Voluntary Specification for Grid-forming Inverters

May 2023

A statement of voluntary threshold requirements and additional capabilities for inverters and other power electronic devices with grid-forming capability

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Important notice

Purpose

To define and specify the ‘core’ technical capabilities that power electronic devices should have in order to be categorised as grid-forming inverters. Where possible, this document also includes expected performance requirements for grid-forming inverters and ‘additional capabilities’ which, although desirable, may not be met by all grid-forming inverters. Although voluntary, this document is intended to help inform future regulatory change in the areas of related technical requirements and standards, service specifications, and procurement processes.

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Version control

Version	Release date	Changes
1.0	29/5/2023	

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1 Introduction

1.1 Context and background

With increasing penetration of inverter-based resources (IBR) and retirement of synchronous generators (SG) in power grids worldwide, new operational challenges with respect to system strength, voltage and frequency control, synchronous inertia, power system protection, and other phenomena will need to be considered by power system operators. Grid-forming (GFM) inverters have the potential capability to address some of the operational challenges associated with high levels of IBR penetration.

In August 2021, AEMO published a white paper on the application of advanced grid-scale inverters in the National Electricity Market (NEM)[1] to highlight the actions needed to progress the development and demonstration of this technology. It noted that an absence of clear specifications makes it challenging for developers to specify their requirements from Original Equipment Manufacturers (OEMs), and for OEMs to design their GFM offerings.

AEMO's Engineering Framework Priority Actions publication[2] from June 2022 takes the white paper's recommendations forward, including an action to collaborate with stakeholders on a voluntary specification for grid-forming inverters:

Action ID	Target end-state objective for action	AEMO commitment for financial year 2022-2023
A3	Define necessary power system support capabilities for grid-forming inverters to guide Original Equipment Manufacturers (OEMs) and developers.	Collaborate with industry on a voluntary specification for grid-forming inverters.

This document represents the culmination of AEMO's efforts in financial year 2022-2023 for Engineering Framework Action A3.

1.2 Document purpose

This 'voluntary specification' is a preliminary document to provide guidance to stakeholders while the regulatory environment around grid-forming technology develops. It specifies the 'core' technical capabilities that power electronic devices should have in order to be categorised as grid-forming inverters. Where possible, expected performance from grid-forming inverters is provided. This document is also intended to help inform future regulatory change in the areas of technical requirements and standards, service specifications, and procurement processes, as outlined in Section 1.5.

1.3 Development of this specification

This specification has been developed in a collaborative effort with stakeholders. AEMO would like to thank and acknowledge the stakeholders across the energy industry that volunteered their time and expertise to contribute to the development of this specification.

[1] https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf

[2] https://aemo.com.au/-/media/files/initiatives/engineering-framework/2022/nem-engineering-framework-priority-actions.pdf?la=en&hash=F5297316185EDBD4390CDE4AE64F48BB

Between November 2022 and February 2023, AEMO held four workshops with OEMs, developers, Network Service Providers (NSPs), consultants, and academics to engage and debate key elements of this specification. Participation from each organisation was limited to two representatives to ensure a balance of voices were heard from large and smaller organisations equally. Some participants also provided feedback one on one with AEMO. During the workshops, participants told AEMO the specification needed to ensure it considers all technology forms, not just grid-forming battery energy storage system (BESS), which helped shape various sections of the Specification.

The insights stakeholders shared were invaluable in helping shape a well-informed and considered specification that AEMO believe will provide a valuable reference point for industry, and a strong foundation for future work.

1.4 Structure of the specification

This specification is broken down into ‘core’ and ‘additional’ grid-forming capabilities.

Compared to grid-following (GFL) inverters[3], some capabilities of GFM inverters can be delivered without making material modifications. For example, software and control algorithms can be used to implement many grid-forming capabilities. The majority of these capabilities will be expected for a device to be considered grid-forming. These are categorised as ‘core’ capabilities.

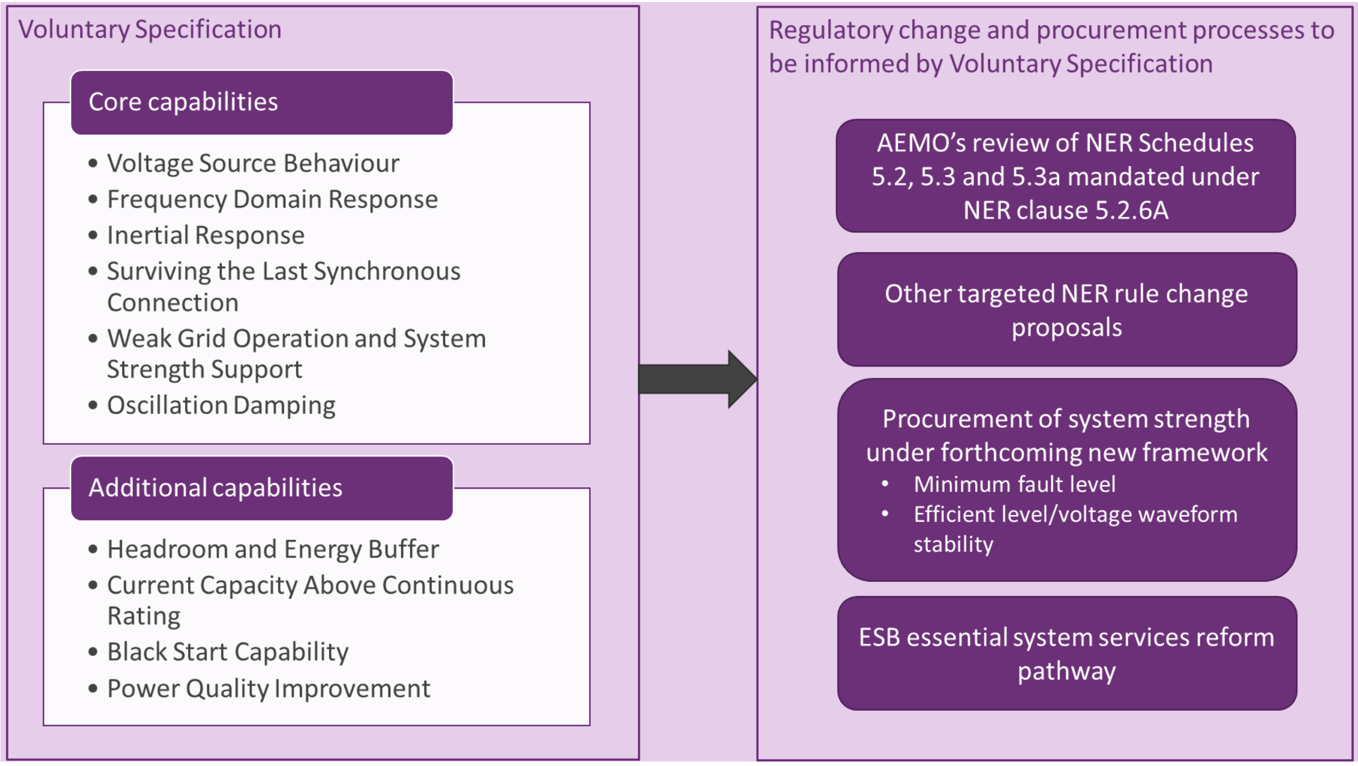
Delivery of other power system support capabilities may require material modifications, such as, additional hardware or changes to operational practices. These modifications may also require the developer and/or operator of the GFM plant to incur additional cost. These have been captured separately under ‘additional’ capabilities and are considered optional extensions to the core capabilities.

1.5 Application of this specification

There are a number of regulatory change and procurement processes that may be informed by this specification, as shown in Figure 1 below.

[3] “Grid-following inverters synchronise to the grid voltage waveform, adjusting their output to track an external voltage reference” (https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf).

Figure 1 Related regulatory change and procurement processes



1.6 Next steps

This voluntary specification represents a starting point on the journey to formally specifying grid-forming capabilities for the NEM. While this is not a consultation document and AEMO is not requesting submissions, AEMO is interested in any feedback industry participants and OEMs have that would help inform ongoing work in this space.

Moving forwards, a key next step in this process is the development of a test plan and metrics for each of the qualitative capabilities within this specification, to quantify requirements and enable demonstration that a device meets the specified capabilities. AEMO has commenced work on this test plan and volunteers from the previous work will be invited to comment on a draft version of this when it is available. This test plan is anticipated to be published during financial year 2024.

Another question requiring further consideration is how the contributions from grid-forming devices should be accounted for in planning studies when considering the availability of different system services, noting that some contributions from grid-forming devices are dependent on the plant's operating point at the time of response (such as inertial response, as outlined in Section 2.3.3).

1.7 How to get involved

For stakeholders wishing to provide feedback on this document, to actively contribute to future work, or to be notified of future updates on AEMO's grid-forming inverter work, please contact AEMO at FutureEnergy@aemo.com.au.

2 Grid-forming inverter specification

This section explains the key specifications of a GFM inverter and, where possible, provides example simulation results to demonstrate the desired performance of the GFM device[4]. GFM specifications have been categorised into two groups: “Core” and “Additional” capabilities.

2.1 What is a grid-forming device?

A key starting point for this specification is to establish a definition for what constitutes a grid-forming device. In the absence of a single agreed international definition, and following extensive discussion with our stakeholder reference group, AEMO proposes the following definition for what it means to be grid-forming in the context of the NEM.

Grid-forming inverter

A grid-forming (GFM) inverter maintains a constant internal voltage phasor in a short time frame, with magnitude and frequency set locally by the inverter, thereby allowing immediate response to a change in the external grid. On a longer timescale, the internal voltage phasor may vary to achieve desired performance.

In this document, the term ‘inverter’ is used in a general sense and is intended to also cover non-generating power electronic devices, such as AC-to-DC converters and STATCOMs.

Whilst this specification is largely targeted towards transmission-connected GFM inverters, AEMO recognises that other types of GFM devices exist and may provide services to the NEM. GFM devices can include STATCOMs with energy buffers, DC converters, and potentially, loads interfaced to the power system with controllable converters.

2.2 Core capabilities versus additional capabilities

Core GFM inverter capabilities are expected to be achievable with no or minimal modification to plant hardware and operational processes when compared with a GFL design, requiring changes mainly to the software and control algorithms of the plant. The majority of these capabilities will be expected of all GFM devices. The GFM device is expected to have the capability to provide some form of small energy buffer by its design or operation to achieve core capabilities, even if said energy buffer is not always available. For example, a STATCOM would need an energy storage to be considered GFM, where the energy storage could be a short-duration battery or super capacitor. By design, for the device to be considered GFM, the energy must also be instantaneously available to the grid, and not delayed by DC-side control algorithms.

Further to these core capabilities, some GFM inverters might be capable of providing additional capabilities that could necessitate material hardware upgrades or changes to operational practices to provide a larger energy

[4] Some of the tests mentioned in this section are proposed by other system operators such as Hawaiian Electric Facility and National Grid.

buffer. Not all GFM inverters need to provide these additional capabilities, but the availability of these capabilities is valuable to support secure operation of the power system with high IBR penetrations.

2.3 Core capabilities

This section provides details on the core capabilities of a GFM inverter, along with illustrative examples where possible.

2.3.1 Voltage source behaviour – response to voltage magnitude and phase changes

A GFM inverter should behave like a voltage source behind an impedance[5] while in normal operation (within current capability limits). Its main control objective in the sub-cycle timeframe is to control its voltage waveform, as opposed to a GFL inverter, which controls its output current as the main objective[6]. The magnitude and phase angle of the internal voltage source should remain nearly constant within the transient timeframe following a disturbance[7]. This is essential for providing the GFM inverter with capabilities like instantaneous active and reactive power response when disturbances occur.

These attributes mean a GFM inverter can inherently resist fast changes in the voltage and phase angle and hence can improve power system stability. In addition, on a longer timescale (multiple power frequency cycles), the reference voltage phasor of a GFM inverter could vary to support the secure operation of the power system.

A GFM inverter may temporarily hit its current limit during transients and not be able to maintain its voltage reference constant. However, within its current limits it should operate as described above[8].

In summary:

- A GFM inverter should form an internal voltage source behind an impedance[9]. The inverter's reference voltage magnitude and frequency should change little on the transient timescale when active and reactive powers are generated[10].
- Active power output of a GFM inverter is determined by the internal voltage phasor (magnitude and phase angle), the Point of Connection (PoC) voltage phasor, the internal impedance of the device, and the sine of the phase angle difference between the internal voltage phasor and the PoC voltage phasor, without needing to directly control the current.
- A GFM inverter shall be capable of synchronising with other generation sources on the power system.

Expected performance

In response to an external voltage magnitude step, the GFM inverter should commence its response to oppose the change in voltage almost instantaneously from the initiation of the voltage step. In National Grid UK's

[5] Reference: ESIG (https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/).

[6] References: NREL (https://www.nrel.gov/docs/fy21osti/73476.pdf).

[7] This definition aligns with https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_Grid_Forming_Technology.pdf.

[8] At the limit, GFM plant may temporarily revert to GFL operation to track the grid voltage phase angle and frequency - Reference: ESIG (https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/).

[9] Lower impedance values help improve grid strength. However, this increases the likelihood of hitting current limits for large phase jumps or voltage magnitude jumps.

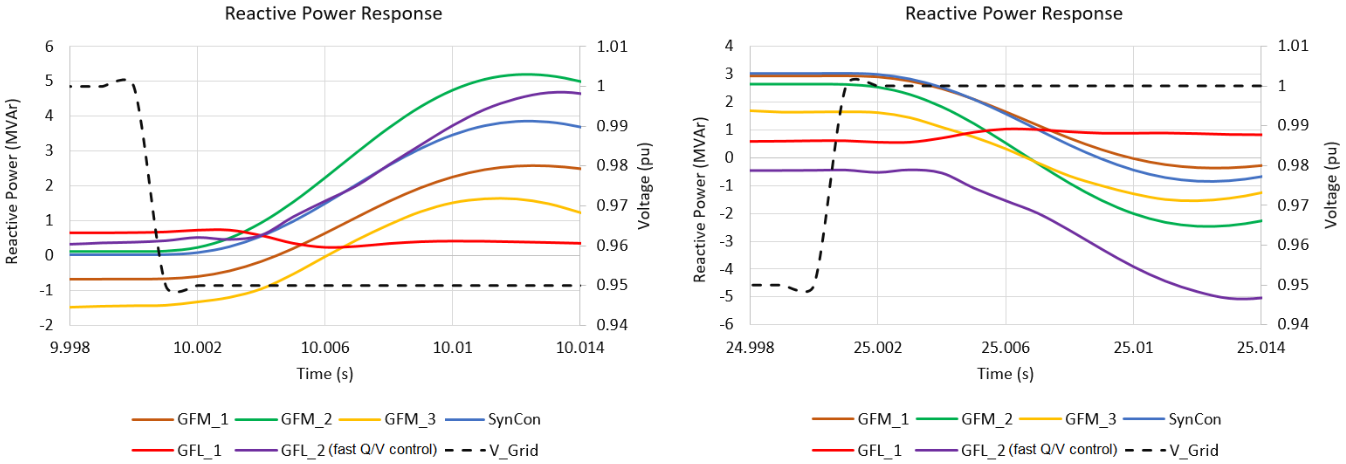
[10] The stiffness of the internal voltage source requires the bandwidths of the voltage control loops to be sufficiently small. A voltage control loop with a smaller bandwidth generally corresponds to a longer rise time and settling time - Reference: ESIG (https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/).

specification, the response time is specified as less than 5 milliseconds[11]. The response will be largely a reactive power response, for conditions where the X/R ratio is large, as is typical for transmission systems. For systems having a lower X/R ratio, the active power component of the response will be larger. The magnitude of the response depends on the impedance between the inverter and the point where the voltage step is applied.

Figure 2 and Figure 3 below show reactive power responses for a short circuit ratio (SCR) of 3 to a 5% step down and up for three GFM inverters, a synchronous condenser, and for comparison, two GFL inverters. The conditions for these simulations have been chosen so that the devices do not encounter current limits.

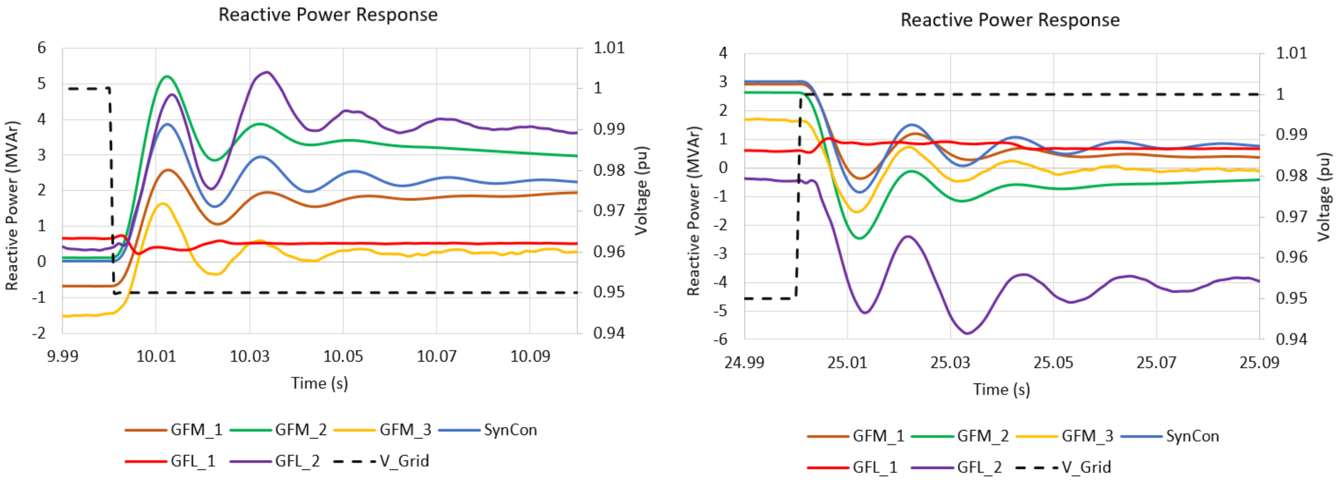
As illustrated in the response from all three GFM inverters and the synchronous condenser, the response commences within 2 to 3 milliseconds, and is similar in shape. The two grid-following inverters show different implementations of GFL inverter technology. The first is a more traditional approach, in which the inverter does not respond in a direction that would oppose the voltage change. The second (GFL_2) is a more modern development where a fast reactive power response to a voltage change is triggered on the inverter. This more closely approaches GFM behaviour for a voltage magnitude step.

Figure 2 Response to a 5% step in voltage magnitude for three GFM inverters, a synchronous condenser and GFL inverter



11 Available online: https://www.nationalgrideso.com/document/183496/download

Figure 3 Response to a 5% step in voltage magnitude for three GFM inverters, a synchronous condenser and GFL inverter (longer timescale)



In response to a step change in phase angle, the GFM inverter should respond almost instantaneously by injecting or absorbing power to oppose the change in phase angle.

Figure 4 and Figure 5 below illustrate, for a SCR of 3, the response to a 20-degree phase jump of three GFM inverters, a synchronous condenser and the two GFL inverters from the previous illustration. The response will largely be in active power, once again depending on the X/R ratio of the system. The conditions for these simulations have been chosen so that the devices do not encounter current limits.

The responses illustrate the close to instantaneous response to oppose the phase jump from the GFM inverters, the synchronous condenser and GFL_2. In this case the response of GFL_2, compared with the GFM inverters and the synchronous condenser it is not sustained, but it is possible that ongoing improvements to the GFL technology will make these responses more similar.

It should be noted that the near instantaneous response is a necessary behaviour but not sufficient to identify an inverter as grid-forming. In particular, it is important to also consider the longer-term response of the device, shown further in Section 2.3.5.

Figure 4 Response to a 20-degree phase angle step for three GFM inverters, a synchronous condenser and GFL inverter (longer timescale)

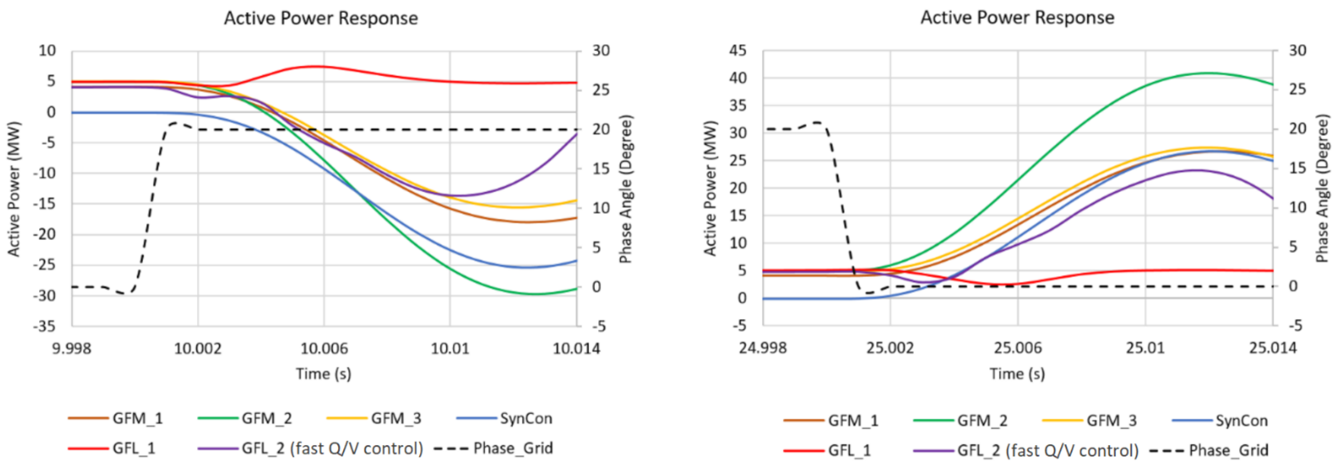
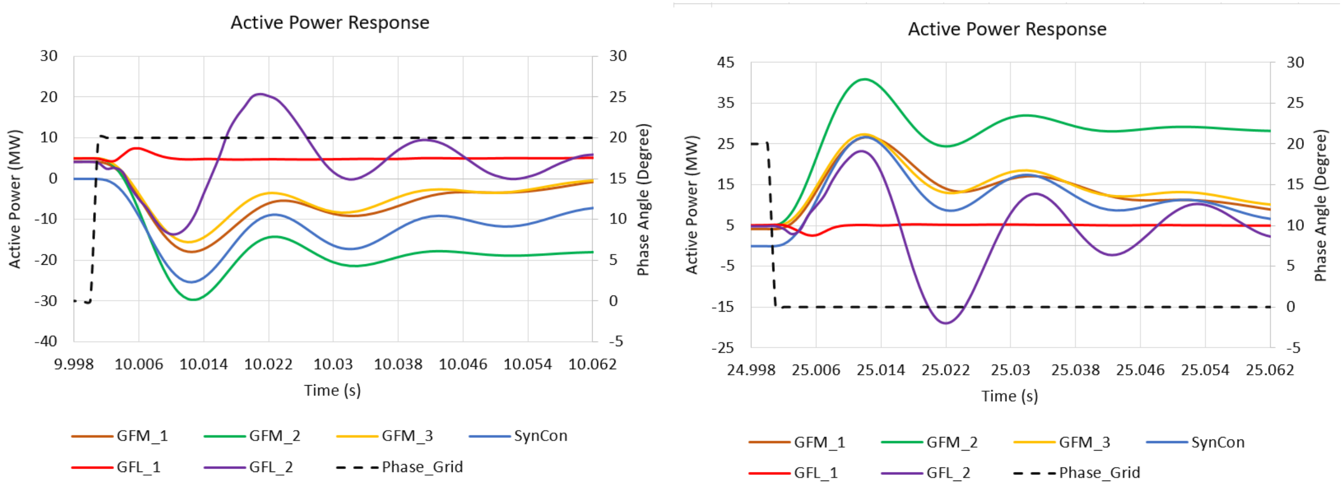


Figure 5 Response to a 20-degree phase angle step for three GFM inverters, a synchronous condenser and GFL inverter



Expected performance for operation at limits

Inverters have limited capacity and the energy sources that supply them also have limits on their output. This specification expects that inverters may at times be operated at a limit but should have capability to operate as GFM without (initially) being on a limit. A device must have this capability by design to be considered GFM under this specification. Such designs could include:

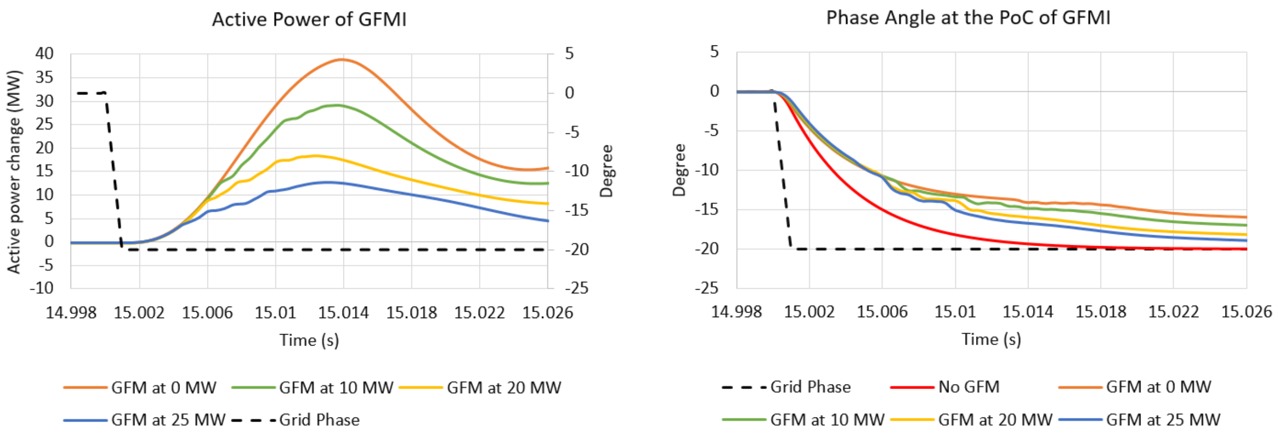
- The ability to maintain headroom by backing off output.
- A dedicated energy buffer for the purpose of facilitating grid-forming capability.
- Overload capability or oversizing of inverters.

In both the voltage magnitude step response and the voltage phase step response cases, operation into limits should not affect the initiation of the response (provided the inverter is not initially at a limit of its operation), but can limit the magnitude of the response. The response when the inverter is at a limit, and in transition to and from a limit condition, must be smooth and stable. This specification anticipates that the extent to which a GFM inverter can provide GFM performance will depend on the extent of the response before hitting a limit and also the nature of the response once the limit is encountered.

As an example, Figure 6 below shows active power responses for a phase angle jump of -20 degrees for the same GFM inverter dispatched to different pre-disturbance active power output levels. The GFM inverter has a maximum continuous output of 25 MW but also implements some short time overload capability. The different initial dispatch conditions allow for different levels of headroom in the GFM inverter's active power response to the phase angle jump. The change in active power output of the GFM inverter and the resultant measured phase angle at its PoC are shown in the diagrams below and demonstrate that:

- Under all dispatch conditions, there is an initial active power response from the GFM inverter opposing the phase angle jump, the effect of which can be observed by comparing the red ('No GFM') trace on the right with the other traces in that graph.
- With greater levels of headroom available, the GFM inverter can provide a larger active power response which in turn has a greater effect on limiting the observed disturbance in the voltage phase angle of the PoC bus.

Figure 6 Example response to a 20-degree phase angle step for a GFM inverter operating with different initial active power dispatch and hence different margin to its limits



Note: All measured phase angle signals are filtered.

If the inverter is initially operating at a limit and a disturbance occurs that would tend to cause a response in the direction of the limit, then no response would be expected. If, on the other hand, a device operating at a limit is subject to a disturbance that would move it away from the limit, that response should be near instantaneous, and smooth.

There are many potential types and implementations of limits, which can have different impacts on the plant's performance as a grid-forming inverter. In general, the implementation of the response at any limit (as opposed to the limit itself) should be checked to ensure it is not detrimental to stability. Response at a limit should also not lead to reduced harmonic performance, compared with non-limited operation (for example, clipping of current waveforms).

2.3.2 Frequency domain response

GFM resources are characterised by specific frequency domain performance. Impedance magnitude obtained from, for example, an impedance scan test can be used to determine the GFM frequency domain characteristic. The GFM resource's voltage source behaviour can be illustrated by the impedance magnitude around the fundamental frequency.

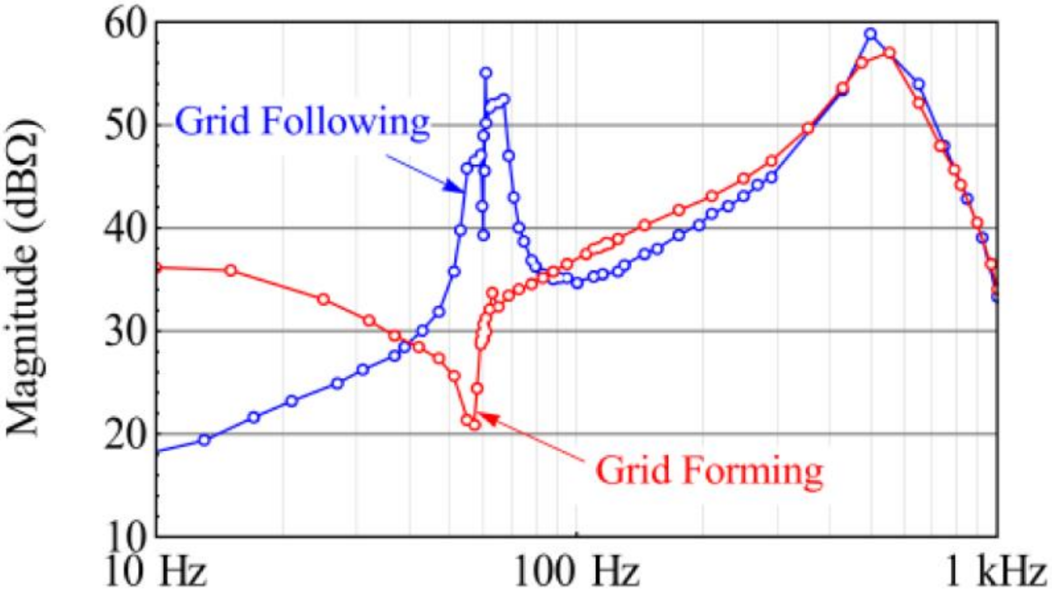
Expected performance[12]

A GFM inverter should exhibit a low impedance magnitude (or equivalently high admittance magnitude) around the fundamental power system frequency (that is, 50 Hz). This is because the GFM inverter is exhibiting a voltage source behaviour at the fundamental frequency. Figure 7 shows an example from National Renewable Energy Laboratory (NREL) of the impedance magnitude characteristics of an inverter operating in GFM mode compared to the same inverter in GFL mode[13]. Impedance scans of other GFM and GFL inverters might vary from those shown in Figure 7. In the future, it may be possible to define a standard impedance scan procedure that can be used to define and quantify GFM capability.

[12] Reference: NREL (https://www.nrel.gov/docs/fy19osti/73173.pdf).

[13] Positive sequence impedance of a 2.2 MVA inverter for GFL and GFM operating modes. NREL "Measuring Commercial Wind Turbine Impedances for Stability Analysis" at https://www.nrel.gov/docs/fy20osti/77668.pdf.

Figure 7 Example of frequency domain performance of an inverter in grid-forming and grid-following mode



Plot source: National Renewable Energy Laboratory (NREL)

2.3.3 Inertial response

Emulating the effects of synchronous inertia, a synthetic inertial response from GFM inverters should be inherent, providing a near-instantaneous active power response from an inverter-based device to a grid disturbance. The initiation of this response is an inherent outcome of the changing voltage angle between the GFM inverter's voltage internal source and its Point of Connection (PoC) that occurs during a change in system frequency, with the magnitude of this response then shaped over a short timeframe by control system action to manage the voltage angle and resulting active power transfer (within device limits).

A GFM inverter providing a synthetic inertial response makes an inherent transient response, surrounded by a control loop designed to mimic the active power inertial response from a synchronous machine following a sudden change in the supply-demand balance.

AEMO has chosen to define *ability to provide* synthetic inertial response as a core capability without specifying the need to provide this capability across the inverter's full operating range. In conjunction with this, the additional capability to maintain headroom or an energy buffer could be utilised to ensure a synthetic inertial response can be delivered across the desired operating range. This differs from some other international specifications, and not all GFM implementations currently have this capability. This capability is a function of the implementation algorithm, not requiring substantial modification, and therefore can be classed as core capability. However, it is recognised that for inverters to provide meaningful amounts of synthetic inertial response in both directions they would likely require a suitable energy buffer or adequate headroom.

This energy buffer could be provided in a number of ways, including by:

- Maintaining headroom between the output and maximum output of the plant.
- Using overload capability of the inverter.
- Oversizing the plant (that is, specifying greater inverter aggregate capacity) for the plant's intended maximum output.

This is discussed further in Section 2.4.1.

In summary:

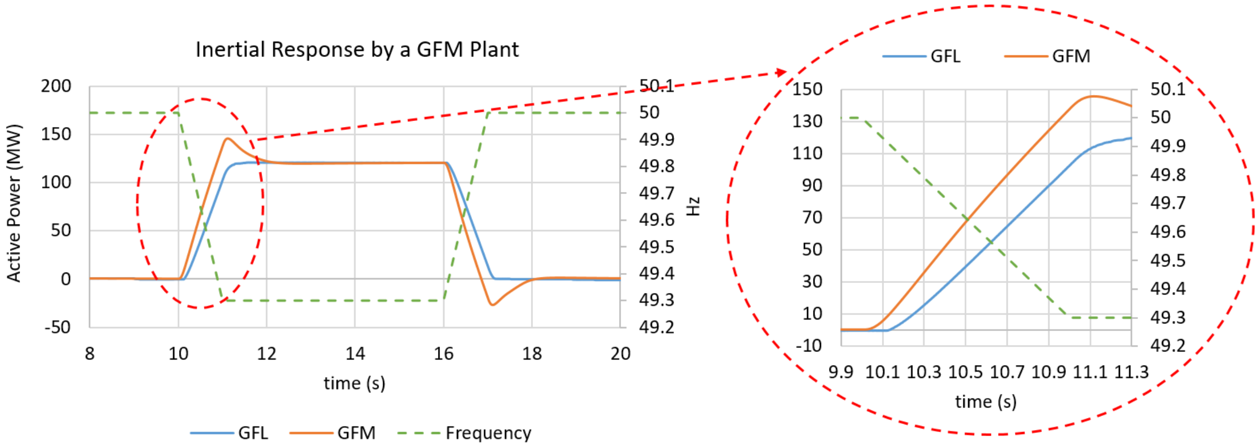
- GFM inverters should have the ability to provide synthetic inertial response in the form of fast change in active power during system transients such as load or generation trip or a system split which results in a frequency change.
- The initiation of the GFM synthetic inertial response should be inherent; that is, it should not require the calculation of frequency or rate of change of frequency (RoCoF) from measurement of the grid voltage waveform. Further shaping of the inertial response post-initiation can utilise such calculation.
- The resistance to frequency changes in GFM inverters should be bi-directional; that is, resisting frequency change for both raising or falling frequency events.
- If configurable, the inertia constant of a GFM inverter may be set in a range wider than that of synchronous machines[14] and will need to be tuned based on both local and broader network conditions and requirements.

Expected performance

A GFM inverter with synthetic inertial response capability should have the ability to provide an active power response in the transient time frame from when the supply-demand imbalance occurs. Figure 8 and Figure 9 show examples of inertial response by a GFM plant, as compared to no inertial response by a GFL plant.

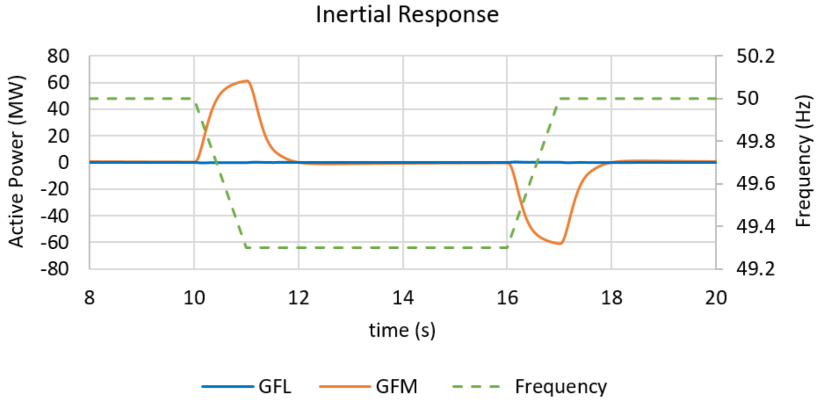
In Figure 8, both GFM and GFL inverters are providing primary frequency response as well. As seen, the inertial response in the GFM inverter is immediate while the frequency response by the GFL inverter is delayed due the need for measurement, detection, and control. Note that it is possible for the GFL inverter to provide a response proportional to RoCoF, but the delay is inherent in the need for measurement of frequency. In Figure 9, in which the primary frequency response of both GFM and GFL plants are disabled, the inertial response of the GFM inverter is clearly demonstrated.

Figure 8 Inertial response by a GFM plant compared with a GFL plant, both plants having primary frequency response based on droop



[14] A high inertia constant may increase power oscillations, particularly in strong systems.

Figure 9 Inertial response by a GFM plant (with no primary frequency response)



2.3.4 Surviving the loss of the last synchronous connection

A key difference between a GFL inverter and a GFM inverter is its ability to operate in a power system without the presence of other synchronous machines or grid-forming inverters.

For the purposes of this specification and the NEM, the focus at this time is on two scenarios:

1. A system split in which one or more GFM and GFL inverters are left operating in a part of the power system that does not have any operational synchronous machines.
2. The situation in which the generation dispatch schedules a small amount of synchronous generation in one dispatch interval and none in the next, or when the last remaining synchronous generator trips.

Clearly both of these scenarios are plausible under a high renewable generation penetration future. The reverse, where GFM inverters need to synchronise with synchronous machines or other GFM inverters is also necessary.

The two scenarios described above have some commonalities and some different challenges. Both require the GFM inverter to remain in continuous operation throughout the transition between these states. The main difference between the scenarios is that scenario one could initially have a higher system strength (lower system impedance) seen by the GFM than in scenario two. Scenario one could potentially have a large change in impedance during the transition, whereas scenario two will have a small change in impedance but from an initially high impedance (low system strength) level.

In summary, considering both scenarios, GFM inverters should:

- Operate stably in a grid that does not contain any other GFM inverters or synchronous machines, as per its designed capabilities, including for power system disturbances that do not cause the protection system of the plant to disconnect the GFM inverter.
- Remain in uninterrupted operation for a transition from a grid containing synchronous machines to one that does not, without external controls or communications, provided the power transfer capability of the grid is not exceeded.
- Operate stably with other GFM inverters, in the absence of synchronous machines.
- Remain in uninterrupted operation when synchronous generation is reconnected or when the GFM inverter reconnects to the grid, whether into a weak grid or a strong grid, provided the resultant state of the system is within the operating envelope of the GFM inverter.
- Provide frequency and reactive support, unaffected by the transition from one power system state to another.

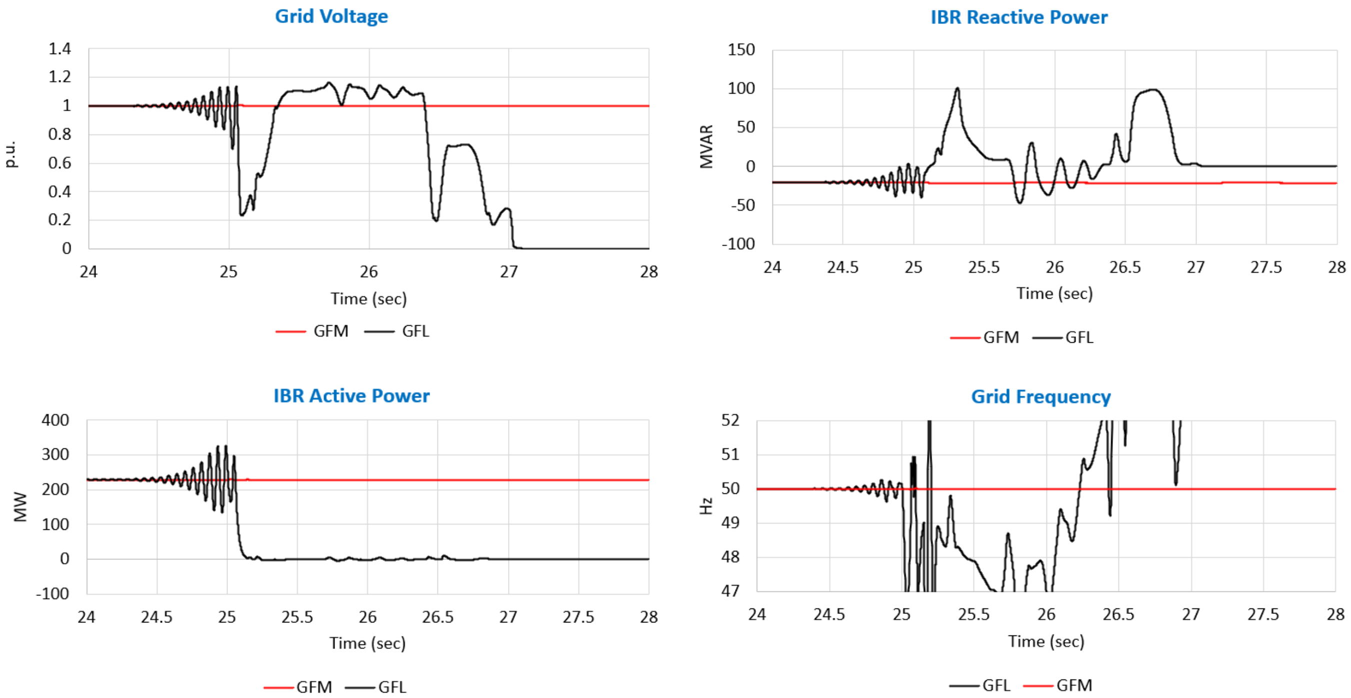
The continuous operation of the GFM inverters, after the loss of the last synchronous connection, depends on the design capability of the inverter and the relevant operational procedures.

It should be noted that the enablement or disablement of this capability should be agreed in advance with the relevant NSPs and AEMO.

Expected performance

Figure 10 shows an example of a simulation of GFM inverter performance compared to a GFL inverter, where the last synchronous connection to the grid is lost. In the GFM example case, voltage, frequency, and active and reactive power outputs show a mild transient and remain stable following the disconnection of the last synchronous connection.

Figure 10 Surviving the loss of the last synchronous connection



Note: the last synchronous connection to the grid is lost at t=24 s.

This simulation was set up with supply and demand unchanged during the transition, and with the synchronous machine initially providing no active or reactive power. In practice, large transients may occur for initially unequal supply and demand, or changes in reactive power within the boundaries of the islanded network. The GFM should remain in uninterrupted operation provided it remains within its current limits, and subject to power transfer capability of the network not being exceeded.

2.3.5 Weak grid operation and system strength support

A GFM inverter should be able to stably operate in remote and weak parts of the grid, without support from nearby synchronous machines, noting that all limits should be respected. The stiff voltage reference of a GFM inverter during power system disturbances should also improve the stability of nearby GFL inverters. In summary:

- A GFM inverter should operate stably under a very low short circuit ratio, as defined by the system operator, both under normal operating conditions and when exposed to power system disturbances.

- A GFM inverter should provide system strength support to nearby GFL inverters and enhance their stable operation during and following power system disturbances[15].
- A GFM inverter should provide positive damping for oscillations in the power system that are sensitive to system strength.

Expected performance

An example of system strength improvement by GFM inverters is shown in Figure 11. The base case was made oscillatory by altering the control settings on a GFL inverter and altering the SCR from 2 to 1.1, which demonstrates that the oscillation is sensitive to system strength. The figure compares the response with three different GFM inverters and a synchronous condenser in the left plot and two types of GFL inverter in the right plot. Both types of GFL inverter become unstable and trip, whereas the synchronous condenser and GFM inverters are all able to stabilise the grid.

Figure 11 System strength improvement by GFM plant

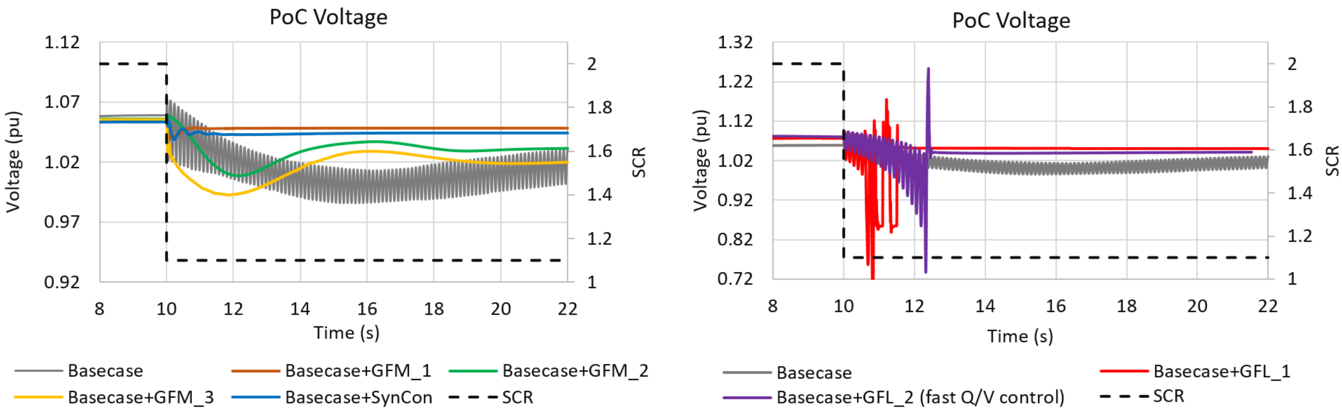
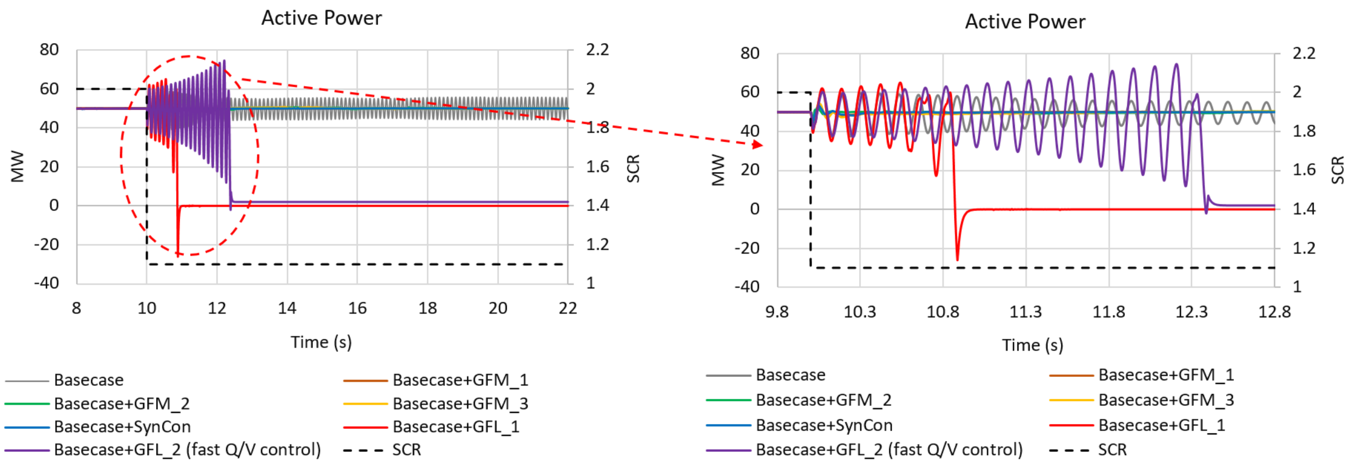


Figure 12 shows the active power response for the same test conditions, with an expanded version on the right plot.

Figure 12 System strength and phase jump improvement by GFM plant



[15] In practice, there will be a limit to the capacity of GFL inverters that a GFM inverter can support for stable operation in a weak grid. This may depend on the design of the GFL as well as the GFM plants, and also the SCR of the grid.

2.3.6 Oscillation damping

Following a large or small disturbance, the active and reactive power output of a GFM inverter should be adequately damped. In addition, a GFM inverter should be able to provide positive damping to network oscillations in the sub-synchronous frequency range[16]. The successful delivery of damping will need to be assessed on a project-specific basis.

In summary:

- The GFM inverter should be capable of being tuned so that following a disturbance its output is adequately damped. Typically, the damping characteristics of a GFM inverter are tuneable via software, unlike synchronous machines, where some key damping parameters are consequences of machine design. Actual damping characteristics for GFM inverters will need to be determined and tuned based on network characteristics, and to enhance overall system stability.
- The control system of a GFM should be able to add damping to the system for the following oscillatory phenomena:
  - Sub-synchronous oscillations associated with GFL inverter control interactions (either between GFL inverters or between GFL inverter and grid) which are influenced by low system strength conditions.[17] This requirement is strongly related to the "supporting weak grid operation" previously detailed and is a core requirement for GFM inverters in international work.[18]
  - Rotor angle modes of oscillation through the provision of damping power akin to that provided by synchronous machine damper windings.[19] Where relevant, this should include damping for inter-area modes of oscillation.
  - Oscillations at harmonic frequencies which result from interactions of electrical and control resonances.[20]
- The positive sequence impedance response of a GFM inverter should ideally have a phase angle between -90-degrees and +90-degrees (or equivalently have a positive real part, that is, resistance), across a wide range of sub-synchronous frequencies, to be able to contribute positively to the oscillations damping under most conditions[21].

Expected performance

A small-signal impedance scan across a wide range of frequencies can be used to evaluate the oscillation damping characteristics of a GFM inverter. A GFM inverter should ideally show an impedance phase angle between -90-degree and +90-degree, at most frequencies from 10 hertz (Hz) to 500 Hz. Figure 13 shows an

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[16] Reference: National Grid (https://www.nationalgrideso.com/document/183496/download)

[17] According to Hatziargyriou, N et al. (2020), Stability Definitions and Characterization of Dynamic Behavior in Systems with High Penetration of Power Electronic Interfaced Technologies, inverter control interactions in the sub-synchronous range are often associated with low system strength conditions.

[18] ENTSO-E and UNIFI both refer to the need for GFM inverters to prevent adverse control interactions of GFL IBRs. See Kroposki, B (2022) and ENTSO-E (2020, High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid-Forming Converters (https://euagenda.eu/upload/publications/untitled-292051-ea.pdf)

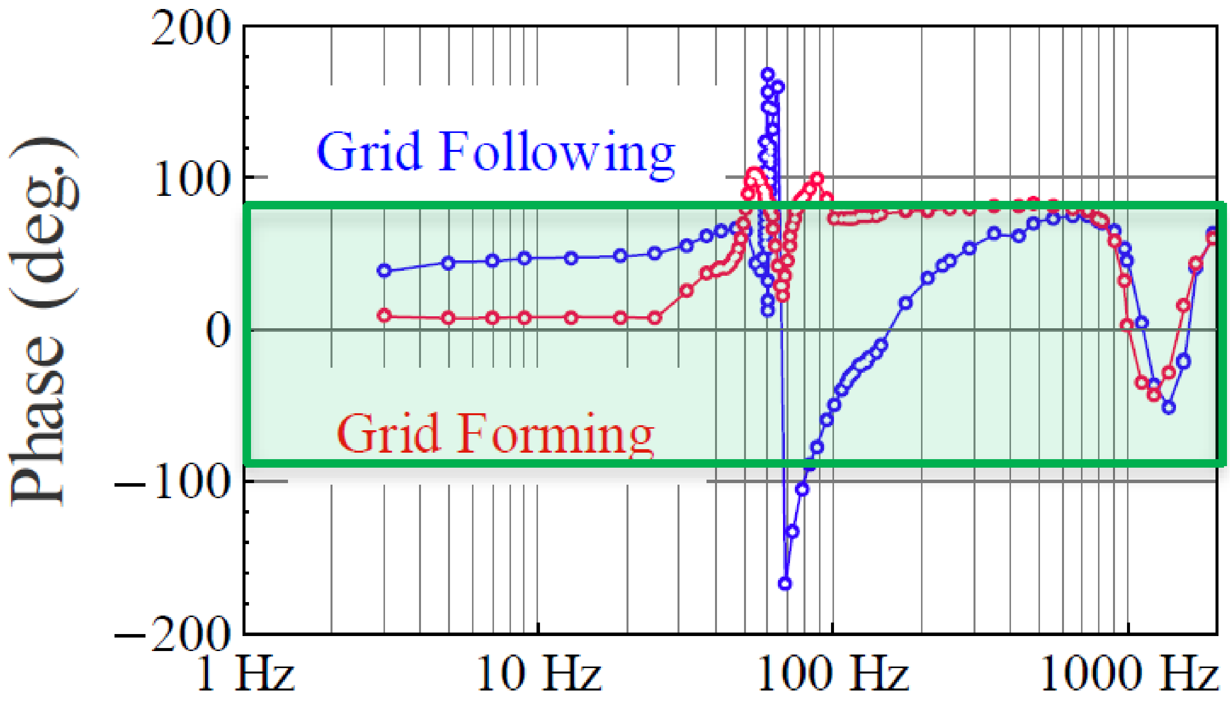
[19] National Grid CG0137 stipulates requirements for active power damping for this purpose.

[20] See ENTSO-E (2020, High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid-Forming Converters, URL: https://euagenda.eu/upload/publications/untitled-292051-ea.pdf and Kroposki, B (2022), Specifications for Grid-forming Inverter-based Resources Version 1, (https://drive.google.com/file/d/19YRpERnsssEJ62H_Tb0edtxHrZI37ZkK/view?usp=sharing)

[21] Reference: ESIG (https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/)

example of the impedance phase angle characteristics of a GFM versus a GFL inverter, noting that these should be interpreted as indicative and not necessarily representative of ideal or expected performance characteristics.

Figure 13 Impedance phase angle characteristics of a GFM inverter – example



Plot source: National Renewable Energy Laboratory (NREL)

2.4 Additional capabilities

The additional GFM capabilities described below are not to be expected from all GFM inverters but, if provided, will enable robust delivery of core capabilities across an agreed extended operating range or add more complex capabilities, such as, black start capability. Material hardware upgrades such as a larger energy buffer and a larger over-current capability (when compared with a GFL design) or changes to operational practices may be required in order to provide the additional GFM capabilities described in this section. AEMO's current understanding is that only a portion of GFM plant would need to provide these additional capabilities to maintain a secure power system. Compensation for the cost of these changes or incentives for delivering these capabilities is outside the scope of this specification.

For use of this specification in the procurement of (future) services, the operational boundaries for the services should be provided in the context of the connection location. This might include, for example, specification of RoCoF, voltage magnitude and angle step, or voltage imbalance, noting responses are also affected by the design parameters (for example, impedance and inertia constant). The performance will also need to be established in the context of meeting the existing requirements of the technical standards and primary frequency control in addition to any specified service level.

2.4.1 Headroom and energy buffer

As discussed in Section 2.3.1, operation at or into limits restricts the capability of a GFM inverter to provide GFM performance. To maximise GFM performance would require the GFM inverter to have a buffer between its output and any limit of the inverter or the energy source. The amount of buffer needed to respond without hitting a limit is dependent on the nature of the disturbance and the type of response required. It may also be influenced by the design of the GFM inverter. For example, the response to a phase jump, without a limit, depends on the impedance of the GFM inverter as well as the size of the phase jump.

Synthetic inertial response, for example, requires a suitable energy buffer, in addition to the corresponding inverter capacity. The size of the response, and the size of the energy buffer needed, depends on the inertia constant setting (if relevant to the implementation), as well as the RoCoF of the disturbance. Limited current ratings and DC-side power or voltage constraints of GFM inverters can limit their synthetic inertial response, as illustrated in Figure 14.

Figure 14 Energy contribution from an example GFM BESS under various operating conditions

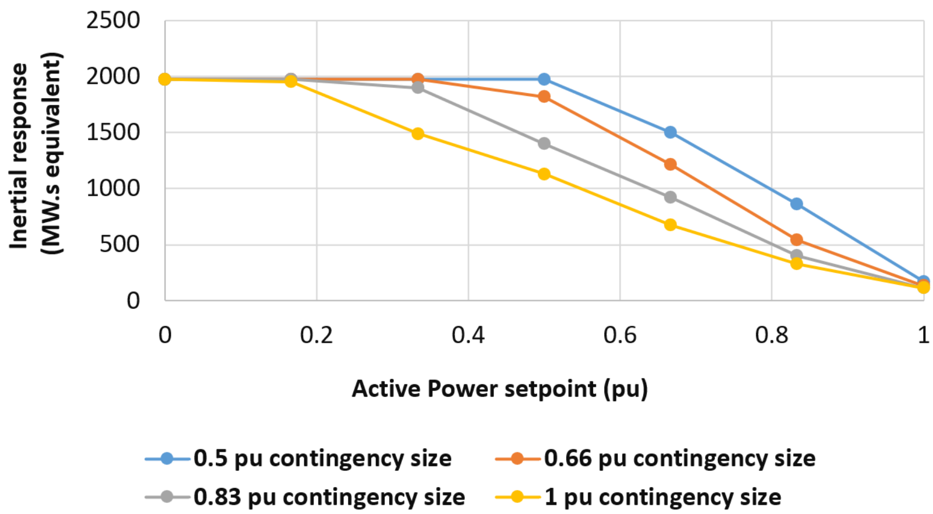


Figure 14 presents the synthetic inertial contribution calculated for an example GFM BESS, under various operating conditions and when exposed to different sizes of contingency.

The GFM BESS was exposed to a certain size of MW contingency (ΔP_{MW}) and the RoCoF was measured in a 0.5s window[22], for this example, at the PoC of the GFM BESS. Then, the swing equation was used to calculate the inertia contribution of the GFM BESS in MWs. This was repeated for different sizes of contingency and for different pre-disturbance active power setpoints of the GFM BESS. In Figure 14, the horizontal axis is the pre-disturbance active power setpoint of the GFM BESS in per unit.

As shown, at low active power setpoints (below 0.2 pu in this example), the plant can provide full inertial response (around 2,000 megawatt seconds (MWs)) as per its design. As the active power setpoint increases, the inertia contribution of the GFM BESS starts to reduce due to lower available headroom before the plant hits its thermal limit. For larger sizes of contingency, the plant reaches its thermal limit at lower active power setpoints, limiting its inertia contribution. This is because the magnitude of the inertial response is naturally greater for larger contingency sizes. For example, for a 1 pu contingency size (the yellow trace), equal to the size of the plant, the

[22] The time window used here is an example only. It was selected to isolate the pure inertial contribution of the GFM. This time window will be subject to future market design, frequency management policy, and product design.

inertia contribution starts to reduce as soon as the active power setpoint increases beyond 0 pu. For a 0.5 pu contingency size (the blue trace), the inertia contribution starts to reduce only at active power setpoints above 0.5 pu.

In summary, the figure shows that the inertia contribution of a GFM BESS can be limited due to the thermal limit of the plant, depending on its operating point and the size of contingency.

2.4.2 Current capacity above continuous rating

The additional capability to operate temporarily at a current output greater than continuously rated levels, also known as overload capability, enables a GFM inverter to replicate synchronous machine behaviour more easily during large voltage or frequency disturbances. It can allow GFM inverters to support protection systems that are currently designed around synchronous machine fault levels. It also helps GFM inverters to simultaneously inject both positive- and negative-sequence current components during asymmetric faults.

High over-current capability is also required for providing system restart capability as well as a greater magnitude or duration of inertial response. Overload capabilities are generally specified in terms of maximum level and duration, for example “150% rated current for 2 seconds”, and may also specify a lower output for a longer duration.

For comparison, a synchronous machine might achieve 250%[23] maximum continuous current of the generating system for 0.5 seconds (considering typical generator transformer impedance). Specific overcurrent magnitudes and times should be assessed on a project-specific basis and may be influenced by incentives or requirements of procurement or market schemes.

Note that while some manufacturers provide overload capability as part of their GFM specification, oversizing of the GFM system’s combined inverters compared with its maximum intended output is another way to achieve current capacity above continuous rating. The decision between alternative solutions might be based on commercial considerations.

2.4.3 Black start capability

GFM inverters may have additional capability to initiate or support a system restart process following a system black event. For this purpose, GFM plants need:

- Sufficient available stored energy to charge the DC link capacitor and energize a part of the grid;
- High short-term overload capability to supply inrush currents during the energization of transformers and distribution feeders or starting auxiliary motors of conventional synchronous generators;[24]
- Soft start capability meaning that GFM inverter can ramp its reference voltage from zero to the nominal voltage with any ramp rate, to avoid excessive inrush currents when energizing transformers and transmission lines[25];
- A ground reference for a black start path (avoid energizing delta-delta transformer);
- Reserve sufficient energy or availability of other energy source, to support black start needs when specified; and

[23] S5.2.5.5 (V) of National Electricity Rules states this is the minimum that synchronous generators must provide

[24] Reference: Hawaiian Electric Company (https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20220504_cbre_rfp/maui_transmittal_exhibit_9.pdf)

[25] Reference: ESIG (https://www.esig.energy/grid-forming-technology-in-energy-systems-integration/)

- Capability to energise all auxiliary systems necessary to operate the GFM plant, without connection to the grid.

The specific quantities for the above requirements (that is, the level of short-term overload required) for a particular GFM plant are strongly dependent on its role in the specific black start or system restoration sequence.

Note that under-voltage protection would need to be designed to allow for soft-start capability.

2.4.4 Power quality improvement

GFM inverters may improve various aspects of power quality within the power system, because of their voltage source characteristics:

- Harmonics: a GFM inverter could provide “passive, damping response in the harmonic frequency range” thereby reducing harmonic voltage distortion within the power system. This performance could be superior to that of synchronous machines, at least for low order harmonics, due to the flexibility to control the response of a GFM inverter within the harmonic frequency range[26].
- Unbalance: a GFM inverter’s voltage source behaviour should act to reduce the level of unbalance caused by disturbances, which could be achieved by the inverter emulating a balanced voltage source which naturally injects positive and negative sequence currents depending upon the nature of the voltage disturbance applied.
- Flicker: flicker within power systems covers phenomena across time scales ranging from less than a second to minutes. Faster flicker phenomena should be improved by GFM inverters due to their inherent voltage source behaviour, whereas slower phenomena could be improved by either GFL or GFM inverters.

Provision of the above capabilities could have an impact on the rating which is required for the GFM inverter to achieve its core capabilities. For instance, a GFM inverter which reduces harmonic voltage distortion in the grid would sink harmonic currents. These harmonic currents could reduce the fundamental frequency current that the GFM inverter injects as part its response to a phase angle jump or a RoCoF event prior to reaching current limits. This means that background harmonic levels may need to be considered when sizing a GFM plant for a specified application.

The power quality performance of GFM inverters is an area for further development. In future it may be possible to specify GFM inverter performance expectations more definitively.

[26] See ENTSO-E (2020, High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid-Forming Converters, URL: https://euagenda.eu/upload/publications/untitled-292051-ea.pdf and Kroposki, B. (2022), Specifications for Grid-forming Inverter-based Resources Version 1 (https://drive.google.com/file/d/19YRpERnsssEJ62H_Tb0edtxHrZI37ZkK/view?usp=sharing).

Abbreviations

Abbreviation	Full term
AC	alternating current
BESS	Battery Energy Storage System
DC	direct current
GFL	grid-following
GFM	grid-forming
IBR	inverter-based resources
MW	megawatts
NEM	National Electricity Market
NSPs	network service providers
Pu	per unit
RoCoF	rate of change of frequency
SCR	short-circuit rating