Specifications for Grid-forming Inverter-based Resources

Version 1

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Abbreviations

CCT critical clearing time. 8

GFL grid-following. 5
GFM grid-forming. 5

HVDC high voltage direct current. 6

IBRs inverter-based resources. 5

MPPT maximum power point tracking. 6

NERC North American Electric Reliability Corporation. 5

PV Photovoltaics. 6

ROCOF rate-of-change of frequency. 8

SCR short circuit ratio. 8
STATCOM static synchronous compensator. 6

UNIFI UNiversal Interoperability for grid-Forming Inverters. 5
UPS uninterruptible power supply. 6

VUF voltage unbalance factor. 10

Contents

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)[1] are integrated into the power system [1]. To manage this situation today, system operators and utilities need accurate mathematical IBR models to assess their stability and performance under a variety of operating conditions. It is, however, challenging to acquire the design and control details, as manufacturers are understandably averse to disclosing intellectual property (IP)-protected control algorithms [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, performance verification, and power system stability assurance. 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.

The UNiversal Interoperability for grid-Forming Inverters (UNIFI) Consortium is addressing fundamental challenges facing the integration of GFM inverters in electric grids alongside rotating machines and other IBRs. This document defines a set of **UNIFI Specifications for GFM IBRs** that provides requirements from both a power system-level as well as functional requirements at the inverter level that are intended to provide means for vendor-agnostic operation of GFM IBRs at any scale in electric power systems. The specifications are clearly identified and attributed to an IBR plant or an IBR unit throughout the document, where applicable.

1.1 Grid Forming (GFM) Controls

The North American Electric Reliability Corporation (NERC) defined GFM controls in the following manner:

> "GFM IBR controls maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame. This allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during challenging network conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid." [6]

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 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.

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

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[1] The term "IBR" is defined in IEEE Std 2800-2022 as an inverter-based resource connected to a transmission or sub-transmission system. For purposes of this document, an IBR is taken to mean an inverter-based resource connected anywhere in the system, including distribution.

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, so it does not maintain a fixed voltage magnitude or phase angle on those timescales. On longer timescales (a couple of seconds), 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, for a disturbance outside the normal operating range of voltage 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. Thus, it 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 may limit the capability of the IBR to provide any of these services.[2]

The operation described above is primarily based on conventional/legacy GFL IBR plants. However, newer IBR plants with GFL controls can provide frequency and voltage response much faster than 1 second. As a result, the demarcation line between the definition of GFL and GFM can become blurred and as such, UNIFI recommends the use of performance specifications and functional requirements to determine the necessary and required operation from IBR plants.

1.2 Scope

The UNIFI Specifications for GFM IBRs establish functional requirements and performance criteria for integrating GFM IBRs in electric power systems at any scale. This may include devices used at the local customer, microgrid, distribution, and transmission scale. 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), static synchronous compensator (STATCOM), uninterruptible power supply (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.

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 Limitation

Local system conditions and scenarios, hardware device limits, and limitations of the source behind the IBR 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 the extent to which the performance criteria can be relaxed under a mutual agreement with all the parties such as manufacturers, developers, and system owners/operators. Further, performance requirements for GFL plants, such as the performance requirements laid out in standards such as the IEEE 2800-2022 [5] or ENTSO-E [7] Requirements for Generators and for GFL inverters as in the IEEE 1547-2018 [4], will also apply to GFM plants and IBRs unless explicitly identified in this document or in other documents as inapplicable. There are circumstances in which a requirement of a standard such as IEEE 1547-2018 or IEEE 2800-2022 is

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[2] The timeframes specified in this section are intended as general descriptions rather than requirements or hard limits as subtransient and transient times are a function of machine characteristics.

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, a GFM IBR should not necessarily be expected to exhibit the same level of performance as a GFL IBR in the fast restoration of active and/or reactive power immediately after a major grid event, since a GFL IBR has a natural advantage over GFM IBR in the performance of active and/or reactive power regulation. The synchronization-related performance criteria in this document do not apply to the GFM IBR that is designed to act as the only grid-forming resource in a power system, including where synchronization with other resources including synchronous machines and other GFM IBRs is not required (for example, a single GFM IBR powering an off-grid power system).

2 Universal Performance Requirements for GFM IBRs

This section describes universal performance requirements from GFM resources connected to an electric power system. These universal performance requirements are to be provided regardless of the type of GFM resource, the operating condition of the resource, and the strength of the grid to which it is connected. Further, there can be an overlap between the expectations listed in this section and the performance expectations of GFL resources.

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). 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. How fast a system changes after an event is often described as being dependent on system strength. Specific areas of power systems—and sometimes entire power systems—are often described as being strong or weak systems. This qualitative description refers to the extent the voltage or frequency changes in response to disturbances, which 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.

2.1.1 Autonomously Support the Grid

Both GFL and 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. 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, regardless of whether it is GFL or GFM. Note that there are other allowable operating modes for GFL such as fixed power factor mode. Further, like GFL IBRs, GFM IBRs are expected to operate in a stable manner when connected in parallel with rotating machines, GFL or GFM assets. If a grid event occurs that leaves a GFM IBR connected to a weak grid (i.e voltage sensitivity and low inertia) the GFM IBR should be able to seamlessly respond to this event (based only on its local measurements) and 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, 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. Over longer time scales, it is possible the plant itself will receive outside communications of new dispatch setpoints or curtailment from an operator working to manage the grid event.

2.1.2 Dispatchability of Power Output

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 a grid operator command or by a locally determined goal, based upon a market clearing solution, like a GFL IBR. For a GFM IBR whose primary input is a variable resource (e.g., wind or solar), it may be set to maximum available output power (unless expressly asked by the grid operator or local measurements 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 a remote command. See Section 3.3 for additional information on GFM IBR communication considerations.

2.1.3 Provide Positive Damping of Voltage and Frequency Oscillations

It is expected that a GFM IBR will present a non-negative resistance or damping to the grid within a frequency range of common grid electrical resonances to prevent the initiation of any adverse interactions or oscillations. 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, using locally measured signals and without observability of the network and control algorithms of other devices connected to the power system. The GFM IBR is also expected to not introduce any new unstable oscillatory modes into the power system. 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

A GFM IBR is expected to share (e.g. incrementally increase power burden) with other generation resources using the principles of droop akin to the operation of conventional synchronous generators or GFL IBRs. 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. The expectation is that the system will achieve a (potentially off-nominal) steady-state operating point within the normal operating voltage and frequency ranges while ensuring proper power sharing, after a disturbance. As an example, on the transmission system, this property is typically achieved from resources via droop on frequency for sharing of active power [8] and droop on voltage for sharing of reactive power.

2.1.5 Robust Operation in Grids with Low System Strength

A GFM IBR is expected to operate stably when connected to a power system with low system strength and to improve the strength of the network in the region of connection during normal operations via a reduction in the sensitivity of voltage to current injection and a reduction in the rate of change of frequency during an event. This improvement in system strength is 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 impedance profile of the GFM IBR, which in turn can be dependent on software, controls design, and tuning.

2.1.6 Voltage Balancing

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

When it operates within its negative sequence and total current capability, the GFM IBR should aid in reducing the voltage unbalance factor (VUF) [9] measured at the point of connection of a GFM IBR plant. The GFM IBR plant's negative sequence current capability should be sufficient to meet the load characteristics of the network as determined by site- and system-specific detailed studies. 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.

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) can cause voltage and frequency excursions outside of the normal operating ranges. Under abnormal grid conditions, the GFM IBR should perform according to the following requirements.

2.2.1 Ride-through Behavior

A GFM IBR is expected to inject current during and after a voltage sag to aid in voltage recovery. The current to be injected is expected to have a characteristic that helps maintain the voltage at each GFM IBR terminal close to its pre-disturbance value subject to physical limitations of the GFM IBR unit. If during the fault or other event that results in voltage going outside normal limits the GFM IBR's output current reaches its limit, it is expected that the GFM IBR will continue to inject current within its ratings. The purpose of this is to meet protection requirements such as negative-sequence current with certain phase angle for directional elements, and/or to support network swing dynamics for the benefit of system-wide stability subject to hardware equipment limitations and capabilities. Upon fault clearance, it is expected that the GFM IBR support stability of other devices in the post-fault network. A GFM is *not* expected to inject a high magnitude of fault current (such as 6 per unit fault current obtained from rotating machines) for any fault, symmetrical or asymmetrical unless the GFM IBR has been specifically designed with this feature.

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 an agreed-upon and predictable manner 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 as quickly as possible during and after a major grid event.

Additionally, the GFM IBR should trip for faults that occur on the power system only when such tripping is allowed or required by IEEE 1547-2018 or IEEE 2800-2022 or other appliable requirements or standards as appropriate.

2.2.2 Response to Asymmetrical Faults

During asymmetrical faults, a GFM IBR is expected to maintain a balanced internal voltage to the extent possible within its physical limits. This naturally results in the GFM IBR outputting unbalanced currents, including negative sequence currents. It is expected that the negative sequence current can be regulated to meet the protection requirements (e.g., the angle of the negative sequence current with respect to negative sequence voltage may be required).

2.2.3 Response to Abnormal Frequency

As long as the frequency does not exceed the must-not-trip region defined by the interconnecting utility or by IEEE 1547-2018 or IEEE 2800-2022 or other applicable requirements or standards, a GFM IBR is expected to modulate active power as required during and after a frequency excursion event to aid in frequency recovery and stability, similar to a GFL IBR. In the sub-transient time frame, the power to be injected is expected to have a similar effect to that of resisting frequency change by maintaining frequency at each GFM IBR unit's terminals as close as possible to its nominal value subject to physical limits of the GFM IBR unit. Beyond the sub-transient time frame, the GFM IBR is expected to respond to frequency adjustments by internal or external controllers to synchronize with other resources. Over longer time frames, the energy source behind the converter, such as the size of dc capacitors, battery charge levels, wind speed, and turbine characteristics, or solar irradiance, may constrain the ability to deliver sustained active power.

2.2.4 Response to Phase Jumps and Voltage Steps

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 without exceeding equipment limits. Similarly, a GFM IBR is expected to absorb or inject reactive/active power to reduce changes in the positive sequence voltage magnitude. Further, following the event, a GFM IBR is expected to contribute towards positive damping of any oscillations that may arise.

2.2.5 Intentional Islanding

When intentional islanding occurs (islanding of an area in a larger interconnected transmission system, or formation of a microgrid in the distribution network, and across all three phases), a GFM IBR (this is designed to maintain an intentional island) is expected to be capable of continuing to support the evolution of a stable voltage and frequency of the island/microgrid. Stabilization of the island's voltage and frequency however 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; IBRs and (iv) 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 over-voltage and/or frequency protection settings as defined by the interconnecting utility or by applicable standards or respective protection studies.

3 Additional GFM Capabilities and Considerations

This section describes additional capabilities that may be implemented in coordination with the power 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 Black Start and System Restoration

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

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

1. Provide a soft start to loads (i.e., by ramping up the output voltage at a programmable rate) which would alleviate inrush currents.
2. Supply transformer, cold-load, and other inrush current needed. 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 over-current capability.
3. Provide a steady voltage reference for GFM and GFL IBRs and other resources to synchronize to and facilitate a smooth system restoration. 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. Operate in parallel with other black-start GFM IBRs 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.

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.

3.2 Regulating Voltage Harmonics

The harmonic distortion of the line-to-neutral voltage waveforms produced by a GFM IBR or GFM IBR plant should comply with the requirements of the interconnected utility. As a result, a GFM IBR's may inject harmonic currents to aid in reducing the amplitude of voltage harmonics at their point of connection.

3.3 Communications between System Operator and IBR plant

When communications are required between the GFM IBR units or plant and the system operator, a *cyber-secure communications*[10] method should be used. The power system and the GFM IBR should continue to operate 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 using one of the communications protocols specified in IEEE 1547-2018.

3.4 Secondary Voltage and Frequency Signal Response

GFM IBR plants 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 is expected to adjust its output to operate at a new steady state without introducing instability.

3.5 IBR Short-term Rated Current

The IBR short-term rated current (ISRC) is the output of current in excess of the continuous rated current for a time-limited period, but without exceeding the IBR's absolute maximum current capability, so that the IBR remains able to regulate 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. This capability might also impact the response of unbalanced faults wherein the current on one phase exceeds that of the others. An example IRSC specification would be "1.5 times full-rated current for 2 s". If the ISRC capability is not provided by the GFM IBR and it is used to support transformer inrush and motor starting, then the inverter should be sized properly such that its continuous current capability is sufficient in supplying the inrush current.

3.6 Constraints Due to Input Source

Site-specific integration and operation studies should consider the ratings of the GFM IBRs utilized. The speed of response may be constrained by the basic limitations of the DC source behind the GFM inverter. 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.

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 behavior of the GFM IBR when approaching or encountering physical limits is expected to be captured in the manufacturer's electro-magnetic transient (EMT) 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. The EMT model should also specify what measurements and thresholds are used to activate and deactivate the fault response of the GFM IBRs. For example, fault response can be activated by a certain peak RMS current threshold, however, the deactivation of the fault response and transition back to droop-based operation can be based on the positive-sequence voltage recovery.

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