio (SCR) at the GFM IBR connection point shall be set to 3~~10.~~
- The system equivalent X/R shall be set to 6.
- The BESS is dispatched to 50% of continuous rating.

Phase jump test sequence

a. Angle of voltage source behind the equivalent grid impedance is decreased instantaneously by 10 degrees.
b. ~~A few~~Five seconds[47] later, angle of voltage source is increased by 10 degrees.
c. Angle of voltage source behind the equivalent grid impedance is decreased instantaneously by 25~~30~~ degrees.
d. ~~A few~~Five seconds later, angle of voltage source is increased by 25~~30~~ degrees.
~~e. Angle of voltage source behind the equivalent grid impedance is decreased instantaneously by 60 degrees.~~[48]
~~f. A few seconds later, angle of voltage source is increased by 60 degrees.~~

Phase jump success criteria

a. Instantaneous active power output of the plant should quickly respond to oppose the angle change for each of the 10 degree voltage phase angle jumps, with a peak active power change of at least 0.2 pu on the rated active power base.

   Example: 100 MW rated plant should temporarily increase active power output from 50 MW to at least 70 MW when source voltage angle is decreased by 10 degrees, and should temporarily decrease active power from 50 to 30 MW or below when voltage source angle is increased by 10 degrees.

b. For each of the 10 degree voltage phase angle jumps, response time to 90% of initial change in instantaneous active power should occur within 15ms[49].
c. Active power settles to pre-disturbance level shortly after all phase jumps.
~~d. If active power / current reaches limits for the 60 degree phase change, the plant should return to pre-event power levels in a stable manner.~~

[47] The five seconds is provided as a default value. The time between phase jumps could be extended beyond five seconds if a stable operating point is not reached within that time.
~~[48] A +/- 60 degree phase angle change is extreme and not anticipated to be a condition within the MISO region in the near-term or mid-term time horizons. The sucsess criteria focuses on smaller phase angle changes, with criteria also accounting for potentially high impedance between POI and inverter terminals.~~
[49] The 90% minimum threshold is applied to the minimum active power change of 0.2 pu on the rated active power base. Further, the active power should not reduce below the power output prior to the 10 degree angle jump for at least 50 milliseconds.

Commented [PD12]: Rev 0.2: Modified SCR to be 3 to match AEMO testing approach.

Commented [PD13]: Rev 0.2: Added specific value based on stakeholder feedback. MISO and AEMO use five seconds in example tests.

Commented [PD14]: Rev 0.2: modified the phase jump test to be consistent with ride-through performance requirements adopted from IEEE 2800. While different applications of this phase angle step, MISO views this as greater consistency among different requirements.

Commented [PD15]: Rev 0.2: Removed 60 degree phase jump based on feedback and additional MISO investigation.

AES reiterates its prior comments that a 60-degree phase change is outside the realm of likelihood, and far beyond the IEEE 2800 requirements. AES request MISO provide further justification on why it believes a test of a 60-degree phase jump is warranted. AES believes that stopping the test at 30 degrees would provide results of more realistic grid conditions that might be observed in operations and is in compliance with IEEE 2800.

Commented [PD16]: Rev 0.2: Added footnote to clarify how the 90% threshold is applied -- it related to criteria 'a.' above.
Also, MISO added guidance in the footnote because MISO became aware that GFL responses may include very fast current spikes, followed by steep reductions in active power to below pre-disturbance levels. While MISO is not prepared to codify this in the requirement, MISO wants to make Interconnection Customers aware that this is an unexpected response for GFM plants.

Commented [PD17]: Rev 0.2: Removed 60 degree phase jump for reasons stated above.

~~e.~~d. Any oscillation shall be settled.
~~f.~~e. Any distortion observed in phase quantities should dissipate over time.

Short Circuit Ratio (SCR) ramp down with fault test

The SCR ramp down with fault test evaluates GFM IBR control stability under declining system strength conditions (i.e., weak grid). The test starts with higher SCR values before introducing a fault and stepping down SCR while simultaneously clearing the fault. This sequence is repeated several times until very weak grid conditions are simulated. Test set-up B is used with the following conditions:

- The short circuit ratio (SCR) at the GFM IBR connection point shall be set to 20.
- The system equivalent X/R shall be set to 6.
- The BESS is dispatched to 100% of continuous rating.

SCR ramp down with fault test sequence

a. SCR at connection point stepped down repeatedly: 10, 3, 2, 1.5, 1.25.
b. 6-cycle 2 phase-to-ground fault is applied with minimum fault depth of 0.5pu just before each SCR transition. SCR transition occurs at fault clearing time.[50]

SCR ramp down with fault success criteria

a. Plant real and reactive power output should be well controlled and plant should not trip or reduce power for any extended period of time down to the minimum SCR in the test

[50] MISO suggests a default value of 10 seconds between faults, though the time should be chosen to allow settling from the prior fault before initiating another fault.

Example Test Results

MISO performed the test sequences detailed in the Conformance Assessment Procedures section for an OEM-provided GFM plant model (i.e., both inverter controls and power plant controller modeled) to demonstrate the testing process and existing equipment capabilities. Examples of sucsessful test results are shown in the figures on the left-hand side below.

To draw a contrast, MISO also performed the tests on a GFL plant model from the same OEM; the GFL plant failed all tests except for the ROCOF test. GFL results that do not pass success criteria are shown in the figures on the right-hand side below.

An example of a droop calculation is shown with the ROCOF test results. This calculation is included to demonstrate a method for determining whether final frequency or voltage values are expected based on the plant's droop and deadband settings. The values are used to determine pass or fail results when applying success criteria in the ROCOF and LLSM test sequences.

Commented [PD18]: Rev 0.2: added new section with example test results. For readability, the new content is shown without redlines after initial paragraph.

LLSM CASE 1 – CHARGING

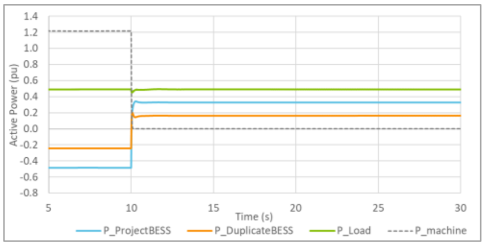


Figure 10. GFM model – LLSM Case 1 - active power response after SM trip

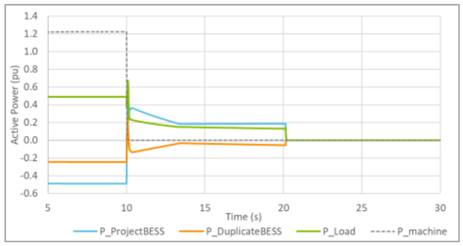


Figure 11. GFL model – LLSM Case 1 - active power response after SM trip

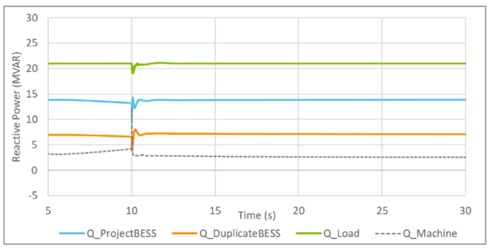


Figure 12. GFM model – LLSM Case 1 - reactive power response after SM trip

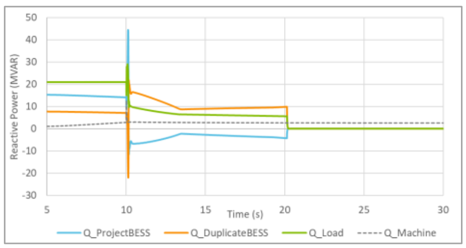


Figure 13. GFL model - LLSM Case 1 - active power response after SM trip

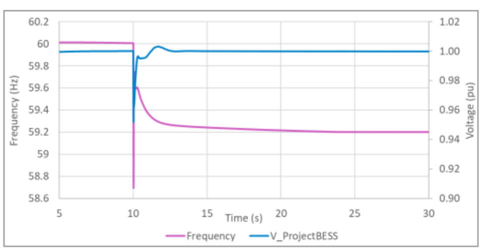


Figure 14. GFM model – LLSM Case 1 – frequency and voltage

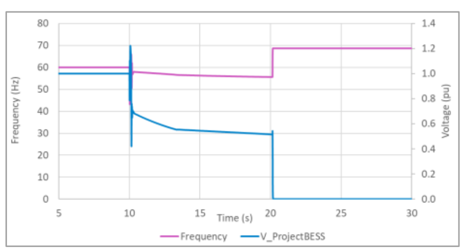


Figure 15. GFL model – LLSM Case 1 – frequency and voltage

LLSM CASE 2 – LIMITS

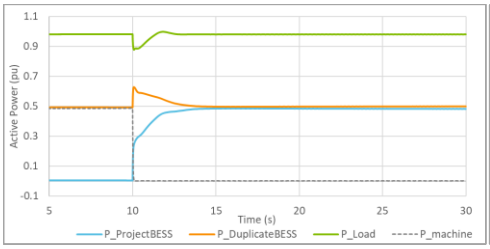


Figure 16. GFM model – LLSM Case 2 - active power response after SM trip

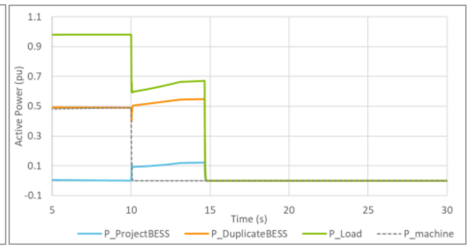


Figure 17. GFL model – LLSM Case 2 - active power response after SM trip

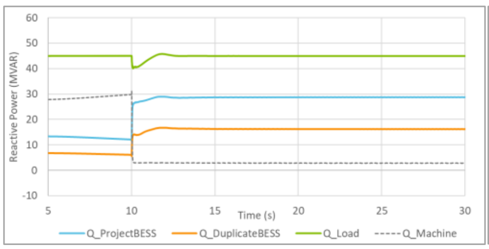


Figure 18. GFM model – LLSM Case 2 - reactive power response after SM trip

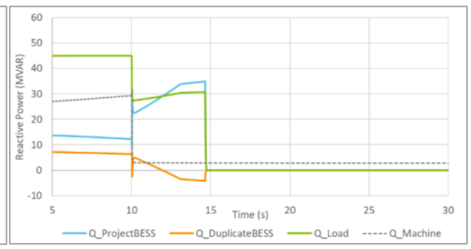


Figure 19. GFL model – LLSM Case 2 - reactive power response after SM trip

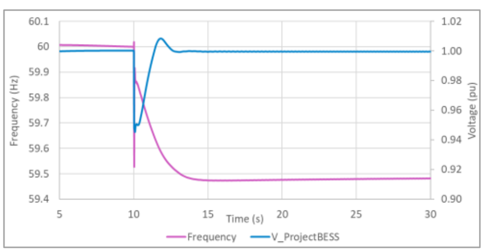


Figure 20. GFM model – LLSM Case 2 – frequency and voltage

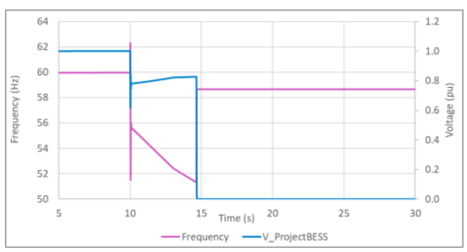


Figure 21. GFL model – LLSM Case 2 – frequency and voltage

LLSM CASE 3 – POWER BALANCE

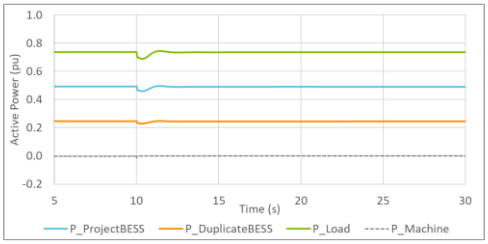


Figure 2222. GFM model – LLSM Case 3 - active power response after SM trip

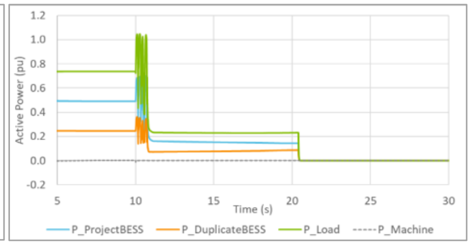


Figure 23. GFL model – LLSM Case 3 - active power response after SM trip

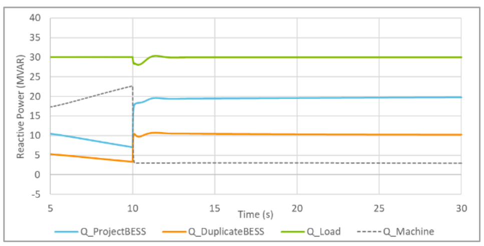


Figure 24. GFM model – LLSM Case 3 - reactive power response after SM trip

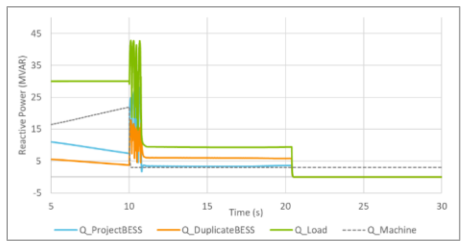


Figure 25. GFL model – LLSM Case 3 - reactive power response after SM trip

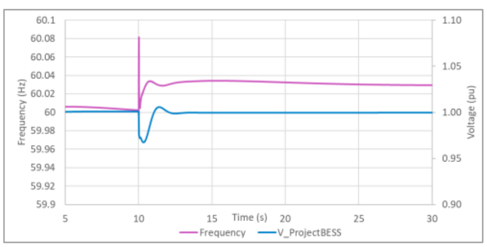


Figure 26. GFM model – LLSM Case 3 – frequency and voltage

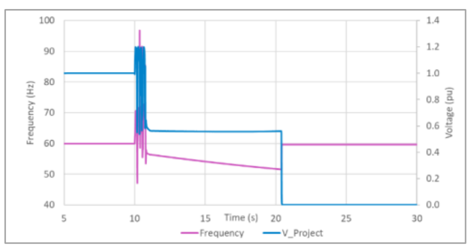


Figure 27. GFL model – LLSM Case 3 – frequency and voltage

ROCOF TEST

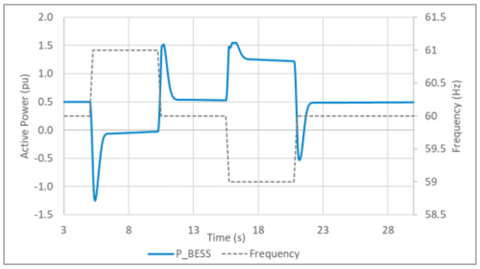


Figure 2828. GFM model – ROCOF active power response

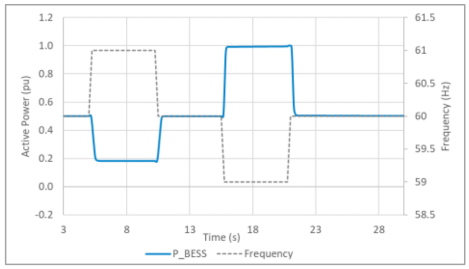


Figure 29. GFL model – ROCOF active power response

Note: While both models pass the ROCOF test criteria, the GFM model shows an immediate inertial response to the change in frequency while GFL has a droop response that acts on a slower timeframe.

GFM Model Example Droop Calculation – when frequency increases to 61 Hz:
Over-frequency droop equation

$$p = p_{pre} + \frac{f_{nom} - f + db_{OF}}{f_{nom} \times k_{OF}}$$

Where:
p is the final active power output in p.u.
p_{pre} is the pre-disturbance active power output
f_{nom} is the nominal frequency in Hz
f is the post-disturbance frequency in Hz
db_{OF} is the over-frequency deadband in Hz
k_{OF} is the droop for over-frequency events, the per unit change in frequency corresponding to 1 per unit change in power output

Site controller frequency response droop = $k_{OF,SC} = 33 \text{ MW/Hz} = 0.030303 \text{ Hz/MW} = 0.05 \text{ pu droop}$
Site controller over-frequency deadband = $db_{OF,SC} = 0.03\ Hz$
GFM inverter droop = $k_{OF,INV} = 0.4 \text{ pu/Hz} = 40 \text{ MW/Hz} = 0.025 \text{ Hz/MW} = 0.0416667 \text{ pu droop}$
GFM inverter under-frequency deadband = $db_{OF,INV} = 0.5\ Hz$
p_{pre} = 50 MW = 0.5 pu

$$p = p_{pre} + \frac{f_{nom} - f + db_{OF}}{f_{nom} \times k_{OF}} + \frac{f_{nom} - f + db_{OF}}{f_{nom} \times k_{OF}}$$

$$p = 0.5\ pu + \frac{60\ Hz - 61\ Hz + 0.03\ Hz}{60\ Hz \times 0.05\ pu} + \frac{60\ Hz - 61\ Hz + 0.5\ Hz}{60\ Hz \times 0.04166667\ pu}$$

$$p = 0.5\ pu + \frac{-0.97\ Hz}{3\ Hz} + \frac{-0.5\ Hz}{2.5\ Hz}$$

$$p = 0.5\ pu - 0.323\ pu - 0.2\ pu = -0.023\ pu = -2.3\ MW$$

Expected = -2.3 MW Actual = -2.5 MW

PHASE JUMP TEST

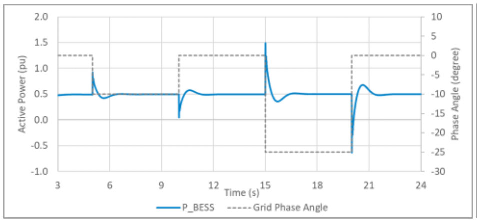


Figure 30. GFM model – phase jump active power response

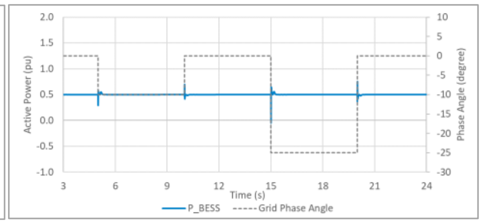


Figure 31. GFL model – phase jump active power response

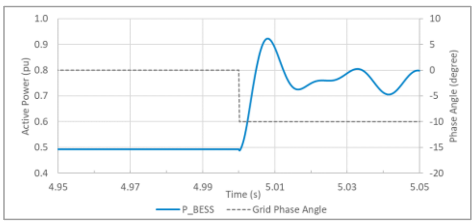


Figure 32. GFM model – close up of 10 degree phase jump down active power response

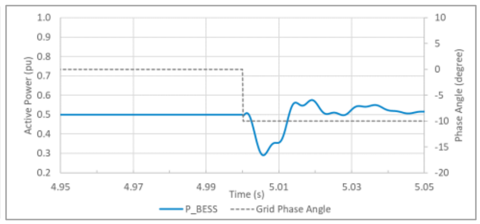


Figure 33. GFL model – close up of 10 degree phase jump down active power response

SCR TEST

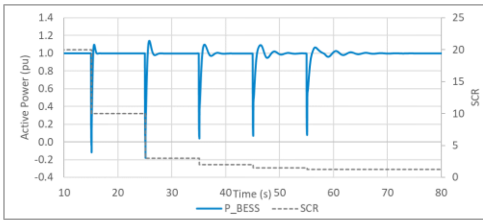


Figure 34. GFM model – SCR test active power response

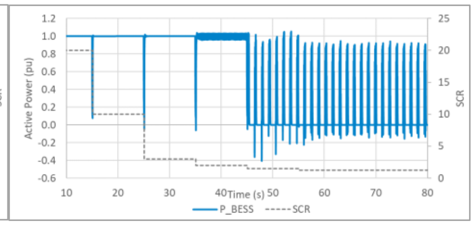


Figure 35. GFL model – SCR test active power response

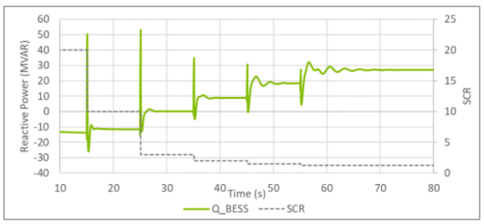


Figure 36. GFM model – SCR test reactive power response

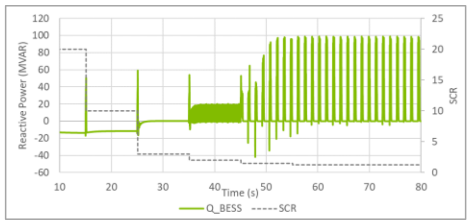


Figure 37. GFL model – SCR test reactive power response

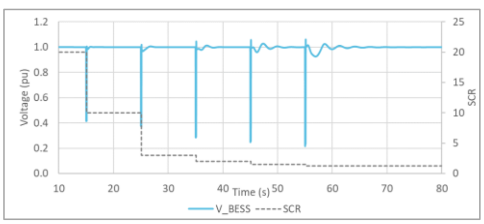


Figure 38. GFM model – voltage during SCR test

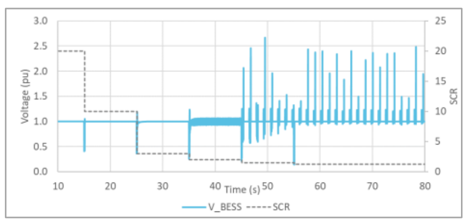
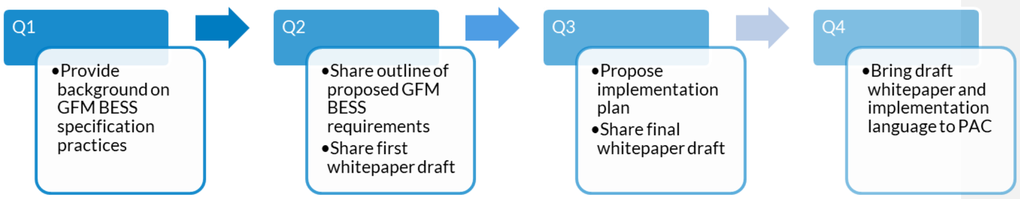


Figure 39. GFL model – voltage during SCR test

Appendix

STAKEHOLDER ENGAGEMENT DETAILS



	Date	GFM BESS topic objectives
IPWG	January 30	Inform stakeholders of IBR performance planned for development in 2024.
IPWG	March 12	Provide foundational information on GFM BESS specification practices.
IPWG	May 2	Share outline of initial proposed GFM BESS requirements. **Formal feedback request**.
IPWG	June 4	Share first revision of GFM BESS specifications whitepaper. **Formal feedback request**.
IPWG	July 23	Respond to stakeholder feedback and share second version of whitepaper. Introduce proposed GFM BESS implementation plan. **Formal feedback request**.
IPWG	September 3	Respond to stakeholder feedback and share near-final whitepaper, subject to PAC review.
PAC	October 16	GFM BESS performance requirements proposal. **Formal feedback request**.
PAC	November 13	GFM BESS share feedback responses and modifications.

Meeting materials:

January 30 IPWG (slides 13-16):

- 20240130 IPWG Item 04 IBR Performance Requirements.pdf

March 12 IPWG:

- 20240312 IPWG Item 04b BESS Grid Forming Controls (PAC-2024-2).pdf
- 20240312 IPWG Item 04a GFM Need Drivers Technology Landscape (PAC-2024-2)_ESIG.pdf

May 2 IPWG:

- 20240502 IPWG Item 04b GFM BESS Performance (PAC-2024-2).pdf

June 4 IPWG:

- 20240604 IPWG Item 04b GFM BESS Performance (PAC-2024-2).pdf
- 20240604 IPWG Item 04b Draft GFM BESS Performance Requirements Whitepaper (PAC-2024-2).pdf

SUMMARY OF KEY INDUSTRY RESOURCES CONSIDERED IN MISO GFM IBR REQUIREMENTS DEVELOPMENT

Entity	Document	Link	Year
FINGRID	Grid Code Specifications for Grid Energy Storage Systems SJV2019	https://www.fingrid.fi/globalassets/dokumentit/en/customers/grid-connection/grid-energy-storage-systems-sjv2019.pdf	2021
FINGRID	Specific Study Requirements for Grid Energy Storage Systems	https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/specific-study-requirements-for-grid-energy-storage-systems-en.pdf	2023
FINGRID	Modelling instruction for PSS/E and PSCAD models	https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/fingrid-modelling-instruction-for-psse-and-pscad-models-2024_01_12-002.pdf	2024
NERC	White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems	https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf	2023
AEMO	Voluntary Specification for Grid-forming Inverters	https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf	2023
AEMO	Application of Advanced Grid-scale Inverters in the NEM	https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf	2021
AEMO	Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework	https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf?la=en	2024
NGESO	Great Britain Grid Forming Best Practice Guide	https://www.nationalgrideso.com/document/278491/download	2023
NGESO	GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability	https://www.nationalgrideso.com/document/159296/download	2021
UNIFI	Specifications for Grid-forming Inverter-based Resources Version 1	https://www.energy.gov/sites/default/files/2023-09/Specs%20for%20GFM%20IBRs%20Version%201.pdf	2022
HECO	Hawaiian Electric Facility Technical Model Requirements and Review Process	https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20210901_cbre_rfp/20210825_redline_lmi_appxb_att3.pdf	2021

IEEE 2800-2022 ADOPTION SUMMARY TABLE FROM MISO'S GENERATOR INTERCONNECTION AGREEMENT REDLINES*

IEEE 2800-2022 Subclause	Required by Appendix G for DPP-2022 and later	Required by Appendix G for DPP-2023 and later (proposed)	Current exception
4.1 Introduction			X
4.2 Reference Point of Applicability	X		
4.3 Applicable Voltages and Frequencies	X		
4.4 Measurement Accuracy	X		
4.5 Operational Measurement and Communication Capability			X
4.6 Control Capability			X
4.7 Prioritization of IBR Responses	X		
4.8 Isolation Devices			X
4.9 Inadvertent Energization of TS			X
4.10 Enter Service	X		
4.11 Interconnection Integrity			X
4.12 Integration with TS grounding			X
5.1 Reactive Power Capability		X	
5.2 Voltage and Reactive Power Modes		X	
6.1 Primary Frequency Response		X	
6.2 Fast Frequency Response			X
7.1 Introduction	X		
7.2.1 Voltage protection			X
7.2.2.1 Voltage disturbance ride-through: General	X		
7.2.2.2 Voltage disturbances within continuous operation	X		
7.2.2.3 Low- and high-voltage ride-through	X		
7.2.2.4 Consecutive voltage deviations ride-through		X	
7.2.2.5 Dynamic voltage support	X		
7.2.2.6 Restore output after voltage ride-through	X		
7.2.3 Transient overvoltage	X		
7.3.1 Mandatory frequency tripping			X
7.3.2 Frequency disturbance ride-through	X		
7.4 Return to service	X		

*Table is from MISO's current IEEE 2800 adoption proposal for DPP-2023. The DPP-2022 requirements are in the most recent version of MISO's tariff GIA. However, the DPP-2023 requirements are currently proposed in IPWG and have yet to be filed with FERC. A version of the Tariff redlines with MISO's proposed redlines and this table is available at: 20240604 IPWG Item 04a Attachment X Appendix 6 GIA (PAC-2024-2)_redline.docx

INFORMATIONAL TEST RESULTS FOR TESTS NO LONGER REQUIRED

Commented [PD19]: Rev 0.2: Test results for the previous LLSM Case 1, which is no longer included, are shown here for reference. MISO views this case as covered by other cases.

LLSM – Discharging Case

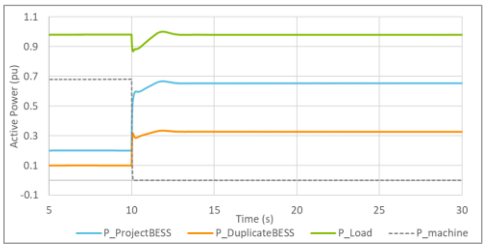


Figure 40. GFM model – LLSM discharging test - active power response after SM trip

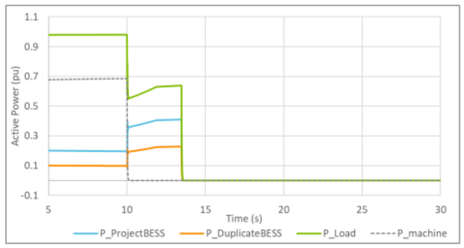


Figure 41. GFL model - LLSM discharging test - active power response after SM trip

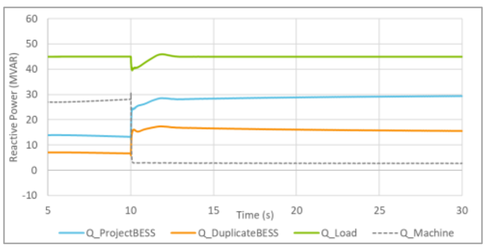


Figure 42. GFM model – LLSM discharging test - reactive power response after SM trip

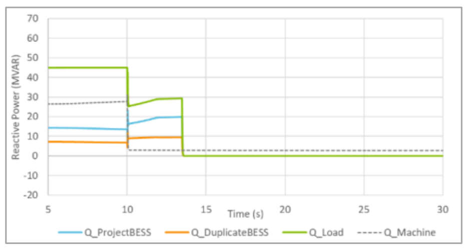


Figure 43. GFL model – LLSM discharging test - reactive power response after SM trip

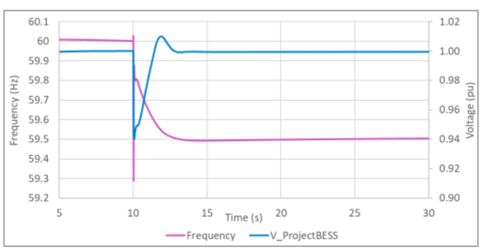


Figure 44. GFM model – LLSM discharging test – frequency and voltage

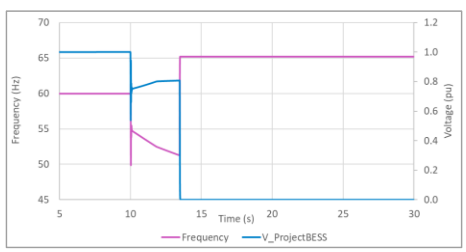


Figure 45. GFL model – LLSM discharging test – frequency and voltage

Phase Jump Test – Including 60 Degree Phase Jump

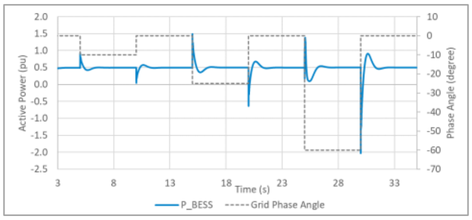


Figure 46. GFM Model – 60-degree phase jump active power response

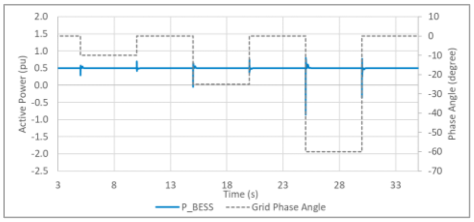


Figure 47. GFL Model - 60-degree phase jump active power response