UNIFI Specifications for Grid-forming Inverter-based Resources

Version 3

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National Laboratory of the Rockies
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nlr.gov

Contributors

The following people contributed to the development of this document and/or participated in the UNIFI Working Group on Specifications.

Ben Kroposki (National Laboratory of the Rockies)
Deepak Ramasubramanian (Electric Power Research Institute)
Andy Hoke (National Laboratory of the Rockies)
Dominic Gross (University of Wisconsin, Madison)
Wenzong Wang (Electric Power Research Institute)
Aminul Huque (Electric Power Research Institute)
Jose Cordova (Electric Power Research Institute)
Jens Boemer (Electric Power Research Institute)
Gab-Su Seo (National Laboratory of the Rockies)
Shahil Shah (National Laboratory of the Rockies)
Ramanathan Thiagarajan (National Laboratory of the Rockies)
Shuan Dong (National Laboratory of the Rockies)
Jin Tan (National Laboratory of the Rockies)
Jing Wang (National Laboratory of the Rockies)
Subhankar Ganguly (National Laboratory of the Rockies)
Michael Ropp (Sandia National Laboratories)
Jack Flicker (Sandia National Laboratories)
Charlie Hanley (Sandia National Laboratories)
Wei Du (Pacific Northwest National Laboratory)
Pedro Arsuaga (General Electric)
Sebastian Achilles (General Electric)
Philip Hart (General Electric)
Siddharth Pant (General Electric)
Rojan Bhattarai (General Electric)
Dustin Howard (General Electric)
Maozhong Gong (General Electric)
Arvind Tiwari Kumar (General Electric)
Julia Matevosyan (Energy Systems Integration Group)
Alex Shattuck (Energy Systems Integration Group)
Lee Luis (Commonwealth Edison Utility)
Honghao Zheng (Commonwealth Edison Utility)
Manish Patel (Southern Company)
Reza Pourramezan, (NYPA)
Brad Rockwell (KIUC)
Cameron Kruse (KIUC)
Richard Vetter (KIUC)
Addison Li (HECO)
Adi Mulawarman (Xcel Energy)
Brent Lease (Xcel Energy)
Xiaochuan Luo (ISO-NE)
Rajat Majumder (Ørsted North America)
Alyssa Jenkins (Mitsubishi Electric Power Products, Inc.)
Ulrich Muenz (Siemens)
Nicholas Cherouvim (Siemens Energy)
André Schön, (Siemens Energy)
Shahab Karrari (Siemens Energy)
Mian Wang (Siemens Energy)
Lucas Meubrink (SMA)
Benjamin Palethorpe (Shell)
Donny Zimmanck (Enphase Energy)_
M A Awal (EPC Power)
David Michaud (EPC Power)
Reynaldo Nuqui (Hitachi Energy)
Javier Villegas Nunez (Hitachi Energy)
Bryan Buterbaugh (Hitachi Energy)

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Marija Vujacic (Hitachi Energy)
Mahesh Morjaria (Terabase Energy)
Vijay Vittal (Arizona State University)
Raja Ayyanar (Arizona State University)
D. Venkatramanan (University of Minnesota)
Sairaj Dhople (University of Minnesota)
David Lubkeman (North Carolina State University)
Iqbal Husain (North Carolina State University)
Deepak Divan (Georgia Institute of Technology)
Joseph Benzaquen (Georgia Institute of Technology)
Brian Johnson (University of Texas – Austin)
Debjyoti Chatterjee (University of Texas – Austin)
Ali Mehrizi-Sani (Virginia Tech)

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List of Acronyms

ac	alternating current
BESS	battery energy storage system
CCT	critical clearing time
dc	direct current
EMT	electromagnetic transient
GFL	grid-following
GFM	grid-forming
HVDC	high voltage direct current
IBR	inverter-based resource
MPPT	maximum power point tracking
NERC	North American Electric Reliability Corporation
PDT	phasor-domain transient
PV	photovoltaic
ROCOF	rate of change of frequency
SCR	short circuit ratio
STATCOM	static synchronous compensator
UNIFI	UNiversal Interoperability for grid-Forming Inverters
UPS	uninterruptible power supply
VUF	voltage unbalance factor

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Definitions

Refer to other documents such as IEEE Std 2800 or IEEE Std 1547 for definitions of terms not defined here.

Grid forming (GFM): Maintains an internal voltage phasor, i.e., ac voltage magnitude and angle, that is constant or nearly constant in the sub-transient to transient time frame

Inverter-based resource (IBR): Any source of electric power that is connected to the electric power system via a power electronic interface.

Inverter-based resource (IBR plant): A grouping of one or more IBR units and possibly supplemental IBR devices operated by a common facility-level controller along with a collector system.

Inverter-based resource (IBR unit): An individual IBR device or a grouping of multiple such devices connected together at a single point of connection (POC).

Subtransient time frame: The first two to five cycles following a disturbance.

Transient time frame: The period lasting from the end of the subtransient time frame until approximately the first half second following a disturbance.

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1 Overview

At present, power system operations and controls are primarily dictated by and designed for the physical characteristics of synchronous machines. The fundamental form and feasible functionalities of power systems are rapidly evolving as more inverter-based resources (IBRs) are integrated [1]. In this document, the term 'inverter-based resource' is used in a general sense and is intended to cover plants/assets consisting of one or more inverters connected to generation, storage, and transmission/distribution-asset power electronic devices (e.g. HVDC converters, STATCOMs, etc.). An IBR can be connected anywhere in the power system, including transmission, distribution, and customer premises. The individual power electronic devices such as inverters and wind turbine generators within an IBR plant are referred to as IBR units.

To manage the integration of large amounts of IBRs, system planners need accurate IBR simulation models to assess their stability and performance under a variety of operating conditions. It is, however, challenging to acquire such models for various reasons, and if provided, internal control details are often not accessible to the user [2; 3]. Increasing use of nonlinear and adaptive control, dynamically varying system topology and configuration, and wirelessly transmitted software updates to millions of IBRs from scores of manufacturers further compound challenges associated with scalable system-level analysis. In addition, performance verification and power system stability assurance are needed to ensure proper performance of the IBRs under grid operations. Communications and distributed optimization paradigms have been proposed as solutions to the challenges highlighted above, but they do not offer options for real-time control and power system stabilization. Furthermore, cybersecurity requirements can introduce delays and challenges in this regard. Existing standards [4; 5] in this broad area are in different stages of adoption. At present these standards focus primarily on grid-following (GFL) technologies, and thus their requirements are generally not designed to ensure acceptable power system operation with grid-forming (GFM) resources. In some cases, those requirements may not be appropriate for or may even inadvertently limit the use of GFM resources.

Currently, each inverter manufacturer may have a slightly different perception or position regarding the notion of GFM and its performance. As a result, for the same event on the power grid, there can be variation in response across manufacturers. This variation results in an increased uncertainty in response across the system, which can have undesired consequences, as experienced in recent years with existing inverter technology through multiple events around the world. To avoid running into a similar situation with a widespread adoption of GFM technology, development of performance specifications is important as they can help provide guidelines to inverter manufacturers regarding the approach to be taken with respect to design and implementation of newer inverter products and associated delivery of services.

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To this end, the UNiversal Interoperability for grid-Forming Inverters (UNIFI) Consortium is addressing fundamental challenges facing the integration of GFM inverters into the power system alongside rotating machines and other IBRs. This document defines a set of UNIFI specifications for GFM IBRs that provides functional requirements at the inverter level for vendor-agnostic operation of GFM IBRs at any scale in electric power systems. The specifications in Sections 2 and 3 are general enough that they can be applied to an IBR plant or an IBR unit. The test procedures in Section 5 are intended to apply to IBR units; it may also be possible to apply them to IBR plants in many cases, though the UNIFI team has not vetted them for that purpose. The frequency-domain specifications in Section 6 are also intended for IBR units. Future work should address plant-level conformity assessment with GFM performance requirements.

1.1 Grid-Forming (GFM) Controls

The UNIFI Consortium defines GFM IBR controls as follows in accordance with the North American Electric Reliability Corporation (NERC) [6] definition:

> "GFM IBR controls maintain an internal *voltage* phasor, i.e., ac voltage magnitude and angle, that is constant or nearly constant in the sub-transient to transient time frame."

The time frames specified in this section are intended as general descriptions rather than requirements or hard limits as sub-transient and transient times are a function of machine characteristics. This definition means that the GFM IBR will nearly immediately (in the sub-transient time frame) begin to respond to changes in the external system and attempt to maintain IBR control during challenging network conditions to maintain grid stability. In GFM IBRs, the voltage phasor is controlled to maintain synchronism with other devices in the grid at steady-state conditions while regulating the active and reactive power appropriately to support the grid.

This contrasts with conventional GFL IBR controls wherein immediately after a disturbance (0-5 cycles), within the normal operating range of voltage, the output *current* phasor magnitude and angle remain nearly unchanged, and the current phasor begins changing only within the transient time frame (tens of cycles) to strictly control the active and reactive power being injected into the network. This change in current is the result of the action of outer loop controls within the GFL IBR.

For a disturbance within the normal operating range of voltage, on the shortest (sub-transient) timescales (roughly 0-5 cycles after a disturbance), a conventional (or legacy) GFL inverter's control objective is to maintain its output current. Subsequently, in the transient timescale (tens of cycles), its objective is to maintain the desired active power and reactive power or change it according to a transient setpoint change, e.g. due to frequency-droop operation, so it does not maintain a fixed voltage magnitude or phase angle on those timescales. On longer timescales (a couple of seconds for conventional/legacy GFL plants and 50 ms to a couple of seconds for new

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GFL IBR plants), it can also pursue other control objectives such as maximum power point tracking (MPPT), frequency response, and voltage regulation (usually based on commands provided by a plant controller).

On the other hand, a GFM inverter's control objective, on the shortest (sub-transient) timescales (roughly 0–5 cycles after a disturbance), is to maintain the desired voltage magnitude and phase angle and prioritize the support of voltage magnitude and frequency at its terminals. Because of its implicit prioritization of attempting to maintain voltage magnitude and phase angle in the sub-transient time frame, a GFM inverter does not maintain fixed active or reactive power on those timescales. On longer timescales, a GFM inverter that is designed to operate on a power system with other GFM devices or synchronous machines adjusts its voltage and frequency to synchronize with other sources.

The primary energy source and IBR rating may limit the capability of the IBR to provide capabilities and services.

Newer IBR plants with GFL controls can provide fast frequency and voltage response within the sub-transient timeframe. As a result, the demarcation line between GFL and GFM can become blurred in terms of responses to disturbances and as such, UNIFI recommends the use of performance specifications and functional requirements to determine the necessary and required operation from IBR plants.

IBRs can potentially have a large spectrum of control objectives and the terms GFL and GFM may be too general. The GFL/GFM distinction may fail to reflect the relevant variation in the spectrum of IBRs' capabilities and cause the importance of existing IBRs' capabilities to be underestimated.

Because different types of GFM IBRs have different capabilities and limitations, this document proposes four tiers of GFM device capability, as summarized in Table 1 and further detailed in Appendix A. Each GFM tier builds on the capabilities of the tier below. GFM Tier 1 devices exhibit GFM capabilities only in the reactive power-voltage dimension because they are not required to be capable of maintaining an active power reserve; a GFM static synchronous compensator (STATCOM) is an example of a GFM Tier 1 device. GFM Tier 2 devices add limited GFM capability in the active power-frequency dimension; an E-STATCOM (a STATCOM with a few seconds of energy storage) is an example of a device that fits in GFM Tier 2. GFM Tier 3 devices have full GFM capability in the active power-frequency dimension and can support islanded operation; a GFM battery energy storage system (BESS) is an example. GFM Tier 4 adds black start capability. See Section 0 and Appendix A for additional details.

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Table 1. GFM Performance Tiers

GFM Tier	Key Function(s)	Examples of Resource Types	Notes
1	Voltage magnitude support	GFM STATCOM	
2	Voltage angle/frequency support & minimum islanding capability	GFM E-STATCOM, GFM wind turbine (Type 3 and Type 4), GFM PV	Active power contribution is subject to complex intermittency, asymmetry, headroom, and resonance (for GFM IBRs with rotating machines) aspects.
3	Voltage angle/frequency support & extended islanding capability	GFM BESS	
4	Black start	GFM BESS with black start	

Section 0 and Appendix A also contain details of frequency-domain specifications for the GFM tiers. These frequency-domain specifications are recommended normative requirements. Manufacturers of GFM devices are encouraged to review the frequency-domain tests, try them out on their devices, and provide feedback to the UNIFI Consortium. It is possible that the frequency-domain specifications will be extended to higher frequencies in future revisions.

A key aspect of GFM control is that it allows an IBR to act as a voltage source behind an impedance within some limits and within some frequency range. Recent work by the Energy Systems Integration Group [7] has detailed methods of characterizing this behavior in the frequency domain. For resources that exhibit this behavior, a summary of the characterization method is provided in Section 6.3, and corresponding requirements are included in the frequency-domain specification in 6.1.

1.2 Scope

The UNIFI Specifications for GFM IBRs establish functional requirements and performance criteria for integrating GFM IBRs into electric power systems at any scale. This may include devices used at the local customer, microgrid, distribution, and transmission scales. These specifications cover all grid-forming technologies applications including, but not limited to battery storage, solar photovoltaics (PV), wind turbines, high voltage direct current (HVDC) systems, static synchronous compensators (STATCOMs), uninterruptible power supplies (UPS), supercapacitors, fuel cells, or other yet-to-be-invented technologies. While each may have different dc side and energy limitations, this specification focuses on the ac side performance requirements as they relate to interoperability between GFM IBRs and the power system.

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1.3 Purpose

The purpose of the UNIFI Specifications for Grid-forming Inverter-based Resources is to provide uniform technical requirements for the interconnection, integration, and interoperability of GFM IBRs of any size in electric power systems of any scale.

1.4 Limitations

Local system conditions and scenarios, hardware device limits, and limitations of the source behind the IBR (e.g., energy storage state of charge, wind turbine mechanical constraints, non-linear DC source characteristics) can impact the ability of a GFM resource to meet the performance criteria. In such situations, detailed studies and assessments should be carried out to determine whether and to what extent the performance criteria can be relaxed under a mutual agreement with all the parties such as manufacturers, developers, and system planners. Further, performance requirements for GFL plants, such as the performance requirements laid out in standards such as IEEE 2800-2022 [5], ENTSO-E [8] Requirements for Generators, and IEEE 1547-2018 [4], generally also apply to GFM IBRs. There are circumstances in which a requirement of a standard such as IEEE 1547-2018 or IEEE 2800-2022 is not practical for a GFM IBR and exceptions may be warranted until these standards can be updated to fully account for GFM inverters. For example, since GFM IBRs are prioritizing voltage response, they may not control power as quickly as GFL IBRs. The synchronization-related performance criteria in this document do not apply to a GFM IBR that is designed to act as the only grid-forming resource in a power system, without the need to synchronize with other GFM sources or other power systems.

This document specifies GFM capabilities but does not specify the utilization of those capabilities. In general, a capability is an inherent property of a device or plant, and its utilization refers to how it is operated. See Clause 1.4 of IEEE 2800 for a discussion of capability versus utilization.

Constraints on power, energy, and current can impact the utilization of GFM capabilities. For example, an operator would need to maintain headroom to ensure a GFM Tier 3 device can meet Tier 3 performance expectations at any given moment, but operation of the device or the plant it is part of is not in the scope of this document. The capability associated with each GFM Tier is an inherent characteristic of the GFM device, but how it is operated is not. In other words, if a Tier 3 GFM device is sometimes operated without active power headroom, its GFM performance may be limited at those times, but that does not mean the device itself is not in GFM Tier 3.

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1.5 Constraints Due to Input Source

Site-specific integration and operation studies should consider the ratings of the GFM IBRs utilized. The GFM IBR may specify performance metrics (e.g. the speed and duration of power response to disturbance or other parameters) that may be constrained by the basic limitations of the DC source. The GFM IBR's input source can influence the performance of the inverter and may impact its ability to provide specific grid services. For example, a wind turbine's speed of response to frequency variations in the grid may be slower than a battery energy storage system's speed of response.

A GFM IBR's ability to respond to disturbances depends on both the IBR's capability and how the IBR is operated; specifically, when at or near a power, energy, or current limit, the GFM performance may be reduced. This document specifies the IBR's capability, but it does not specify how the IBR should be operated. Because a GFM IBR is required to be dispatchable (per section 2.1.2), it should be possible to operate it such that a margin relative to the IBR's power and energy limits is maintained if desired.

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2 Performance Requirements for GFM IBRs

This section describes performance requirements for GFM resources connected to an electric power system based on the GFM tiers described Appendix A. These performance requirements are to be provided regardless of the type of GFM resource and the strength of the grid to which it is connected. There can be an overlap between some of the expectations listed in this section for GFM and the performance expectations of GFL resources. As understanding of the applicability of GFM technology evolves, different sets of requirements may be established depending on the power system type and scale that the GFM IBR is or will be interconnected to.

These requirements may not completely apply to GFM inverters that are not intended to parallel with larger power grids and operate only in a stand-alone mode. Further requirements might be needed for stand-alone operations.

The first column of Table 2 summarizes the GFM requirements, and each requirement is described in more detail in the remainder of this section. Table 2 also states which requirements are unique to GFM IBRs and which are not.

For the requirements that are unique to GFM IBRs, Table 2 points to which test procedure(s) from Section 5 apply to that requirement. This document does not generally provide test procedures for requirements that are not unique to GFM; for such requirements, conformity assessment should refer to applicable interconnection standards, grid operator requirements, or regional requirements. The test procedures focus on GFM Tier 3 and above, and the test criteria focus on the equipment level. See Section 5 for additional information and test details.

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Table 2. Overview of Requirements and Tests

Requirement	GFM Has a Unique Requirement?	Applicable Test
2.1.1: Autonomously Support the Grid	No	NA
2.1.2: Dispatchability of Power Output	No	NA
2.1.3: Provide Positive Damping of Voltage and Frequency Oscillations	Some GFL could comply depending on oscillation frequency	Frequency scan tests in Section 0 and Appendix A. Also spot-checked in various time-domain tests in Section 5.
2.1.4: Active and Reactive Power Sharing across Generation Resources	No	5.9: Loss of Grid Connection Test
2.1.5: Operation in Grids with Low System Strength	Yes, for very weak grids	5.3: System Strength Test
2.1.6: Operation under System Unbalance	Some GFL comply	5.4: Unbalance Step-Up Test
2.2.1: Voltage Ride-Through Capability	No	Refer to relevant interconnection standard, e.g. IEEE 2800 or IEEE 1547
2.2.2: Performance During Symmetrical Faults	Some GFL comply	5.5: Fault Test (informative)
2.2.3: Performance During Asymmetrical Faults	Some GFL comply	5.5: Fault Test (informative)
2.2.4: Abnormal Frequency Ride-Through Capability	No	Refer to relevant interconnection standard, e.g. IEEE 2800 or IEEE 1547
2.2.5: Performance in Response to Frequency Deviations	Yes, in subtransient timeframe.	5.6: Response to Frequency Change Test
2.2.6: Performance During Phase Jumps and Voltage Steps	Yes	5.7: Phase Angle Jump Test 5.8: Small Voltage Step Test
3.1: Intentional Islanding	Yes	5.9: Loss of Grid Connection Test
3.2: Black Start and System Restoration	Yes	Requirements are application-specific; no generic test provided here.
3.3: Regulating Voltage Harmonics	Some GFL comply at least partially	No consensus on quantitative GFM-specific requirement; no test provided here. Relevant interconnection standard applies.
3.4: Communications between System Operator and IBR Plant	No	NA
3.5: Secondary Voltage and Frequency Signal Response	No	NA

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2.1 Performance Requirements for Operation Within Normal Grid Operating Conditions

Normal operations for electric power system locations are defined by operation within a narrow range around nominal voltage and frequency (referred to as normal voltage and frequency ranges), with the ability to go outside of those ranges for short periods of time (for events such as motor starting, step load change, step generation change, and other similar events on the system). Normal operational conditions for a power system are typically given by a standard (e.g., ANSI C84.1). To maintain reliable grid operations, it is essential that power system generators be able to maintain voltage and frequency within the specified ranges during normal operation and return the system to normal operational ranges after an event that would take them outside the ranges.

2.1.1 Autonomously Support the Grid

2.1.1.1 Requirements

GFM IBRs are expected to autonomously respond to changes (both transient and steady state) in their locally measured signals (e.g., terminals of IBR or point of interconnection (POI) voltage, current, and frequency) to support the local power system per the appropriate GFM performance tier.

2.1.1.2 Comments

For example, in the transmission network, if an IBR's locally measured voltage drops, the IBR or IBR plant may be expected to increase its reactive power output to help raise the power system voltage to a pre-defined scheduled voltage, regardless of whether it is GFL or GFM. Note that there are other allowable operating modes for GFL such as fixed power factor mode. If a grid event occurs that leaves a GFM IBR connected to a weak grid (i.e., voltage sensitivity and/or low inertia) the GFM IBR should be able to continue to help maintain nominal voltage and frequency of the grid, up to the level it can support. The level of support from the GFM IBR plant may be related directly to its hardware limitations (e.g., current rating of IBR, energy storage state of charge, etc.), or it may be limited by downstream or system side devices such as transformer or cable thermal limits external to the IBR or IBR plant itself. This autonomous grid support should occur over the sub-transient and transient timescale. Over longer time scales, it is possible the plant itself will receive outside communications of new dispatch setpoints or curtailment from a system operator working to manage the grid event.

2.1.2 Dispatchability of Power Output

2.1.2.1 Requirements

When operating as part of an interconnected grid, a GFM IBR plant's steady state power output, within the normal range of voltage magnitude and frequency, should be dispatchable either through system operator control or by a locally determined goal that may be based upon a market clearing solution. GFM resources in Tiers 1 are not required to have dispatchable active power, but shall have dispatchable reactive power. Tier 2 GFM resources may or may not have

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dispatchable active power, but shall have dispatchable reactive power. Tier 3 and Tier 4 GFM resources shall have dispatchable active and reactive power capability.

2.1.2.2 Comments

For a GFM IBR whose primary input is a variable resource (e.g., wind or solar), it may be set to export maximum available output power as determined by wind speed or solar irradiance (unless expressly asked by the system operator or local controls to adjust power). A GFM IBR with energy storage as its primary resource may change its power output based on available capacity. If there arises a constraint on the network that requires the GFM IBR's steady state power output to be changed, it should be possible to do so by remote control. The dispatchability of a GFM IBR is determined by the operating point of the GFM IBR and subject to any headroom available. Limits of GFM IBR should be understood by the dispatcher. See Section 3.4 for additional information on GFM IBR communication considerations.

2.1.3 Provide Positive Damping of Voltage and Frequency Oscillations

2.1.3.1 Requirements

It is expected that a GFM IBR will present a non-negative resistance or damping to the grid within the frequency range of common grid electrical resonances to prevent the initiation of any adverse interactions or oscillations. See Section 6 and Appendix A for details of the applicability of this requirement to different GFM tiers and quantified frequency-domain requirements.

2.1.3.2 Comments

Specific details on the magnitude of damping are expected to be provided by the system planner on a system specific basis. The GFM IBR should avoid negative damping effects with low-frequency resonances related to series compensation of transmission lines. GFM IBR should also avoid higher frequency resonances due to shunt capacitances or line/cable charging, and resonances due to control interactions with GFL IBRs. If a resonance or oscillation occurs, the GFM IBR should provide damping within its capabilities, using locally measured signals and without observability of the network and control algorithms of other devices connected to the power system.[1] Exceptions to this requirement may be warranted in circumstances where an internal resonance within the IBR coincides with a grid resonance, in which case the IBR may prioritize self-protection over providing damping. The GFM IBR is also expected to not introduce any new unstable oscillatory modes into the power system or exacerbate existing

[1] Some IBRs such as wind turbines also require internal damping power to damp out drive train and tower oscillations. The power variation due to the provision of this damping power should be considered as the baseline behavior. GFM performance requirements should be specified and evaluated as a superposition on top of this baseline performance. For example, if there is a small power dip at a particular instant to damp drivetrain oscillations, and a phase jump happens at the same instant, the power/energy increase due to the phase jump would be less than the power increase that would be seen if the phase jump happed at a different instant when the drivetrain damping caused the power to increase.

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oscillatory modes. This requirement is not intended to imply that all GFM IBRs must have capabilities similar to power system stabilizers. Non-negative damping may be achieved as a result of the GFM control itself.

2.1.4 Active and Reactive Power Sharing Across Generation Resources

2.1.4.1 Requirements

A GFM IBR is expected to autonomously share power (e.g., incrementally increase or decrease power burden within its capability) with other generation resources at all times using the principles of droop akin to the operation of conventional synchronous generators or GFL IBRs. IBRs in all GFM Tiers shall share reactive power. For Tier 1 GFM IBRs, only reactive power sharing is required. Tier 2 has limited active power sharing capability, and Tiers 3 and 4 have full active power sharing capability.

2.1.4.2 Comments

As an example, on the transmission system, this property is typically achieved from resources via droop on frequency for sharing of active power [9] and droop on voltage for sharing of reactive power. It is expected that principles of droop will most likely be employed, at one or more timescales, to achieve this autonomous power sharing and supply/load balance. Here, droop is not meant to signify the type of GFM control but rather implies the property of interoperation that any GFM control type must possess. In other words, this requirement is not meant to imply that the GFM control structure known as "droop-based GFM" is required; other control structures are permitted as long as a droop output characteristic is presented to the grid. The expectation is that the system will achieve a steady-state operating point (potentially off-nominal) within the normal operating voltage and frequency ranges while ensuring proper power sharing and balance between total supply and total generation, after a disturbance. Headroom to provide droop can be mandated or maintained and may be dependent on economic and market procurements.

2.1.5 Operation in Grids With Low System Strength

2.1.5.1 Requirements

A GFM IBR is expected to operate stably when connected to a power system with a low system strength, as evaluated in the test described in Section 5.

2.1.5.2 Comments

This requirement validates GFM performance at low SCR in a simple test system. Operation in the specific system where the IBR will be installed should be evaluated separately. Operating below the SCR levels tested in Section 5 should also be possible if the GFM IBR is permitted to reduce active power to account for steady state network power flow limitations.

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System strength is a term used to describe how much and how fast a system's voltage (and, in some definitions, frequency) change after a disturbance. The system strength can impact the settings for control algorithms in IBRs. There are several metrics that are used to evaluate the relative strength of a power system at a location. These include the short circuit ratio (SCR), the rate-of-change of frequency (ROCOF) during grid disturbances, the critical clearing time (CCT) of short-circuit faults to ensure stable operation after fault clearance, and the rate of change of voltage in response to changes in current injection to the grid (i.e., apparent source impedance). These metrics have been developed based on the operational characteristics of synchronous generators and may not be appropriate as metrics of system strength in systems with high levels of IBRs because of the absence of rotating inertia and synchronizing torque. Conventionally, GFL inverters may have operational challenges/constraints in weak systems. To overcome this, GFM inverters can be considered as a solution. However, the concept of strong and weak networks, and the metrics used to quantify the strength of a network can vary from one system to another and one operating condition to another.

Improvements in system strength due to GFM IBRs are expected to be within GFM IBR equipment limits and may not entail injection of current beyond GFM IBRs' rated capability. Instead, this improvement can be correlated with the response of the GFM IBR current and/or power to small changes in system voltage magnitude, voltage phase angle, or frequency, which in turn can be dependent on software, controls design, and tuning.

2.1.6 Operation Under System Unbalance

2.1.6.1 Requirements

A GFM IBR should not actively oppose or prevent the flow of negative sequence current for small levels of voltage unbalance.

2.1.6.2 Comments

If the provision of large amounts of negative sequence current introduces stress to equipment, reduction or limitation of the magnitude of the current may be allowed after discussion with the system operator. In such a case, a continuous negative sequence current limit may be imposed besides the total current limit. Instead of opposing the flow of negative sequence current, a GFM IBR should provide negative sequence current within its negative sequence current capability and total current capability to facilitate voltage balance. In addition, provision of negative sequence current from GFM can help existing protection devices in detection of unbalanced faults. Asymmetric inverter protections may need to be updated to allow for negative sequence current while in GFM.

When it operates within its negative sequence and total current capability, the GFM IBR should aid in reducing the voltage unbalance factor (VUF) [10] measured at the point of connection of a GFM IBR plant. In the case of a GFM IBR interconnected on a single phase (e.g., in residential applications), the voltage balancing requirement may not be applicable.

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2.2 Performance Requirements for Operation Outside Normal Conditions

Abnormal conditions on the electric power system (e.g., temporary and permanent faults, oscillations, motor stalls, delayed voltage recovery, generation loss, load loss, blackouts) are characterized by voltage and frequency excursions outside of the normal operating ranges.

The GFM IBR can trip for abnormal conditions when such tripping is allowed or required by IEEE 1547-2018 or IEEE 2800-2022 or other applicable requirements or standards as appropriate.

Under abnormal grid conditions, the GFM IBR should perform according to the following requirements.

2.2.1 Voltage Ride-Through Capability

2.2.1.1 Requirements

A GFM IBR is expected to ride-through events that result in operations outside normal limits. The ride-through capability should follow applicable standards (e.g. IEEE 1547, IEEE 2800) or grid operator requirements. This includes not just voltage ride-through, but also ride through of other events specified by the relevant standard or system planner such as voltage phase angle jumps,

2.2.1.2 Comments

During and immediately after a major grid event, it is recommended that a GFM IBR adhere to the following principles, listed in order of priority:

1. Self-protection: The GFM IBR should be allowed to prevent its current, active power, energy or any other critical variable from exceeding—even momentarily—a pre-specified maximum capability.

2. System-wide stability: To the extent possible, provided that the GFM IBR has not yet encountered any equipment-related constraints and hence does not need to employ self-protection, the GFM IBR should retain its grid-forming behavior throughout and immediately after the event and operate in a manner agreed-upon between plant owner, inverter OEM, and system planner/operator that prioritizes system-wide stability.

3. Optimality: To the extent possible, provided that priorities of self-protection and system-wide stability are both first met, the GFM IBRs should also adhere to (or return to) their desired power and/or reactive power setpoints after a major grid event.

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2.2.2 Performance During Symmetrical Faults

2.2.2.1 Requirements

During symmetrical undervoltage events (e.g. due to faults) and symmetrical overvoltage events, a GFM IBR is expected to maintain a balanced internal voltage to the extent possible within its physical limits. The GFM IBR should inject current to oppose the change in voltage.

2.2.2.2 Comments

The maximum current injected during faults is defined as the IBR short-term rated current (ISRC). The ISRC can be more than the continuous rated current for a time-limited period, but without exceeding the IBR's absolute maximum current capability, to increase the range of conditions under which the IBR is able to support voltage and frequency. The GFM IBR data sheet should provide a magnitude and duration for ISRC that enables the GFM inverter to support protection operations or events like transformer inrush and motor starting. For example, an ISRC could be given as "provides 1.5 times full-rated current for 2 s". This value can also be programmable in terms of magnitude and time setting to coordinate with other protection devices. This capability might also impact the response of unbalanced faults wherein the current on one phase exceeds that of the others (see 2.2.3). The intent is to allow OEMs to provide what system operators request. The need for current overload capacity will differ between systems.

The purpose of this requirement is to meet the needs of protection elements such as overcurrent, distance, and directional elements. Upon fault clearance, the GFM IBR is expected to support the stability of other devices in the post-fault network.

2.2.3 Performance During Asymmetrical Faults

2.2.3.1 Requirements

During asymmetrical faults, a GFM IBR is expected to maintain a balanced voltage to the extent possible within its physical limits. This naturally results in the GFM IBR outputting unbalanced currents, including negative sequence currents.

2.2.4 Abnormal Frequency Ride-Through Capability

2.2.4.1 Requirements

As long as the frequency remains within the must-not-trip region defined by the system planner or by the applicable standard (e.g. IEEE 1547-2018, IEEE 2800-2022, or other applicable requirements or standards), a GFM IBR is expected to ride through frequency events.

2.2.4.2 Comments

Reserved.

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2.2.5 Performance in Response to Frequency Deviations

2.2.5.1 Requirements

A GFM IBR is expected to modulate active power as required during and after frequency changes to aid in frequency recovery and stability. Tier 1 GFM IBRs are excepted from this requirement.

2.2.5.2 Comments

In the sub-transient time frame, the power to be injected is expected to have a similar effect to that of resisting frequency change subject to the physical limits of the GFM IBR unit and the source behind the GFM IBR.[2] This behavior can manifest as a form of fast frequency response and can aid in reduction of ROCOF of the network, though it may not fit the specific definition of fast frequency response used in some regions. Beyond the sub-transient time frame, the GFM IBR is expected to respond to frequency adjustments by internal or external controllers to share power (droop) with other resources. Over longer time frames, the energy source behind the GFM IBR may constrain the ability to deliver sustained active power.

2.2.6 Performance During Phase Jumps and Voltage Steps

2.2.6.1 Requirements

A GFM IBR is expected to absorb or inject active and/or reactive power to resist changes in positive sequence voltage phase angle and is expected to do so unless it exceeds an equipment limit.[3] Similarly, a GFM IBR is expected to absorb or inject reactive/active power to reduce changes in the positive sequence voltage magnitude. Active power injection is not required for Tier 1 GFM IBRs.

[2] See footnote 1.
[3] See footnote 1.

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3 Additional GFM Capabilities

This section describes additional capabilities that may be implemented in coordination with the system operator. These considerations will vary from site to site, so they should not be considered universal requirements for GFM IBR units or GFM IBR plants.

3.1 Intentional Islanding

3.1.1 General

Intentional islands are parts of electrical power systems that operate separately from the main power grid. Examples include islanding of an area in a larger interconnected transmission system or formation of a microgrid in the distribution network. Intentional islanding covers both planned and unplanned events.

3.1.2 Requirements

A GFM IBR that is designed to maintain an intentional island (i.e. Tier 3 and Tier 4 GFM IBRs) is expected to be capable of maintaining stable voltage and frequency when intentional islanding occurs.

3.1.3 Comments

Not all GFM IBRs within the intentional island may have intentional islanding capability. For example, an intentional island could contain Tier 1 or Tier 2 IBRs in addition to the Tier 3 or Tier 4 IBR(s) that sustain the island. This capability depends on certain conditions, such as: (i) there is sufficient aggregate generation within the island to meet the aggregate load, accounting for variations in generation; (ii) the remaining network within the island has sufficient power transfer capability such that the aggregate generation within the island can be transmitted to the aggregate load within the island; and (iii) there is sufficient GFM capability, either from one or multiple plants, to maintain stable island operations to meet auxiliary functions (including mechanical loading demands for wind or other technologies) for all the resources within the island. Once the operation of the island has stabilized, the GFM IBR plant's voltage and frequency operating ranges should be adequately set to allow continuous operation over the load range of the island without tripping on voltage and/or frequency protection settings as defined by the system planner or by applicable standards or respective protection studies. Other standards such as IEEE 1547 and IEEE 1547.4 may contain relevant information [4]. [11].

This document does not cover unintentional islanding.

3.2 Black Start and System Restoration

3.2.1 General

GFM IBRs in GFM Tier 4 are designed and programmed to provide black start services. If implemented, these black start services should be coordinated with system operators to help in

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system restoration from black-out conditions. Having GFM IBRs with black start capabilities may be essential in high IBR penetration grids since the black start capability may no longer be provided by synchronous machines. Not all GFM IBRs are expected to be able to provide black-start services since it may require additional hardware, design, and functionalities, and therefore implementing black-start capability may incur additional cost and require special coordination with system operators.

3.2.2 Requirements

Those GFM IBRs that are designated to provide black start services should be designed to be able to:

1. Start and establish the voltage without an external voltage or frequency reference at the ac terminals.

2. Supply transformer, cold-load, and other inrush current needed within the GFM IBR limits. This process is a key step in black start since it may cause significant inrush current, especially from transformers and motor loads, which is, in general, more challenging when using IBRs than synchronous generators due to lower overcurrent capability. To facilitate restoration, it may be useful to soft start loads (i.e., by ramping up the output voltage at a programmable rate).

3. Provide a steady voltage reference for GFM and GFL IBRs and other resources to synchronize to and facilitate a smooth system restoration including synchronization with other restored portions of the grid. Note some GFM IBRs may be configured to synchronize their own voltage and phase angle to a primary GFM that is providing the voltage waveform for the entire system.

4. If designed to operate in parallel with other black-start GFM IBRs, it should be able to achieve collective black start. This is optional and only needed for black start using multiple GFM IBRs. This technique is used when the baseline load exceeds one single GFM IBR's capability. This functionality may incur additional complexity, but it would increase flexibility and survivability of the system.

3.2.3 Comments

The capabilities described here are generic; system operators may specify further requirements such as start-up time from blackout, voltage and frequency regulation range, minimum energy requirement, and duration of the service.

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3.3 Regulating Voltage Harmonics

3.3.1 Requirements

The harmonic distortion of the line-to-neutral voltage waveforms produced by a GFM IBR plant should comply with the requirements of the system planner. As a result, a GFM IBR may inject harmonic currents at its point of interconnection to aid in reducing the amplitude of voltage harmonics induced by other power system components. It is not required that GFM IBRs actively mitigate voltage harmonics emanating from the AC grid side.

3.4 Communications Between System Operator and IBR Plant

3.4.1 Requirements

When communications are required between the GFM IBR units or plant and the system operator, a *cyber-secure communications* [12] method should be used. The power system and the GFM IBR should continue to function as specified by the system operator when communications are delayed or interrupted. It is expected that signals from the power system operator or an aggregator would have an update rate on the order of seconds and represent a secondary control signal (primary control being autonomous controls inside the IBR unit) for providing power flow set points or other commands. Faster communications may be needed to respond to transient conditions. A GFM IBR or IBR plant and associated equipment may also provide signals back to the power system operator. Examples of these signals include status signals such as online devices, switch states, capacity and headroom, and metered values such as frequency, voltage, or power flows. Distribution-connected GFM IBRs will be required to have the capability of communicating as specified by the system operator and respective interconnection standard.

3.5 Secondary Voltage and Frequency Signal Response

3.5.1 Requirements

GFM IBR plants that are expected to participate in secondary control, should be able to receive an external signal that enables power flow control from a system operator. This is known as the secondary control signal since the IBR unit or IBR plant receives an external signal to adjust power output. Once it receives new setpoints, the GFM IBR plant is expected to operate (within the GFM IBR's limits) at the new steady state condition within the time specified by the system operator. Tier 1 GFM IBRs are not required to be capable of participating in secondary frequency control. Tier 2 GFM IBRs may also be excepted from this requirement.

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4 Modeling and Documentation

When designing and planning the integration of GFM IBR in power systems it is often helpful to be able to accurately model the behavior of the GFM IBR under a wide range of operating parameters. The model should accurately represent all operational modes available in the IBR and the documentation should describe how to configure the modes and parameters. The behavior of the GFM IBR when approaching or encountering physical limits is expected to be captured in the manufacturer's provided and validated electro-magnetic transient (EMT) model and phasor-domain transient (PDT) model to allow for accurate simulation of the GFM IBR's response to various events. For example, the EMT model should include fault current shaping behavior of the GFM IBR, such as the waveform of current during the fault and its duration if the fault current is designed to last only for a short period of time.

Because EMT simulations are a primary means of validating GFM performance, the EMT model of a GFM IBR should be validated. A validated EMT model is one whose output has been compared to hardware test data and shown to match sufficiently. IEEE P2800.2 contains hardware test procedures and model validation procedures; these can be leveraged for GFM IBR unit model validation. Annex G of IEEE 2800-2022 also includes recommendations for modeling IBR plants.

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5 GFM Conformity Assessment Procedures

These GFM conformity assessment procedures consist of simulation tests that rely on an EMT model of the IBR, which is assumed to have been validated against the actual GFM IBR hardware. Procedures for model validation against hardware tests are not provided in this document; they can be found, for example, in IEEE P2800.2 [13].

This section contains test procedures designed to confirm GFM equipment performance. The tests are written to assess the capabilities of GFM Tier 3 or Tier 4 IBRs only. This is because, at the time of this writing, limited UNIFI experience exists with non-BESS GFM IBRs, so there is not yet a consensus in industry on quantitative GFM performance criteria for other IBR Tiers. Some tests may be able to be used for GFM Tier 1 and Tier 2 IBRs directly, and other tests may be able to be used with modifications; the applicability of these tests for IBRs that are not in Tier 3 or Tier 4 is not in the scope of this document. In addition, this document does not contain any test for black start capability of Tier 4 IBRs because black start capability is application specific.

These tests are intended to be used for equipment-level GFM capability verification, so the IBR model under test represents an individual GFM unit. The GFM unit may be scaled up as is typical in aggregated IBR plant models. A transformer should be included in the model if the OEM recommends that. A plant controller may be included in the model under test if desired. The test report should state what was included in the model under test.

It may also be possible to run these tests on complete IBR plant models, but that is not required by this document. The applicability of these tests and the appropriateness of the test criteria for complex IBR plants containing other devices in addition to the GFM IBRs is outside the scope of this document. For example, these tests may or may not be appropriate for hybrid plants where some resources are GFM and others are GFL.

These tests are not intended to assess an IBR plant's capability to perform in site-specific applications. A potential future version of this document may include plant-level conformity assessment procedures.

Failing one test by small margin may not be grounds for exclusion of a technology if its performance in the desired application is favorable. For example, existing synchronous machine technology may not pass all tests.

Most of these test procedures were derived from tests already in use by industry. For example, various grid operators starting with Hawaiian Electric have applied similar simulation-based tests to determine whether an IBR is or is not GFM [14]. Part of Hawaiian Electric's test, which is targeted at GFM BESS, was incorporated into NERC's GFM BESS specification [15], versions of which are now in use or proposed by AEMO, ERCOT, MISO, and others [16-18]. Other groups are also developing GFM test procedures; most recently, the Energy Systems Integration

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Group published *Testing the Performance of Grid-Forming Resources: Test Methods and Performance Metrics for Evaluating the Voltage Source Behavior of Grid-Forming Resources* [7].

The frequency-domain GFM specifications in Section 0 and Appendix A contain frequency-domain tests. The frequency-domain tests are intended for informational purposes and not for conformity assessment currently. It is possible that the frequency-domain tests may become required (i.e. normative) in the future, so GFM IBR OEMs are encouraged to try them in preparation and provide feedback to the UNIFI team. The method for evaluating GFM voltage-source behavior in Section 6 also leverages frequency domain test procedures based on [7].

5.1 Test Setups

All tests proposed here are run using one of two simple test systems. All per-unitized quantities are defined on the basis of the IBR's rated active power. Test setup 1 (Figure 1) is used for all tests except for the loss of voltage source test. It uses a variable impedance Z = R + jX. The magnitude of Z is defined in terms of the SCR seen by the IBR; |Z| = 1/SCR, in per unit terms on the basis of the IBR rating. The voltage source is ideal (zero impedance) with controllable magnitude, phase and frequency. Unless otherwise specified, the frequency of the source is the nominal system frequency, and its voltage is balanced. The fault can be configured to connect two or three phases to ground through a controllable impedance.

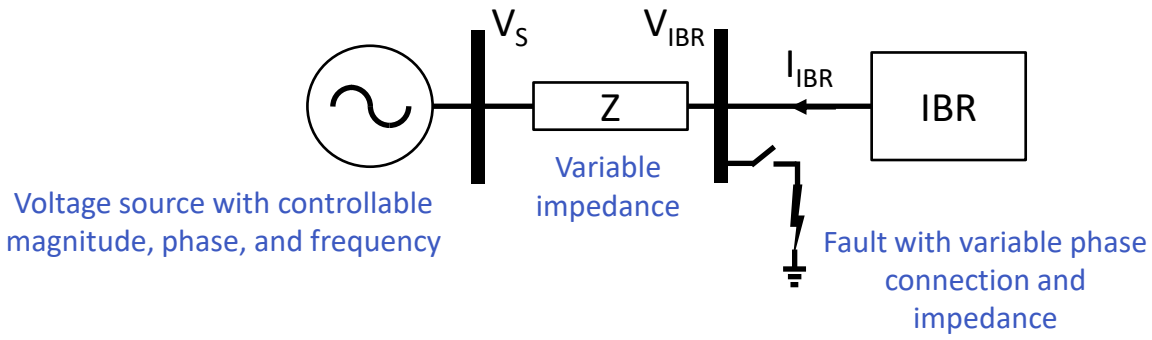

Figure 1. Test setup 1

Test setup 2 (Figure 2) is used for the loss of grid connection test. The load has a power factor of 0.95 and is a constant impedance load with an adjustable nominal power level.

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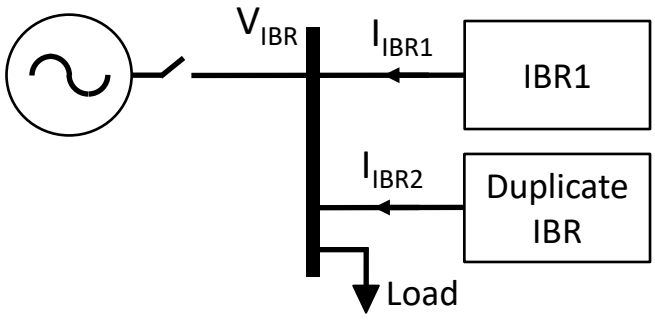

Figure 2. Test setup 2

To be considered GFM, the IBR under test shall pass all tests using the same control settings, parameters, and firmware. A power plant controller may be included in the tests.

5.2 Test Reporting

The test report shall include:

- IBR product model identifiers (e.g. model name/number, software and firmware versions, etc.). The same model shall be used for all tests.
- Record of IBR configuration used for testing. For example, this may take the form of a list of IBR parameters that were changed from default values during testing, if any. (The same parameters shall be used for all tests.)_
- Power plant controller product model identifier (e.g. model name/number, software and firmware versions, etc.), if used.
- Recording of power plant controller configuration used for testing. For example, this may take the form of a list of power plant controller parameters that were changed from default values during testing, if any. (The same parameters shall be used for all tests.)_
- Plots of the results of each test showing IBR active power, reactive power, voltage, and frequency, as well as other parameters mentioned in the criteria of each test. Active power shall be measured on an instantaneous basis (no filtering, or filter time constant ≤ 1 ms) unless otherwise specified. The plots shall be appropriately scaled to show whether the IBR meets each test criteria; in some cases, this may require showing both zoomed in and zoomed out versions of some plots.

5.3 System Strength Test

This test verifies the IBR's capability to operate stably in weak grid conditions by stepping down the SCR successively while faults are applied. The voltage of the source may be adjusted within

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the normal operating region to obtain a solvable power flow as low SCR. The IBR voltage control also helps obtain a solvable power flow as SCR decreases.

5.3.1 Procedure

1. Connect the IBR model to test setup 1. Configure the following initial conditions:
    - SCR at IBR bus: 10.
    - X/R ratio = 6.
    - IBR active power P = 1.0 p.u.; reactive power Q = 0.
2. Apply a 3-phase bolted (zero-impedance) fault for four line cycles. At the time the fault clears, step the SCR to 5, maintaining X/R constant. Allow the transient to subside.
3. Repeat step 2 four times, stepping SCR down 3, 1.5, and 1.2.
4. Repeat steps 1 through 3 substituting a two-phase-to-ground 6-cycle fault with fault impedance selected such that the residual positive-sequence voltage at the IBR is ≤ 0.5 p.u.

5.3.2 Criteria

The IBR shall not trip at any point. Outside the fault periods, P shall not drop below 0.95 p.u. for more than 1 second and V_{IBR} shall not drop below 0.95 p.u. for more than 1 second. P and Q shall be well controlled. Any oscillation shall be damped.

5.4 Unbalance Step-Up Test

This test verifies the IBR's capability to resist voltage imbalance in the normal operating region at various active power levels.

5.4.1 Procedure

1. Connect the IBR model to test setup 1. Configure the following initial conditions:
    - SCR at IBR bus: 10.
    - X/R ratio = 6.
    - IBR active power P = 1.0 p.u.; reactive power Q = 0.
2. Step the negative-sequence voltage of the source, V_{S2}, up from 0 to 0.01 p.u. Allow the transient to subside.
3. Repeat step 2 two times, stepping V_{S2} to 0.02 and 0.03 p.u.

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4. Repeat steps 1 through 3 three times, changing P to 0.5, -0.5, and -1.0 p.u.

5.4.2 Criteria

When V_{S2} is non-zero, the negative sequence voltage the IBR bus, V_{IBR2}, shall be less than V_{S2}. For informational purposes, record the steady-state values of V_{IBR2} and I_{IBR2} (the negative-sequence current of the IBR) following each step in V_{S2}.

5.5 Fault Test

This test provides information on the response of the IBR to selected faults. The test is for informational purposes only; no pass-fail criteria are provided. Prescriptive fault current performance requirements are not recommended until industry gains more experience and insight.

5.5.1 Procedure

This test is repeated under each of the scenarios described in Table 3.

Table 3. Conditions for Fault Tests

Scenario	IBR Active Power Set Point	Fault Type	Fault Impedance
1	1.0 p.u. discharging	3 phase to ground	0.02 p.u., resistive
2	0.5 p.u. discharging	3 phase to ground	0.02 p.u., resistive
3	1.0 p.u. charging	3 phase to ground	0.02 p.u., resistive
4	0.5 p.u. charging	3 phase to ground	0.02 p.u., resistive
5	1.0 p.u. discharging	2 phase to ground	0
6	0.5 p.u. discharging	2 phase to ground	0
7	1.0 p.u. charging	2 phase to ground	0
8	0.5 p.u. charging	2 phase to ground	0

1. Connect the IBR model to test setup 1. Configure the following initial conditions:
   - SCR at IBR bus: 10.
   - X/R ratio = 6.
   - IBR active power per Table 3; reactive power Q = 0.
2. Allow the system to start up and reach equilibrium. Apply the fault per Table 3 and remove it after 6 line cycles. After the fault is removed, allow the transient to subside.
3. Repeat steps 1 and 2 for each of the remaining scenarios in Table 3.

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5.5.2 Criteria

No pass-fail criteria are provided for this test. For test scenarios 1-4, record the IBR active and reactive current magnitudes, and the voltage, V_{IBR}. For test scenarios 5-8, record the IBR positive and negative sequence current magnitudes and angles as well as the positive and negative sequence voltages at the IBR bus, V_{IBR1} and V_{IBR2}.

5.6 Response to Frequency Change Test

This test verifies the IBR's capability to resist frequency changes and operate stably during frequency transients. The frequency profile applied is shown in Figure 3 and described in steps 2-4 below.

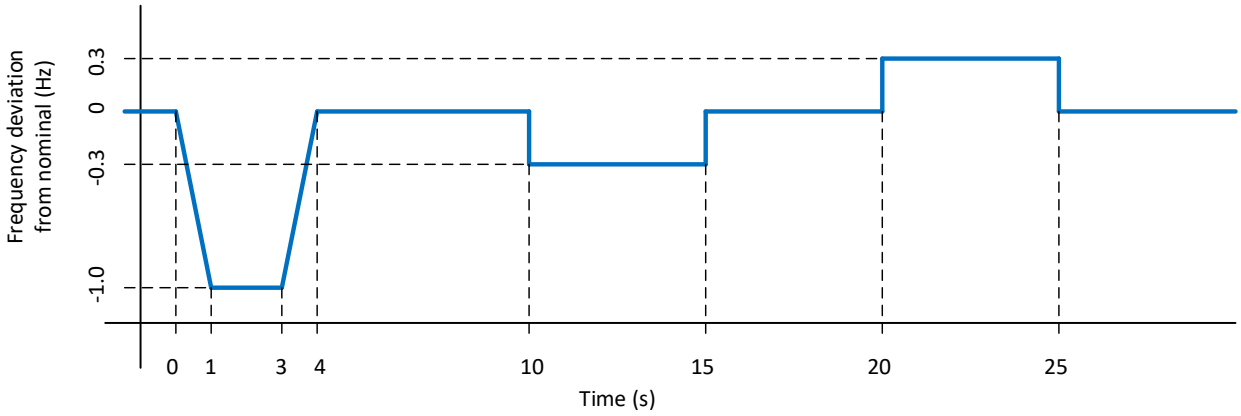

Figure 3. Test frequency profile

5.6.1 Procedure

1. Connect the IBR model to test setup 1. Configure the following initial conditions:
   - SCR at IBR bus: 3.
   - X/R ratio = 6.
   - IBR active power P = 0; reactive power Q = 0.
2. Reduce the frequency at 1 Hz/s for one second. Hold the frequency steady for 2 seconds. Increase the frequency at 1 Hz/s for one second (so that it returns to the nominal value). Hold the frequency steady for 6 seconds
3. Step the frequency down to 0.3 Hz below the nominal frequency. Hold the frequency steady for 5 seconds. Step the frequency back up to the nominal value. Hold the frequency steady for 5 seconds.

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4. Step the frequency up to 0.3 Hz above the nominal frequency. Hold the frequency steady for 5 seconds. Step the frequency back down to the nominal value. Hold the frequency steady for 5 seconds.

5.6.2 Criteria

P and Q shall be well controlled. The voltage and frequency at the IBR bus shall not deviate from their steady-state levels by more than 5% for more than 100 ms. When the frequency is not ramping, V_{IBR} shall settle to a stable point in the normal operating region and P shall settle according to the IBR's droop and deadband settings. Any oscillation shall be damped.

Calculate and report H:

$H = f_n * \Delta E = f_n * (E_1 - E_0)$

Here, f_n is the nominal frequency of the system (50 or 60 Hz), E_1 is the integral of the active power injected by the IBR during the first 500 ms of step 2, and E_0 is the integral of the active power injected by the IBR during the 500 ms prior to step 2 (typically near zero), both per-unitized on the basis of the IBR rated active power. ΔE, the energy injected during the first 500 ms of the ROCOF event, is illustrated in Figure 4.

H shall be greater than 2.5 seconds.

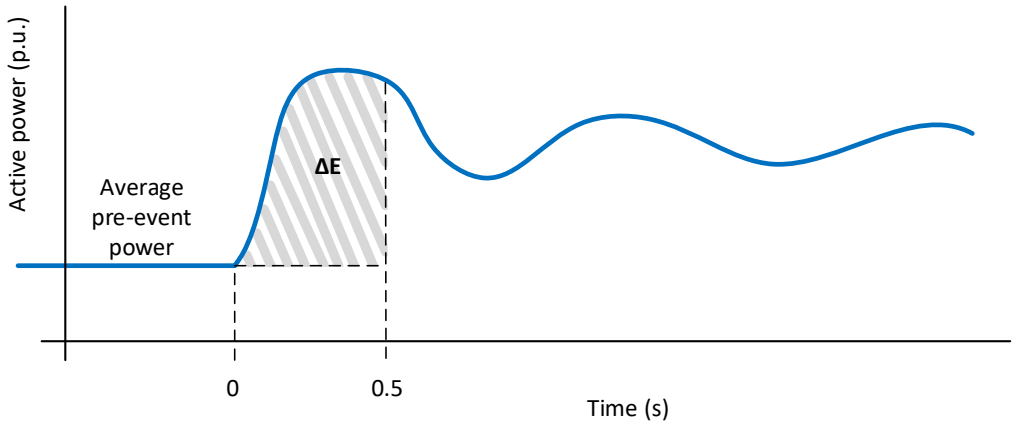

Figure 4. Measuring ΔE, the increased energy injected during the first 500 ms of the ROCOF event

5.7 Phase Angle Jump Test

This test verifies the IBR's capability to resist and operate stably during sudden changes in voltage phase angle. Phase angle in this test refers to the positive sequence phase angle, such that all three phases move together during phase angle jumps.

5.7.1 Procedure

1. Connect the IBR model to test setup 1. Configure the following initial conditions:

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- SCR at IBR bus: 3.
- X/R ratio = 6.
- IBR active power P = 1.0 p.u.; reactive power Q = 0.

2. Step the phase angle of the voltage of the source, V_S, down 10 degrees. Allow the transient to subside.
3. Step the phase angle of the voltage of the source, V_S, up 10 degrees. Allow the transient to subside.
4. Step the phase angle of the voltage of the source, V_S, down 25 degrees. Allow the transient to subside.
5. Step the phase angle of the voltage of the source, V_S, up 25 degrees. Allow the transient to subside.

5.7.2 Criteria

In steps 2 and 3, the positive sequence active power of the IBR shall change by at least 0.2 p.u. in the direction that opposes the phase jump unless limited by the IBR's current or power limit. At least 90% of the required 0.2 p.u. change in active power shall occur during the first line cycle following the phase jump. The change in active power shall be sustained for at least 3 line cycles.

In steps 4 and 5, any oscillations shall be damped.

5.8 Small Voltage Step Test

This test verifies the IBR's capability to resist and operate stably during sudden changes in voltage magnitude.

5.8.1 Procedure

1. Connect the IBR model to test setup 1. Configure the following initial conditions:
   - Z = 0.
   - IBR active power P = 1.0 p.u.; reactive power Q = 0.
2. Step the magnitude of the voltage of the source, V_S, down 0.03 p.u. Allow the transient to subside.
3. Step the magnitude of the voltage of the source, V_S, up 0.03 p.u. Allow the transient to subside.

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4. Step the magnitude of the voltage of the source, V_S, up 0.03 p.u. more. Allow the transient to subside.

5. Step the magnitude of the voltage of the source, V_S, down 0.03 p.u. Allow the transient to subside.

5.8.2 Criteria

Following each voltage step, the positive sequence reactive power of the IBR shall change within 6 line cycles by at least 0.03 p.u. in the direction that opposes the voltage change. At least 90% of the IBR's initial change in reactive power (the change that occurs in the first 6 line cycles) shall occur during the first line cycle following the phase jump.

Any oscillations shall be damped.

5.9 Loss of Grid Connection Test

This test verifies the IBR's capability to operate stably and supply a load following the loss of its connection to the external power system.

This test is not intended to assess an IBR plant's capability to support system-specific islanding applications.

5.9.1 Procedure

This test is repeated under the three initial conditions listed in Table 4. For this test, it is not permitted to send the IBR the status of the switch connecting it to the ac voltage source.

Table 4. Initial Conditions for Loss of Grid Connection Tests

Scenario	Project IBR Power, P1	Duplicate IBR Power, P2	Load Power, P3
1: discharging	0.3 p.u. discharging	0.1 p.u. discharging	1.3 p.u.
2: charging	0.6 p.u. charging	0.4 p.u. charging	0.7 p.u.
3: limit test	0	1 p.u. discharging	1.65 p.u.

1. Connect two instances of the IBR model to test setup 2. Configure the initial conditions from Table 4.

2. Allow the system to reach steady state after startup, then disconnect the ac voltage source. Allow the simulation to continue for at least 10 seconds.

3. Repeat for each of the remaining conditions in Table 4.

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5.9.2 Criteria

Following each disconnection of the voltage source, the IBR's active and reactive power shall be well controlled. The total active and reactive power of both IBRs shall increase by 90% of the load deficit (assuming voltage = 0.8 p.u.) within 1 cycle or less. The active power load deficit at 0.8 p.u. voltage is defined as $0.8^2 \cdot 0.9 \cdot (P3-P1-P2)$, and the reactive power load deficit is 0.29 times the active power deficit. When evaluating this test criteria, it is important that instantaneous active and reactive power measurements be used, or if filtered, filtering time constants be ≤ 1 ms; some EMT software applies filtering to power metering by default.

The intent of these criteria is to confirm that the IBR under test is indeed holding its voltage magnitude and phase nearly constant in the subtransient time frame, as required for Tier 3 GFM IBRs. The numerical criteria exist for that purpose and not based on any specific power system's needs.

The active and reactive power shall settle according to their droop settings. Voltage and frequency shall not oscillate excessively and shall settle within 5 seconds inside their continuous operating regions as defined by the appropriate interconnection standard. Any oscillations shall be damped within 10 seconds to a low level.[4]

Voltage does not deviate beyond [0.8 1.10] p.u. for longer than 0.1 s throughout the test.

[4] Numerical bounds on oscillation damping are not provided for this test. When the IBR equipment is eventually used in a system, an interconnection study may determine acceptable performance based on system needs.

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6 Frequency-Domain Specifications

This section describes methods of assessing GFM capability using frequency-domain tests. Section 6.1 specifies GFM performance criteria, some of which are defined using "dynamic droop" frequency scans (as further detailed in 6.2 and Appendix A), and others of which are defined based on other types of frequency scans (as further detailed in 6.3). These requirements are designed to confirm whether an IBR has the small-signal dynamic characteristics associated with GFM capability.

The UNIFI team seeks feedback from industry on these frequency-domain methods of assessing GFM capability, which may be included as normative requirements in near-future international standards for GFM equipment.

6.1 Recommended Frequency Domain Specifications

GFM IBRs should meet the frequency-domain requirements specified in Table 5 and Table 6. The last column of Table 5 states which of the GFM Tiers defined in Section 1 the requirement applies to.

Table 6 applies to IBRs in all four GFM Tiers. The requirement for "high-frequency voltage-phasor stiffness" in Table 6 should be met by conforming to at least one of the three requirements shown, labelled "passive", "low-gain", and "voltage source behind impedance".

Table 7 and Table 8 provide further information on the parameters used in Table 5 and Table 6.

Deviations from this specification to allow for primary energy resource limitations may be permitted considering the following recommendations:

- Deviations should be limited to within the range from $f_{p,\min}$ to 40 Hz.
- Deviations should be documented. The documentation should include the technical justification (e.g. the OEM's documentation of the reason for the deviation).

While a deviation from this specification may not prevent an IBR from qualifying as GFM, a system operator or planner may need to assess a risk of oscillation related to the deviation.

Appendix A provides additional background information and details on the dynamic droop-based frequency-domain specification.

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Table 5. Frequency-Domain Specifications for IBR Unit Capabilities Within the Continuous Operation Region Under Balanced Conditions—Applicable to GFM IBRs With Active Power Capability as Indicated in Last Column

Input / Output	Capability and applicable frequency range	Specifications: Frequency ω/P	Specifications: Voltage V/Q	Notes	Applicable GFM Tiers
Input: P, Q **Output:** ω, V Sometimes called 'dynamic droop' [a]	**Steady state droop** $f_p \in [f_{p,\min}, f'_p]$ Approximately 0.01 Hz to 0.1 Hz, specified based on grid needs.	Upper bound on $\lvert\omega/P\rvert$ increases[§] from $m_p(0) + 0.01$ p.u. at $f_{p,\min}$ to m''_P at f'_p with corresponding symmetric lower bound. Bound on $\lvert\angle\,\omega/P\rvert$ increase[§] from $5°$ at $f_{p,\min}$ to $90° + \varepsilon_1$ * at f'_p	Upper bound on $\lvert V/Q\rvert$ increases[§] from $m_q(0) + 0.01$ p.u. at $f_{p,\min}$ to m''_Q at f'_p with corresponding symmetric lower bound. Bound on $\lvert\angle\,V/Q\rvert$ increase[§] from $5°$ at $f_{p,\min}$ to $90° + \varepsilon_1$ * at f'_p	Frequency bounds shift towards lower values for resources with large physical inertia, or VSM with large, emulated inertia time constants, and vice versa. * tolerance ε_1 to accommodate numerical/implementation aspects of control and test procedure [§] linear increase on log plot	V/Q : All GFM Tiers ω/P: Tier 3 and above
	Rate-of-change support $f_p \in [f'_p, f''_p]$ Approximately 0.1 Hz to 0.5 Hz, specified based on grid needs.	$\lvert\omega/P\rvert \le m''_P$ $\lvert\angle\,\omega/P\rvert \le 90° + \varepsilon_1$ *	$\lvert V/Q\rvert \le m''_Q$ $\lvert\angle\,V/Q\rvert \le 90° + \varepsilon_1$*		V/Q : All GFM Tiers ω/P: Tier 2 and above
	Low frequency oscillation damping $f_p \in [f''_p, f'''_p]$ Starting from approximately 0.5 Hz with upper limit f'''_p that depends on IBR characteristics.	$\lvert\omega/P\rvert$ below an upper bound that starts at m''_P at f''_p and decreases ten times for a ten times increase of f_p (straight line in log-log plot) $\lvert\angle\,\omega/P\rvert \le 90° + \varepsilon_1$*	$\lvert V/Q\,\rvert \le m''_Q$ $\lvert\angle\,V/Q\rvert \le 90° + \varepsilon_1$*		V/Q : All GFM Tiers ω/P: Tier 2 and above

[a] Groß, Dominic, Deepak Ramasubramanian, Benjamin Paz. December 2022. Universal input-output model of GFM functions and data-driven verification methods. UNIFI-2022-4-1.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Table 6. Frequency-Domain Specifications for IBR Unit Capabilities Within the Continuous Operation Region Under Balanced Conditions—Applicable to All GFM IBRs

<table>
<tr><th rowspan="2">Input / Output</th><th rowspan="2">Capability
and applicable frequency range</th><th colspan="4">Specifications</th><th rowspan="2">Notes</th></tr>
<tr><th colspan="2">Frequency
ω/P</th><th colspan="2">Voltage
V/Q</th></tr>
<tr><td rowspan="3">Input: P, Q
Output: ω, V

Sometimes called ‘dynamic droop’</td><td colspan="2">Power synchronization
$f_p \in [f_{p,\min}, f_p''']$

Starting from approximately 0.01 Hz with upper limit f_p''' that depends on IBR characteristics.</td><td colspan="2">$|\omega/P|$ below an upper bound that is equal to m_P'' at f_p'' and decreases ten times for a ten times increase of f_p between $f_{p,\min}$ and f_p''' (straight line in log-log plot)

$|\angle\, \omega/P| \le 90° + \varepsilon_1$*</td><td colspan="2">All V/Q functions from Table 5</td><td>Synchronization through feedback from power to frequency without requiring steady-state droop.

* tolerance to accommodate numerical/implementation aspects of control and test procedure</td></tr>
<tr><td rowspan="2">High-frequency voltage phasor stiffness

$f_p \in [f_p''', 40\ \text{Hz}]$

Lower limit f_p''' that depends on IBR characteristics.</td><td>“Passive”

Typical range for f_p''' is approximately 4 Hz to 10 Hz.</td><td colspan="2">$|\omega/P|$ below an upper bound that increases$ ten times for ten times increase of f_p
(straight line in log-log plot)

$|\angle\, \omega/P| \le 90° + \varepsilon_1$*</td><td colspan="2">$|V/Q| \le 1$ p.u./p.u.

$|\angle\, V/Q| \le 90° + \varepsilon_1$*</td><td>* tolerance to accommodate numerical/implementation aspects of control and test procedure

$ starting from the gain at f_p'''</td></tr>
<tr><td>“Low gain”

Typical value for f_p''' is approximately 10 Hz.</td><td colspan="2">$|\omega/P| \le m_{low}$

no $|\angle\, \omega/P|$ phase specification</td><td colspan="2">$|V/Q| \le m_{low}$

no $|\angle\, V/Q|$ phase specification</td><td></td></tr>
<tr><td rowspan="3">Input: θ, V
Output: P, Q

Sometimes called ‘power-domain scan’

&

Input: I
Output: V

Sometimes called ‘impedance scan’</td><td rowspan="3">“Voltage source behind impedance” [7]

Typical range for f_p''' consists of any values smaller than approximately 5 Hz, which provides a property like a voltage behind a reactor.

One realization example recommends:

$f_p''' = 4$ Hz</td><td>Active power
P/θ</td><td>Reactive power
Q/V</td><td colspan="2">Impedance
$Z = V/I$</td><td rowspan="3">† The magnitude response of P/θ and Q/V should be almost constant over the prescribed frequency range. No index is given to check this property.</td></tr>
<tr><td colspan="2"><u>Magnitude response</u>†</td><td colspan="2" rowspan="2"><u>Equivalent inductance</u>
estimated using positive-sequence impedance, Z
within $f_{\text{nom}} \pm f_{Z,\text{width}}$
frequency range, except for within
$f_{\text{nom}} \pm f_{Z,\text{exception}}$</td></tr>
<tr><td>$|\text{P}/\theta| > |\mathbf{P/\theta}|_{\min}$</td><td>$|\text{Q}/\text{V}| > |\mathbf{Q/V}|_{\min}$</td></tr>
<tr><td colspan="2"><u>Phase response</u></td><td colspan="2" rowspan="2">estimated inductance
$L \le L_{\max}$</td><td rowspan="2">* permissible magnitude of phase angle error.

**wrapped angle within [0, 360°]</td></tr>
<tr><td>$|\angle\, P/\theta^{**} - 180°| < \varepsilon_2$*</td><td>$|\angle\, Q/\text{V}^{**} - 180°| < \varepsilon_2$*</td></tr>
</table>

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Table 7 and Table 8 list key parameters to be specified based on grid needs. These values are starting points and may be adjusted as we gain more knowledge and industry input. Default values are given for cases where the required value is not specified.

- For IBR units that use a "passive" or "low gain" realization of GFM control, the parameters specified in Table 7 should be adjustable within a specified 'range of available settings/design'.
- For IBR units that use a "voltage source behind impedance" realization of GFM control, the parameters specified in Table 8 should be adjustable within a specified 'range of available settings/design'.
- In addition, the frequency parameters f_p shall be specified such a that $f'_p < f''_p < f'''_p$.

Table 7. Parameters for IBR Unit Capabilities Described by Transfer Functions That Use *P* and *Q* as Inputs and *ω* and *V* as Outputs, Respectively

Parameter	Recommended Range of Available Settings/Design	Default Value	Interpretation/Comment
$m_P(0)$, $m_Q(0)$	0.01 p.u./p.u. to 0.05 p.u./p.u.	0.05 p.u./p.u.	Steady-state droop coefficients for frequency/active power and voltage magnitude/reactive power
ε_1	1° to 10°	10°	(total error) Tolerance to accommodate numerical/implementation aspects of control and test procedure
m_{low}	0.005 p.u./p.u. to 0.02 p.u./p.u.	0.01 p.u./p.u..	Upper bound for ω/P when ω/P is not passive
m''_P, m''_Q	0.01 p.u./p.u. to 0.1 p.u./p.u.	0.1 p.u./p.u.	Upper bound on transient droop at roll-off frequency f''_p
$f_{p,\min}$	0.001 Hz to 0.01 Hz	0.01 Hz	Lowest frequency of interest for primary control
f'_p	0.01 Hz to 0.1 Hz	0.1 Hz	Bandwidth limit of higher-level controls that provide dispatch
f''_p	0.1 Hz to 20 Hz	0.5 Hz	Roll-off of frequency/active power response. For a VSM with inertia constant H and steady-state droop $m_p(0)$, one obtains $f''_p = \frac{1}{2\,H\,m_P(0)}$
f'''_p	0.5 Hz to 20 Hz	≥4 Hz	Frequency at which the IBR unit output impedance or inner control loops dominate the response. Depends on the GFM device characteristics including primary energy source where present.

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Table 8. Parameters for IBR Unit Capabilities Described by Transfer Functions That Use *Q*, *P*, and *V* as Inputs and θ, *V*, and *I* as Outputs, Respectively

Parameter	Recommended Range of Available Settings/Design	Default Value	Interpretation/Comment
$\lvert P/\theta \rvert_{min}$	0.5 to 10 p.u./radian	0.5 p.u./radian	p.u. active power output per radian phase jump
$\lvert Q/V \rvert_{min}$	0.5 to 10 p.u./p.u.	0.5 p.u./p.u.	p.u. reactive power output per p.u. change in the voltage magnitude
ε_2	10 to 60°	20°	Permissible magnitude of phase angle error.
$f_{Z,width}$	40 to 100 Hz	40 Hz	Frequency range around nominal grid frequency for which a maximum equivalent inductance is specified.
$f_{Z,exception}$	4 to 10 Hz	10 Hz	A frequency range around nominal grid frequency for which the maximum equivalent inductance specification does not apply.
f_{nom}	50 or 60 Hz	50 Hz in most of Europe, Africa, Asia, and Oceania 60 Hz in North America, parts of South America, and parts of East Asia	Nominal frequency of the ac power system.
L_{max}	0.1 to 0.75 p.u.	0.75 p.u.	Maximum equivalent inductance. The default value of 0.75 p.u. is equivalent to SCR of 1.33

6.2 Dynamic Droop

These UNIFI dynamic droop frequency-domain specifications are developed with the intent of helping promote (i) do-no-harm dynamic behavior from a GFM IBR, (ii) robustness of operation, (iii) safe and stable interoperability among various devices, and (iv) dynamic performance improvements for the entire bulk system. Previous publications on the topic include [19] and [20].

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The focus of the specifications in this section is on bulk system connected IBRs. Different criteria may be needed for GFM IBRs used in distribution-connected or microgrid applications. These specifications do not include requirements to support stability of GFM IBR units interacting within an IBR plant.

While these specifications do help with identifying/characterizing GFM versus GFL behavior, they go beyond this single purpose and aim to achieve improved stability and robustness of an IBR as it provides various services to the network. Hence, while a subset of these specifications does help address the question of whether a resource is GFM or not, the broader set of specifications outlined in this section aims to provide checks and criteria to identify if a device will operate in a stable manner with the rest of the network.

See Appendix A for more information on dynamic droop-based GFM specifications.

6.3 Voltage Source Behavior

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. This core voltage source behavior is important for improving grid strength and mitigating stability problems associated with low system strength. Because we want a GFM resource to behave as a voltage source with a reactor during the short time frame following a grid disturbance, this section presents the frequency-domain response of an ideal voltage source with a reactor in a desired short time frame after a disturbance, as seen from the POI. The frequency-domain response of an ideal voltage source with a reactor is then used to define the frequency-domain specifications for quantifying the voltage source behavior of GFM resources. The reader is referred to an ESIG report titled "Testing the Performance of Grid-Forming Resources: Test Methods and Performance Metrics for Evaluating the Voltage Source Behavior of Grid-Forming Resources" released in September 2025 [7] for more details on the frequency-domain characterization and specifications for quantifying the voltage source behavior of GFM resources including its theoretical framework and few practical examples[5].

[5] Energy Systems Integration Group. 2025. 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 GFM Testing Project Team. https://www.esig.energy/gfm-performance-testing/.

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6.3.1 Frequency-Domain Response

6.3.1.1 Reactive Power Response

The reactive power response of an ideal voltage source with a reactor can 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. This Q/V transfer function has the characteristics of a second-order low-pass filter with a negative gain and with the corner frequency being the same as the fundamental frequency[6]. Moreover, if the steady-state gain of the Q/V transfer function in VAR/Volt gain 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. The response of the Q/V transfer function 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.

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^o 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^o within a specified frequency range such as 4 to 40 Hz.

6.3.1.2 Active Power Response

The active power response of an ideal voltage source with a reactor can be described in the frequency domain by a transfer function from the phase of the three-phase voltages at the POI, θ,

[6] S. Shah, et al., "A testing framework for grid-forming resources," 2023 IEEE Power and Energy Society General Meeting, Orlando, FL. https://docs.nrel.gov/docs/fy23osti/84604.pdf

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to the active power output, *P*, of the voltage source with a reactor. Same as the Q/V transfer function, the P/θ transfer function for an ideal voltage source with a reactor has the characteristics of a second-order low-pass filter with a negative gain and with the corner frequency being the same as the fundamental frequency. 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 similar performance parameters as the Q/V transfer function.

6.3.1.3 Impedance Response

Because the impedance of an ideal voltage source with a reactor is the same as that of the reactor, i.e., 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.

6.3.2 Frequency-Domain Specifications

This section presents frequency-domain specifications for quantifying the voltage source behavior of GFM resources using frequency-domain tests including the impedance scan, Q/V scan, and P/θ scan. 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.

6.3.2.1 Q/V Scan

The performance metrics in Table 9 are suggested for quantifying the voltage source behavior of a GFM resource using Q/V scan. Note that Q/V scan quantifies the voltage source behavior only for the reactive power response.

Table 9. Performance Metrics for a GFM Resource Based on a Q/V Scan Test

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

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 prescribed 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.

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6.3.2.2 P/θ Scan

The performance metrics in Table 10 are suggested for quantifying the voltage source behavior of a GFM resource using P/θ scan. Note that P/θ scan quantifies the voltage source behavior only for the active power response.

Table 10. Performance Metrics for a GFM Resource Based on a P/θ Scan Test

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

Performance Metric	Suggested Specification
Magnitude response	The magnitude of the P/q 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/q 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.

6.3.2.3 Impedance Scan

The performance metrics in Table 11 are suggested for quantifying the voltage source behavior of a GFM resource using V/I or impedance scan.

Table 11. Performance Metric for a GFM Resource Based on an Impedance Scan Test

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

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 **f1 ± 40 Hz** frequency range except for a narrow band around the fundamental frequency (e.g., **f1 ± 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.

6.3.2.4 Summary

Voltage source behavior is the core function expected from GFM resources to improve grid strength and support stability of bulk power systems. This section has documented three frequency-domain test methods for evaluating the voltage source behavior from GFM resources.

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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. 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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Appendix A. Frequency-Domain Specifications

A.1 Introduction

These UNIFI frequency-domain specifications are developed with the intent of helping promote/ensure (i) do-no-harm dynamic behavior from a GFM IBR, (ii) robustness of operation, (iii) safe and stable interoperability amongst various devices, and (iv) dynamic performance improvements for the entire bulk system.

While these specifications do help with identifying/characterizing GFM versus GFL behavior, they go beyond this single purpose and aim to achieve improved stability and robustness of an IBR as it provides various services to the network. Hence, while a subset of these specifications does help address the question of whether a resource is GFM or not, the broader set of specifications outlined in this document aim to provide checks and criteria to identify if a device will operate in a stable manner with the rest of the network.

A.2 Dynamic Droop Coefficients

We model the small-signal dynamics of an IBR using the dynamic droop model

$$\begin{bmatrix} \Delta\omega(j\omega_p) \\ \Delta V(j\omega_p) \end{bmatrix} = -\begin{bmatrix} m_P(j\omega_p) & \xi_Q(j\omega_p) \\ \xi_P(j\omega_p) & m_Q(j\omega_p) \end{bmatrix} \begin{bmatrix} \Delta P(j\omega_p) \\ \Delta Q(j\omega_p) \end{bmatrix} \quad (1)$$

where $\Delta\omega$, ΔV, ΔP, and ΔQ denote deviations of the AC voltage frequency, AC voltage magnitude, active power, and reactive power from their setpoints. The dynamic droop model has a straightforward interpretation and low dependence on the operating point for common GFM controls operating away from the IBR limits and frequencies ω_p below the nominal system frequency. These transfer functions (as defined by the dynamic droop model) are deliberately chosen because the behavior specified by these transfer functions can help characterize the impact the IBR has on the network, rather than only characterizing how an IBR responds to a specific network event. Focusing on the former, i.e., characterizing the impact the IBR has on the network, allows for the definition of more generalized frequency domain specifications that can help promote the notion of the IBR being a 'good citizen' in the network with respect to stability and interoperability. The latter, i.e., characterizing how an IBR responds to a specific network event, while informative and useful, may serve only as a necessary condition of behavior and does not ensure interoperability of IBRs or stability of the network.

Notably, the dynamic droop model fully characterizes the small-signal dynamics of an IBR by extending the standard steady-state droop coefficients, m_P and m_Q, to frequency dependent droop coefficients $m_P(j\omega_p)$ and $m_Q(j\omega_p)$ that can be understood as the droop response to active and reactive power oscillations. For instance, $m_P(j\omega_p)$ is a complex number modeling the gain and phase shift of the response of the IBR frequency to an active power oscillation with frequency ω_p.

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Figure A-1 illustrates the response of the frequency of the IBR voltage to a to 8 Hz active power oscillation. The first subplot shows the response for a dynamic active power droop coefficient $m_P(j\omega_p)$ that has zero phase and 5% gain. In this case, the frequency deviation $\Delta\omega$ has opposite sign to the power deviation ΔP and an active power deviation of 0.1 pu results in a frequency deviation of 0.005 pu. The second subplot illustrates that the frequency deviation doubles for a dynamic active power droop coefficient $m_P(j\omega_p)$ with 10% gain. As expected from the standard $P-f$ droop relationship, the frequency deviation $\Delta\omega$ has opposite sign to the power deviation ΔP if $m_P(j\omega_p)$ has zero phase. The third subplot illustrates the response modeled by a dynamic active power droop coefficient $m_P(j\omega_p)$ with 5% gain and 90° phase. In this case, the frequency deviation $\Delta\omega$ no longer maintains opposite sign to the power deviation ΔP at all times. Instead, for half the oscillation (bold red), the sign of the frequency deviation is incorrect (e.g., positive ΔP results in positive $\Delta\omega$). The final subplot illustrates the response modeled by a dynamic active power droop coefficient $m_P(j\omega_p)$ with 5% gain and 180° phase. In this case, the frequency response always has incorrect sign and represents positive feedback (i.e., negative damping) that destabilizes the frequency dynamics of the overall system.

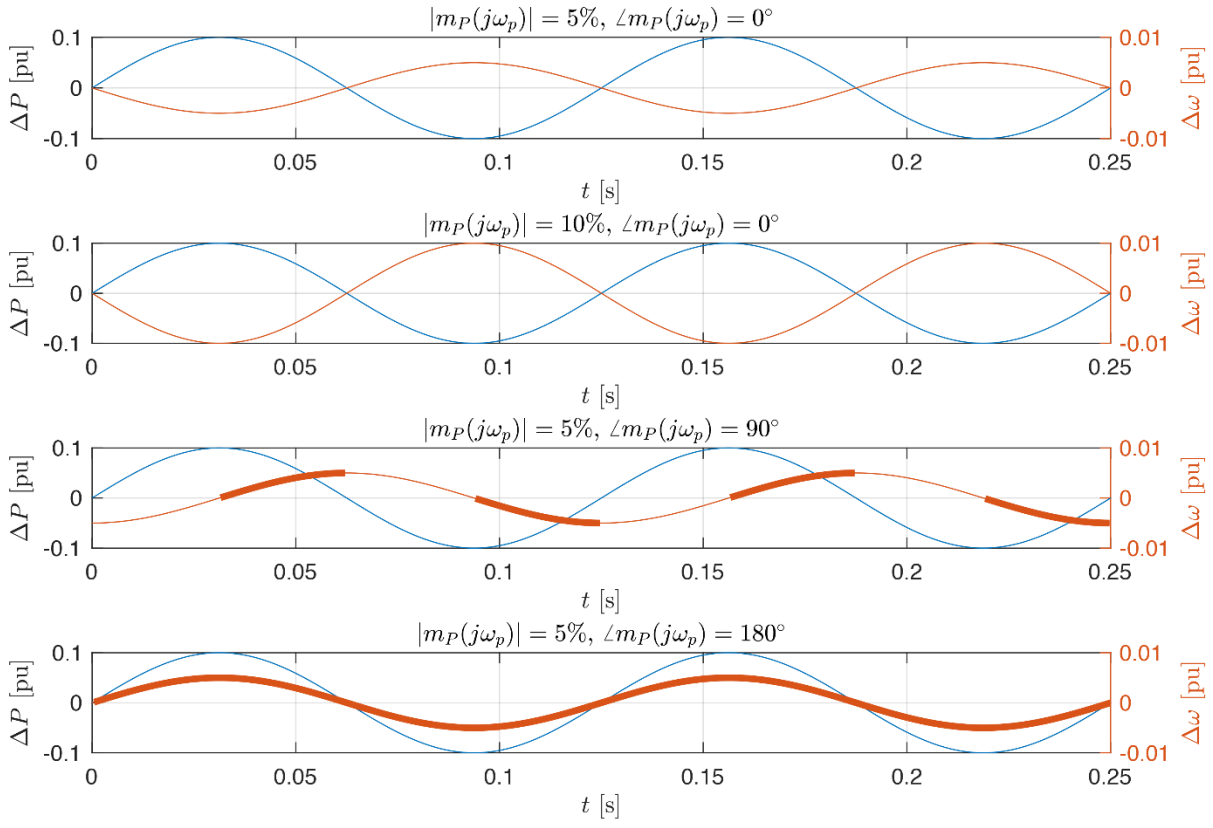

Figure A-1. Frequency response to 8 Hz active power perturbation

This example illustrates the importance of the phase information contained in the model (1) for characterizing the IBR response (both for GFL and GFM IBRs). In the remainder, we will call

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the dynamic droop coefficients $m_P(j\omega_p)$ and $m_Q(j\omega_p)$ passive if their phase is between -90° and 90°. Notably, a key distinguishing feature of GFM IBRs is that they either preserve passivity over a wider frequency range than GFL IBRs or feature low gain at frequencies for which passivity is lost.

Next, we note that $m_P(j\omega_p)$ and $m_Q(j\omega_p)$ of a given IBR can be compactly represented graphically as a Bode plot with units of Hz instead of rad/s and gain in per unit instead of decibel. Figure A-2 shows Bode plots of $m_P(j\omega_p)$ obtained from an EMT simulation of GFM droop control[7] and GFL droop control[8], both with 5% steady-state droop.

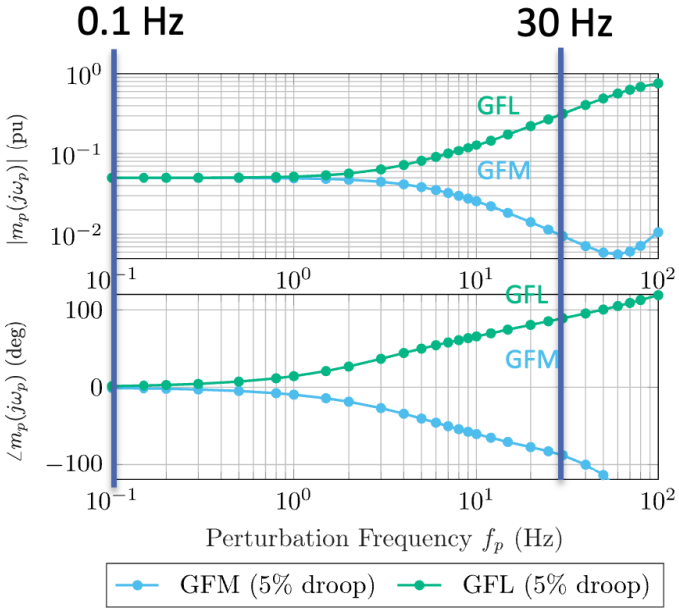

Figure A-2. Bode plot of $m_P(j\omega_p)$ for typical implementations of GFM and GFL droop control

The gain of $m_P(j\omega_p)$ decreases for GFM control as the frequency ω_p of active power perturbations increases, i.e., the GFM IBR suppresses high-frequency oscillations. In contrast, for GFL control, the gain $m_P(j\omega_p)$ increases as the frequency ω_p of active power perturbations increases resulting in reduced damping of active power / frequency oscillations.

Figure A-3 shows the corresponding time-domain response of the GFM and GFL IBR with $m_p(j\omega_p)$ as shown in Figure A-2 to a 0.1 Hz and 30 Hz active power oscillation. The response at 0.1 Hz is identical and close to ideal steady-state droop. In contrast, at 30 Hz both GFM and

[7] With proportional-integral inner voltage and current loops in controller dq-frame.
[8] With synchronous-reference-frame PLL and proportional-integral current loop in controller dq-frame. Droop curves are evaluated using frequency (obtained from the PLL) and voltage magnitude to compute active and reactive power references. These are converted to active and reactive current references provided to the inner current loop.

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GFL control reach 90° phase shift and the frequency deviation $\Delta\omega$ has the wrong sign for half the oscillation (bold in Figure A-3). However, while the GFL IBR exhibits large frequency deviations, the GFM IBR exhibits small frequency deviations, i.e., stiffly controls frequency as desired.

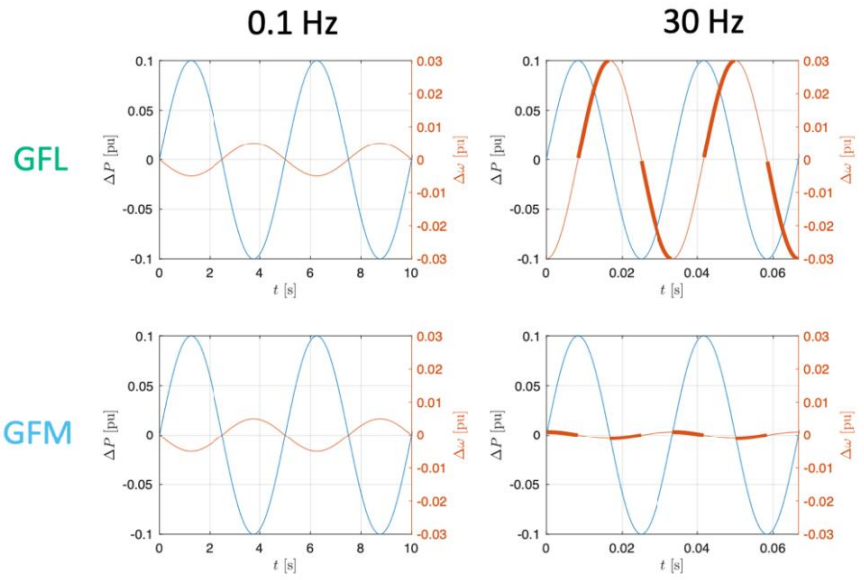

Figure A-3. Response of GFM and GFL controls with $m_P(j\omega_p)$ as shown in Figure A-2 to a 0.1 Hz and a 30 Hz active power oscillation

A.3 Specifications

Frequency Ranges for Dynamic Droop Specifications

Dynamics below 0.01 Hz are largely governed by system-level and plant-level controls, and no meaningful difference exists between GFM and GFL controls. On the other hand, dynamics beyond double line frequency do not significantly contribute to system-wide interaction and frequency synchronization of devices. Hence, we restrict our attention to the frequency range of 0.01 Hz to 40 Hz. Finally, we note that the off-diagonal elements $\xi_Q(j2\pi f_p)$ and $\xi_P(j2\pi f_p)$ are typically negligible at low frequencies but may have to be considered as f_p approaches the line frequency.

In the remainder, the frequency domain specifications for $m_P(j2\pi f_p)$ and $m_Q(j2\pi f_p)$ are divided into four frequency regions[9]. The region $f_p \in [f_{p,\min}, f_p']$ parameterizes the dynamic response on longer time scales[10] and is the key distinguishing factor between various GFM tiers.

[9] $\xi_q(j\omega_p)$ and $\xi_p(j\omega_p)$ typically have negligible gain for $f_p < 10$ Hz and start to increase significantly beyond this bound. Future versions of the specifications will provide specifications on $\xi_q(j\omega_p)$ and $\xi_p(j\omega_p)$.

[10] Slower dynamics (e.g., with frequencies below $f_{p,\min}$) are usually fully governed by plant and/or system-level controls (e.g., AGC) and not relevant to distinguish between GFL and GFM IBRs.

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For instance, Tier 1 GFM STATCOMS cannot provide a sustained droop response over long timescales, but Tier 3 GFM BESS systems would be required to do so.

The region $f_p \in [f_p', f_p'']$ parameterizes the region of rate-of-change support that is the key to distinguish between Tier 1 and Tier 2. For instance, a Tier 2 GFM E-STATCOM or wind turbine would be required to provide frequency support for a brief duration while a Tier 1 GFM STATCOM is not required to do so.

The region $f_p \in [f_p'', f_p''']$ with $f_p''' \geq f_p''$ mutually agreed upon between grid operator and OEM characterizes low frequency oscillation damping provided through decreasing magnitude of $m_P(j2\pi f_p)$, i.e., decreased sensitivity of the GFM IBR frequency to active power oscillations.

Finally, the region $f_p \geq f_p'''$ characterizes the response considered to be outside of the bandwidth of GFM reference dynamics in which dynamics are predominantly governed by fast acting controls (e.g., current controllers) and/or circuit dynamics. This region is crucial to distinguish between GFM and GFL dynamics.

Please see Table 7 and Table 8 in Section 6 and for typical ranges of the frequencies $f_{p,\min}$ to f_p'''.

GFM IBR Specifications: Power Synchronization and High-Frequency Voltage Phasor Stiffness

Necessary frequency domain specifications for GFM IBR units and functional capabilities are outlined in Table 6 in Section 6. To this end, we distinguish between two types of GFM dynamics. The dynamic droop specifications on $m_P(j2\pi f_p)$ in Table 6 encode minimum requirements for GFM IBRs without frequency support functions and aim to rule out adverse interactions. The specifications for the two types of GFM responses specified in Table 6 (i.e., passive and low gain) are illustrated in Figure A-4 and Figure A-5. Notably, the specifications in Figure A-4 and Figure A-5 allow for PI-type active power-frequency droop control whose gain $|m_P(j2\pi f_p)| \to \infty$ as $f_p \to 0$. Moreover, we require that the upper bound on $|m_P(j2\pi f_p)|$ decreases as f_p increases to encode the basic property of GFM control (i.e., keeping frequency stiff for high frequency perturbations). Finally, the phase is restricted to $\pm(90° + \varepsilon_1)$ below f_p''' to prevent a droop response with incorrect sign (on average over one cycle of an oscillation)[11].

[11] Under ideal conditions (i.e., lossless filter, no control/actuation delays, etc.) the phase bound should be -90 to 90 degrees. It has been increased to account for practical implementation considerations of controls, IBR hardware, and the data-driven method used for testing and verification.

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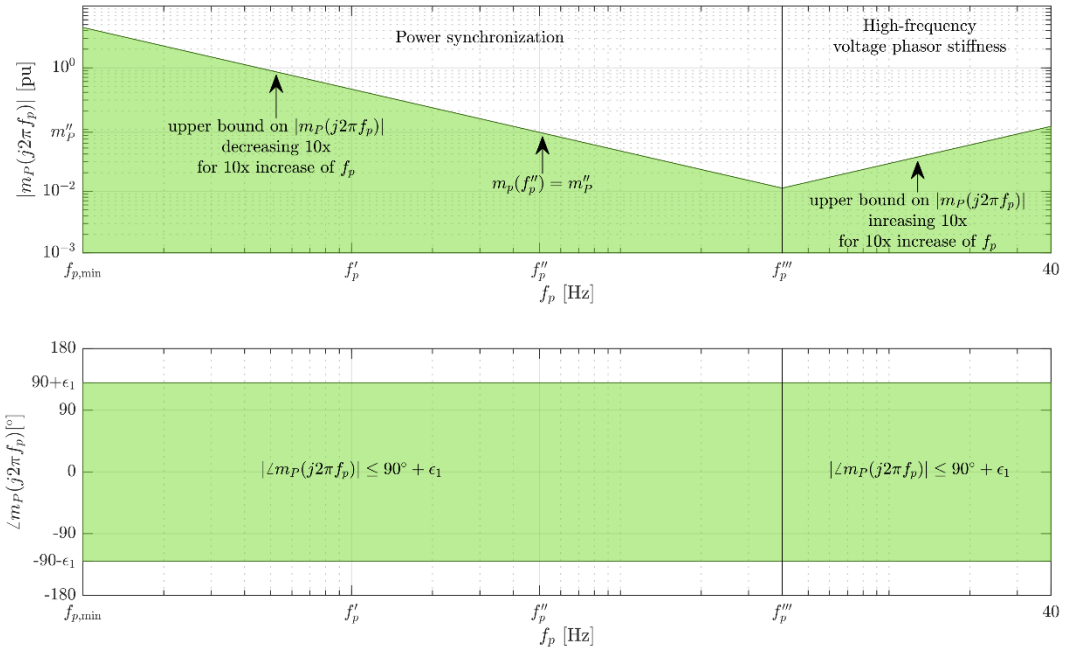

Figure A-4. Specification on $m_P(j2\pi f_p)$ for power synchronization and passive high-frequency voltage phasor stiffness (see Table 6)

Beyond f_p''', the specifications for passive high-frequency voltage phasors shown in Figure A-4 restrict the phase to $\pm(90° + \varepsilon_1)$ and permit an increasing gain to allow for the impact of output impedance of a GFM converter controlled as a voltage source behind an impedance. In contrast, the specifications shown in Figure A-5 allow for arbitrary phase beyond f_p''' and minimize the impact of negative damping when the droop response is more than $90° + \varepsilon_1$ out of phase by requiring $|m_P(j2\pi f_p)| \leq m_{\text{low}}$ for $f_p > f_p'''$ (i.e., keeping frequency stiff). The gain m_{low} should be selected in accordance with the smallest short circuit ratio (SCR) and largest grid reactance-to-resistance ratio expected at the point of interconnection.

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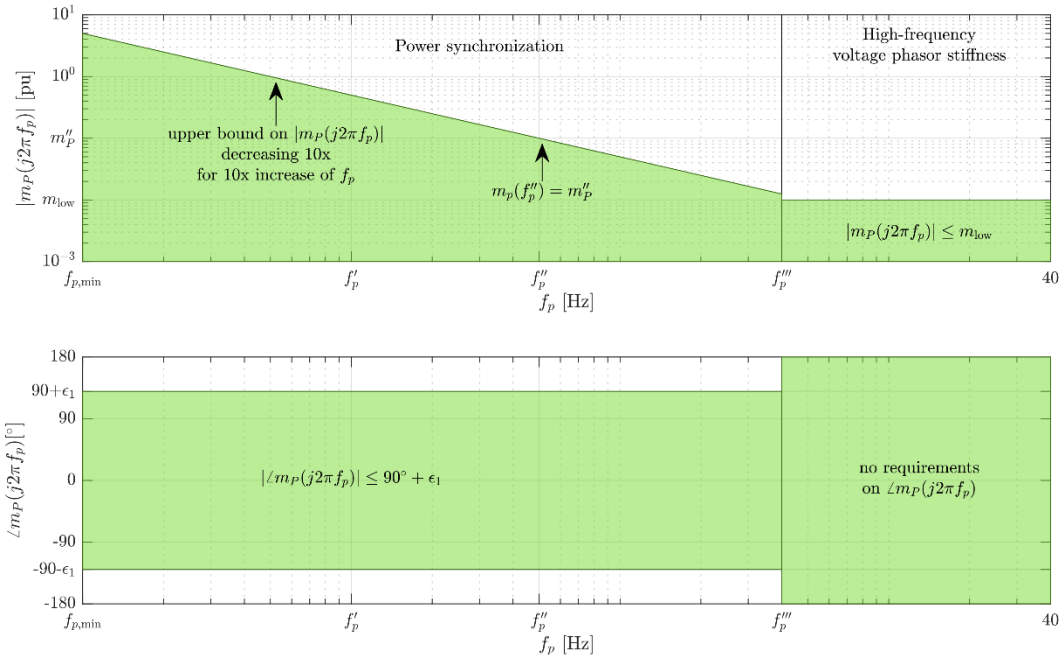

Figure A-5. Specification on $m_P(j2\pi f_p)$ for power synchronization and low-gain high-frequency voltage phasor stiffness (see Table 6)

The corresponding reactive power – voltage droop specifications are shown in Figure A-6 (passive) and Figure A-7 (low gain). In the lower frequency range, $m_Q(j2\pi f_p)$ must closely match the steady-state droop specification, i.e., $m_Q(j2\pi f_p) \approx m_Q(0)$ and $\angle m_Q(j2\pi f_p) \approx 0$. Next, a deviation in gain and phase is permitted until f_p'. Between f_p' and f_p''' the gain shall be bounded by m_Q''. Finally, the phase is restricted to $\pm(90° + \varepsilon_1)$ below f_p''' to prevent a droop response with incorrect sign (on average over one cycle of an oscillation).

Beyond f_p''' the specifications for passive high-frequency voltage phasors shown in Figure A-6 restricts the phase to $\pm(90° + \varepsilon_1)$ and allows a gain of up to 1 p.u./p.u. to allow for the impact of the output impedance of a GFM converter controlled as a voltage source behind an impedance. In contrast, the specifications shown in Figure A-7 allow for arbitrary phase beyond f_p''' and minimize the impact of negative damping when the droop response is more than $90° + \varepsilon_1$ out of phase by requiring $|m_Q(j2\pi f_p)| \leq m_{\text{low}}$ for $f_p > f_p'''$ (i.e., keeping voltage magnitude stiff). The gain m_{low} should be selected in accordance with the smallest short circuit ratio (SCR) and largest grid reactance-to-resistance ratio expected at the point of interconnection[12].

[12] For $f_p''' \ll f_0$ and a Thevenin equivalent grid reactance X_g and resistance R_g in p.u. one obtains $m_{\text{low}} \approx \frac{f_p'''}{f_0} X_g$. In contrast, if $f_p''' \to f_0$, then $m_{\text{low}} \to R_g$. A more accurate and detailed analysis will be made available in a forthcoming UNIFI report.

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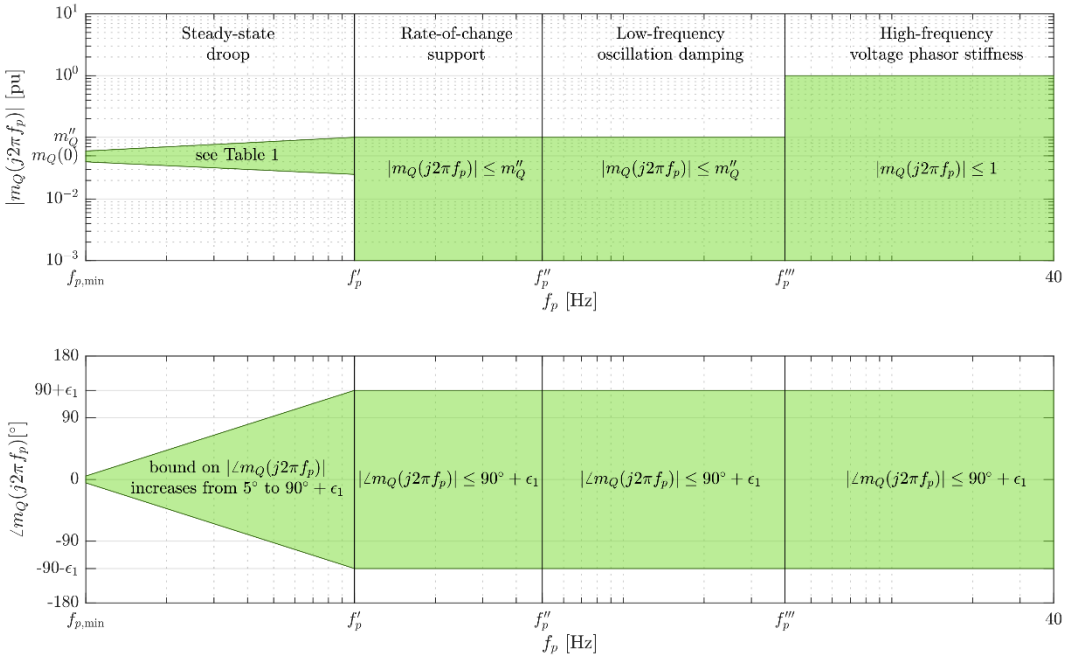

Figure A-6. Specification on $m_Q(j2\pi f_p)$ for power synchronization and passive high-frequency voltage phasor stiffness (see Table 6).

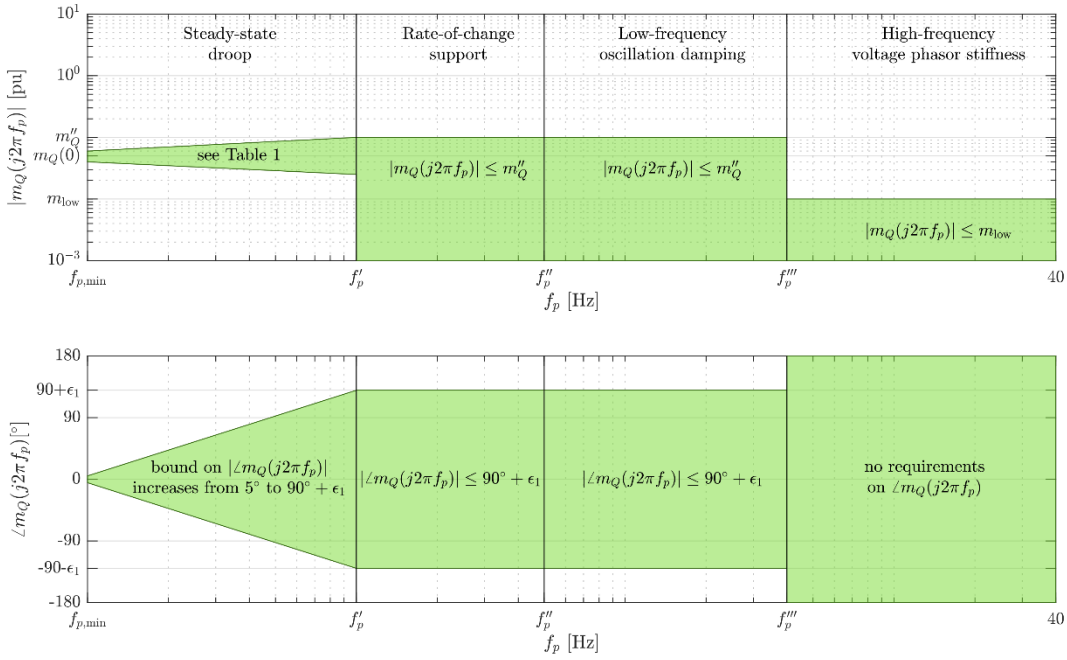

Figure A-7. Specification on $m_Q(j2\pi f_p)$ for power synchronization and low-gain high-frequency voltage phasor stiffness (see Table 6)

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Dynamic Response Specifications

While the specifications presented in the previous subsection encode the key GFM characteristics, further specifications on $m_P(j2\pi f_p)$ are needed to distinguish between various tiers of GFM capabilities. Notably, these additional specifications are not strictly related to distinguishing between GFL and GFM control. These requirements are summarized in Table 5 in Section 6 and illustrated in Figure A-8.

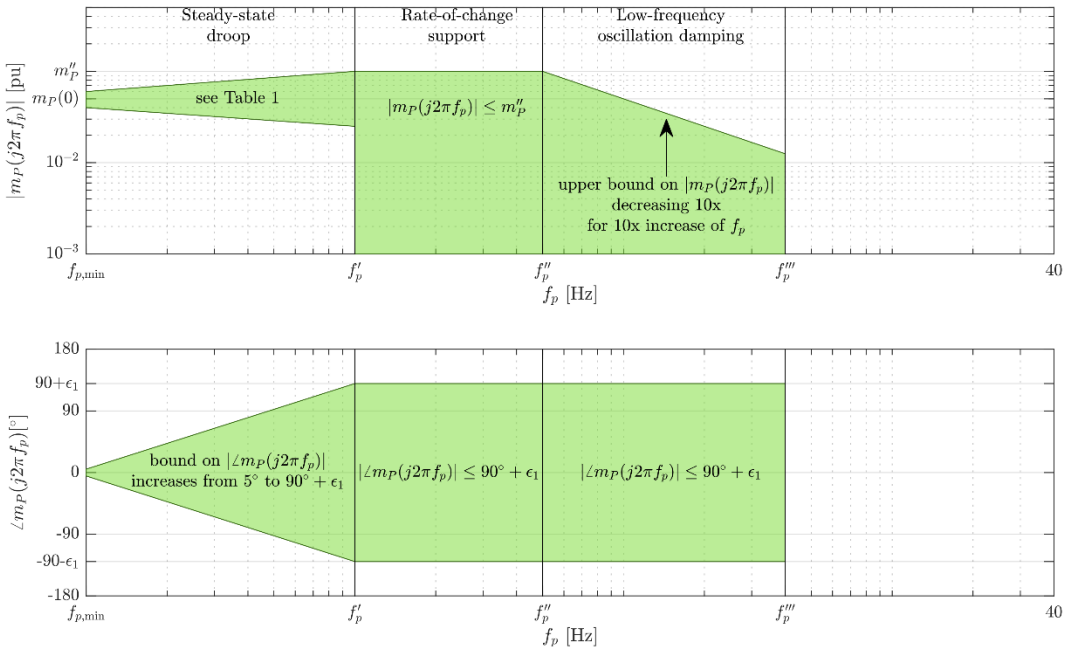

Figure A-8. Specification on $m_P(j2\pi f_p)$ for steady-state droop, rate-of-change support, and low-frequency oscillation damping (see Table 5)

More stringent requirements on $m_p(j2\pi f_p)$ that formalize provision of short-duration and long-duration frequency support, as shown in Figure 6, apply to higher GFM capability tiers.

Notably, steady-state frequency support is encoded by the steady-state droop specification shown in Figure A-8. In other words, between $f_{p,\min}$ and f_p' requires that $m_P(j2\pi f_p)$ closely matches the steady-state droop specification, i.e., $m_P(j2\pi f_p) \approx m_P(0)$ and $\angle m_P(j2\pi f_p) \approx 0$. Next, a deviation in gain and phase is permitted until f_p'. Between f_p' and f_p'' the gain $|m_P(j2\pi f_p)|$ shall be bounded by m_P''. Finally, between f_p'' and f_p''' the gain is required to decrease to encode an inertia response (i.e., increasing stiffness of frequency). Notably, for a GFM VSM with inertia constant H and steady-state droop $m_p(0)$ one obtains $f_p'' = \frac{1}{2\,H\,m_p(0)}$. Finally, the phase is restricted to $\pm(90° + \varepsilon_1)$ below f_p''' to prevent a droop response with incorrect sign (on average over one cycle of an oscillation).

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GFM Tiers

By combining functional capabilities as documented in Table 5 and Table 6 (see Section 6), various tiers of GFM capabilities can be defined. In particular, the bounds on $m_P(j2\pi f_p)$ and $m_Q(j2\pi f_p)$ for each tier can be obtained by taking the intersection of the bounds on $m_P(j2\pi f_p)$ and $m_Q(j2\pi f_p)$ for each applicable functional capability.

For all tiers, the dynamic droop coefficient $m_Q(j2\pi f_p)$ must either satisfy the bounds in Figure A-6 (passive high-frequency voltage phasor stiffness) or satisfy the bounds in Figure A-7 (low-gain high-frequency voltage phasor stiffness). Since these specifications on $m_Q(j2\pi f_p)$ do not require a controllable resource or significant energy storage in the IBR, they are applied to all tiers of GFM capabilities. In contrast, functional requirements modeled through bounds on $m_P(j2\pi f_p)$ significantly depend on the resource and energy storage elements of the IBRs and are categorized into various tiers.

Tier 1 GFM

The Tier 1 GFM requires power synchronization and high-frequency voltage phasor stiffness according to either the passive (e.g., Figure A-4) or low-gain (e.g., Figure A-5) specification. This specification encodes minimum requirements for GFM IBRs without frequency support functions to rule out adverse interactions. Examples of equipment meeting these specifications are synchronous condensers and STATCOMs.

Tier 2 GFM

In addition to the requirements on Tier 1, the specifications on $m_P(j2\pi f_p)$ for Tier 2 require rate-of-change support and low-frequency oscillation damping. This results in the overall specifications as shown in Figure A-9 for passive high-frequency voltage phasor stiffness and Figure A-10 for low-gain high-frequency voltage phasor stiffness. Notably, in either specification, the maximum dynamic droop gain is bounded by m_P'' between f_p' and f_p''. Moreover, f_p'' again has a similar interpretation as the cut-off frequency $f_p'' = \frac{1}{2\,H\,m_p(0)}$ of a synchronous generator or GFM VSM with inertia constant H and steady-state droop $m_p(0)$. We note that Tier 2 does not require steady-state frequency support, i.e., $|m_P(j2\pi f_p)| \to \infty$ as $f_p \to 0$ (e.g., PI-type active power-frequency droop control) is allowed. Examples for devices that can meet such specifications include E-STATCOMs and GFM wind turbines.

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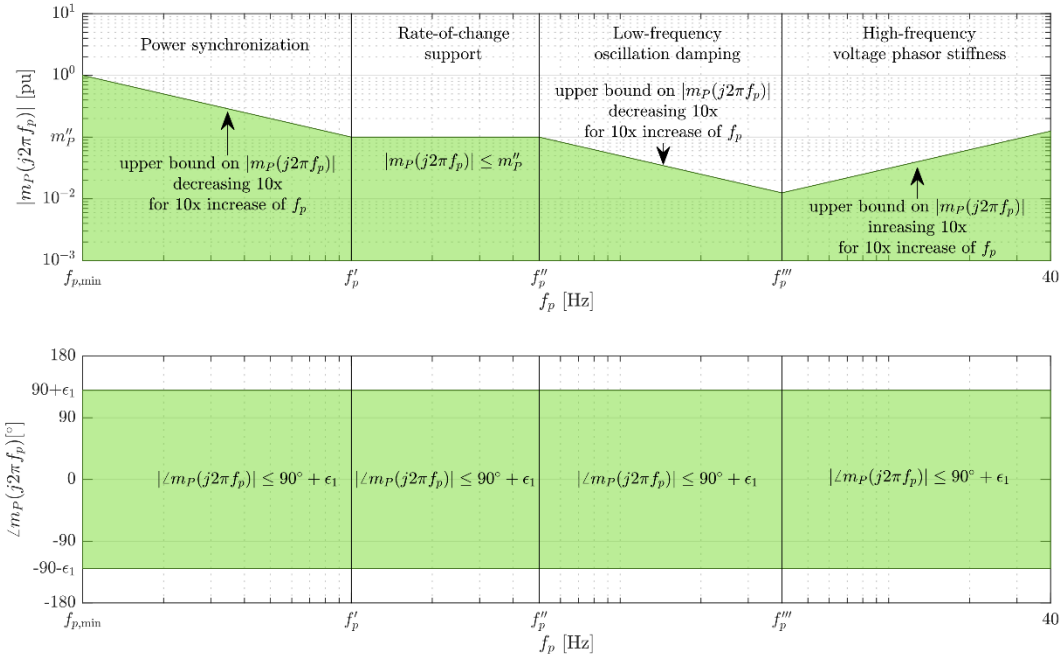

Figure A-9. Specification on $m_P(j2\pi f_p)$ for Tier 2 GFM with passive high-frequency voltage phasor stiffness

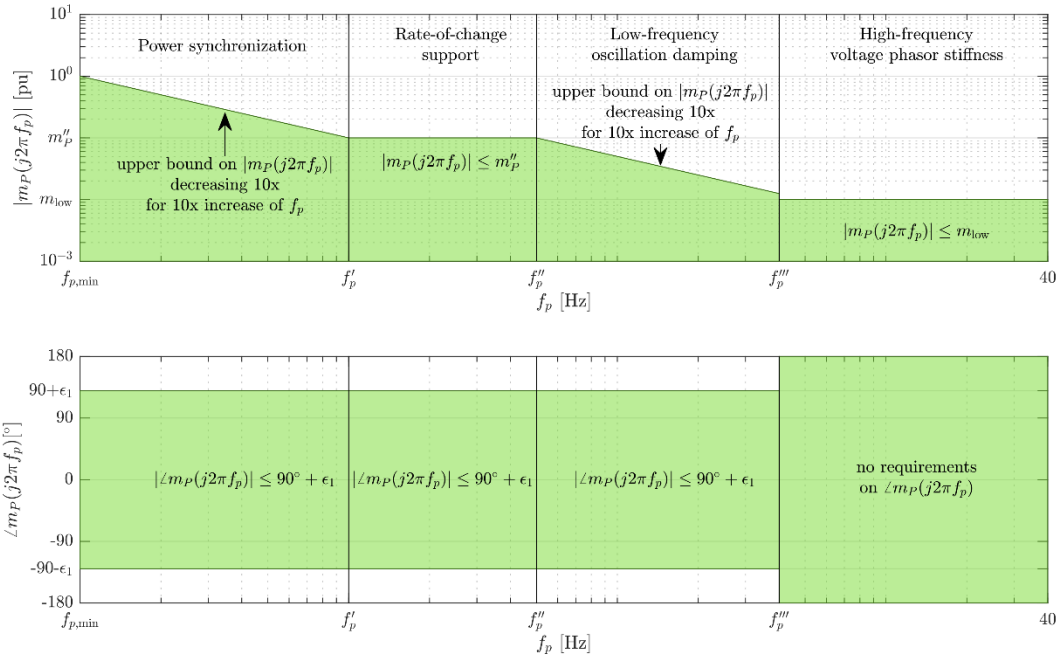

Figure A-10. Specification on $m_P(j2\pi f_p)$ for Tier 2 GFM with low-gain high-frequency voltage phasor stiffness

Tier 3 GFM

In addition to the requirements on Tier 2, the specifications on $m_P(j2\pi f_p)$ for Tier 3 require steady-state droop. This results in the overall specifications as shown in Figure A-11 for passive

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high-frequency voltage phasor stiffness and Figure A-12 for low-gain high-frequency voltage phasor stiffness. In particular, in the lowest frequency range, $m_P(j2\pi f_p)$ must closely match the steady-state droop specification, i.e., $m_P(j2\pi f_p) \approx m_P(0)$ and $\angle m_P(j2\pi f_p) \approx 0$. Examples for devices that can meet such specifications include GFM BESS and synchronous generators.

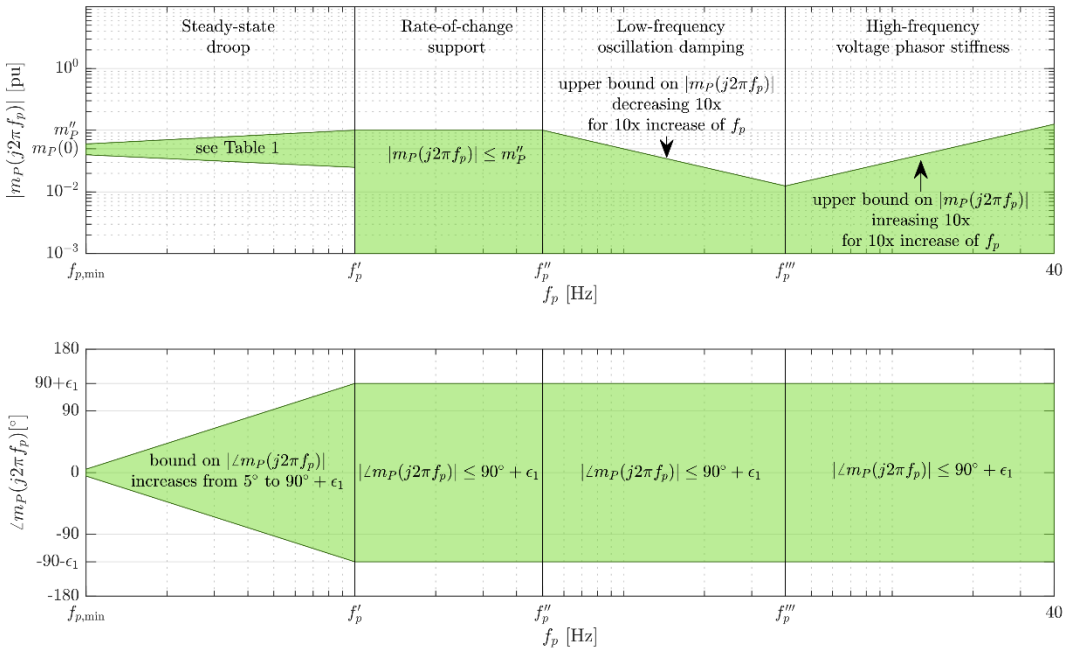

Figure A-11. Specification on $m_P(j2\pi f_p)$ for Tier 3 GFM with passive high-frequency voltage phasor stiffness

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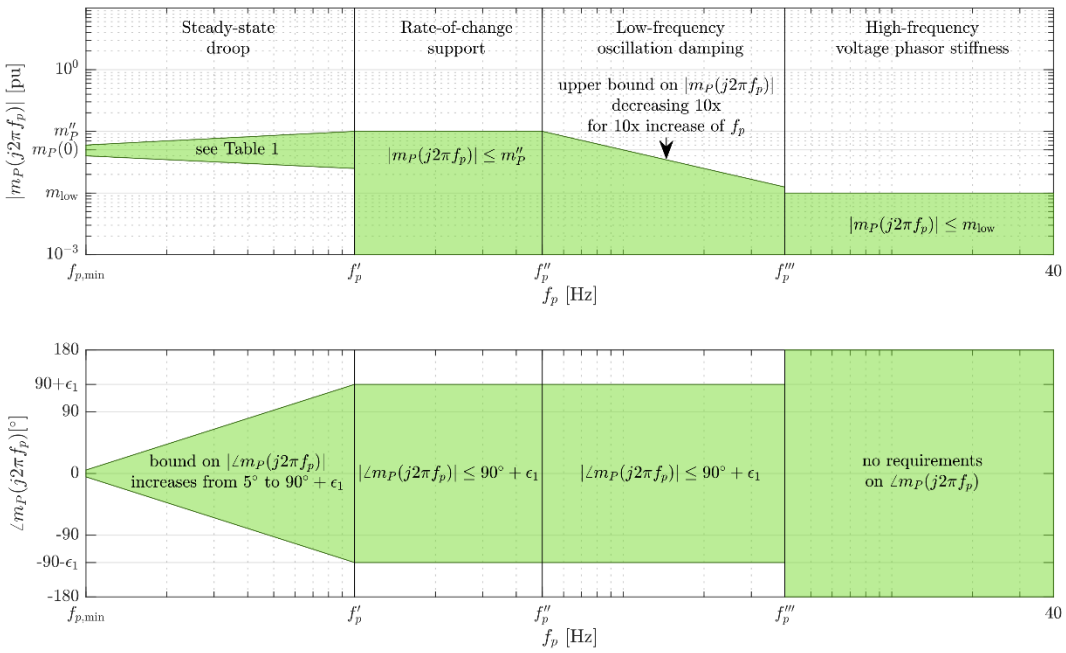

Figure A-12. Specification on $m_P(j2\pi f_p)$ for Tier 3 GFM with low-gain high-frequency voltage phasor stiffness

Tier 4 GFM

The specifications on $m_P(j2\pi f_p)$ and $m_Q(j2\pi f_p)$ are identical to Tier 3 GFM. Additional requirements for black start should be formulated in the time domain based on application-specific requirements.

A.4 Data-Driven Conformity Verification

To certify compliance with the specification, the test setup shown in Figure A-13 can be used to validate that the Bode plots of $m_P(j\omega_p)$ and $m_Q(j\omega_p)$ with $\omega_p = 2\pi f_p$ are within the bounds outlined in Section 2. The overall approach consists of sinusoidal perturbations injected into the angle and magnitude of an AC voltage source[13] with frequency ω_g and magnitude V_g given by

$$V_g = V^* + A_V \sin(\omega_p t),$$
$$\omega_g = \omega_0 + A_\omega \sin(\omega_p t).$$

Here, ω_0 denotes the nominal frequency, V^* denotes the nominal voltage, and A_V and A_ω are the amplitudes of the sinusoidal disturbance injected at the voltage source. The voltage source angle

[13] Future versions of the certification procedure may replace the shunt connected AC voltage source used to perturb the system with a shunt connected current source. Preliminary tests for GFM droop control without inner loops resulted in identical results to those obtained with a voltage source. An advantage of using a shunt-connected current source for perturbations is that GFL controls are expected to fail under such circumstances (i.e., it should generally not be possible to even record dynamic droop coefficients).

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is given by $\theta_g = \int_0^t \omega_g(\tau)\ \mathrm{d}\tau$. The gains A_V and A_ω need to be large enough to ensure sufficient excitation of the IBR dynamics, yet small enough to ensure that the IBR does not get close to its limits. Implementations of the test setup shown in Figure A-13 in EMT simulations use $A_V = A_\omega = 0.001$ per unit as a starting point for IBRs that conform to the specifications at the default values listed in Table 7 (see Section 6).

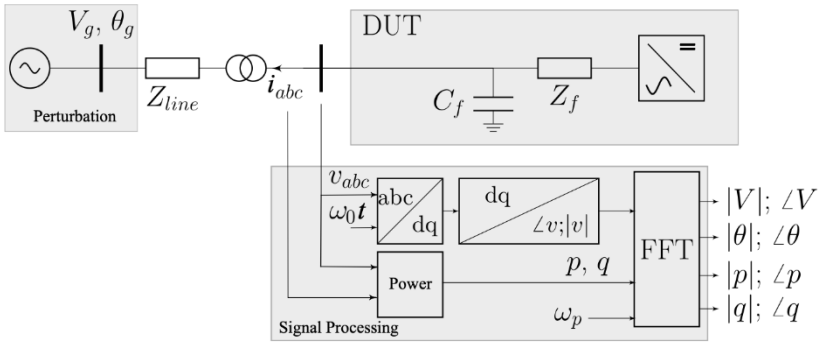

Figure A-13. Test setup and signal processing[14] for frequency sweep

The three-phase voltage and current (flowing out of the IBR) waveforms are captured at a reference point. The reference point does not have to coincide with the bus of the perturbation source and is solely determined by the location at which current and voltage measurements are taken. For example, if a transformer is present, the reference point could be before or after the transformer depending on whether the transformer is considered part of the IBR. Simulations or experiments are conducted that separately perturb frequency (i.e., $A_\omega > 0, A_V = 0$) and magnitude (i.e., $A_V > 0, A_\omega = 0$) until[15] signals have settled into a periodic steady-state at the frequency ω_p. Next, the instantaneous active power P and instantaneous reactive power Q are computed. Moreover, the voltage phase angle θ, and voltage magnitude V are computed in a dq frame rotating with angle $\omega_0 t$, oriented such that the positive 'd' axis is aligned with the positive real axis, and the positive 'q' axis is aligned with the positive imaginary axis.

The amplitude and phase shift of the oscillations in the signals V, θ, P, and Q are recovered by computing their Fourier series coefficients corresponding to ω_p. This allows representation of the phase shift and magnitude of the perturbations as complex numbers ΔV, $\Delta\theta$, ΔP, and ΔQ. Moreover, the magnitude and phase shift of the IBR frequency perturbation can be recovered as $\Delta\omega = j\ \omega_p \Delta\theta$. The complex perturbation signals can be collected in matrices

[14] J. Bui, D. Groß, and D. Ramasubramanian, "Implementation of the UNIFI frequency domain interoperability tests in EMT simulation tools," 2024.

[15] A typical choice for the simulation time is $3\tau'' + \frac{10}{f_0}$ seconds, where $\tau'' = \frac{1}{2\pi f_p''}$ denotes the time constant associated with the expected cut-off frequency f_p''.

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$$Y(j\omega_p) = \begin{bmatrix} \Delta\omega_\omega(j\omega_p) & \Delta\omega_V(j\omega_p) \\ \Delta V_\omega(j\omega_p) & \Delta V_V(j\omega_p) \end{bmatrix}, \text{ and}$$
$$U(j\omega_p) = \begin{bmatrix} \Delta P_\omega(j\omega_p) & \Delta P_V(j\omega_p) \\ \Delta Q_\omega(j\omega_p) & \Delta Q_V(j\omega_p) \end{bmatrix},$$

where the subscripts $()_\omega$ and $()_V$ denote the data collected using frequency and magnitude perturbations, respectively. The dynamic droop model can then be immediately recovered by, e.g., computing

$$\begin{bmatrix} m_P(j\omega_p) & \xi_Q(j\omega_p) \\ \xi_P(j\omega_p) & m_Q(j\omega_p) \end{bmatrix}.$$

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