

# Grid-forming Technology Access Standards

Approach Paper

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**We acknowledge that, wherever we work, we do so on Aboriginal and Torres Strait Islander lands. We pay respect to the world's oldest continuing culture and First Nations peoples' deep and continuing connection to Country; and hope that our work can benefit both people and Country.**

'Journey of unity: AEMO's Reconciliation Path' by Lani Balzan

AEMO Group is proud to have launched its first [Reconciliation Action Plan](#) in May 2024. 'Journey of unity: AEMO's Reconciliation Path' was created by Wiradjuri artist Lani Balzan to visually narrate our ongoing journey towards reconciliation — a collaborative endeavour that honours First Nations cultures, fosters mutual understanding, and paves the way for a brighter, more inclusive future.

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## Consultation notice

AEMO is now consulting on this approach paper and invites written submissions from interested persons on the issues identified to [contact.connections@aemo.com.au](mailto:contact.connections@aemo.com.au) by 5:00pm (AEST) on 26 September 2025.

Submissions may include alternative or additional proposals you consider may better meet the objectives of this consultation and the National Electricity Objective (NEO) in section 7 of the NEL. Please include supporting reasons.

Before making a submission, please read and take note of AEMO's consultation submission guidelines, which can be found at <https://aemo.com.au/consultations>. Subject to those guidelines, submissions will be published on AEMO's website.

Please identify any parts of your submission that you wish to remain confidential and explain why. AEMO may still publish that information if it does not consider it to be confidential but will consult with you before doing so. Material identified as confidential may be given less weight in the decision-making process than material that is published.

Submissions received after the closing date and time will not be valid, and AEMO is not obliged to consider them. Any late submissions should explain the reason for lateness and the detriment to you if AEMO does not consider your submission.

Interested persons can request a meeting with AEMO to discuss any particularly complex, sensitive or confidential matters relating to the proposal. Meeting requests must be received by the end of the submission period and include reasons for the request. AEMO will try to accommodate reasonable meeting requests but, where appropriate, we may hold joint meetings with other stakeholders or convene a meeting with a broader industry group. Subject to confidentiality restrictions, AEMO will publish a summary of matters discussed at stakeholder meetings.

## Executive Summary

### Purpose and context

AEMO has observed a rapid increase in the deployment of grid-forming (GFM) based plants, highlighting the need to revisit and refine the technical requirements in NER Schedule 5.2.5 to fully leverage GFM plant capabilities. To support the integration of this technology, AEMO initiated a targeted technical review in October 2024, focusing specifically on GFM technology.

AEMO has undertaken a range of investigations<sup>1</sup> to inform this approach paper. This includes support for ARENA-funded GFM projects<sup>2</sup>, reviews of international technical standards, surveys conducted with Original Equipment Manufacturers (OEMs) and Network Service Providers (NSPs), and engineering roadmap activities<sup>3</sup>. Notably, AEMO's GFM Voluntary Specification<sup>4</sup> has identified key GFM capabilities forming the foundation of this technical review. While GFM inverters offer several enhanced capabilities compared to grid-following (GFL) inverters, AEMO recognises that they may also exhibit distinct limitations under certain conditions. AEMO seeks to strike a balanced approach, recognising that reduced performance in certain aspects may be acceptable if the overall capabilities of GFM deliver superior outcomes for the power system and support the NEO.

The guiding principles in developing technical requirements for GFM plant include:

- Providing clarity on the definition of a GFM plant for the guidance of applying proper assessment criteria to different technologies, e.g., GFM vs GFL, with the recognition that technology-agnostic requirements may not work well for all inverter types and control system designs.
- Removing impediments and promoting capabilities for the connection of plant that are required to satisfy the requirements and conditions of NER Schedule 5.2 to connect to the power system with GFM control, with the aim for the best system performance, accounting for both the capabilities and limitations of GFM inverters.
- Supporting, and not inadvertently hindering, the ability of GFM plant to contribute positively to system strength. Noting that determining GFM's role in meeting "minimum" or "efficient" levels of system strength is outside the scope of this consultation.

### Summary of initial recommendations

Firstly, AEMO proposes a clear definition of a GFM plant within the asynchronous category in NER Schedule 5.2. GFM plants are characterised by an ability to independently establish and regulate an internal voltage phase or behaving as a voltage source behind an impedance, and to autonomously oppose rapid changes in voltage magnitude, frequency, and phase angle within a sub-cycle timeframe<sup>5</sup>. This enables a practical distinction between GFM and GFL technology and facilitates the development of access standards tailored to each. It also provides clarity for both proponents and NSPs during the connection process.

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<sup>1</sup> See Appendix C. Key Learnings.

<sup>2</sup> Australian Government, 2022. "ARENA backs eight grid scale batteries worth \$2.7 billion". Available at: <https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/>

<sup>3</sup> AEMO, 2025. Engineering Roadmaps. Available at: <https://aemo.com.au/initiatives/major-programs/engineering-roadmap/engineering-roadmap-execution-reports>

<sup>4</sup> AEMO, 2023. "Voluntary Specification for Grid-Forming Inverters. Available at <https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E>

<sup>5</sup> AEMO proposes this voltage source behaviour must be sustained under all normal and disturbed conditions, except when limited by over-current thresholds or energy buffer constraints.

Secondly, AEMO recommends that Schedule 5.2 plants with GFM inverters are recognised as a subset of asynchronous technology within NER Schedule 5.2. This classification acknowledges the technical similarity between GFM and GFL technology, while also recognising the limitations of GFM compared to GFL plants and synchronous machines. At the same time, it clearly distinguishes the unique capabilities that GFM technology can offer to the power system.

Thirdly, AEMO proposes a set of changes to NER S5.2.5, as summarised in Table 1. These changes clarify how existing standards should be retained or modified to reflect the distinctive characteristics of GFM plant. They also identify the specific GFM capabilities that should be explicitly supported, as well as those considered out of scope<sup>6</sup>, considering inherent limitations, control trade-offs, impacts on power system performance and alignment with existing and emerging market services in the NEM. AEMO invites stakeholder feedback on these proposals, which will inform the proposed access standards to be submitted to the AEMC for consideration as a rule change request at the conclusion of this consultation process.

**Table 1 Summary of proposed review of technical requirements in NER S5.2.5**

S5.2.5 clauses	Targeted GFM capabilities	Proposed review of technical requirements
S5.2.5.5A Responses to disturbances following contingency events	<ul style="list-style-type: none"> <li>Voltage source behaviour during contingency events</li> </ul>	<ul style="list-style-type: none"> <li>Reactive current injection performance</li> <li>Criteria for response initiation</li> <li>Commencement time performance</li> <li>Rise time performance</li> <li>Active current performance</li> <li>Negative sequence current performance</li> <li>Post-fault recovery performance</li> </ul>
S5.2.5.10 Detection and response to unstable operation	<ul style="list-style-type: none"> <li>nil</li> </ul>	<ul style="list-style-type: none"> <li>Detection of and protection from loss of synchronism</li> </ul>
S5.2.5.13 Voltage and reactive power control	<ul style="list-style-type: none"> <li>Oscillation damping</li> </ul>	<ul style="list-style-type: none"> <li>Response to power systems oscillations</li> </ul>
S5.2.5.15 Short circuit ratio	<ul style="list-style-type: none"> <li>Stable operation under weak network conditions</li> </ul>	<ul style="list-style-type: none"> <li>Minimum SCR for stable operations</li> <li>Separate settings for withstand SCR</li> </ul>
New clause 1 – Response to phase angle jumps	<ul style="list-style-type: none"> <li>Voltage source behaviour</li> </ul>	<ul style="list-style-type: none"> <li>Capability to withstand and suppress voltage phase angle change</li> </ul>
Include under “General requirements” of relevant clauses	<ul style="list-style-type: none"> <li>nil</li> </ul>	<ul style="list-style-type: none"> <li>GFM inverter must maintain stability when operating at its current limits.</li> </ul>

<sup>6</sup> Black start, islanding operation, active suppression of harmonics, wider system strength support beyond the connection point and guaranteed provision of inertia are considered out of scope for the GFM access standard review because they will instead be addressed through separate frameworks, project-specific arrangements, or future ancillary services markets.

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## 1. Consultation timeline

This consultation aims to define access standards for GFM technology that are fit-for-purpose and align with the NEO. AEMO invites stakeholder feedback on these proposals, which will inform the proposed access standards to be submitted to the AEMC for consideration as a rule change request.

AEMO's process and expected timeline for this consultation is outlined below. As the consultation progresses, future dates may be adjusted, and additional steps may be included as needed.

**Table 2 Consultation timeline**

Consultation steps	Dates
OEM and NSP Surveys, 1:1 industry engagement on approach	October 2024 – June 2025
Approach paper published	25 August 2025
Submissions due on approach paper	26 September 2025
Industry workshops on Rule change	Q4 2025
Draft Rule change proposal with draft report published	Q1 2026
Submissions due on draft Rule change proposal	Q1 2026
Final Rule change proposal submitted to the AEMC	Q2 2026

AEMO thanks all stakeholders involved to date for their feedback, which has been considered in preparing this approach paper, and looks forward to further engagement.

## 2. Background

### 2.1. Context for this consultation

In 2023, the technical requirements in Schedule 5.2 of the NER were reviewed in accordance with NER 5.2.6A, published as *AEMO's review of technical requirements for connection*<sup>7</sup> (ASR). The ASR recommended the need for several immediate rule change proposals, primarily aimed at improving the resilience of the power system, streamlining the connection process and supporting the connection of technologies such as GFM, which have since then been progressively developed as *Improving the NEM access standards – Package 1*<sup>8</sup> (Package 1), and *Improving the NEM access standards – Package 2*<sup>9</sup> (Package 2).

The Package 1 final determination highlighted the need to remove impediments for connecting GFM inverters as a key objective. The final determination discussed that existing access standards were formulated for older technologies and have been adapted in successive rule changes for asynchronous technologies, which to date have been mainly grid-following (GFL). As a result, the drafting of some standards can inadvertently present unnecessary barriers for GFM inverter connections, including:

- The access standards do not account for some beneficial GFM behaviours, such as response to phase angle jumps and inertial response, and in some cases effectively discourage proponents from enabling these responses in GFM inverters.
- Some technology-specific technical requirements may encourage development of GFM inverters in a direction that is not well aligned to best power system performance.

As discussed in the ASR, supporting the integration of GFM inverters in the technical standards by amending or adapting relevant technical requirements to ensure they do not inadvertently hinder the connection of GFM technology and the beneficial capabilities it might provide is an imminent and important objective which is the focus of this consultation. This objective is further reinforced by the growing need to accommodate inverter-based resource (IBR) technologies while maintaining system stability and reliability. Accordingly, this consultation focuses on proposing targeted amendments to the NER Schedule 5.2 access standards that will enable appropriate and efficient connection of GFM inverters, while aligning with broader power system planning and operational objectives.

### 2.2. Methodology

The methodology taken by AEMO to develop this approach paper comprises the following key activities:

- Survey of concluded and ongoing regulatory developments relevant to GFM technical assessment and requirements in Australia and internationally, Appendix C.1 to C.3.
- Survey of international GFM technical requirements and key technical literature, Appendix C.4.
- Survey conducted with original equipment manufacturers (OEMs) and network service providers (NSPs), Appendix D.

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<sup>7</sup> AEMO, 2022. "AEMO review of technical requirements for connection (NER clause 5.2.6A)". Available at <https://aemo.com.au/consultations/current-and-closed-consultations/aemo-review-of-technical-requirements-for-connection>.

<sup>8</sup> AEMC, 2025. "Improving the NEM access standards – Package 1". Available at <https://www.aemc.gov.au/rule-changes/improving-nem-access-standards-package-1>.

<sup>9</sup> AEMC, 2025. "Improving the NEM access standards – Package 2". Available at <https://www.aemc.gov.au/rule-changes/improving-nem-access-standards-package-2>.

- Simulation studies conducted by AEMO with vendor-specific models of GFM inverters from several OEMs.
- Determining the range of possible performances among different types of IBRs and different control system designs with the GFM philosophy.

This multi-faceted approach provides a balanced view of current capabilities, implementation challenges, and opportunities for standardisation across a wide range of GFM technologies.

## 2.3. Exclusions

This approach paper does not include detailed discussions on the following:

- GFM model testing and validation.
- Developing new modelling requirements for GFM or a revision of Power System Model Guidelines.
- GFM for inverter-based loads and high voltage direct current (HVDC) links.
- Methodology for assessing GFM access standards.
- Changes to existing requirements for synchronous and asynchronous plant.
- Changes to system standards, system strength impact assessment guidelines, system strength requirements or any technical requirement that applies to NSPs.

These exclusions ensure that the consultation remains focused on defining technical access standards while recognising that adjacent issues such as modelling, validation, and broader system-level frameworks will require separate and co-ordinated regulatory workstreams.

### 3. Summary of Issues

This section outlines AEMO's proposed definition of a plant that implements GFM control and is subject to the technical requirements under NER Schedule 5.2.5 (hereinafter referred to as Schedule 5.2 GFM plant) and the proposed approach to incorporating GFM requirements into NER Schedule 5.2.5. It also details the initial proposed changes and new clauses that AEMO considers are necessary in comparison to the existing S5.2.5 access standards<sup>10</sup> of the NER. At the end of this section, further investigations for GFM technical requirements are summarised.

Each subsection highlights key issues relevant to the integration of Schedule 5.2 GFM plant, followed by targeted stakeholder questions. These issues and questions were informed by AEMO's practical learnings across activities, including AEMC Rule Change Package 1, support for ARENA-funded GFM projects, technical requirement from international TSOs, and insights from surveys conducted by AEMO with OEMs and NSPs. Details of these learnings have been provided in Appendix C and Appendix D.

#### 3.1. Definition of a GFM plant and its application

##### 3.1.1. Issue #1: Definition of a GFM plant

Currently, there is no definition of Schedule 5.2 GFM plant in the NER and a plant with GFM technology is assessed against the technical requirements developed for asynchronous plant. These technical requirements were developed considering the capabilities and limitations of GFL plant, which exhibit notable differences to GFM plant in several aspects, including response to contingency events. On the other hand, while many GFM technologies emulate some aspects of the behaviour of synchronous generators, there still exists clear differences between GFM and synchronous generators, each with their own capabilities and limitations. This means that the technical requirements for synchronous generators are not suitable for assessing the performance of GFM technologies based on fast controls of power electronics inverters. Thus, it is imperative to have a clear definition for Schedule 5.2 GFM plant, so that they can be properly distinguished from GFL plants and synchronous generators and assessed with appropriate technical requirements and criteria.

AEMO proposes that Schedule 5.2 GFM plant should be defined by its ability to behave as a voltage source that autonomously suppresses fast disturbances in voltage magnitude, frequency, and phase angle, within a sub-cycle timeframe (i.e. less than 20 ms). This capability must be sustained under all operating conditions, except when limited by:

- Inverter over-current protection thresholds; or
- Energy buffer constraints (e.g. low battery state of charge (SoC)).

Capabilities such as black start, full emulation of synchronous generator dynamics, explicit over-current injection, or guaranteed energy headroom may be valuable in specific applications but are not essential to the core definition of GFM capability.

A clear and operational definition of GFM capability is also necessary to guide NSPs in determining whether a proposed connection should be assessed under GFL or GFM access standards, particularly as the requirements for the two will diverge if GFM-specific standards are implemented as proposed in this paper.

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<sup>10</sup> AEMO has not proposed any changes to the following clauses: S5.2.5.1, S5.2.5.2, S5.2.5.3, S5.2.5.4, S5.2.5.6, S5.2.5.8, S5.2.5.9, S5.2.5.11, S5.2.5.12, and S5.2.5.14.

### 3.1.2. Proposed recommendation

#### **Core defining attribute: voltage source behaviour**

AEMO proposes that the most fundamental distinguishing feature of a GFM inverter is its voltage source behaviour, defined as follows:

- A GFM inverter must independently establish and regulate an internal voltage phasor and operate as a voltage source behind an impedance without reliance on the external grid.
- It must autonomously respond to disturbances by opposing fast changes in voltage magnitude, frequency and phase angle within a sub-cycle (i.e. <20 ms). This voltage source behaviour must persist during system normal and disturbance conditions unless current-limiting thresholds are exceeded, or the energy source is insufficient to sustain the response over the defined timeframe.

This definition contrasts with GFL inverter behaviour, which synchronises to and follows an external voltage reference and is fundamentally current-source devices.

The use of a deterministic timeframe, rather than qualitative terms such as “near instantaneous”, is intended to support objective compliance assessment and clarity for both proponents and NSPs. While a faster suppression response may be possible for some technologies, setting the expectation at 20 ms strikes a balance between technical rigour, practical achievability and assessment feasibility across a range of GFM designs.

As a natural consequence of their voltage source control objective, GFM inverters tend to oppose rapid deviations in phase voltage magnitude, frequency, and angle, including negative-sequence disturbances in unbalanced conditions, similar to synchronous machines. However, this inherent behaviour does not preclude implementations where controlled injection of negative-sequence current is necessary to support protection operation or satisfy specific Fault Ride-Through (FRT) requirements.

Accordingly, the definition of voltage source behaviour should accommodate both controlled opposition to and strategic provision of negative-sequence components, as required to meet broader system-level performance and protection objectives. The specific implementation may vary depending on the plant design, fault type, and coordination needs.

To support clarity and consistency, the GFM classification should be applied to the plant configuration that can reliably demonstrate this behaviour across all operating conditions. Applying the classification selectively, such as delivering GFM functionality during normal operation but reverting to GFL behaviour during disturbances, then seeking assessment criteria based on the least-challenging compliance pathways, potentially at or below the current MAS, may reduce the effectiveness of the standard, contradicting the NEO. Proponents are therefore encouraged to engage early to confirm whether their proposed implementation aligns with the intended GFM performance expectations.

#### **Other distinguishing (but non-defining) attributes**

While not part of the definition, the following characteristics further distinguish the operation of GFM plant from those with GFL control:

##### **Inertial response**

GFM inverters can inherently provide a synthetic inertia response<sup>11</sup> by providing a near-instantaneous active power to a grid disturbance. However, unlike synchronous inertia, this response is energy-constrained and highly dependent on headroom and the available energy buffer. Consequently, a fixed “inertia constant” cannot be deterministically defined for all operating conditions.

#### Operation under weak or no grid conditions

GFM inverters typically exhibit greater robustness under low system strength conditions, i.e. low SCR at the connection point, than GFL inverters. However, using withstand SCR as a defining attribute is problematic, as:

- The achievable SCR varies with control design and tuning.
- Performance depends on plant-specific impedance characteristics and interaction with access standards other than S5.2.5.15, e.g., S5.2.5.5, S5.2.5.5A, S5.2.5.11, S5.2.5.13.
- SCR is often assessed using SMIB studies, which may not fully capture system-level behaviours.

Additionally, while GFM inverters can support stable operation in the absence of synchronous machines (e.g. during black start or in islanded modes), requiring this in all cases would introduce disproportionate complexity into the definition and compliance assessments. Instead, we propose that some of these advanced capabilities be tested through structured frameworks (e.g. dynamic model acceptance test (DMAT) or simulation-based verification) without forming part of the baseline definition.

#### Question for Issue #1

**Do you agree with AEMO’s proposed definition for Schedule 5.2 GFM plant? Why or why not?**

### 3.1.3. Issue #2: Application of GFM definition and technical requirements to hybrid plants

Several practical hybrid configurations are now emerging across the NEM and globally, with diverse technology mixes and coupling arrangements. These configurations are based on wind and/or solar generation which may employ GFM technologies, with the coupling of GFM-BESS at DC (i.e., the dc-link of inverters) or AC (e.g., at the connection point or other locations within the site) side. These different arrangements have important implications for system performance, controllability, and the appropriate application of access standards.

### 3.1.4. Proposed recommendation

AEMO is exploring the practical and economic options that can promote hybrid plants’ GFM capability. The first option is location-oriented application of GFM-related access standards:

- Plant-wide application: Applying GFM requirements at the connection point, irrespective of whether all subcomponents are GFM-capable.
- Component-level application: Applying GFM requirements only to the GFM portion, with separate performance assessments for the GFL assets.

<sup>11</sup> AEMO, 2023. “Voluntary Specification for Grid-Forming Inverters. Available at <https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E>

While plant-wide application promotes system-level consistency, it may impose impractical obligations on GFL components; conversely, component-level application allows greater flexibility but introduces fragmentation in compliance and operational behaviour.

An alternative option is to adopt a hybridised performance-based framework which may offer a more technically robust and practically implementable solution:

- Connection point-level Generator Performance Standards (GPS) should define the aggregate behaviours required of the plant (e.g. fast fault current support, post-fault voltage recovery) where such performance aspects can be expected from both the GFL and GFM. This will exclude aspects such as phase angle jump suppression.
- Subsystem-level GPS (e.g. for GFM BESS and GFL PV or WTGs) can then demonstrate how both technology types contribute to these behaviours. Additional GFM-specific requirements would apply at the subcomponent level to the portion of the plant providing GFM capability.

In practice, this approach may necessitate:

- A three-tiered GPS structure: one each for the GFM subsystem, GFL subsystem, and the plant-level connection point.
- Coordinated control strategies and harmonised tripping logic, ensuring that the GFL portion supports, or at least does not inhibit, the GFM functionality.

While this enables a more nuanced and technically appropriate application of performance requirements, it also introduces greater complexity in terms of GPS preparation, compliance assessment, and negotiation. The need for the GPS document capturing multiple sub-systems may increase the time and effort required during the connection process. Therefore, AEMO invites stakeholders' view on the application of GFM-related technical requirements to hybrid plants.

#### Question for Issue #2

**What do you think is the best approach to apply GFM-related technical requirements for assessing hybrid-plant with GFM technology?**

## 3.2. Potential pathways to include the proposed GFM requirements within existing rules

### 3.2.1. Issue #3: Pathway to include GFM requirements under Schedule 5.2

#### Within synchronous generation requirements

One potential pathway considered was to include Schedule 5.2 GFM plant within the existing synchronous generation requirements, reflecting certain performance similarities such as voltage source behaviour, and under appropriate conditions, inertial response and contribution to oscillation damping. Aligning with synchronous generators in this way could simplify regulatory arrangements and provide familiar benchmarks based on proven standards.

However, this approach overlooks key differences between the two technologies. GFM inverters have limited fault and overload current capability compared to synchronous machines, and their response is based on programmable control algorithms rather than inherent physical dynamics, which introduces the need to

prioritise and carefully tune their behaviour. While GFM control can respond more quickly than the mechanical response of synchronous machines, this speed also requires deliberate management to avoid conflicts or instability.

Moreover, while GFM technologies can operate effectively under certain weak grid conditions, the mechanism by which they achieve this behaviour differs significantly from that of synchronous generators, relying primarily on fast control actions rather than inherent physical characteristics. Stakeholder feedback (Appendix D.6) also cautioned that over-emulating synchronous generator requirements risks importing their limitations and failing to capitalise on the unique capabilities of GFM technology. Given these considerations, this pathway was not pursued, as its disadvantages outweigh the potential benefits.

### **Separate GFM requirements within Schedule 5.2**

While recognising the unique nature of the capabilities of GFM technology, AEMO does not support establishing a fully separate, third set of technical requirements for GFM technology outside of or alongside the existing asynchronous and synchronous categories in NER Schedule 5.2. Although a separate set of requirements would clearly distinguish GFM from both GFL and synchronous generators, thereby avoiding confusion and allowing tailored obligations aligned with its strengths and limitations, these benefits can be achieved within the existing asynchronous framework outlined in Schedule 5.2 through well-calibrated requirements. Creating a third category risks introducing unnecessary complexity to the NER, contradicting stakeholder preferences for simplicity and clarity, and potentially resulting in rigid or overly prescriptive obligations that may stifle innovation or fail to accommodate evolving technologies.

#### **3.2.2. Proposed recommendation**

The pathway AEMO proposes is to include Schedule 5.2 GFM plant within the asynchronous category under the NER, alongside GFL inverters, but with access standards that explicitly recognise both the enhanced capabilities and certain limitations of GFM technology. This approach maintains the clarity that GFM plants remain asynchronous under the current framework. It acknowledges the similarities and differences between GFM and GFL inverters, enabling the development of suitable, performance-based standards focused on outcomes at the connection point rather than internal design features. Building on the existing asynchronous framework provides continuity and simplicity, while allowing the enhanced performance of GFM to deliver tangible benefits to system security and resilience.

Stakeholder feedback from surveys (Appendix D.6.1) strongly supported this pathway, noting that creating three fully distinct sets of standards for synchronous, GFM, and GFL technologies would add unnecessary complexity, risk misalignment with the capabilities of these technologies, and potentially force Schedule 5.2 GFM plant to emulate synchronous generators unnecessarily. At the same time, AEMO acknowledges that this approach requires careful calibration to ensure Schedule 5.2 GFM plant is not simply held to the same standards as GFL, as this could undermine its potential benefits to the power system. It is also recognised that substantial amendments to the asynchronous category may still be needed to accommodate the unique characteristics of GFM technology fully.

For these reasons, AEMO prefers this pathway as the most practical and effective means of integrating Schedule 5.2 GFM plant into the regulatory framework. It incorporates Schedule 5.2 GFM plant as a distinct option under the asynchronous category, with bespoke outcome-focused and performance-based requirements calibrated to its capabilities, limitations, and system needs. This provides the most effective balance between clarity, simplicity, and alignment with the NEO. This approach appropriately acknowledges the similarities and differences between GFM and other technologies, while avoiding the risks and inefficiencies associated with establishing a fully separate regulatory pathway.

#### Question for Issue #3

**Do you agree with AEMO’s proposed approach for integration of GFM technical requirements into NER S5.2 under the existing asynchronous category? Why or why not?**

### 3.3. Responses to disturbances following contingency events (S5.2.5.5A)

#### 3.3.1. Issue #4: Response initiation and voltage source behaviour

The existing requirements under S5.2.5.5 of the NER requires voltage thresholds for Schedule 5.2 plant to commence injecting reactive current following over or under-voltage contingency. Although this is commonly achievable for GFL plants which rely on threshold-based criteria to initiate fault response, AEMO acknowledges this is not the case for GFM inverters. Package 1 has allowed Schedule 5.2 plant to negotiate a response-initiating condition that is different from the default thresholds of 80% and 120% of nominal voltage for under- and over-voltage conditions. This change addresses concerns that fixed voltage thresholds may not be appropriate for technologies such as GFM.

At the same time, AEMO observes that there are no appropriate technical requirements for situations where a voltage disturbance causes a voltage dip at the connection point in the range between 0.9 p.u. and the point where the response-initiating condition for Schedule 5.2 GFM plant has been met. In practice, the voltage dip in this range is often seen in shallow or distant faults. Schedule 5.2 GFM plant can play an important role in suppressing the disturbance to improve system resilience. Hence, a proper technical requirement should be in place to promote this capability.

#### 3.3.2. Proposed recommendation

If a contingency does not trigger the response-initiating condition of Schedule 5.2 GFM plant, this may imply the plant has not reached its current limit and is still in full GFM control. Thus, AEMO recommends that the voltage source behaviour of the plants be the focus of the technical requirements, i.e., a fast response to oppose the voltage disturbance and overall performance to minimise the in-fault voltage deviation from the pre-disturbance condition. Further investigation will be undertaken to validate this proposal.

#### Question for Issue #4

**Do you agree with AEMO’s proposed approach for assessing GFM plant voltage source behaviour in a contingency where its response initiation condition is not triggered?**

#### 3.3.3. Issue #5: Performance of reactive current injection

##### Reactive current injection ratio

While the K-factor (the ratio of reactive current injection to voltage deviation) is traditionally associated with GFL inverters, synchronous generators are also subject to reactive current injection expectations that can be expressed through an implicit K-factor. Therefore, it is reasonable to expect some analogous capability from GFM inverters.

Due to the inherent variability in GFM technologies, driven by differing voltage source control implementations, current-limiting strategies, and internal control loop dynamics, a fixed numerical K-factor may not be broadly

applicable across all GFM technologies. Unlike GFL inverters, which respond via programmed proportional current injection, GFM inverters act based on internal voltage regulation objectives, often resulting in more complex and non-linear current behaviour.

### Commencement time and rise time

Package 1 has proposed commencement times of 10 ms and 20 ms for the AAS and MAS, respectively. The practicality of achieving a 10 ms commencement time, along with the impact of simulation-induced delays on compliance assessment, will be subject to further investigation.

In Package 1, the term “*maximum change*” was replaced with “*mean sustained change*” in the definition of rise time to better reflect the long-term dynamics and external influences<sup>12</sup>, and to account for the response of GFM technologies. Notably, since the proposal of this rule change, more GFM technologies have entered the NEM, exhibiting diverse responses in terms of in-fault reactive current injection. Hence, the rise time definition should be specifically reviewed for Schedule 5.2 GFM plant once it initiates a reactive current injection response, sustain a fast reactive current at a level close to its current limit.

#### 3.3.4. Proposed recommendation

AEMO acknowledges that the inverter-level active power–frequency control loop may engage during a large disturbance; however, AEMO considers that priority in such events should be given to voltage support and suppressing the active power response appropriately benefits system stability.

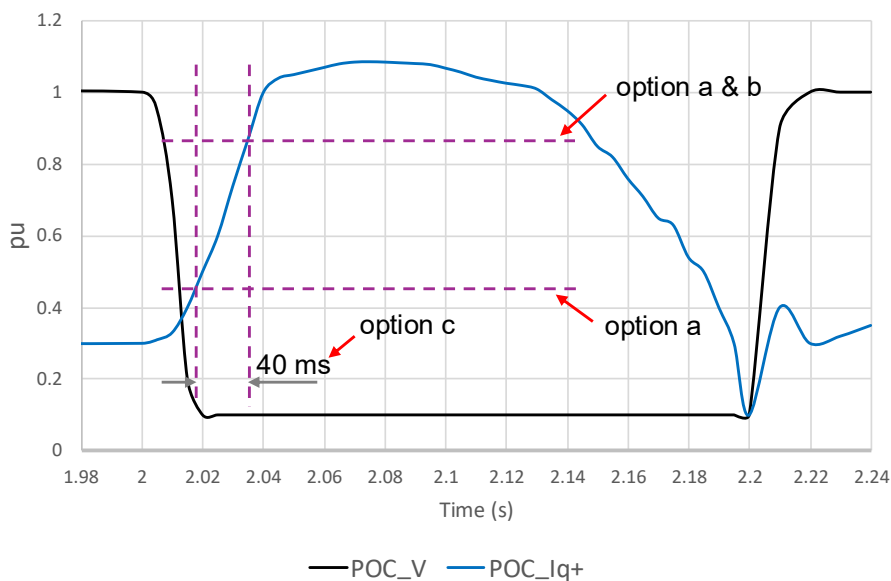
Accordingly, AEMO proposes to revisit the definition of rise time for Schedule 5.2 GFM plant, ensuring the system fully benefits from their voltage source capability during large disturbances. Options being considered include:

- a. Proposing an alternative reference for vertical limits where rise time starts and ends
- b. Adjusting the upper limiter where rise time ends
- c. Adjusting the duration of rise time
- d. A combination of the options above.

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<sup>12</sup> AEMC. National Electricity Amendment (Improving the NEM access standards – Package 1) Rule 2025, 22 May 2025. See page 81, Section 4.11.2. Available at [https://www.aemc.gov.au/sites/default/files/2025-05/ERC0393\\_Final%20determination.pdf](https://www.aemc.gov.au/sites/default/files/2025-05/ERC0393_Final%20determination.pdf).

**Figure 1 Options considered for rise time of Schedule 5.2 GFM plant**



**Question for Issue #5**

**Do you agree with AEMO’s proposed approach that commencement and rise time of GFM plants should be reviewed? Why or why not?**

**3.3.5. Issue #6: Negative-sequence current control**

AEMO’s proposed definition of voltage source behaviour of a GFM inverter in Section 3.1 already captures their natural tendency to counteract voltage disturbances, including negative-sequence components during unbalanced faults. However, this inherent behaviour may not be sufficient to support protection schemes that rely explicitly on negative-sequence current for fault directionality or relay sensitivity. Stakeholder feedback (refer Appendix D.4) confirms that some protection relays depend on measurable negative-sequence current to operate reliably under such conditions.

**3.3.6. Proposed recommendation**

Further investigation is needed to determine whether GFM inverters should be required to support a minimum level of negative sequence current or at least demonstrate that their inherent response is adequate to support protection functionality.

Any future requirement should preserve flexibility in control design while ensuring system interoperability. For example, a blanket mandate for explicit negative-sequence injection may not be appropriate, given total current envelope limits and variations in GFM control strategies.

AEMO therefore proposes to assess whether an explicit provision under S5.2.5.5 or S5.2.5.5A is warranted to complement the general voltage source behaviour requirement.

**Question for Issue #6**

**What criteria shall be applied to assess a GFM plant’s negative sequence current performance?**

### 3.3.7. Issue #7: In-fault active power/current performance

AEMO notes that clause S5.2.5.5A of the NER emphasises reactive current ( $I_q$ ) performance, with comparatively limited focus on the behaviour of active power/current for asynchronous plants, discussed in Appendix D.1. The active power/current performance of GFL plant has generally not raised concern. These systems typically prioritise reactive current ( $I_q$ ) injection during faults and suppress active current ( $I_d$ ), especially as fault severity increases, supporting system voltage and aligning with existing expectations.

In contrast, a GFM plant exhibits different active power/current behaviour due to its voltage source behaviour which adjusts the internal voltage angle for synchronisation and can activate over-current protection schemes at the onset of a fault, reflecting their limited current-handling capability. As a result, if requirements are not clear, the in-fault  $I_d$  response of GFM plant can potentially lead to adverse impacts on power system performance, including but not limited to:

- Decline in reactive current ( $I_q$ ) injection at the connection point due to voltage angle separation, causing less support to in-fault network voltage support.
- Potential voltage instability or collapse, driven by increase in active current during the fault.
- Active power spike at fault clearance caused by resynchronisation transients.
- Reduction in active power output during shallow faults.

### 3.3.8. Proposed recommendation

These observations highlight the need for technical requirements of active power/current performance of a GFM plant to ensure consistent and secure system performance during contingency events. Notably, the identified issues mostly arise when in current-limiting mode, where the voltage source behaviour is constrained by limited over-current capability. Future technical requirements should focus on the overall system response, noting that the highest possible response is not always desirable, particularly under weak grid conditions. The balance between active and reactive current should be informed by system-level needs, rather than enforced through a fixed ratio.

Furthermore, AEMO emphasises reactive current support to voltage stability, while allowing limited active power/current contribution to support synchronisation. One potential approach may involve specifying acceptable limits for variation in internal voltage phase angle or defining a permissible range for active power/current at the unit-level or connection point during faults. AEMO will undertake further studies to assess the technical feasibility of such requirements.

#### Question for Issue #7

**What technical requirements if any should be applied to GFM plant's in-fault active power/current performance?**

### 3.3.9. Issue #8: Post-fault recovery performance

Package 1 has introduced the definition of “end of a disturbance” for the measurement of post-fault active power recovery time. This removes the impediments for the connection of Schedule 5.2 GFM plant. AEMO supports applying this definition as it offers flexibility in how recovery timeframes are assessed. This also enables improved voltage support, avoids instability under low system strength conditions, and reflects justified design constraints. With the understanding that Schedule 5.2 GFM plant may have slow active power recovery due to

the control scheme, project-specific negotiation can be used to define an appropriate recovery profile that meets broader system needs.

However, based on real-world experience, voltage recovery should also be considered alongside active power performance. This is not based on an expectation that Schedule 5.2 GFM plant will necessarily improve voltage recovery, but rather that it must not exacerbate or prolong the post-fault disturbance.

### 3.3.10. Proposed recommendation

GFM inverters should comply with NER clause S5.1a.4, avoiding behaviours that lead to sustained over-voltages. It is also expected that post-fault voltage recovery, with respect to under-voltages, is not degraded following the connection of Schedule 5.2 GFM plant. For example, inappropriate reactive power responses or poorly coordinated control actions must not result in degraded voltage recovery compared to the network's pre-connection condition. While deterministic voltage recovery timeframes may not be suitable due to site-specific factors, GFM behaviour should demonstrably support a stable return to normal voltage levels without adversely affecting neighbouring plants or overall power system security.

#### Question for Issue #8

**Do you agree with AEMO's proposed approach for assessing the post-fault voltage recovery performance of GFM plants? Why or why not?**

## 3.4. Partial load rejection (S5.2.5.7)

### 3.4.1. Issue #9: Application of partial load rejection to GFM plant

In its final rule on the Package 1, the AEMC limited the application of clause S5.2.5.7 of the NER (Partial load rejection) to synchronous generation only. This clause was originally drafted for synchronous generating systems, recognising that some synchronous machines may have difficulty maintaining stable prime mover operation following a load rejection event.

Although the clause was extended in 2018 to include all generating systems, and later in 2021 to include integrated resource systems, AEMO's experience with real projects has not identified any benefit in applying this requirement to Schedule 5.2 GFM plant. In its determination, the AEMC noted it had received some comments suggesting potential relevance of this requirement to GFM inverters but considered this outside the immediate scope.

### 3.4.2. Proposed recommendation

AEMO believes that even for Schedule 5.2 GFM plant, this requirement would provide benefit only during islanded operation, a scenario not central to the development of access standards. Unless stakeholders provide evidence demonstrating a need to apply this clause, the focus should remain on more informative and relevant access standards, where the tangible benefits and limitations of Schedule 5.2 GFM plant have been clearly identified.

### 3.5. Detection and response to unstable operation (S5.2.5.10)

#### 3.5.1. Issue #10: Instability of Schedule 5.2 GFM plant

In Package 1, synchronous units must include pole slip protection, while asynchronous units must implement configurable detection, disconnection, and response schemes based on instability in voltage, reactive power, and active power. While GFM inverters may emulate synchronous behaviour, they lack physical poles and exhibit faster, control-based responses, making direct application of pole slip logic inappropriate. Conversely, applying the asynchronous unit framework may also be insufficient, as it may not capture angle instability or emulated rotor dynamics observed in practice. AEMO has noted abnormal behaviours in GFM inverters under certain conditions which are not observed in either Schedule 5.2 plant with GFL controls or conventional synchronous generators.

#### 3.5.2. Proposed recommendation

AEMO proposes further investigation into the appropriate application of NER clause S5.2.5.10 to Schedule 5.2 GFM plant, noting that these devices do not neatly align with either synchronous or asynchronous production unit definitions. This includes whether existing synchronous or asynchronous pathways are appropriate or whether a GFM-specific protection framework should be introduced under NER S5.2.5.10 to ensure stable system performance and appropriate response to instability.

#### Question for Issue #9

**What technical requirement shall be considered for detecting GFM-specific instability?**

### 3.6. Response to oscillations (part of NER S5.2.5.13)

#### 3.6.1. Issue #11: Oscillation-neutral response and oscillation damping

##### Oscillation-neutral response

Schedule 5.2 GFM plant must be designed and tuned such that their operation does not degrade power system damping or cause sustained oscillations across any relevant frequency range. This includes:

- Tolerating system-wide or local oscillations in the sub-synchronous, fundamental, and super-synchronous frequency ranges, up to a maximum frequency consistent with inverter control bandwidth (typically up to 300 Hz, unless otherwise agreed with AEMO and the NSP).
- Ensuring stable operation in low system strength conditions, particularly where other IBRs are electrically close.
- Avoiding adverse interactions that could amplify existing modes or trigger poorly damped behaviour.

##### Oscillations damping

Where Schedule 5.2 GFM plant is designed to emulate synchronous generator behaviour, it is capable of providing active damping of power system oscillations, consistent with or functionally equivalent to a PSS. This includes:

- Providing positive damping of inter-area or intra-plant modes where system needs are identified.

- Ensuring that the provision of damping does not negatively impact system stability at other frequencies or deteriorate GFM performance under other credible conditions.

### 3.6.2. Proposed recommendation

AEMO proposes to extend NER S5.2.5.13 to include explicit provisions for damping power system oscillations by Schedule 5.2 GFM plant, consistent with the intent of existing requirements for synchronous generating systems.

The proposed access standard would include:

- A MAS requiring that the plants control design does not cause, contribute to, or exacerbate power system damping (oscillation-neutral response).
- An AAS applying to plants designed to provide active damping, consistent with a PSS-like function (oscillation damping).

#### Question for Issue #10

**Do you agree with AEMO's proposed approach to include explicit provisions for GFM plant to provide power system oscillation damping? Why or why not?**

## 3.7. Short circuit ratio (NER S5.2.5.15)

### 3.7.1. Issue #12: Minimum SCR of stable operation and associated settings

Currently, Schedule 5.2 plant (regardless of whether it employs GMF or GFL technology) must be capable of operating stably and remaining connected for an SCR of 3 (denoted as “minimum SCR” in this section). Since GFM plant is inherently more capable of stable operation under weak network conditions, a minimum SCR of 3 has become less meaningful for them compared to their GFL counterparts.

It is also important to ensure consistency between the parameters used to demonstrate the capability of meeting minimum SCR requirement and those used to demonstrate compliance with other access standards, in line with NER 5.12.1(a). While different parameter sets are currently allowed, one for demonstrating stable operation under the lower of minimum SCR and proposed SCR and another for performance standards of other access standards, this approach will require careful consideration. This is because using different settings for different tests may lead to a situation where, in actual operation, Schedule 5.2 GFM plant behaves indistinguishably from a lower-performing GFL inverter, thereby undermining the intended benefits of GFM capability.

### 3.7.2. Proposed recommendation

With broad stakeholder support (refer Appendix D.2.3), AEMO proposes to lower the value of minimum SCR requirement for Schedule 5.2 GFM plant, to the range of 1.2 to 1.8, which could define the respective AAS and MAS. Further work will be required to demonstrate the feasibility and justification of the new minimum SCR.

When the difference between the minimum site-specific SCR and the minimum SCR requirement under S5.2.5.15 is small (e.g., below 3), AEMO expects a single set of control parameters for the inverter and/or the PPC to be applied across all conditions under S5.2.5.15 and other relevant access standards. Proposals for separate parameters may be considered only where it can be justified by technical limitations and where the difference between withstand and minimum site-specific SCR warrants such an approach. This will ensure the consistency and preserve the intended benefits of GFM capability.

**Question for Issue #11****Do you agree with AEMO's proposed changes to S5.2.5.15?**

## 3.8. Response to phase angle jumps (new proposed clause)

### 3.8.1. Issue #13: GFM capability under phase angle jumps

#### Capability of withstanding phase angle jumps

AEMO considers phase angle jump withstand to be an essential capability for all GFM plant. However, a range of implementation options are under consideration, including specifying this requirement as a MAS only, or having both a MAS and an AAS to reflect differing capabilities.

We welcome stakeholder feedback on alternative numerical values, supported by underlying technical or operational reasons, particularly where they reflect OEM capabilities or plant-specific limitations.

#### Capability of suppressing phase angle jumps

Suppression of voltage phase angle jumps is a fundamental attribute of GFM inverter behaviour and forms a key part of what distinguishes GFM from GFL technologies. This capability is inherently tied to the concept of a voltage source: a GFM inverter aims to maintain a stable voltage waveform, both in magnitude and phase, even during system disturbances. As such, suppression of abrupt phase angle deviations is not merely an ancillary function but a defining aspect of the expected dynamic performance.

For this reason, it is proposed that the suppression of phase angle jumps be included as part of the MAS for Schedule 5.2 GFM plant. The requirement should specify that GFM inverters must initiate their response by changing their active power to suppress a phase angle jump at the connection point within 20 ms. This time frame ensures that the plants contribute to maintaining system synchronism and stability in real time, particularly under weak grid conditions where fast-acting voltage sources are critical for system resilience. This does not imply that the full suppression response must be completed within 20 ms, but rather that the GFM inverter must initiate a meaningful and effective response within this timeframe. AEMO acknowledges that the response of Schedule 5.2 GFM plant is dependent on factors such as pre-disturbance current headroom. These limitations will be taken into account when developing the proposed access standards.

### 3.8.2. Proposed recommendation

In defining this requirement, it is also important to recognise that the suppression of phase angle jump must be effective without introducing instability or oscillatory behaviour in the local or system-wide response. Therefore, the response must be both fast and well-damped, consistent with the broader expectations of GFM performance across all access standards.

AEMO notes that neither the withstand nor suppression of phase angle jump is currently addressed in the NER. As such, the development of a new clause, potentially designated S5.2.5.17, is required to capture these capabilities explicitly. As discussed, both aspects are fundamental to the performance of Schedule 5.2 GFM plant and could therefore be incorporated as part of a MAS alone or alternatively defined with different numerical thresholds for the MAS and AAS to accommodate varying levels of capability across technologies.

Schedule 5.2 GFM plant is proposed to withstand voltage phase angle jumps of at least 40 degrees and up to 60 degrees at the connection point under credible contingency events, consistent with the thresholds adopted or proposed in other jurisdictions.

Stakeholder feedback is welcome, including on whether alternative response times may be more appropriate for specific technology types, or whether differentiated performance levels (e.g. MAS and AAS) should be adopted to reflect differing capabilities across the current generation of GFM inverters.

#### Question for Issue #12

**Do you agree with AEMO's proposed technical requirements of withstanding and suppressing phase angle changes, including the specified numeric thresholds?**

## 3.9. Operation at limits

### 3.9.1. Issue #14: Stability and grid support at the current limit

A widely recognised issue affecting the stability and response of GFM plant is its limited over-current capability. This typically arises when GFM inverter operates at its current limits during steady state conditions and when it responds to large grid disturbances. The GFM inverter may exhibit undesirable behaviour or at least lose some of its GFM capabilities due to transitions between full GFM control and current-limit control during a contingency event. It may also be unable to deliver a smooth and stable FRT response due to the activation of current limiting controls. In some instances, the GFM inverter may exhibit a loss of synchronism. Note that this issue does not apply to GFL inverters. Although they are also current-limited devices, they always operate in current-controlled mode, so there is no distinction between operating at full current or below full current.

Additionally, excessive inertial response from GFM inverters can reduce reactive power support and worsen voltage conditions during disturbances. While respecting current limits, inverters must maintain stable voltage source behaviour and support voltage and frequency recovery. Inertial response must not compromise system stability or lead to loss of voltage source characteristics.

Therefore, while acknowledging the limitations of GFM inverters, and without requiring significant overcurrent capability, it is important to define the expected performance under current limitation to ensure the GFM does not become unstable or negatively impact the system. At the same time, if the expected behaviour of the GFM under the current limitation is not explicitly defined, there may be an unrealistic assumption that the GFM plant will maintain full GFM functionality, which is not practical.

### 3.9.2. Proposed recommendation

#### Stability at the current limit

AEMO proposes that Schedule 5.2 GFM plant must maintain stable operation when operating at active current or total current limits. This includes:

- Avoiding control instabilities or oscillatory behaviour when current saturation is reached.
- Ensuring seamless control transitions between unconstrained and current-limited operation.
- Withstanding disturbances without entering unstable or poorly damped modes, even when temporarily unable to deliver full response due to current limiting.

This requirement applies under normal operation, during transitions in and out of a fault, in fault and post-fault conditions, and across a range of system strength conditions, e.g. specified with minimum and maximum SCR. AEMO proposes that it be formalised as a general requirement in relevant clauses, applicable to all Schedule 5.2 GFM plant.

### Grid support at the current limit

When a GFM inverter reaches its current limit, it may be unable to increase its output. However, it must continue to behave in a stable and supportive manner within its available current envelope. Specifically, the inverter must maintain voltage source behaviour and support the stable recovery of voltage and frequency, provided this does not require current beyond its defined limits.

To ensure consistent application across all relevant performance obligations, AEMO recommends introducing the requirement of maintaining stability at the current limit as a sub-clause in the “General requirements” of the clauses within NER Schedule 5.2.5 related to responses to disturbances where GFM inverter may operate at its current limits.

#### Question for Issue #13

**Do you agree with AEMO’s proposed technical requirements of maintaining stability during steady operation and grid support at the current limit? Why or why not?**

## 3.10. Summary of actions for further investigation

The following items represent areas where AEMO has not yet formed a policy and where further investigation is required. In most cases, this will involve a combination of detailed simulation studies and further engagement with stakeholders. These topics will remain open to ensure that any future requirements are evidence-based, technically justified, and consistent with system needs.

- Whether the variable reactive current response of GFM systems remains acceptable, or whether it could pose risks to system security, including an adverse impact on protection systems, that would warrant additional performance requirements.
- The merit of using quantities other than voltage to capture the initiation of the FRT response, as proposed by one of the respondents.
- The specification of an appropriate commencement time for the AAS, without being constrained by the limitations of measuring sub-cycle quantities in simulation studies.
- The merit of defining a maximum permissible active current reduction, taking into account system strength and the nature of the disturbance.
- The performance of Schedule 5.2 GFM plant during single- and two-phase auto-reclose events.
- The extent to which plant behaviour could cause exceedance of 1.1 p.u. network voltage during post-fault recovery, even under relatively high system strength conditions.
- The risk of delayed voltage recovery caused by Schedule 5.2 GFM plant with limited emulation of synchronous machine voltage dynamics.
- The potential need for protection from loss of synchronism in Schedule 5.2 GFM plant.

- The likelihood of a loss of synchronism due to the emulated rotor angle exceeding a certain value, or the impact of a long-duration fault, or a change in voltage angle during a fault.
- The coordination of multiple Schedule 5.2 GFM plants under low system strength conditions.
- Adverse impacts of GFM response with significant overload capability on system stability, particularly when operating near the voltage collapse point.
- Physical and mechanical limitations of wind turbines operating in GFM mode.
- Minimum headroom or reserving headroom for different GFM technologies to ensure GFM capability under all operating conditions.
- The potential impact of the PPC on GFM capability.
- The risk of GFM instability under high system strength conditions.
- Identification of the key control characteristics that may contribute to perceived limitations under high system strength conditions.
- Potential interactions between multiple GFM units in strong grid environments, and whether coordinated control strategies may mitigate any emerging risks.
- The most appropriate treatment of negative-sequence current support from GFM inverters during unbalanced faults, and whether explicit requirements should be developed.
- Determining the most suitable pathway for assessing compliance of hybrid plants comprising both GFM and GFL portions.

## Appendix A. Glossary

Term or acronym	Meaning
AAS	Automatic Access Standards
AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
ASR	Access Standard Review
AVR	Automatic Voltage Regulators
BESS	Battery Energy Storage Systems
CBF	Circuit Breaker Failure
CUO	Continuous Uninterrupted Operation
DC	Direct Current
DERMS	Distributed Energy Resource Management System
DMAT	Dynamic Model Acceptance Test
DNSP	Distribution Network Service Provider
dq	Direct Quadrature
EMT	Electromagnetic Transient
FCAS	Frequency Control Ancillary Services
FRT	Fault Ride-Through
GFL	Grid-Following
GFM	Grid-Forming
GPS	Generator Performance Standard
HECO	Hawaiian Electric Company
HIL	Hardware-in-the-Loop
HVDC	High Voltage Direct Current
IBR	Inverter-Based Resource
IRS	Integrated-Renewables Systems
MAS	Minimum Access Standards
ms	Milliseconds
MVA	Megavolt-Ampere
NEM	National Electricity Market
NEO	National Electricity Objective
NER	National Electricity Rules
NERC	North American Electric Reliability Corporation
NESO	National Electricity System Operator
NSP	Network Service Provider
OEM	Original Equipment Manufacturer
PLL	Phase-Locked Loop

Term or acronym	Meaning
POD	Power Oscillation Damping
PPC	Power Plants Controller
PSCAD	Power Systems Computer Aided Design
PSS	Power System Stabiliser
PSS®E	Power System Simulator for Engineering
p.u.	Per unit
I <sub>q</sub>	Reactive current
RMS	Root Mean Square
RoCoF	Rate of Change of Frequency
SCR	Short Circuit Ratio
SMIB	Single-Machine Infinite Bus
SoC	State-of-Charge
SPAR	Single-Phase Auto-Reclosure
SRAS	System Restart Ancillary Services
SSIAG	System Strength and Inertia Advisory Group
STATCOM	Static Synchronous Compensator
TNSP	Transmission Network Service Provider
TSO	Transmission System Operator
WTG	Wind Turbine Generators

## Appendix B. Consultation Questions

### Questions

1. Do you agree with AEMO's proposed definition for GFM plants? Why or why not?
2. What do you think is the best approach to apply GFM-related technical requirements for assessing hybrid-plants with GFM technology?
3. Do you agree with AEMO's proposed approach for integration of GFM technical requirements into NER S5.2 under the existing asynchronous category? Why or why not?
4. Do you agree with AEMO's proposed approach for assessing GFM plant voltage source behaviour in a contingency where its response initiation condition is not triggered?
5. Do you agree with AEMO's proposed approach that commencement and rise time of GFM plants should be reviewed? Why or why not?
6. What criteria shall be applied to assess a GFM plant's negative sequence current performance?
7. What technical requirements if any should be applied to GFM plant's in-fault active power/current performance?
8. Do you agree with AEMO's proposed approach for assessing the post-fault voltage recovery performance of GFM plants? Why or why not?
9. What technical requirement shall be considered for detecting GFM-specific instability?
10. Do you agree with AEMO's proposed approach to include explicit provisions for GFM plant to provide power system oscillation damping? Why or why not?
11. Do you agree with AEMO's proposed changes to S5.2.5.15?
12. Do you agree with AEMO's proposed technical requirements of withstanding and suppressing phase angle changes, including the specified numeric thresholds?
13. Do you agree with AEMO's proposed technical requirements of maintaining stability during steady operation and grid support at the current limit? Why or why not?

## Appendix C. Key Learnings

### C.1 Learnings from AEMO's ASR

The following points summarise key aspects of the ASR relevant to GFM technology, focusing on updates to the Automatic Access Standards (AAS) and Minimum Access Standards (MAS) that directly apply to Schedule 5.2 GFM plant or affect how their performance is assessed. The summary covers changes to current injection behaviour, active power recovery, unit-level voltage control, and system support capabilities such as frequency and phase angle response. These refinements reflect a clearer recognition of GFM characteristics in the regulatory framework and set clearer technical expectations for their integration. Based on high-level investigations, these findings warrant further analysis as part of this GFM-specific review process and provide a useful starting point for identifying key issues and options to be considered in developing the rule change proposal.

#### 1. Rise time, settling time, and commencement time for reactive current ( $I_q$ ) injection:

- For GFM inverters, a classical step-response assessment (e.g. rise time and settling time) may not be meaningful during faults, as the input signal is typically not a clean step change. The resulting response is shaped by non-linear internal control dynamics rather than exhibiting a conventional step-like behaviour.
- The GFM response may not "settle" within the fault duration due to its variable behaviour during fault conditions. This does not imply instability; rather, it reflects the continuous voltage regulation objective of GFM during faults.
- The AEMC's Package 1 final determination removes the settling time requirement from the AAS and introduces a period of 10-millisecond window within which reactive current must oppose voltage disturbance. This change reflects realistic performance expectations for GFM and similar technologies.

#### 2. Commencement of reactive current injection and measurement location:

- GFM inverters do not rely on discrete thresholds (e.g. 85 – 90% undervoltage) to initiate current injection. Instead, they begin reacting immediately to voltage deviations as part of their inner-loop control objective.
- The existing requirement in NER S5.2.5.5(g)(1) implicitly assumes centralised or Power Plant Controller (PPC)-based control, which is not how GFM operates. GFM response is continuous and decentralised.
- The NER now allows commencement time and rise time to be measured at locations other than the connection point, recognising the distributed control and measurement nature of many GFM implementations.
- These changes recognise that reactive current behaviour from GFM is voltage-error-driven and localised, not dependent on a system-wide controller transition.

#### 3. Active power recovery after a fault:

- GFM inverters may not follow a simple ramp back of active power after fault clearance, particularly if frequency and voltage conditions remain unsettled.

- The updated AAS and MAS under Package 1 tie the definition of active power recovery to the time when power reaches 95% of the pre-fault level, consistent with the approach used in the recent MAS update for GFL, which occurred in April 2023.
- This is more appropriate for GFM systems where power control may be treated as a secondary objective to frequency or voltage control loops following a fault.

#### 4. Voltage control at the unit level and implications for GFM:

- GFM inverters inherently operate with unit-level voltage control, and this is highly beneficial under low system strength conditions.
- Unlike PPC-based schemes, GFM does not depend on external setpoint broadcasts or communication delays, making it more stable and resilient in weak grids.
- Changes to NER S5.2.5.13 support rate-limited setpoint change and explicitly allow unit-level control to be applied to GFM systems, recognising this as a strength of the technology.

#### 5. Continuous uninterrupted operation (CUO) definition considers frequency and phase angle response:

- The revised CUO definition explicitly accommodates frequency response and synthetic inertia behaviour from GFM inverters, including responses to phase angle jumps.
- These changes ensure that GFM inverters are not penalised for providing stabilising action through their virtual synchronous behaviour, which is a core feature of many GFM control strategies.

## C.2 Learning from support for GFM projects funded by ARENA

AEMO has carried out studies on the PSCAD models of GFM plants of the vendors involved in ARENA's conditional funding to grid-scale battery projects across Australia<sup>13</sup>. A key objective of the studies was to identify the challenges associated with connecting Integrated-Renewables Systems (IRS) that incorporate GFM technologies, when assessed against the technical requirements of NER Schedule 5.2 (version 227 or earlier). Notably, the studies focus on GFM battery energy storage systems (BESSs), which represent the majority of IRS with GFM technologies in the NEM.

The studies have identified several common performance shortfalls and limitations of GFM BESS in meeting the AAS of NER version 227 or earlier. The shortfalls, which are concentrated in NER S5.2.5.5 and S5.2.5.13, are primarily related to the voltage source behaviour and the implementation of swing equations in coordination with over-current protection mechanisms triggered by disturbances.

### C.2.1 Voltage disturbance-related shortfalls due to voltage source behaviour

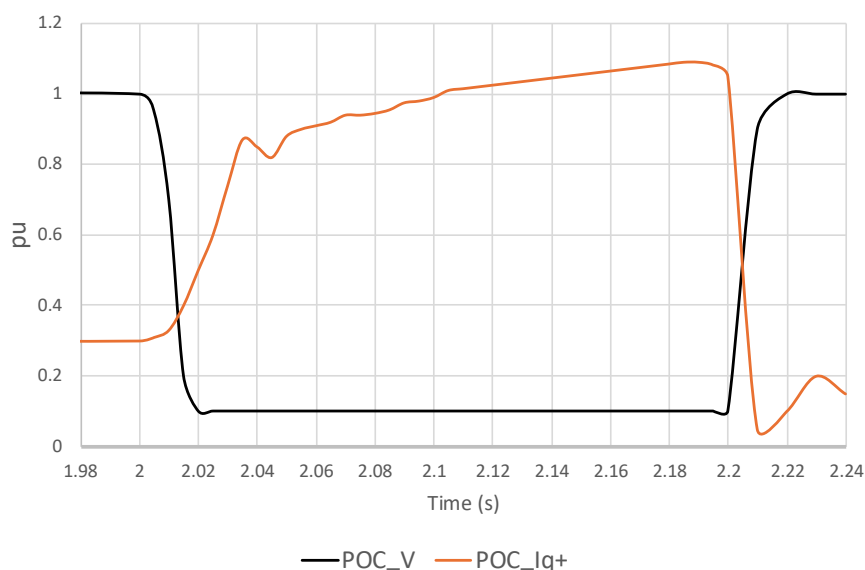
Different from GFL technologies, which operate inverters as a current source, GFM technologies establish an internal voltage phasor through control strategies, allowing inverters to act as voltage sources behind an impedance when sufficient current headroom is provided. This means the inverter-level output current is not the direct control objective, although some control strategies include an inner current control loop to assist with current limiting. However, in general, AEMO has observed that GFM inverters that implemented fast current control did not demonstrate a material improvement in rise time or settling time. Consequently, GFM plants

<sup>13</sup> Australian Government, 2022. "ARENA backs eight grid scale batteries worth \$2.7 billion". Available at: <https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/>

cannot achieve the same fast current response as GFL plants. This leads to performance shortfalls associated with the requirement for reactive current in NER S5.2.5.5 and reactive power in NER S5.2.5.13.

Regarding the performance shortfall in NER S5.2.5.5, AEMO has observed that GFM plant faces challenges in meeting the AAS requirement of a 40 ms reactive current rise time. While GFM plants typically exhibit a fast initial reactive current response at the onset of a voltage disturbance, attributable to their voltage source behaviour, some GFM technologies are unable to sustain this rapid response to achieve a reactive current peak within a short timeframe. Instead, these plants may experience a slower secondary rise in reactive current, resulting in the peak occurring later in the fault.

**Figure 2 Positive-sequence reactive current of grid-forming BESS may exhibit an initial rapid rise followed by a slower increase at the onset of a voltage disturbance.**



Generally, the underlying causes are related to the dynamics of voltage control and the availability of the current headroom, which is dynamically allocated to active and reactive current, thereby impacting the performance of reactive current. Furthermore, the limited over-current capability can lead to a decline in reactive current towards the end of a long-duration fault.

AEMO has also observed that some GFM plants exhibit slow rise and settling times in their responses to 5% voltage reference step changes. This is because when the terminal voltage changes in response to a reactive power command from the PPC to the inverters, the internal voltage reference of the GFM inverters has not been changed. In resisting this terminal voltage change (to maintain voltage stiffness), the GFM inverter exhibits a slower reactive power response compared to the GFL plants.

### C.2.2 Voltage disturbance-related shortfalls due to the swing equation

AEMO has noticed that the majority of GFM technologies in the NEM employ the swing equation or its variants in the power–frequency control loop, emulating synchronous generator rotor dynamics and providing synthetic inertia. However, the implementation of the swing equation can lead to a longer post-fault active power recovery time. Typical responses observed by AEMO include:

- The swing equation reacts to the voltage phase angle difference before and after the fault is cleared, causing an opposite active power spike, which delays the recovery process.

- The swing equation cannot achieve the same dynamics as current control in GFL inverters to restore active power to the pre-fault level.

### C.2.3 Potential issues due to limited over-current capability

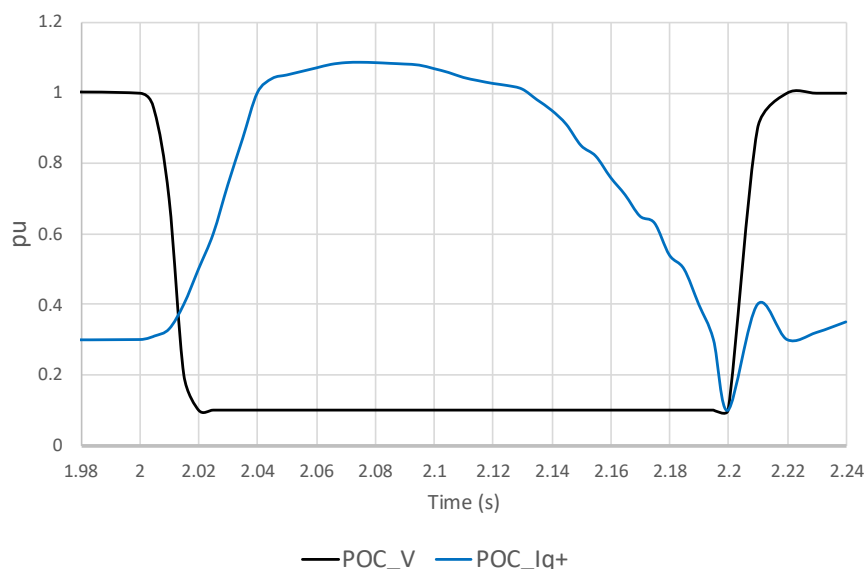
The limited over-current capability of GFM inverters presents two key challenges. While the voltage source behaviour allows GFM inverters to respond very quickly, often within a sub-cycle, to disturbances, it must still be recognised that GFM inverters, like their GFL counterparts, use current-sensitive semiconductor switching devices. These devices require rapid protection against excessive over-currents, which constrains the inverter's ability to sustain high fault currents. Second, their ability to contribute over-current during a disturbance is inherently limited, typically to less than 150% of their rated continuous current.

To manage this limitation, AEMO has observed that GFM technologies, under study, employ a current-limiting control mechanism. This enables inverters to dynamically transition between a normal GFM mode and a current-limiting mode when pre-defined triggering conditions are exceeded. However, this approach introduces operational challenges, as observed in AEMO's plant-level and wide-area studies. These include, but are not limited to:

- A decline in reactive current support towards the end of a long-duration fault, sometimes dropping below pre-fault levels.
- Angle instability due to sub-optimal timing of mode transitions.
- In-fault mode retriggering.

Such issues can adversely impact power system security if not adequately mitigated.

**Figure 3 Positive-sequence reactive current at the connection point declines during the fault and drops below the pre-disturbance level.**



It is worth noting that some of the challenges faced by GFM plants, as outlined above, have been acknowledged in Package 1 which has primarily focused on GFL plants. In response, adjustments have been made to several technical requirements, effective from August 2025. Notably, these include changes to reactive current rise time and post-fault active power recovery time in NER S5.2.5.5, as well as the reactive power rise time in NER S5.2.5.13.

AEMO has observed a growing trend in which the unique characteristics of GFM technologies are used to negotiate reduced performance standards. This is largely attributable to the lack of defined technical requirements within NER Schedule 5.2 for assessing such characteristics. As a result, the potential of GFM inverters to provide critical voltage source support, both locally and system-wide, may be compromised, despite this being essential for maintaining power system security as synchronous generation retires from the NEM.

### C.3 AEMO's voluntary specification for grid-forming inverters

AEMO's Voluntary Specification for grid-forming Inverters provides a structured, performance-based framework that defines the functional capabilities expected of GFM inverters in both normal and disturbed system conditions. It distinguishes between core capabilities, which are essential for safe and stable operation, and additional capabilities, which can offer enhanced system support depending on local needs. This specification provides valuable context for interpreting recent changes in the access standards and serves as a reference point for this approach paper.

#### C.3.1 Core capabilities

The core capabilities reflect the minimum expectations for a GFM inverter to behave in a system-supportive manner and safely operate under a range of network conditions. These include:

- Voltage source behaviour: GFM inverters should regulate terminal voltage in a controlled manner, maintaining a nearly constant internal voltage phasor and responding near-instantaneously to changes in external voltage magnitude and phase angle, provided current limits are not exceeded. This is fundamental to operating as a voltage source rather than a current follower.
- Phase angles jump immunity: The inverter should remain synchronised and stable during sudden changes in grid phase angle, such as those associated with fault clearance or switching events, without needing to switch modes or lose synchronisation.
- Frequency-domain passivity: GFM units are expected to exhibit passive behaviour across a broad frequency range, helping to avoid resonant amplification or unstable interactions with other devices or the network.
- Inertial response: The inverter should emulate inertial behaviour by injecting active power proportionally to rate of change of frequency (RoCoF). This includes the ability to respond instantly based on internal energy buffering, offering support similar to synchronous inertia.
- Survivability following loss of synchronous machines: GFM inverters should maintain voltage and frequency references even when no synchronous machines are online, providing a critical grid-forming function under system restoration or islanded scenarios.
- Operation under weak grid conditions. The GFM unit must be able to provide stabilising current in low system strength environments, supporting local voltage control and contributing positively to system strength.
- Oscillation damping. The inverter should have sufficient bandwidth to detect and suppress electromechanical or control mode oscillations, providing additional grid stability in complex IBR-dominated systems.

### C.3.2 Additional capabilities

The specification also outlines additional capabilities that are not universally required but can deliver meaningful system value in specific operational contexts:

- **Energy headroom and buffering.** Ensures the inverter can sustain active power support without immediate saturation or de-rating, particularly important for providing inertial and frequency response.
- **Current capacity above continuous rating.** Allows for temporary over-current capability to meet transient fault current injection or support without prematurely activating protection or thermal limits.
- **Black start capability.** The ability to energise network sections independently and participate in coordinated restoration efforts, especially in systems with limited synchronous machine availability.
- **Power quality support.** Inverters may contribute to reducing voltage harmonics, flicker, or other disturbances, particularly in distribution-connected or embedded applications.

### C.3.3 Implications for access standards and rule change development

These capability definitions directly reinforce several key updates made in AEMO's recent ASR and the subsequent Package 1, including:

- The shift from prescriptive response metrics (e.g. fixed rise times and current thresholds) towards performance-based assessment aligned with inverter control behaviour.
- Recognition of unit-level voltage control in GFM implementations, especially under weak grid conditions.
- Support for inertial and oscillation damping capabilities is a valuable, though not yet mandatory, feature that may warrant future treatment in standards or incentive frameworks.

While this was based on high-level investigations, the alignment with AEMO's Voluntary Specification provides a strong foundation for more detailed rule change work. It clarifies the types of GFM behaviour that are already achievable with current technology and suggests a roadmap for how technical standards may evolve to capture these benefits in a scalable, vendor-neutral way.

Further investigation, being undertaken as part of this approach paper and subsequent work, is required to determine which of these capabilities should be formally mandated, under what conditions, and how compliance should be assessed. Nevertheless, the voluntary specification offers a technically robust and forward-looking foundation for defining GFM performance expectations in the NEM.

## C.4 Summary of international performance requirements

Table 3 compares GFM capability requirements across selected international jurisdictions, including ACER, Fingrid, German TSOs, HECO, NERC, and NESO, and aligns these with AEMO's voluntary specification.

**Table 3 Summary of international requirements for GFM inverters**

Capability	ENTSO-E <sup>14</sup>	Fingrid <sup>15</sup>	German TSOs <sup>16</sup>	HECO <sup>17</sup>	NERC <sup>18</sup>	NESO <sup>19</sup>	AEMO's Voluntary Spec <sup>20</sup>	Recommendation in this approach paper
Voltage source behaviour	✓	✓	✓	✓	✓	✓	✓	✓
Sub-cycle suppression of voltage magnitude changes	✓	✓	✓	✓	✓	✓	✓	✓
Sub-cycle suppression of voltage phase angle jump	✓	✓	✓	✓	✓	✓	✓	✓

<sup>14</sup> European Network Transmission System Operators for Electricity (ENTSO-E), May 2024. "Grid forming capability of power park modules". Available at: [https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/20240503\\_First\\_interim\\_report\\_in\\_technical\\_requirements.pdf](https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/20240503_First_interim_report_in_technical_requirements.pdf).

<sup>15</sup> Fingrid, January 2025. "Grid code specification for grid energy storage systems". Available at: <https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/sjv2024--unofficial-english-translation.pdf>.

<sup>16</sup> Available at: [https://www.netztransparenz.de/xsproxy/api/staticfiles/ntp-relaunch/dokumente/zuordnung\\_unklar/grundlegende-anforderungen-an-netzbildende-umrichter/220504\\_-\\_4-tso\\_paper\\_on\\_requirements\\_for\\_grid-forming\\_converters.pdf](https://www.netztransparenz.de/xsproxy/api/staticfiles/ntp-relaunch/dokumente/zuordnung_unklar/grundlegende-anforderungen-an-netzbildende-umrichter/220504_-_4-tso_paper_on_requirements_for_grid-forming_converters.pdf).

<sup>17</sup> Hawaiian Electric Company (HECO), 23 August 2021. "Hawaiian electricity facility technical model requirements and review process". Available at: [https://www.hawaiianelectric.com/documents/clean\\_energy\\_hawaii/selling\\_power\\_to\\_the\\_utility/competitive\\_bidding/20210901\\_cbre\\_rfp/20210825\\_redline\\_lanai\\_appxb\\_att3.pdf](https://www.hawaiianelectric.com/documents/clean_energy_hawaii/selling_power_to_the_utility/competitive_bidding/20210901_cbre_rfp/20210825_redline_lanai_appxb_att3.pdf).

<sup>18</sup> North American Electric Reliability Corporation (NERC), September 2023. "White paper: grid forming functional specifications for BPS-connected battery energy storage systems". Available at: [https://www.nerc.com/comm/RSTC\\_Reliability\\_Guidelines/White\\_Paper\\_GFM\\_Functional\\_Specification.pdf](https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf).

<sup>19</sup> National Electricity System Operator (NESO), May 2024. "Guidance Notes for Grid Forming Plants". Available at: <https://www.neso.energy/document/289921/download>.

<sup>20</sup> AEMO, 2023. "Voluntary Specification for Grid-forming Inverters". Available at <https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E>

Capability	ENSTO-E <sup>14</sup>	Fingrid <sup>15</sup>	German TSOs <sup>16</sup>	HECO <sup>17</sup>	NERC <sup>18</sup>	NESO <sup>19</sup>	AEMO's Voluntary Spec <sup>20</sup>	Recommendation in this approach paper
Sub-cycle suppression of rapid frequency changes	✓	✓	✓	✓	✓	✓	✓	✓
System strength support	X	✓	X	X	✓	✓	✓	X
Weak grid operation	X	X	X	✓	X	✓	✓	✓
Control stability	X	X	✓	✓	X	X	X	X
Reducing/preventing adverse control interactions	X	X	✓	X	X	X	✓	Requires further investigation
Passivity	X	✓	✓	X	X	✓	✓	Requires further investigation
Oscillation damping	X	✓	✓	X	✓	✓	✓	Requires further investigation



Capability	ENSTO-E <sup>14</sup>	Fingrid <sup>15</sup>	German TSOs <sup>16</sup>	HECO <sup>17</sup>	NERC <sup>18</sup>	NESO <sup>19</sup>	AEMO's Voluntary Spec <sup>20</sup>	Recommendation in this approach paper
Synchronising power	X	✓	X	X	X	X	X	X
Negative-sequence current support	X	X	✓	X	X	X	✓	Requires further investigation

These preliminary views serve as inputs to the detailed technical review and consultation, where each capability is examined in the context of its potential application in the NEM. Where the final column states “Requires further investigation”, it indicates that the literature review did not provide enough evidence to support a well-informed preliminary view. In some cases, such as oscillation damping, there is a likely need for a requirement; however, the appropriate scope of that requirement (e.g. targeting local modes versus intra-plant or inter-area oscillations) remains unclear and warrants further investigation.

The following capabilities will be further assessed for technical validity:

- **Voltage source behaviour.** Recognised across nearly all jurisdictions as a fundamental aspect of GFM operation. Its role is further clarified through the associated sub-cycle capabilities. It is considered important for a more detailed investigation in the context of future access standard development. Notably, this capability encompasses the behaviours captured by the sub-cycle suppression of voltage magnitude, phase angle jump, and frequency changes.
- **Sub-cycle suppression of voltage magnitude, phase angle jump, and frequency changes.** Among the most consistently required capabilities internationally. These features ensure a fast response to disturbances and form a cornerstone of high-performance GFM behaviour.
- **System strength support.** It appears in several specifications, though with variation in how it is defined or implemented. A key question is whether this capability should be embedded within access standards, treated as a system service, or addressed through a combination of both. Importantly, any future requirements will need to be coordinated with AEMO’s system strength frameworks and impact assessment guidelines to ensure alignment and avoid duplication.
- **Weak grid operation.** While not universally mandated, it is especially relevant to the NEM, given the increasing prevalence of low SCR conditions. The requirement is generally applicable to both GFM and GFL inverters, though their capabilities and limitations differ significantly under such conditions.
- **Control stability and interaction mitigation.** Explicitly addressed in a limited number of jurisdictions, often indirectly through other requirements. These aspects are challenging to assess through standardised testing and are often captured by proxy through requirements related to weak grid operation, passivity, or voltage source performance.
- **Passivity**<sup>21</sup>. Acknowledged as a technically important capability to minimise adverse impedance interactions and promote system stability. However, few jurisdictions require it formally, primarily due to the lack of a universally accepted assessment methodology. Its role in system integration and contribution to oscillation damping will be further evaluated in Appendix D.2.1.
- **Oscillation damping (via control).** Either explicitly required or implied in several jurisdictions, particularly where maintaining system stability under high IBR penetration is a concern. This typically refers to active control measures designed to replicate the damping of electromechanical oscillations historically provided by synchronous machines (and, to a lesser extent, SVCs with power oscillation damping), as well as mitigating electrical oscillations arising from IBR control interactions and grid coupling. In the NEM, this capability may warrant closer consideration under low system strength conditions, including whether its application should be limited to local modes or extended to cover wider-area oscillatory modes.

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<sup>21</sup> Passivity is a property of a system that means it does not generate energy on its own, it can only store or dissipate energy that it receives. If a system is non-passive, it may amplify small or large disturbances, increasing the risk of oscillations or instability, especially when interacting with other non-passive elements.

- **Synchronising power<sup>22</sup>.** This is rarely specified as a discrete capability in current international standards. While it may not be a priority for direct inclusion in access standards, its underlying physical behaviour may be captured through requirements set out for voltage source behaviour.
- **Negative-sequence current support.** An emerging requirement in some jurisdictions, particularly for handling unbalanced faults and ensuring protection coordination. Although not yet widespread, it is of growing importance.

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<sup>22</sup> Synchronising power is defined as the rate at which the synchronous power output of a synchronous machine changes with respect to a change in the load angle. In other words, it is the derivative of the power output with respect to the load angle in a synchronous machine. In GFM inverters, control strategies are often designed to emulate synchronising power by establishing a positive power–angle relationship that helps maintain angular stability, similar to the behaviour of synchronous machines.

## Appendix D. NSP and OEM Survey Feedback

### D.1 FRT response

#### D.1.1 NSP feedback

**Concerns about explicit FRT mode requirements.** It was suggested that there should not be an explicit requirement for an FRT mode because:

- Some GFM plants and certain GFL Type 3 wind turbines do not have a dedicated FRT mode at the inverter level, and
- The NER does not require FRT mode; instead, the framework assumes plants will inherently meet FRT capabilities.

One respondent indicated their agreement with the removal of a voltage threshold for FRT activation but does not support initiating the response at a voltage as low as 0.8 p.u., or even lower in some practical cases.

The following alternatives for FRT activation in GFM plants were considered:

- Rate of change of voltage magnitude.
- Rate of change of frequency.
- Phase angle jump.
- Sudden impedance change.
- Voltage sensitivity of reactive power ( $\Delta Q/\Delta V$ ).
- Instantaneous fault current or root mean square (RMS) fault current.
- A hybrid approach comprising two or more of the above.

A complementary view was when considering the reactive current injection of GFM plants during system faults, aiming to reproduce the characteristics of synchronous generation. Triggering switching logic during system faults may bring the risk of instability, especially as system strength reduces.

**Concerns about active current ( $i_d$ ) suppression.** Some respondents suggested that it is both necessary and, in some cases, desirable for GFM plants to suppress active current in favour of reactive current during a fault. However, determining the “optimal” value for this reduction requires further analysis. One respondent suggests a workable default by allowing the active current to curtail down to 70% of the maximum rated current in scenarios where a higher active current was available, meaning reactive current may reach up to 70% of the maximum rated current (this assumes the worst case of no over-current capability and uses:

$$i_{\text{total}} = \sqrt{i_d^2 + i_q^2} = \sqrt{0.7^2 + 0.7^2} = 0.9899).$$

Note: If pre-fault active current is small, reactive current ( $i_q$ ) can approach 100% of the maximum rating.

However, it was noted that the active current should not drop to zero during faults to maintain system stability. Therefore:

- A minimum of 1 p.u. or more total current should be maintained, ensuring a controlled breakdown between reactive current and active current in both positive and negative-sequence components.

- A maximum allowable limit should be set on active current reduction during voltage dips to prevent excessive suppression and ensure a stable and effective fault response.

**Concerns about voltage angle disturbance.** One response expressed concern about the impact on voltage angle disturbance when active current is largely reduced during faults. The most critical consideration in determining the acceptance or otherwise of an active current reduction is ensuring that GFM plants can:

- Successfully ride through network faults, and
- Provide robust post-fault recovery support for the power system.

It was suggested that whether this behaviour is acceptable ultimately depends on specific system conditions and stability requirements. Prioritising reactive current to support voltage recovery during faults is often justified, particularly in weak grids, but entirely neglecting the contribution of active current can exacerbate frequency excursions and compromise system stability. Hence, active current reduction should be allowed but carefully optimised.

Extending this point, a key challenge in weak systems is the cross-coupling effect between  $i_d$  and  $i_q$  during faults. This coupling becomes more pronounced under faulted or low-voltage conditions, where  $i_d$  can have a direct influence on voltage stability. Therefore, rather than setting  $i_d$  to zero arbitrarily, the balance between  $i_d$  and  $i_q$  should be driven by system-level needs.

**Concerns about current limitations.** One respondent highlighted the inherently current-limited nature of all IBRs, including GFM inverters. During fault conditions, GFM inverters are likely to reach their current saturation limits, at which point they may either switch to a current control mode, or if they remain in GFM mode, their response may become effectively governed by current control behaviour. This raises important considerations around how GFM plants should synchronise and coordinate with other IBRs under such conditions, particularly with respect to assigning the appropriate ratio of active and reactive current contributions.

**Concerns about reactive current reduction.** A concern raised based on practical experience is the significant reduction in reactive current injection during fault conditions, despite an initially high injection level (potentially up to 1 p.u.). In some instances, the reactive current delivered by the plants fell below the pre-fault level, indicating that the plants may have been absorbing reactive power from the system, thereby potentially worsening system stability.

**Ride-through for auto-reclose events.** The existing rules provide limited guidance on evaluating generation performance during automatic transmission line reclosing, particularly single-phase auto-reclosure (SPAR) events, which may last up to 1 second. This poses greater challenges for GFM plants compared to synchronous generation, due to the current-limited nature of GFM plants that may prevent adequate negative-sequence current control to counter the imbalance caused by SPAR. Additionally, unbalanced conditions during SPAR can lead to DC-link voltage oscillations or imbalance, further complicating the inverter's ability to remain synchronised and stable. Assessing GFM plants FRT capability for SPAR events would enhance confidence in its fundamental GFM capabilities. No additional details were provided by the respondent on this matter.

**Response to long-duration faults:** Varied views were provided regarding the potential limitations of GFM under long-duration faults, such as CBF. Some respondents indicated that GFM will behave similarly to GFL, while others pointed out that GFM current limitations and, in particular, rotor angle instability, also known as transient instability, could be key limiting factors. This is analogous to synchronous machines, which become unstable if a fault exceeds their critical clearing time.

Unlike GFL inverters, which rely on external phase tracking, GFM inverters maintain voltage and frequency during faults. However, strict current limits in GFM inverters could restrict their ability to sustain adequate fault current injection for extended durations, potentially impacting system stability.

**Concerns on GFM post-fault active power recovery being slower than GFL.** It was noted that slower active power recovery may be an intentional design trade-off to support voltage stability and manage mechanical stress, particularly in wind-based GFM systems. They emphasised that this behaviour is not a technical deficiency but reflects a system-oriented control approach. It was also pointed out that the AEMC's revised definition of the "end of disturbance" provides added flexibility in recovery expectations. Another respondent indicated a secondary impact of post-fault active and reactive power recovery behaviour of GFM inverter which in some cases has led to momentary exceedance of 1.1 p.u. in network voltage, thereby breaching the requirements of clause S5.1a.4. This behaviour has been observed even under relatively high system strength conditions.

**Voltage recovery concerns.** One respondent strongly supported the proposal to introduce voltage recovery as a new metric for assessing the post-fault performance of GFM plants, alongside post-fault active power recovery. They discussed that following fault clearance, it is essential for GFM plants to quickly re-synchronise with the grid by autonomously aligning both their voltage magnitude and frequency with healthy grid conditions. While power swing equations traditionally aid frequency synchronisation, voltage magnitude synchronisation poses additional challenges. To address these, it was suggested that control strategies such as Automatic Voltage Regulators (AVR), PLL, and voltage swing equation-like algorithms can be employed to achieve more stable and autonomous voltage recovery.

In addition to voltage recovery, the respondent suggested considering other metrics that assess post-fault voltage and frequency synchronisation to evaluate the speed and stability with which the GFM plants re-establishes synchronisation after a fault.

The following additional points were also raised, suggesting that:

- All plants (GFM or GFL) should promptly re-regulate voltage after a fault if operating in voltage control mode.
- The GFM plants should assist in the recovery of the GFL plants by supporting voltage recovery (as synchronous generation does). The GFM plants should not be allowed to slow down voltage recovery due to limited implementations of synchronous generation characteristics.

**Setting achievable AAS targets for GFM.** It was noted that if GFMs using swing equations cannot meet a 100 ms response time, the question should shift to:

- What is the best response time they can achieve?
- What should the AAS be for such cases?
- What trade-offs exist between post-fault recovery speed and other performance aspects?

### D.1.2 OEM feedback

**Voltage threshold for FRT activation:** Most respondents agreed that GFM technology behaves similarly to synchronous machines in terms of FRT activation, making a distinct voltage threshold to enable or disable normal operation versus FRT mode unnecessary.

**Reactive current:** One respondent indicated that GFM resources do not control active and reactive current. As a result, the reactive current is a calculated and derived quantity rather than a directly controlled variable in the

real system. The default iq typically assumes a positive-sequence value, but in practice, the grid is rarely perfectly balanced, and GFM control naturally adjusts to measured conditions at the terminals, resulting in small residual negative-sequence components at the connection point.

**Commencement time:** No concerns were raised by respondents, indicating that a sub-cycle response ranging between 5 and 20 ms is achievable in practice. One response highlighted that commencement time is effectively the same as rise time, meaning that the iq injection begins almost instantaneously at the inverter terminals. It was also discussed that the exact observed commencement time in simulation-based compliance studies can be affected by phasor measurement delays and other post-processing algorithms used in EMT simulation tools, leading to a potential discrepancy between the actual converter response and what is recorded in simulation-based compliance studies.

**Rise time:** Responses provided on rise time vary to some extent, ranging from very easy to meet to somewhat challenging for the AAS assessment. This variation reflects differences in technology implementations, control strategies, and system conditions. One response noted that the rise time is inherently fast in GFM systems as the control response is instantaneous in relation to voltage deviations. The response is typically within half a fundamental period, as GFM technology inherently regulates terminal voltage and synchronises with the system dynamically.

**Settling time:** Responses on settling time for GFM technology vary based on different control strategies, network conditions, and interpretation of requirements. The key points raised include:

- Comparison with synchronous machines, indicating that synchronous machines are not subject to strict settling time requirements, and GFM should be treated similarly.
- Concerns over defining a universal requirement, highlighting the FRT response in GFM is naturally triggered by voltage disturbances, meaning that the settling process of active and reactive current is inherently managed within the control scheme as the terminal voltage and phase angle stabilise.
- Some responses suggest that defining a fixed numerical settling time requirement may not be appropriate, as GFM stabilisation occurs dynamically based on real time grid conditions.
- Another response indicated that the GFM control will adjust the angle slowly through the FRT response, and therefore, the angle does not stay constant like a GFL controller would. Therefore, the concept of “settling” is only relevant to the frame of reference of the angle that is measured.
- Strong dependence on testing conditions, stating indicating settling time should not be strictly defined without first specifying test conditions to ensure consistency.

**Reactive current injection ratio (K-factor):** Some responses suggested key differences in GFM vs. GFL control methods, as well as the challenges of defining a fixed coefficient for GFM systems. The key points raised include:

- **No fixed K-factor relationship in GFM:** Multiple responses indicate that GFM control does not follow a fixed voltage-reactive current coefficient (K-factor) relationship as it is often programmed in GFL systems, particularly for GFM implementations that do not employ a fast current control loop in addition to the mandatory voltage control loop. Unlike GFL systems, where reactive current injection is directly proportional to voltage drop, GFM inherently regulates voltage, making a strict K-factor definition less meaningful. In unbalanced fault scenarios, the GFM control naturally adjusts to minimise voltage impact on healthy phases, further complicating the application of a fixed K-factor. While not a directly controllable quantity for GFM, a few responses indicated that control strategies can be shaped to achieve a similar response.

- **Similarities with synchronous machines:** Some responses suggest that GFM should be treated similarly to synchronous machines, which do not have a pre-defined voltage-based activation threshold.

**Measurement/assessment point:** Some respondents suggested measuring reactive current injection, commencement time, rise time, and settling time (if retained) at the unit terminals rather than the connection point. This approach aims to eliminate the influence of plants and network impedances, including those from transformers and balance of plants, ensuring a more accurate assessment of the unit's inherent response.

**Post-fault active power recovery performance:** Several respondents raised concerns regarding the 100 ms active power recovery requirement following a fault, stating that such a fast response is unrealistic for GFM and likely unnecessary. The slowest response indicated was 500 ms, including two GFM wind turbine OEMs surveyed.

However, a third GFM wind turbine OEM recommended relaxing the power recovery time requirement for wind-based GFM systems to around 1 second, citing the need to balance mechanical constraints and maintain grid voltage stability. They noted that rapid active power recovery can impose undue stress on mechanical components and may conflict with control strategies that prioritise overall system stability. No further information was provided on how this differs from GFL wind turbine performance, noting that GFL wind turbines can generally achieve an active power recovery time of at least 500 ms.

Some respondents noted that active power recovery in GFM is strongly coupled with reactive power behaviour, particularly under low system strength conditions. Faster recovery may not always be achievable without compromising stability.

### D.1.3 AEMO's Response

**Response initiation criteria and reactive current expectations.** AEMO supports the view that an effective FRT performance does not require a dedicated FRT mode, provided that the control systems are suitably designed to manage fault conditions. This aligns with the behaviour of synchronous machines, which inherently provide a coherent response to voltage dips without suspending normal control objectives or initiating a separate mode during faults. AEMO supports not defining a voltage threshold for the initiation of FRT response in the proposed new requirements, consistent with the approach taken for synchronous machines. However, it is agreed that it would not be appropriate for the FRT response to initiate only when voltages fall as low as 0.8 p.u. or lower. The expectation is for an inherent and prompt response consistent with voltage source behaviour.

While synchronous generator responses are not triggered by a specific voltage threshold, it is important to note that the current requirements for synchronous generators are defined in terms of reactive current injection or absorption relative to the percentage of voltage change. Therefore, adopting the current requirements for synchronous generators implies that the requirement for reactive current injection as a function of the extent of voltage change will continue to apply. This reflects the fact that, in both synchronous generators and GFM inverters, reactive current is not a directly controlled variable but rather emerges from the system's inherent voltage source behaviour.

However, it is recognised that defining a fixed voltage-reactive current coefficient (K-factor) may present challenges for some GFM systems. The response of a synchronous generator during faults is far less variable than that of a GFM inverter, making the application of a single fixed K-factor less practical for GFM technologies. Nevertheless, we will further investigate whether the more variable reactive current response of GFM systems remains acceptable, or whether it could pose risks to system security, including an adverse impact on protection systems, which would warrant additional performance requirements.

AEMO also notes concerns raised based on practical experience, where significant reductions in reactive current injection have been observed during fault conditions, despite an initially high injection level (potentially up to 1 p.u.). In some cases, the reactive current delivered by plants has fallen below the pre-fault level, suggesting that the plants may have begun absorbing reactive power from the system, potentially exacerbating system instability. We consider it important to ensure that Schedule 5.2 GFM plants technical requirements avoids such undesirable outcomes. The importance of maintaining a relatively consistent reactive current response throughout the fault has already been recognised in the AEMC's final determination of Package 1 rule change, and we propose to use this as a starting point when developing technical requirements for GFM systems. It is also noted that the impact of response variability in GFM inverters will not be assessed solely based on fault current magnitude. Other factors, including variations in phase angle and apparent output impedance as governed by the inverter's control strategy, will also be considered.

We will also investigate the merit of using quantities other than voltage to capture the initiation of the FRT response, as proposed by one of the respondents. However, AEMO is mindful not to introduce metrics that could inadvertently dictate a particular control system design or tuning approach within the inverter, as the detailed control strategy ultimately remains the responsibility of the OEM.

**Speed of the response.** AEMO supports the use of commencement time and rise time as appropriate and meaningful metrics to assess the initial dynamic response of GFM inverters during fault conditions. While phasor-based measurements may introduce some uncertainty in accurately capturing sub-cycle commencement times, this does not detract from the value of these metrics in characterising prompt current injection. AEMO will further investigate the specification of an appropriate commencement time for the AAS, without being constrained by the limitations of measuring sub-cycle quantities in simulation studies. AEMO also supports the removal of a defined settling time requirement, noting that synchronous generators are not subject to such constraints. This position aligns with the AEMC's final determination of Package 1 rule change, which proposes removing settling time from both the AAS and the MAS, with the latter having already been amended in 2023.

**Active current reduction during the fault.** AEMO considers that some level of active current reduction during faults is acceptable, particularly where it enables higher reactive current contribution to support voltage recovery, a key priority in weak grid conditions. This reflects a practical control trade-off, especially under current-limited operation, and aligns with the broader system need for rapid voltage support.

AEMO agrees with the concern raised by respondents that excessive suppression of active current may not always be appropriate, as it can adversely affect other aspects of system stability, including response to voltage angle disturbance and the plants' contribution to frequency support. These impacts become especially relevant when active current is substantially curtailed during the fault.

Furthermore, as system strength decreases, meaning that equivalent system impedances increase, the cross-coupling between active and reactive current becomes more pronounced. Under very weak grid conditions, abrupt changes in active current can lead to unintended adverse impacts on voltage stability. This effect is further exacerbated when the X/R ratio reduces, as is often the case for distribution-connected Schedule 5.2 GFM plant. Accordingly, we believe the balance between active and reactive current should be informed by system-level needs, rather than enforced through a fixed ratio. We propose to investigate the merit of defining a maximum permissible active current reduction, considering system strength and the nature of the disturbance.

It is also important to acknowledge that current limitation in GFM inverters is a physical constraint, not something that can be eliminated through control system tuning. Under faulted or low-voltage conditions, this limitation may be reached, impacting the inverter's ability to continue operating in a true GFM mode. In such cases, allowing a modest reduction in active current may be a practical and beneficial measure to preserve GFM

capability, which is likely to be more critical to overall system stability than the full delivery of active power during the fault.

Nevertheless, we reaffirm the expectation that total current output of at least 1 p.u. should be maintained under all fault conditions, ensuring that the plants continue to contribute meaningfully to system recovery.

**Auto-reclose and long-duration fault considerations.** AEMO acknowledges the valid concern raised by respondents regarding the performance of GFM inverters during single- and two-phase auto-reclose events. While these scenarios are important, they require further investigation, particularly given the current-limited nature of GFM inverters and the potential for extended unbalanced conditions. Although ride-through of auto-reclosure events is generally expected, it is recognised that some portion of the total current will need to be allocated to managing negative-sequence components during the unbalanced event. This may occur either inherently through voltage source behaviour or through explicit sequence-domain control. In either case, this may temporarily limit the plants' ability to contribute to positive-sequence voltage support or active power delivery.

Similar limitations apply to long-duration faults, such as those resulting from Circuit Breaker Failure (CBF) or persistent faults in distribution networks. While AEMO has previously noted the need for GFM inverters to sustain a relatively constant fault current during the primary protection and CBF clearance timeframes, this expectation does not extend to significantly longer durations, especially those associated with distribution network clearance times.

A related concern raised by some respondents is the potential for loss of synchronism in GFM inverters if the fault duration exceeds a certain threshold, similar to the critical clearing time concept for synchronous machines. AEMO has observed responses in practical grid connection projects where abnormal behaviour or instability occurred due to multiple contributing factors. Among these, a rapid increase in voltage phase angle during the fault has been identified as one potential contributor. This will be investigated further during the development of the draft access standards.

In any case, AEMO considers that sustaining fault current beyond typical transmission protection timeframes may not be feasible, as GFM inverters will eventually reach their thermal and current saturation limits. This limitation arises not only from hardware constraints but also from control dynamics, including constrained voltage control due to limited current capability and the swing-equation-based response<sup>23</sup>, both of which can affect the inverter's ability to sustain high current injection during faults.

Moreover, synchronous generators themselves are unlikely to remain connected during such prolonged fault conditions due to loss of synchronism. Accordingly, a reduction in both active and reactive current during very long-duration faults, beyond typical CBF clearance time, is acceptable, in recognition of the thermal limitations of the inverter's semiconductor switching devices.

**Compliance assessment location.** While discussions around response initiation and dynamic behaviour are important, it is equally critical to clarify the default point at which compliance is assessed. AEMO proposes to retain the connection point as the default location for performance and compliance assessment, consistent with current practice for both synchronous generators and GFL plant. This approach ensures alignment with how system impacts are typically evaluated in network studies.

However, we note that both the existing NER and Package 1 allow for flexibility in defining an alternative assessment point, such as at the unit terminals, where agreed by AEMO and the relevant NSP. This flexibility has

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<sup>23</sup> AEMO has observed that the engagement of the swing equation during a fault will lead to the variation of active current, potentially compromising the sustained injection of reactive current due to the inverters' limited current capability.

already been applied in several real-world projects. Accordingly, AEMO supports maintaining this case-by-case negotiation pathway, but does not support adopting unit terminals as the default compliance point for Schedule 5.2 GFM plant.

**Post-fault recovery performance.** AEMO acknowledges the range of feedback received regarding post-fault active power recovery expectations for GFM inverters. Package 1 introduced a revised definition of “the end of a disturbance” which has resulted in a delay to the commencement of measuring active power recovery being applied under the AAS. AEMO supports this revision being applied to Schedule 5.2 GFM plant as well, as it provides valuable flexibility in how recovery timeframes are interpreted and assessed, enabling a more practical and system-aligned approach to evaluating active power recovery.

AEMO agrees that a 100 ms requirement for nearly full active power recovery following a fault is not necessary for all connections and may not be realistic or appropriate in all cases. In some instances, a slower recovery may be an intentional and justified design trade-off to support voltage recovery or manage plants limitations.

Furthermore, it is acknowledged that under very low system strength conditions, a rapid active power recovery could undermine system stability due to the strong coupling between active and reactive power. In such scenarios, a less aggressive active power recovery may be preferable from a system-wide perspective.

AEMO recognises concerns related to non-electrical limitations, such as mechanical stress in wind turbines, which can influence recovery dynamics. That said, similar recovery requirements have generally not been problematic for GFL wind projects, even though they involve the same or very similar turbine hardware. The challenges observed in GFM projects often stem from the specific control strategies used to emulate inertial response. While slower active power recovery than 100 ms may be acceptable in many scenarios, a very slow response, for example, in excess of 500 ms, may not be desirable. GFM control approaches may therefore need further optimisation to strike the right balance between system stability and timely recovery.

Recognising both the flexibility provided by the revised definition of “the end of a disturbance” and the shared understanding between AEMO and NSPs that not all Schedule 5.2 GFM plants will be able to meet the AAS for active power recovery, nor is this always necessary or beneficial under all system conditions, we propose a pragmatic approach.

Specifically, we suggest applying the same access standard framework outlined in the AEMC’s final determination for Package 1.

Project-specific negotiation can then be used, where needed, to agree on a more appropriate active power recovery profile that best meets system needs, even if it does not fully align with the AAS.

While AEMO has not observed any unintended impacts on network voltages resulting from active and reactive power recovery following fault clearance, we will investigate this further to ensure that such post-fault behaviour does not adversely affect system security or the performance of other plants as GFM units transition from faulted to normal operating conditions.

Although several respondents supported the idea of introducing a new requirement on voltage recovery following fault clearance, further consideration indicates that the speed of voltage recovery can be significantly influenced by local system strength and interaction with nearby plants. As such, it may not be feasible to define deterministic voltage recovery timeframes that are applicable to all projects.

Accordingly, AEMO does not propose to introduce a direct requirement on the speed of voltage recovery. Instead, we will investigate the impact of GFM post-fault recovery behaviour on voltage magnitude to assess whether additional guidance or expectations are needed to ensure it does not adversely affect system stability or neighbouring plants performance.

## D.2 Distinctive functionalities of GFM technology

### D.2.1 Power system oscillation damping

#### NSP feedback

Most respondents agree that GFM plant should have a PSS-like function or be capable of damping oscillations. Some suggest that this requirement already exists under S5.2.5.13 if strictly applied.

There is broad support for requiring GFM, particularly GFM BESS, to include PSS-like functionality, as this would assist in damping power system oscillations. Some responses explicitly confirm support for formalising this as a standard.

Both inter-area and intra-area low-frequency oscillations should be considered to evaluate the system damping capabilities of GFM projects.

If GFM plant are designed to replicate synchronous machine behaviour, there should be a requirement for a PSS to:

- Dampen oscillations of the virtual synchronous machine.
- Mitigate interactions with other generating plant.

#### OEM feedback

**Damping capabilities of GFM converters.** GFM converters can actively damp electromechanical oscillations, though their approach is not identical to the PSS function used in synchronous generators. A virtual PSS algorithm can be implemented in GFM converters to replicate the traditional PSS characteristics, but unlike synchronous machines, GFM converters can also use active power directly for damping because they are not constrained by the slower response of a mechanical governor.

In HVDC applications, a PSS-like function can also be added to improve system damping. However, a GFM HVDC converter inherently provides damping without the need for additional controllers, highlighting a key advantage of the technology.

Other approaches to damping discussed by respondents include Power Oscillation Damping (POD), which utilises reactive power to mitigate oscillations, and Sub-synchronous damping control, which uses active power. Importantly, no additional hardware or costs are required to implement a PSS-like function in GFM converters.

**Frequency range for effective damping of fast electrical oscillations.** GFM converters are capable of effectively suppressing electrical oscillations across a broad frequency range, from near-zero hertz up to several hundred hertz, depending on the system design and tuning. This wide operational bandwidth enables them to contribute significantly to damping both slow and fast oscillations in the grid.

**Considerations for damping effectiveness.** The effectiveness of damping depends heavily on the tuning strategy adopted for the GFM controls. While the tuning can be optimised to target specific oscillation modes, focusing narrowly on one mode may compromise effectiveness in other scenarios or even worsen other oscillatory modes. This highlights the importance of carefully balanced tuning strategies that consider the full range of expected grid conditions. Additionally, harmonic frequency damping is generally implemented independently of other control functions, so improvements at harmonic frequencies are unlikely to affect the damping of electromechanical oscillations. Although enhanced STATCOMs can also provide some damping capability, their inherent energy limitations restrict their effectiveness across a wide frequency range compared to GFM converters.

**Challenges in wind farm connections.** In wind farm applications, using active power to provide damping introduces particular challenges. At low frequencies, this approach can pose drivetrain risks, potentially affecting the mechanical integrity of the turbines. Furthermore, effective tuning of damping controllers in wind farms depends on access to a complete aero-elastic model of the turbine, which is not typically available in standard power system modelling software. These factors make the design and implementation of damping in wind farm contexts more complex, underscoring the need for advanced modelling tools and tailored tuning techniques.

### AEMO's response

**Power system oscillation damping.** There is a broad consensus that Schedule 5.2 GFM plant, particularly BESS, can provide a power system stabiliser (PSS)-like function or equivalent mechanism to support the damping of electromechanical oscillations. While not identical to conventional PSS, responses confirm that GFM converters can be tuned to provide effective active damping.

Stakeholders have generally supported the view that, where GFM is designed to replicate synchronous machine behaviour, a PSS-like function can be readily provided. Some respondents favour formalising this expectation through access standards, noting that no additional hardware or cost is typically required. However, it is acknowledged that targeting a single oscillation mode may reduce effectiveness elsewhere or even worsen the damping of other modes. This is particularly relevant for GFM/GFL systems, which can interact with oscillations across a much wider frequency range than synchronous machines, with control bandwidths extending well beyond the 3–4 Hz range typically associated with synchronous machine-driven systems. While this capability may offer value in specific scenarios, its effectiveness cannot be generalised and should be considered on a case-by-case basis, taking into account plant-specific dynamics and system needs.

Further, damping interactions in the sub- and super-synchronous range often stem from system-wide IBR control interactions, which require wide-area electromagnetic transient (EMT) studies that cannot be conducted by an OEM or developer for a given project. When it comes to system-level positive damping contributions, the only practical exception is damping of inter-area modes (<1 Hz), which can be reasonably provided at the plant level, for example, via PPC tuning, and as confirmed by OEMs, without additional cost.

One respondent noted the challenges associated with damping at harmonic frequencies, typically in the range of several hundred Hz to kHz. AEMO notes that harmonic resonance damping lies outside the scope of this discussion on the damping of power system oscillations. Harmonic damping is generally handled by separate controls or components within inverters, and its implementation is isolated from the damping of electromechanical and fast electrical control-driven oscillations.

Lastly, it is understood that using active power modulation for damping in wind farms poses challenges due to drivetrain fatigue risks at low frequencies. Additionally, the relationship between aerodynamic, mechanical, and electrical aspects of wind turbines was noted for this purpose, which cannot be supported by conventional power system simulation tools, making design, tuning, and assessment more complex. These limitations will be considered when formulating MAS applicable to wind-based GFM systems.

**Control system stability and passivity.** Passivity provides a well-established theoretical framework for assessing the inherent stability of IBR control systems, particularly in weak grid conditions.

GFL inverters are inherently non-passive. By design, they rely on phase-locked loops (PLLs) to synchronise with grid voltage, and their control loops often respond in ways that inject energy at certain frequencies when perturbed. This behaviour is generally benign under strong grid conditions. However, in weak grids, it can lead to problematic control interactions and poorly damped oscillations, especially when multiple GFL units operate in close electrical proximity.

In contrast, GFM inverters can be designed to behave passively in the frequency-domain. This means that when small perturbations occur across a broad frequency range (e.g. sub-synchronous, fundamental, or super-synchronous), a passive GFM system will not inject net energy into those modes. Instead, it will absorb or dissipate the energy, effectively damping potential oscillations.

While IBR plants are often referred to as generators in the steady-state sense (supplying real power at 50 Hz), passivity characterises their dynamic response to disturbances. A passive system behaves more like a “sink” than a “source” of energy across a range of frequencies. This becomes increasingly important as synchronous machines, and their inherent damping, are displaced from the system.

Passivity also offers a composability property: if each inverter or plant behaves passively, the collective behaviour of the interconnected system tends to remain stable under linear conditions. This makes passivity an attractive and scalable design principle for future grids dominated by IBRs, particularly where many GFM units may operate in parallel without synchronous generation support.

During recent engagement, some OEMs indicated that impedance scan data across sub-synchronous and super-synchronous frequencies can be provided as part of the connection process. This is a practical and valuable input; however, the methodology for calculating and presenting frequency-domain response data must be clearly defined to ensure consistency across projects. This aligns with broader methodological issues such as defining impedance reference points, selecting appropriate analysis domains, and determining whether to include closed-loop control behaviour. This reinforces the need for a fit-for-purpose methodology under future updates to the Access Standards Assessment Guidelines. To address this, AEMO has been investigating the methodology and tools suitable for assessment in connection process and power system operations in the NEM<sup>24</sup>.

While passivity is a useful and sufficient condition for small-signal stability, its practical application faces several challenges, as highlighted by respondents:

- There is currently no widely used methodology for assessing passivity in grid connection studies.
- Outcomes depend on how impedance is defined (e.g. inverter terminal vs connection point), the analysis domain (e.g. direct-quadrature (dq), sequence, or multi-input multi-output), and whether closed-loop behaviour is represented.
- Limitations in commonly used SCR calculation methodologies, which generally omit the impact of nearby IBR plants and do not adequately distinguish between GFL and GFM behaviour. (Incorrect SCR assumptions will also directly impact Nyquist and passivity-based assessments.)
- Frequency-domain characterisation, particularly at super-synchronous frequencies (hundreds of Hz to kHz), is sensitive to the frequency-dependent behaviour of system components. One respondent noted that default EMT models, which typically capture fundamental and sub-synchronous behaviour well, may not accurately reflect high-frequency dynamics. Caution is therefore advised when interpreting results at higher frequencies.

These are valid technical considerations that warrant further development but are outside the scope of the current rule change process. AEMO intends to address them through revised access standard assessment methodologies, to be developed following the finalisation and AEMC approval of the new GFM access standards.

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<sup>24</sup> AEMO, 2025. Frequency Scanning. Available at [https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/connection-resources/focus-areas-and-initiatives/frequency-scanning#:~:text=Improving%20grid%20stability%20through%20frequency,resource%20\(IBR\)%20related%20interactions.](https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/connection-resources/focus-areas-and-initiatives/frequency-scanning#:~:text=Improving%20grid%20stability%20through%20frequency,resource%20(IBR)%20related%20interactions.)

Regarding broader applicability, it has been suggested that passivity requirements be extended to all generation technologies, including GFL. However, this is not supported. GFL inverters are inherently non-passive by design and requiring them to meet passivity criteria is neither technically appropriate nor realistic. Their stability contribution should continue to be assessed using criteria suited to their control architecture and intended role in the power system.

Similarly, the proposal to manage passivity assessment via a single type test per plant is also not supported. In this context, a single type test refers to conducting frequency-domain passivity verification only once, for the given inverter make, and then assuming applicability to all future deployments of the same product. However, passivity depends on control tuning, which may vary between deployments, especially where site-specific tuning is required to address weak grid or harmonic conditions. A single frequency-domain type test would not reliably capture this variation and could provide a false sense of robustness.

It was also noted that conventional gain and phase margin metrics are overly simplified and fail to capture the network-dependent nature of GFM control stability. This view is agreed with. These metrics are inherently connection point and operating-condition specific, and do not adequately reflect the complexity of GFM control loops. As such, gain and phase margin specifications will not be used in the development of access standards.

Overall, impedance characterisation involving the passivity assessment appears to be the most commonly used method among OEMs for evaluating the internal stability of GFM inverters.

## D.2.2 Control system stability and passivity

### NSP feedback

**Defining and applying passivity requirements.** It was suggested that control system passivity requirements should be better defined across all generation technologies, not just for GFM systems. Some respondents noted that ensuring passivity in the frequency domain can simplify stability analysis; however, it remains unclear whether such requirements are necessary for smaller plants. As an alternative, it was proposed that passivity requirements could apply only to GFM systems above a certain size threshold. To improve efficiency and consistency, it was recommended that AEMO manage the frequency-domain passivity analysis as a “Type Test,” ensuring that a single, comprehensive test is conducted for each plant type, eliminating the need for repetitive testing across multiple applications.

**Recognised the importance of system damping and resonance control.** One respondent strongly supported incorporating a requirement for system damping and resonance control into the new rules, emphasising its significance for maintaining adequate system damping and mitigating sub-synchronous interactions. Specific measurement criteria were suggested for sub-synchronous frequencies, including an approach where passivity is assessed using an attenuation factor. This method evaluates the ratio of voltage magnitude with and without plants in the presence of an oscillation at a given frequency, providing a quantifiable indicator of passivity performance at sub-synchronous frequencies.

**Methodologies for assessing passivity.** Current approaches to assessing passivity vary, with some respondents using EMT time-domain damping tests over a range of oscillation frequencies. However, there was broad agreement on the need to transition towards frequency-domain analysis for a more comprehensive and reliable assessment. The majority of respondents indicated they have not yet assessed passivity formally, and one response highlighted that no widely adopted methodology currently exists for this purpose. This lack of standardisation underscores the need to develop and formalise appropriate methodologies for assessing passivity across technologies.

## OEM feedback

**Tools and methods used.** Various methods are employed to perform stability and passivity assessments, including impedance scanning through physical experiments, hardware-in-the-loop (HIL) simulations, and EMT simulations. Time-domain and frequency-domain stability assessments are often applied in complementary ways. In the time domain, control stability is evaluated based on control accuracy, response time, or settling time of output power, voltage, or current during grid frequency or voltage disturbances, using experiments alongside EMT and HIL simulations. In the frequency domain, respondents commonly apply impedance-based stability criteria, calculating frequency-dependent impedance to ensure passivity and avoid negative damping. Most respondents already use frequency-domain characterisation tools to assess the passivity of their GFM control systems across both sub-synchronous and super-synchronous frequency ranges.

**Application details.** The frequency-domain response is typically assessed within the range of 0.1 Hz to 1500 Hz, with some respondents explicitly aligning with AEMO's Voluntary Specifications for Grid-Forming Inverters, which specify a range of 1 Hz to 1000 Hz. Impedance scan data covering both sub-synchronous and super-synchronous frequency ranges can be provided during the connection process; however, the specific method used to calculate the frequency response must be clearly documented to ensure consistency and transparency in the assessment.

**Design considerations and limitations.** Passivity across the super-synchronous frequency range is generally accounted for during the design process, but respondents noted that while passivity is a sufficient condition for stability, it is not always necessary. Applying passivity as a universal stability criterion could result in unnecessarily high design and equipment costs. Furthermore, ensuring strict passivity across the sub-synchronous frequency range and near the synchronous frequency is not always practical, raising questions about its viability as a universal requirement.

One respondent highlighted that EMT simulation models of passive equipment may not accurately represent high-frequency behaviour, as resistance and reactance at these frequencies can differ significantly from their fundamental values. Therefore, frequency-domain analyses at super-synchronous frequencies should be interpreted with caution. Neither respondent elaborated further on the reasons behind these limitations, which will be explored in follow-up discussions.

**Gain and phase margin.** Some respondents observed that conventional gain and phase margin metrics are overly simplified and fail to account for the network-dependent nature of GFM control stability. These margins are inherently specific to the connection point and operating conditions because they depend on the interaction between the network behaviour and the plants response. Moreover, the control loops in GFM inverters are complex and cannot be fully characterised by gain and phase margins or by a simple proportional-integral regulator gain, given the presence of internal nonlinearities and other dynamic factors that influence stability.

### D.2.3 SCR considerations

#### Network SCR variations

The observed range of SCR at connection points varied significantly among respondents. The lowest recorded minimum SCR was reported as 0.8 at a site equipped with a synchronous condenser and an extensive fast runback scheme, demonstrating the possibility of operating at very low strength under certain conditions. Other reported minimum SCR values were higher, typically in the range of 5 to 10, reflecting more common scenarios in the grid.

The range of maximum SCR values observed was also wide. The largest recorded SCR reached as high as 50, while other respondents reported maximum SCR values more commonly in the range of 25 to 30. These figures

highlight the diversity of grid strength conditions that GFM and other technologies may encounter across different sites and operating contexts.

Respondents also noted considerable variations in SCR at certain locations, with one example reporting a change from 4 to 17, a maximum variation of approximately 13. However, one response questioned the relevance of tracking maximum versus minimum SCR variations, suggesting that such distinctions may offer limited value since all plants are already incentivised to withstand an SCR of 1.2 as part of their connection requirements.

### High SCR considerations

Two respondents indicated that GFMs may have suboptimal performance in strong grid conditions, where voltage and frequency are inherently well regulated, and GFL inverters can operate more efficiently by relying on the grid's stability rather than actively contributing to its regulation.

Another respondent discussed that high SCR instability is often caused by high bandwidth converter controls, which depend on grid damping for stability. As SCR increases, grid damping naturally reduces.

Some respondents highlighted that GFM inverters may face limitations at very high SCR values (e.g., SCR >20). In these conditions, tuning is critical, and challenges for GFM in high SCR conditions are similar to those already experienced with GFL at low SCR conditions.

Potential interactions between multiple GFM units were also noted, emphasising the need for coordinated control strategies.

### Low SCR considerations

#### NSP feedback

**Anticipated reduction in minimum SCR over time.** The current minimum withstand SCR of 3 was originally established based on the capabilities of GFL inverters available at the time. With the advancement of GFM technology, however, it is expected that the minimum required SCR could be lowered as industry capability improves and more robust GFM solutions become standard.

**Support for a lower minimum SCR.** In general, respondents expressed support for AEMO's proposal to reduce the minimum withstand SCR for GFM plants. One respondent even suggested that GFM plants should be capable of stable operation in an islanded system with no synchronous machines at all (SCR = 0), reasoning that as synchronous generators retire, future networks may lack them entirely, necessitating full independence of GFM plants. Other responses proposed a more modest minimum withstand SCR of 1.2, while another recommended a higher value of 2.0 to avoid imposing excessive reactive power capability requirements and to remain aligned NER clause S5.2.5.1.

It was also noted that GFM plants are often tuned to today's lowest system MVA fault level, which results in relatively high SCRs. In future dispatch scenarios, however, the lowest system strength conditions will likely occur when the fault level is shared among multiple IBRs, creating a potential conflict with TNSP obligations under NER 5.12.1(a). This comment suggests that the same parameters should ideally be used to demonstrate compliance with both withstand SCR requirements and other access standards, recognising that plants will operate under lower SCR conditions in the future than they do today.

**Need for updated assessment methodologies.** Some respondents observed that fundamental changes to the rules are necessary to ensure a fair and accurate assessment of GFM plant, which, unlike GFL plants, do not rely on external system strength services. Clauses based on a simple SCR definition can make it difficult to evaluate GFM capabilities appropriately. One respondent proposed an alternative test setup to the currently used

method for assessing withstand SCR. While developing such a test system is beyond the immediate scope of this work, several important questions remain to be addressed before adopting a new methodology, including defining the appropriate size and parameters of the proposed test load, to ensure that the assessment accurately reflects the technical capabilities and intended operation of GFM plants.

## OEM feedback

**Capability of GFM inverters and tuning considerations.** Respondents generally expressed no concern regarding the inherent capability of GFM inverters, with three confirming that an SCR value between 1.0 and 1.2 is achievable. One respondent even noted the ability to withstand an SCR of 0 under islanding conditions, although this scenario lies outside the intent of the discussion, which focused on grid-connected mode where all other technical performance standards are met. However, some respondents emphasised the importance of stable controller tuning across a range of SCRs, recommending that the difference between minimum and maximum SCR should not exceed 10. This is because controller tuning optimised for higher SCRs, requiring slower integral gains to avoid excessive swings and unwanted fault mode entry, may become unstable at lower SCRs, negatively affecting iq injection and recovery times.

**Control modes, operational limits, and challenges under low SCR.** The choice of control mode was highlighted as a factor influencing system response under low SCR conditions. In reactive power control mode, the system may struggle to ride through sudden changes in SCR, although it remains unclear whether plants maintain their voltage source behaviour under such conditions.

In contrast, operation in voltage control mode with a sufficiently slow response could potentially support stable operation at SCRs as low as 0.25. Respondents also noted that GFM technologies lacking a firm energy source face limitations on inertial capability, which becomes highly dependent on accurate frequency measurement, a challenge that is exacerbated in very weak grid conditions.

Under such low system strength scenarios, power flows may also be dictated more by voltage and frequency stability needs than by active power dispatch. Additional concerns were raised about the design of protection systems for GFM wind turbines in very low SCR environments, though further details are yet to be explored in individual follow-up discussions.

**Assessment metrics and broader considerations.** Some respondents recommended using the additional hosting capacity offered by GFM inverters to support nearby GFL plants. However, this suggestion may not fit within the current assessment framework, which relies on confidential EMT models that cannot easily be shared between projects.

Moreover, several respondents argued that SCR alone is insufficient as a metric for evaluating performance under low system strength conditions. They highlighted the importance of considering factors such as the amount of power transferred, the network's capacity, the influence of nearby plants and loads, and the prioritisation of voltage stability during FRT events.

Alternative metrics that capture angle and frequency dynamics more effectively were also proposed. Finally, the dynamic nature of SCR during faults was noted, particularly in GFM plants where the impedance at the point of connection changes dynamically in very weak grids due to coupling between active power, reactive power, voltage, and angle. Interestingly, no respondents identified significant sensitivity of GFM performance to variations in the X/R ratio, suggesting that GFM operation remains stable across a range of network impedance characteristics.

## AEMO's response

**Network SCR variations.** A wide range of SCR values has been reported across the transmission and distribution systems, ranging from as low as 0.8 to as high as 50. One site recorded a variation exceeding 13, highlighting that SCR is not a static parameter and can fluctuate significantly even within a day. AEMO has observed larger variations in practice across different NEM regions during some connection processes.

We disagree with the suggestion that considering SCR variation may not be an important consideration because all plants are incentivised to withstand an SCR of 1.2. Two key reasons underpin this view:

- **Control system limitations across a wide SCR range:** As noted by one respondent, the difference between minimum and maximum SCR can exceed 10 or more. Given that inverter control loops are narrow band by nature, a single set of tuning parameters is unlikely to deliver optimal performance across both very weak and very strong grid conditions. Trade-offs are inevitable and understanding SCR variability is critical to defining fit-for-purpose technical requirements for Schedule 5.2 GFM plants.
- **Withstand SCR demonstration does not imply common control settings:** Meeting the requirement to withstand an SCR of 1.2 can be achieved using one set of tuning parameters, while other performance standards (e.g., damping, fault recovery) may necessitate different settings. Therefore, the parameters used to demonstrate withstand capability at SCR = 1.2 may not reflect those used for broader access standard compliance.

In light of the above, AEMO recommends that the observed SCR range and its variability remain a key consideration in both performance evaluation and the development of access standards. However, we consider it impractical to prescribe a specific numerical threshold for the difference between minimum and maximum SCR values, beyond which performance trade-offs may be required. While such trade-offs may be necessary in practice, they should be addressed through case-by-case negotiation. This should consider the limitations imposed by significant SCR variation, recognising that optimal performance cannot always be simultaneously achieved under both minimum and maximum SCR conditions.

**High SCR considerations.** Regarding potential limitations of GFM performance under high SCR conditions, AEMO acknowledges the concerns raised by respondents. These include observations that GFMs may exhibit suboptimal behaviour in strong grids, where voltage and frequency are already well regulated, and that stability issues could arise due to high bandwidth control interactions or reduced grid damping.

However, we note that AEMO has not observed any degradation of GFM performance under high SCR conditions to date. The suggestion of instability in these scenarios, therefore, remains unverified and will require further investigation to:

- Assess the materiality of any such behaviour under conceivable NEM operating conditions; and
- Identify the control parameters and tuning sensitivities that may contribute to such perceived limitations.

Further work is also needed to evaluate potential interactions between multiple GFM units in strong grid environments and whether coordinated control strategies may mitigate any emerging risks.

**Low SCR considerations.** As correctly noted by respondents, the current minimum withstand SCR of 3 was originally based on the limitations of GFL inverter performance, reflecting the capabilities of such technologies several years ago. However, GFL performance has progressively improved in recent times. More importantly, with the emergence of GFM technology, there is broad support for lowering the minimum required SCR over time to reflect evolving industry capabilities. While many respondents supported a minimum withstand SCR of around 1.2 or even lower, one respondent proposed a slightly more conservative threshold of 2.0 to avoid imposing excessive reactive power capability requirements while maintaining alignment with NER S5.2.5.1.

AEMO also agrees with the observation that some Schedule 5.2 GFM plant are currently tuned to withstand today's lowest fault levels, which will often result in relatively high SCR at the time of commissioning. However, future dispatch scenarios may involve multiple IBRs sharing fault levels, leading to significantly lower operational SCRs. This may warrant considering consistency between the parameters used to demonstrate withstand SCR and those used for demonstrating compliance with access standards, as required under NER 5.12.1(a).

While AEMO's system strength impact assessment guidelines (SSIAG) currently permits the use of two sets of control parameters for GFL inverters, typically one for the minimum site-specific SCR and another for the withstand SCR, different considerations may apply for GFM inverters. In particular, the distinction between the minimum site-specific SCR and the withstand SCR may be more pronounced for GFM technology, potentially warranting a more tailored approach.

Where the difference between the minimum and maximum site-specific SCR and the withstand SCR is small, AEMO expects that a single set of inverter control parameters should be used across all conditions, including for demonstrating withstand capability. However, in cases where this difference is substantial and the use of separate parameter sets can be technically justified, it is essential that performance at the withstand SCR continues to meet the minimum performance standards to be developed for Schedule 5.2 GFM plant.

Once GFM-specific requirements are finalised, there may be merit in revisiting elements of the SSIAG to ensure alignment with the evolving technical and operational expectations for these technologies.

Several points raised warrant further investigation:

- **Stable tuning across wide SCR ranges:** One respondent noted that when the difference between minimum and maximum SCR exceeds 10, maintaining stable control becomes increasingly challenging. Control settings effective at high SCRs, such as slower integral gains to avoid fault mode entry, may result in degraded performance at low SCRs, including poor iq injection and extended recovery times (see AEMO's response under *Network SCR variations*).
- **Impact of control mode:** The plants' response to SCR variations can depend heavily on its control mode. For example, in reactive power control mode, there may be difficulty in maintaining voltage source behaviour under rapidly changing SCR conditions. In contrast, under voltage control mode with sufficiently slow response, stable operation has been reported down to SCR values as low as 0.25.
- **Limitations of SCR as a standalone metric:** Several respondents highlighted that SCR alone is not sufficient for evaluating performance in low system strength environments.

A challenge specifically raised regarding low SCR conditions relates to inertial performance, which is highly dependent on accurate frequency measurement. This becomes increasingly difficult under very weak grid conditions. While the specific concern was raised in relation to non-BESS Schedule 5.2 GFM plant, similar limitations may apply to BESS-based GFM systems. As discussed earlier in this document, the root cause lies in the coupling between active and reactive power: rapid changes in one may inadvertently affect the other, potentially leading to voltage instability during inertial response. AEMO also agrees with the broader view that in low system strength environments, voltage and frequency stability may take precedence over active power

dispatch, and this reality must be factored into how Schedule 5.2 GFM plant are tuned, integrated, and operated.

Some respondents raised considerations around alternative assessment methods, non-standard test setups, and more extreme operating scenarios, such as islanded operation or conditions without any synchronous or GFM sources. These included suggestions to assess performance under SCR = 0, the dynamic nature of SCR during faults, and alternative test configurations, including questions around the size and parameters of the proposed load. While technically relevant, these aspects are outside the scope of the current work, which focuses on grid-connected operation under conditions where all other technical performance standards are met.

#### D.2.4 Phase angle step change capability

##### NSP feedback

**Uncertainty and observations on phase angle step changes.** The expected range of phase angle step changes under System Normal and (N-1) conditions remain uncertain and requires further study to establish clear benchmarks. A value of approximately 30 degrees has been referenced as a potential step change to consider, but this is not yet definitive. Respondents also noted that phase angle step changes are not typically monitored in distribution networks, limiting available data to assess their impact at lower voltages. Under fault conditions, more extreme phase shifts, as large as  $\pm 60$  degrees, have been observed, with such disturbances persisting for up to 430 ms.

**Acceptable response time for 90% active power change at the point of connection.** Most respondents did not specify acceptable response times for achieving a 90% change in active power at the point of connection. One respondent, however, emphasised that active power response should take into account the parallel need for reactive power support to maintain voltage stability, suggesting that these two aspects cannot be treated in isolation when defining performance expectations.

**Angle step change limits and GFM technology constraints.** No specific minimum or maximum values were provided for the phase angle step changes that GFM technology should be capable of withstanding when delivering a fast active power response. Some respondents did point out, however, that the hardware limitations of GFM WTGs could impose practical constraints on the tolerance of angle step changes, highlighting an area that warrants further technical investigation.

#### D.2.5 Phase angle jump withstand capability

##### OEM feedback

**Practical thresholds.** Many respondents confirmed that a phase angle jump of around 60 degrees represents a practical threshold for GFM inverters based on BESS technology. For GFM BESS integrated with wind generation, a 60-degree phase shift can occasionally be sustained, though a more conservative threshold of 45 degrees was more commonly cited as indicative of their general withstand capability. Some respondents considered 20–30 degrees to be a more typical standard, noting that higher thresholds would require project-specific studies. While theoretical limits of  $\pm 90$  degrees were mentioned, practical performance tends to be significantly lower.

One OEM noted that for GFM wind turbines, larger phase jumps can impose substantial drivetrain stress and induce current surges due to the coupled mechanical–electrical response of GFM operation. Another OEM suggested that GFM technology might actually have a lower withstand capability compared to GFL technology, although no explanation or further discussion was provided.

**Potential challenges and low system strength considerations.** A sudden phase angle step change can result in waveform disturbances that may trigger LVRT or FRT detection, particularly under low system strength conditions. Such disturbances are often accompanied by changes in voltage magnitude, requiring the GFM to deliver both active and reactive power responses to counteract the disturbance. The plants' over-current capability also influences how effectively it can handle such events, and beyond 60 degrees, the system may reach its transfer limits. Additionally, respondents highlighted that achieving sufficient phase margin for large phase angle jumps is particularly challenging when operating in very weak grids with SCR around 1.2.

#### D.2.6 Phase angles jump suppression capability

**General response time range.** Respondents agreed that GFM plants should be able to initiate suppression of a phase angle jump within a single cycle, as expected of such technology. When considering the response rise time, defined as reaching 90% of the change in instantaneous active power, reported values ranged from under one cycle to as long as 250 ms, depending on the specific technology and scenario.

**Scenario-dependent responses.** In fault conditions, the inertial response of the GFM can lead to very fast rise times, often under 40 ms. For a sustained power increase, however, the response characteristics differ. While the previously mentioned response times are achievable with BESS-based GFM systems, wind-based GFM systems face constraints in power response, typically limited to around 6% of nominal power per second due to mechanical and aerodynamic limitations.

#### AEMO's response

**Phase angle jump withstand capability.** Most NSP and OEM respondents indicated the need for and capability to withstand a phase angle jump in the range of 30° to 60°, with 30° often cited as the minimum practical and expected benchmark (phase angle jump values of 20° to 30° were also mentioned by an HVDC OEM and a wind OEM). A jump greater than 60° is unlikely to be encountered in real power systems. As noted by one respondent, a phase angle change beyond 60° typically implies that the network's power transfer limit has already been exceeded, making such requirements operationally impractical.

Close-in faults may cause significant phase angle jumps while simultaneously requiring high active and reactive current injections. Given the current-limiting nature of GFM and the typical prioritisation of voltage recovery, plants may not be able to respond with sufficient active current, thereby reducing its effective phase angle jump withstand capability during such events. Under non-fault conditions or remote faults, where reactive current injection demands are lower, a robust phase angle jump withstand performance is expected to be retained.

Under low system strength conditions (e.g., SCR  $\approx$  1.2), a sudden phase angle step change may be accompanied by a voltage disturbance. In such cases, Schedule 5.2 GFM plant are expected to respond with both active and reactive power to stabilise the system, but its over-current limits may constrain this response. Moreover, prioritising a fast active power injection to accommodate a large phase angle jump can compromise voltage stability, suggesting that control strategies which temper active power response may be more suitable in these environments.

Notably, only one respondent indicated they may not be able to withstand a 30° phase angle jump. However, given that other respondents using similar technology reported higher withstand capabilities, this limitation may be addressable through control system tuning and optimisation.

Mechanical limitations of GFM wind turbines that constrain their ability to tolerate large phase angle step changes were noted by two respondents. These practical constraints will be considered in the development of MAS to ensure performance expectations remain technology-neutral yet practically achievable.

**Phase angles jump suppression capability.** The ability to suppress the phase angle jump, in addition to withstanding it, was confirmed by most respondents. AEMO considers this a crucial component of the voltage source behaviour required by all GFM and will conduct further studies and stakeholder consultation to determine appropriate numerical thresholds for inclusion in AAS and MAS.

While most respondents confirmed that response initiation typically occurs within one cycle, consistent with the expected behaviour of a voltage source, there was significant variation in the time reported to reach 90% of the full response. AEMO will further consider whether the 90% response time is a practical and meaningful metric or whether it should be replaced with a more appropriate measure that can be applied consistently across different GFM technologies.

## D.3 Operational limits and practical constraints

### D.3.1 GFM vs. GFL performance comparison and limitations

#### NSP feedback

**Potential Limitations of GFM Performance Compared to GFL.** Several responses highlighted specific aspects where the performance of GFM inverters may be inferior to GFL inverters. Two responses noted that the rise time and settling time requirements under both small-disturbance conditions (NER S5.2.5.13) and fault conditions (NER S5.2.5.5) could be areas where GFM performance may differ unfavourably from GFL. One response indicated that voltage dips during high RoCoF events, attributable to the higher inertia and damping inherent to GFM operation, could pose challenges in meeting the CUO requirement under NER S5.2.5.3.

Another response explicitly stated that there are no conditions under which a GFM technology would fail to match GFL performance. Conversely, one response argued that GFM plants are not necessarily expected to match GFL plant performance in all circumstances. For example, while GFL plant may exhibit a slower post-fault recovery, GFM plant are designed to restore active power more rapidly, akin to synchronous machines. Similarly, GFL plant may display a more aggressive under-frequency response, delivering higher active power support than GFM plant, which adhere more closely to the inertial and droop response characteristics of synchronous generation.

Additionally, one response emphasised that GFM inverters should not be expected to act as active harmonic filters for low-order harmonics such as the 2nd, 3rd, 5th, and 7th. Although GFM inverters can passively damp harmonics within their control bandwidth (typically up to around 300 Hz), intentionally using GFM control to mitigate harmonics can introduce undue control complexity and thermal stress, which may exceed the inverter's hardware capabilities unless specifically designed for such a function. In contrast, GFL inverters, behaving as current sources, are generally better suited to limit harmonic currents precisely and predictably, often without requiring hardware upgrades.

**Need for pole slip protection in GFM plants emulating synchronous machines.** If GFM plant is designed to emulate a synchronous machine, one response suggested that pole slip protection should be implemented. Although such protection is not necessary to safeguard the plant itself, unlike in synchronous machines, it could serve to prevent extreme power outputs from GFM plant that might exacerbate system disturbances during severe events.

**Multi-GFM plants coordination in low system strength conditions.** The coordination of multiple GFM inverters in weak networks was identified as a potential challenge. Without proper coordination, the presence of several GFM units can lead to detrimental interactions, particularly when parts of the network operate near the voltage collapse limit. In these circumstances, GFM inverters with overload capability, functioning similarly to

synchronous condensers, could inadvertently exacerbate voltage-related constraints by increasing the apparent margin. In such scenarios, GFL operation may sometimes offer more advantageous performance.

## OEM feedback

**NER S5.2.5.13: Rise and settling time versus stability.** One respondent raised concerns about the rise and settling time requirements under NER S5.2.5.13, stating that stability should take precedence over strict performance criteria. They also indicated that tuning parameters in an SMIB environment could lead to instability in real-world applications, although no evidence was provided. Some responses suggest further review of recently proposed rule changes to determine if any adjustments to NER S5.2.5.13 are necessary.

**NER S5.2.5.3: RoCoF performance challenges.** One respondent indicated that voltage dips during RoCoF events are expected in an SMIB environment, similar to synchronous machines. Another noted that RoCoF performance under NER S5.2.5.3 may be difficult for projects with a minimum SCR below 2, as even synchronous generators would struggle to ride through a 4 Hz/s disturbance. AEMO's access standards assessment methodology should further investigate these challenges.

**Applicability of access standards to emerging GFM Technologies.** No respondents identified any specific access standard clause or sub-clause as irrelevant or impractical. The only exception is for STATCOMs, where OEMs indicated that clauses related to active power/frequency are not applicable, an understandable position given that STATCOMs do not generate or absorb active power. Furthermore, some OEMs noted that the immaturity of GFM technology, for example, for wind and solar plants, might reveal issues as they develop over time.

**Ability to meet MAS under the current NER.** All respondents confirmed that GFM technology can meet the MAS for asynchronous generation. However, challenges were highlighted in low SCR environments, particularly in demonstrating the best achievable performance at MAS and determining what can and cannot be accurately modelled in PSS<sup>®</sup>E studies, or with SMIB in either PSS/E or PSCAD.

**Unique challenges of GFM WTGs.** It was also highlighted that WTGs using the GFM scheme face additional challenges, particularly during frequency disturbances or phase angle jumps, as the response is impacted by the mechanical characteristics of WTGs. Unlike BESS-based GFM systems, WTGs possess significant rotational inertia and torque, which introduces important trade-offs between speed of response and system stability. Rapid changes in active power output can induce substantial mechanical stress on the drivetrain, potentially affecting long term reliability and triggering protective mechanisms. In some cases, aggressive fast frequency response control has been observed to initiate a pseudo-shutdown procedure for the entire turbine system.

Additionally, WTGs exhibit internal mechanical resonances. To protect the turbine from these, GFM control may deliberately suppress voltage source behaviour within certain frequency bands, referred to as exclusion zones, resulting in deviations from ideal GFM characteristics. These factors make compliance with fast response requirements, such as those under NER S5.2.5.8, particularly challenging for wind-based GFM systems.

## AEMO's response

AEMO acknowledges that no respondents identified any clause or sub-clause within the current access standards as wholly irrelevant or impractical. This reinforces the robustness of the existing framework as a sound foundation for integrating GFM technologies, provided that all relevant differences between GFL and GFM are clearly understood and addressed.

AEMO welcomes the confirmation from all respondents that GFM technologies can meet the current MAS for asynchronous generation. This provides a useful reference point and suggests that any further refinement can be developed from a stable and practical baseline.

That said, AEMO recognises the feedback received regarding potential differences in dynamic performance between GFM and GFL technologies, particularly with respect to slower rise time and settling time under small-disturbance conditions (NER S5.2.5.13), in addition to the fault-related expectations under NER S5.2.5.5, discussed earlier in this document. AEMO supports the view that flexibility may be warranted in interpreting these performance metrics where GFM-specific control behaviours diverge meaningfully from those of traditional GFL systems.

In addition, two areas were highlighted that warrant further investigation. First, the potential need for protection from ‘pole slip’, i.e., loss of synchronism, in Schedule 5.2 GFM plant that emulate synchronous machines to prevent exacerbating extreme power swings that could aggravate system disturbances. Questions such as the likelihood of a loss of synchronism due to the emulated rotor angle exceeding a certain value or the impact of long-duration fault or change in voltage angle during fault on potential loss of synchronism, while both are well understood causes of instability in a synchronous generator, require further investigation in GFM due to faster control and absence of physical machine poles.

Second, the coordination of multiple Schedule 5.2 GFM plant under low system strength conditions. While GFM inverters are generally expected to be less sensitive to low system strength than GFL, they still rely on control systems with similar bandwidths. Poor coordination among multiple GFM inverters could lead to adverse interactions, particularly near voltage collapse points, as suggested by one of the respondents, where their overload behaviour could cause interactions and instabilities. In certain scenarios, GFL operation may offer more controllable outcomes.

These topics warrant careful assessment to determine whether specific technical requirements or coordination mechanisms are needed to manage these risks effectively.

While one of the respondents suggested a faster post-fault active power recovery in GFM plants, this statement does not align with the practical experiences of different GFM makes, as highlighted under the sub-section “post-fault recovery performance”.

AEMO acknowledges the feedback received regarding the physical and mechanical limitations of wind turbines operating in GFM mode. These include challenges associated with frequency disturbances and phase angle jumps, as well as trade-offs between fast active power response and drivetrain stress. While these limitations are well understood, they will be considered in determining appropriate MAS.

Several respondents raised concerns about the limitations of current simulation tools and assessment methodologies used to evaluate compliance with access standards. These included the inability of phasor-domain simulation to represent instantaneous values, the oversimplification of system behaviour in single-machine infinite bus (SMIB) studies, and the constraints of current model assessment practices, particularly those applied under NER S5.2.5.3. One respondent specifically highlighted that SMIB-based approaches are inadequate for capturing the dynamic response of GFM inverters to events such as RoCoF and for determining SCR capabilities and constraints. These concerns are valid and recognised, particularly given the increasing reliance on EMT models to assess GFM performance.

However, a key challenge in this context is the limited ability to conduct broader EMT-based assessments due to restrictions on sharing detailed network and plant models across developers. While these are important technical considerations, they fall outside the immediate scope of this ASR, which is focused on defining fit-for-purpose access standards for GFM technologies. AEMO intends to consider these broader modelling and assessment issues as part of future updates to power system modelling guidelines and access standard assessment methodologies, following the finalisation of relevant access standards by the AEMC.

AEMO agrees with the comment that using GFM inverters as active harmonic filters may not represent their most effective application. Given the current-limited nature of all inverter technologies, diverting their capability towards harmonic compensation could constrain their ability to deliver more critical contributions to power system dynamic performance. Furthermore, it is understood that active filtering by IBRs is generally limited to lower-order harmonics.

In any case, AEMO does not intend to introduce any additional requirements or expectations specific to harmonic performance for GFM inverters. The existing treatment applied to GFL inverters for harmonic studies will continue to apply, subject only to minor methodological refinements if needed.

### D.3.2 Energy availability, dispatch and inertia constraints

#### NSP feedback

It was discussed that the GFM capabilities might be compromised if the storage is depleted or insufficient, i.e. if the energy source is operating near its maximum capacity, it may not have sufficient headroom to respond to sudden changes in grid conditions, such as load increases or faults. Another respondent indicated that GFM sites should be designed to maintain performance regardless of SoC. It was also suggested that sites should have sufficient energy storage or defined operating limits to ensure they always meet GFM capabilities if they claim to be capable of providing them.

These issues are expected to be more significant for future wind and solar GFM implementations, where maintaining headroom may be less feasible. These systems may need to incorporate some form of dedicated storage behind or within the inverter to reliably deliver GFM services.

It was noted that the amount of energy storage required to provide inertia is minuscule compared to total battery capacity. For example, 1000 MW·s is equivalent to only 0.28 MWh. As batteries are typically operated with a minimum SoC, full depletion is avoided, and sufficient head and tail room is generally maintained for safe operation.

#### OEM feedback

**SoC and energy availability.** For technologies reliant on energy storage, the SoC was highlighted as the key factor affecting the ability to sustain GFM operation. One response noted that the energy source availability affects mainly the inertial response, the frequency control, and the damping of low-frequency oscillations below 25 Hz.

The SoC and installed energy capacity of BESS directly influence the amount of synthetic inertia provided to the grid. At nominal SoC levels, the equivalent inertia constant remains stable; however, as the SoC nears its upper or lower limits, the inertia contribution must be reduced to prevent excessive charging or discharging. The available energy storage is inherently linked to the equivalent inertia constant of the GFM inverter, meaning that systems like STATCOMs and HVDC links, while capable of GFM operation, have limited inertia contributions.

To ensure reliable GFM operation across a wide SoC range, an additional buffer should be reserved near the upper and lower operating limits of the energy storage system. The required buffer size may depend on grid conditions and application needs, particularly for services such as black start and inertia provision. SoC management strategies should be flexible, balancing performance with battery lifespan considerations.

The following provides a summary of key points raised in relation to the impact of active power dispatch on GFM capability:

**Response to system events.** When a GFM resource is dispatched at full power, its ability to respond effectively to a negative ROCOF is constrained, as it lacks the downward power headroom required to contribute. Conversely, if the resource is already absorbing its maximum power, it cannot respond effectively to a positive ROCOF because it lacks the upward headroom. Similarly, large phase jumps in the grid can compromise the effectiveness of a GFM's response when it is operating at or near its power limits.

**Headroom management.** GFM inverters are expected to operate within their specified limits of active power, reactive power, frequency, and voltage, but their performance near these limits depends heavily on the available energy headroom. Technology-specific factors further influence this: in wind power applications, GFM capabilities need to be averaged across multiple turbines or sites to achieve reliable overall response. For DC-coupled BESS solutions, a minimum headroom of about 10% of nominal power is often recommended to ensure full GFM performance. Hybrid wind-turbine–BESS–GFM configurations rely on the BESS's energy headroom, whereas GFM solutions based solely on wind turbines are constrained by the instantaneous availability of wind energy.

**Inertia provision.** The ability to deliver a transient inertial response varies significantly between different GFM implementations. OEMs, particularly those producing wind and solar technologies, have divergent views on whether inertia provision should be considered a fundamental, mandatory function of GFM inverters. This lack of consensus reflects the technology-specific challenges and design trade-offs inherent in incorporating inertia into these systems.

**Impact of power dispatch.** The effectiveness of a GFM's inertia provision is closely tied to its current power dispatch level. When the resource operates near its maximum output, the headroom for delivering inertia response is reduced, particularly in applications where power flow is bidirectional.

**Comparison with synchronous machines.** Unlike synchronous machines, which provide constant and inherent inertia through their physical rotating mass, GFMs rely on virtual inertia that is implemented through control algorithms. Consequently, the response characteristics of GFMs differ and depend on their operating conditions and available energy reserves.

**Limitations.** While extending the over-current capability of GFM inverters could theoretically enhance their inertia response, practical limitations such as constraints of the DC energy source and converter current ratings must also be taken into account. Managing inertia provision becomes particularly challenging for grid-forming wind technologies that lack integrated energy storage, as their response is highly variable with wind speed. This variability can affect compliance with access standards, including requirements under clauses like NER S5.2.5.8 and S5.2.5.11. Furthermore, during under-frequency events, energy is drawn from the turbine's rotating mass to provide an inertial response; however, this response is inherently limited in both magnitude and duration because the rotor speed must be restored promptly to avoid stalling the turbine.

## AEMO's response

AEMO agrees with the general observations regarding the dependence of GFM performance on energy availability and dispatch conditions. In particular:

- For BESS-based GFM, adequate headroom, both in power and energy, is essential to maintain a reliable response to grid disturbances such as frequency deviations, ROCOF events, and phase jumps. State-of-charge (SoC) and dispatch levels directly influence this capability.
- Virtual inertia provision, unlike the inherent inertia of synchronous machines, is conditional on available energy and constrained by converter capabilities. This reinforces the importance of effective SoC and buffer management, particularly where inertia delivery is required at a specific connection point.

- Where consistent GFM performance is required across all operating conditions, the deliberate allocation of energy buffers or headroom may be necessary.

Recognising the above, providing a consistent inertial response under all operating conditions is likely to impose additional cost on the project or constrain other revenue-generating activities, such as energy or FCAS dispatch. While the capability to provide inertial response may be included within the access standards, AEMO acknowledges that its practical utilisation will require appropriate compensation through market or non-market mechanisms to ensure its delivery remains economically viable and technically sustainable.

There are several important observations that warrant further investigation, particularly in relation to operational envelope definition, energy management strategies, and implementation feasibility:

- Designing GFM sites to maintain full performance irrespective of SoC may be an ambitious expectation. While technically desirable, the practicalities require careful review, including how buffer margins are defined and maintained across varied applications. Cost implications should also be considered.
- The notion of defining minimum headroom (e.g., 10%) or reserving buffers near SoC limits is useful but context specific. Further clarity is needed on how these thresholds should be set for different technologies (e.g., GFM BESS vs wind-based GFM systems), and whether such requirements can or should be standardised.
- While extended over-current capabilities may enhance inertial response in theory, converter and DC source limitations often present more binding constraints in practice. This interaction warrants more detailed technical treatment.
- Wind-based GFM presents unique challenges, particularly in inertial support under variable wind conditions. The impact on compliance with clauses such as NER S5.2.5.8 and S5.2.5.11, especially during extended under-frequency events, was noted.

Collectively, these points highlight the need to better define the boundary between what constitutes “firm” GFM capability and what remains conditional upon resource availability and system conditions.

Lastly, AEMO notes unique issues associated with GFM provision in HVDC links, including the dependency on the interconnected AC networks and the lack of inherent energy reserves within the DC link. While these matters are important, they fall outside the scope of the GFM ASR for Schedule 5.2 plants and will be addressed in a future review focused specifically on Schedule 5.3a plants, including HVDC links.

### D.3.3 PPC limitations

#### NSP feedback

Most respondents indicated that no abnormal behaviours have been observed to date. However, one NSP discussed that in some technologies, the PPC sends the available headroom back to the inverter during a disturbance, causing the power command to drop, particularly when the PPC does not freeze. After fault clearance, the power command gradually returns to its pre-fault level, but this delays active power recovery.

#### OEM feedback

No respondents identified PPC limitations as a significant constraint for GFM performance.

### D.3.4 Practical experiences with over-current capability

#### NSP feedback

Comparison with STATCOM overload capability, it was noted that similar power electronics-based equipment, such as STATCOMs, includes sizeable short-term overload capabilities. There is uncertainty about why inverter manufacturers do not seem to provide comparable short-term over-current capacity in GFM.

Regarding the impact on protection systems in islanded operation, a case study from the Dalrymple ESCRI BESS project highlighted that:

- Protection system performance depends on the over-current capability of the GFM hardware.
- Downstream protection settings may need significant modification for islanded operation if GFM inverters lack sufficient over-current capability.
- Achieving proper fault grading and discrimination in island mode may be difficult without adequate over-current headroom.

#### OEM feedback

A modest over-current capability between 1.0 and 1.3 p.u. was reported across surveyed GFM plant. However, one respondent advised an over-current capability of 2.0 p.u. for 10 seconds. Several OEMs indicated that extending over-current capability could enhance transient stability and FRT performance, but it would come at the cost of increased hardware requirements and potential thermal constraints. The current limitation of the inverter was noted as a significant factor restricting the dynamic response of GFM inverters. Unlike synchronous machines, GFM inverters have a defined over-current capability, which is typically lower than that of conventional generators.

#### AEMO's response

AEMO acknowledges the range of perspectives on over-current capability in GFM inverters and its potential implications for dynamic performance, protection, and system planning. While over-current capability is not necessarily the key determinant of GFM effectiveness, it can influence aspects such as active and reactive current performance during faults, and impact on protection systems, especially under islanded or weak grid conditions.

- Current limitations are a fundamental characteristic of GFM inverters, with typical short-term over-current capabilities in the range of 1.0 to 1.3 p.u. While higher capabilities (e.g., 2.0 p.u. for several seconds) are technically feasible, they come at a cost.
- Unlike synchronous machines, which inherently deliver multiple services simultaneously, GFMs require prioritisation of current usage in real time, meaning that not all functionalities (e.g., inertia, voltage support, and fault current) can be delivered concurrently under stressed conditions. This prioritisation should be clearly reflected in the GPS, where relevant.

AEMO agrees that the suggestion to explicitly define key performance limitations, such as over-current constraints in the GPS, has merit. Including this information improves transparency around the conditions under which GFM capability may be reduced (e.g. when current limits are reached) and can help set realistic expectations for system-level performance during disturbances.

AEMO supports the inclusion of such information in the GPS, provided it is expressed in a manner that captures the underlying technical limitations without unduly driving cost or complexity. This also complements the

broader objective of ensuring GFM stability and avoiding unintended interactions during high-stress system events.

AEMO notes the concern raised by one NSP regarding a scenario where over-current capability pushed the network beyond its operational limits, contributing to a risk of voltage collapse. While such situations may be less common, they highlight the need for careful coordination between inverter capabilities and network planning assumptions in areas operating near their design margins.

Regarding the comparison with STATCOMs, while both devices rely on power electronic converters, STATCOMs are typically designed with larger thermal margins and passive cooling approaches that allow for short-term overloads. GFMs, by contrast, often include integrated control, protection, and energy management systems, which may prioritise converter protection and efficiency under normal operating conditions. Further insights from manufacturers on this point would be valuable.

## D.4 Impact on protection systems

### D.4.1 Additional fault current attributes for protection relay operation

#### NSP feedback

**Duration of fault current supply.** Some respondents noted that protection relays typically require fault current of sufficient magnitude to be maintained for at least five cycles to ensure correct operation. A related observation, applicable to both transmission and distribution networks, was that for inverters with overload capability, the duration of this overload is critical. In many cases, the overload limit diminishes after a few seconds of operation, meaning that sufficient current may no longer be available during a subsequent unsuccessful auto-reclose attempt, or during very long-duration faults in the distribution network.

**Harmonics, flicker, and waveform stability.** Waveform characteristics such as DC offset, harmonics, flicker, and other transient components can significantly affect filtering and measurement accuracy, particularly during high transient events. The rate of change of current was also identified as an important factor to consider. Additionally, one response emphasised the importance of accounting for motor starting and transformer magnetising currents, as these are closely related to fault current requirements. GFM plants operating in an islanded environment or in systems with low levels of synchronous machine support must have sufficient capability to deliver the necessary current for these applications.

### D.4.2 Negative-sequence current requirements for protection systems

#### NSP feedback

**Purpose of negative-sequence current injection.** The primary purpose of requiring negative-sequence current injection is to prevent excessive voltage rise in the healthy phases during unbalanced faults. Some networks also use negative-sequence protection as part of their fault detection and relay operation strategies, making this capability relevant in certain contexts.

**Networks with negative-sequence current dependency.** Responses varied regarding the importance of negative-sequence current in distribution network protection. While some stakeholders indicated that their networks do not rely on protection schemes that require negative-sequence current injection, others noted that certain protection relays do operate based on detecting negative-sequence current during unbalanced faults. No respondents provided a specific minimum negative-sequence current or current-versus-time injection requirement necessary for relay operation. One respondent also remarked that negative-sequence injection

should not be imposed as a blanket expectation for GFMs, given their voltage-source behaviour during unbalanced faults.

### OEM feedback

**Natural Behaviour of GFM and Negative-Sequence Current.** Respondents emphasised that the natural response of GFM control is to counteract changes in both positive- and negative-sequence voltages, with sequence currents not being directly controlled. This behaviour was noted to be consistent with synchronous machines, where negative-sequence current is naturally constrained by thermal and protection limits. Respondents also highlighted that the total apparent current of the inverter must not be exceeded; therefore, negative-sequence current can only be delivered if sufficient headroom remains within the overall current limit after accounting for the positive-sequence current.

**Control Strategies for Negative-Sequence Response.** Similar to their feedback on the K-factor for positive-sequence current, respondents generally opposed the use of a deadband or explicit threshold activation for negative-sequence current provision. Instead, they advocated for a continuous response proportional to the voltage imbalance, rather than an on–off mechanism. Some GFM OEMs indicated that they do not explicitly implement dedicated negative-sequence current control but rely instead on the inherent behaviour of a voltage source to manage system unbalances, mirroring the way synchronous machines respond. A more practical approach suggested by respondents is to ensure that the healthy phase voltages do not exceed a defined percentage of nominal voltage during unbalanced faults. This aligns with the “control objective” in the recent draft determination of NER S5.2.5.5A(b)(2), which defines the aim as minimising the deviation of each phase voltage from its pre-disturbance value, during both balanced and unbalanced faults, while maintaining stable control.

**Technology-Specific Limitations and Considerations.** Respondents also noted technology-specific constraints in providing negative-sequence current. For example, Modular Multilevel Converters, used in HVDC links and STATCOMs, have inherent limitations due to the need to maintain DC capacitor voltage balance. In addition, Type III WTGs were observed to naturally deliver relatively high negative-sequence current under large voltage unbalances; however, under small unbalances, the thermal limits of the generator become the primary constraint. These observations suggest that while some technologies inherently provide negative-sequence response, their capabilities are bounded by their respective design and operational limits.

## D.4.3 Specific considerations for distribution networks

### NSP feedback

The fault current capability of GFM plants requires careful study to understand its impact on protection systems, particularly when operating in islanded conditions. Some stakeholders also noted that GFM plants may need to sustain fault current provision for longer durations to support extended fault-clearing processes effectively.

Integration challenges also arise because distribution networks are not yet fully incorporated into AEMO’s OPDMS and NEMDE systems, making dispatch during islanding conditions more difficult. To address this, GFM systems must be compatible with DNSP platforms such as distributed energy resource management systems (DERMS) to enable effective active and reactive power management.

Given the limited communication infrastructure often found in distribution networks, GFM plants must be able to operate independently for short periods, accommodating situations with delayed or unavailable communications. This ensures continuity of service even under less-than-ideal communication conditions.

Finally, the ride-through capabilities of GFM resources need to account for the specific characteristics of distribution networks, where long-duration faults and multiple reclosing events are more common than in transmission networks. Some respondents also highlighted that connecting GFM inverters in strong grid areas can introduce challenges compared to GFL inverters, suggesting the need for flexible, negotiated arrangements among customers, NSPs, and AEMO. As a transitional measure, the option of a fallback GFL mode was proposed while industry stakeholders gain more experience with GFM performance.

### AEMO's response

The comment that protection relays typically require a fault current of sufficient magnitude to be sustained for at least five cycles is valid and aligns with discussions earlier in this document. Practical experience with GFM projects has shown that, although an initial high reactive current may be delivered, it often decays rapidly, sometimes falling below pre-fault levels within a short duration. This behaviour has clear implications for the protection system operation. However, AEMO notes that the five-cycle duration reflects a specific case (e.g., a 100 ms fault), and our position is that the fault current response should be sustained with minimal variation throughout the fault, ideally up to the expected duration of a breaker failure fault.

AEMO acknowledges the excellent observation regarding waveform composition. Fault current from IBRs, including GFMs, may not be limited to the fundamental frequency component. Rather, it may include DC offsets, harmonics, interharmonics, and other transient waveform features. These characteristics can impair filtering accuracy and measurement precision, and in turn, affect the correct operation of protection schemes. AEMO agrees that both the magnitude and rate of change of current, as well as the spectral content of the waveform, should be carefully considered when considering GFM fault response performance.

Some disturbances, particularly long-duration faults in distribution networks and auto-reclose events, may require fault current to be sustained for several seconds to align with fault clearing times. However, it is recognised that such extended fault current injection may exceed the capabilities of most current GFM technologies, unless higher-rated semiconductor switching devices are employed. This, in turn, could result in significant cost increases, raising important considerations for practical implementation.

Regarding the need to consider motor starting and transformer inrush currents, it is recognised that Schedule 5.2 GFM plant must have sufficient current delivery capability to support such events. While it is agreed that the lower fault current levels typically associated with GFM inverters can lead to larger and more widespread voltage dips during transformer energisation or large motor starts, particularly when compared to systems with more synchronous machines online, it is important to clarify that the connecting party remains responsible for ensuring that plants remain stable during transformer energisation. They must also ensure that transformer energisation at their connection point does not cause unacceptable voltage disturbances on the network.

More broadly, the system-wide reduction in fault current due to the declining number of synchronous generators and increasing reliance on IBRs may indeed increase the likelihood of voltage dips during energisation events at locations beyond the connection point of Schedule 5.2 GFM plant. AEMO's view is that such impacts should be managed through system strength procurements carried out by TNSPs under their obligations as system strength service providers, to maintain the minimum and efficient level of system strength required across the network.

### Negative-sequence current requirements for protection systems

While practices vary across networks and relay vendors, it is understood that a significant proportion of relays used for directionality assessment, including distance protection and directional over-current schemes, rely on negative-sequence current to accurately determine fault direction. However, no specific minimum negative-

sequence current magnitude or duration requirement was provided to support reliable relay operation. Obtaining a more precise specification may require input from protection specialists within NSP organisations.

AEMO acknowledges the comment that GFM inverters cannot directly control negative-sequence current because they are voltage sources. This is conditionally true for implementations in the abc frame, where the voltage is imposed without decomposition into symmetrical components. However, if the control is implemented in the sequence or dq domain, it is understood that it may be possible to actively shape the voltage waveform to influence and limit negative-sequence current. Therefore, the capability for negative-sequence current control depends not solely on the GFM's voltage source behaviour, but also on the control frame (i.e., abc or dq frame) and strategy.

Respondents also noted that GFM inverters, much like synchronous machines, tend to counteract deviations in both positive and negative-sequence voltages as part of their voltage regulation behaviour. In this respect, negative-sequence currents may not be explicitly controlled but arise naturally from the inverter's voltage response. This is analogous to synchronous machines, where negative-sequence current is constrained by thermal and protection limits, though the mechanisms in GFM inverters differ, relying on control implementation, saturation logic, and virtual impedance settings.

Unlike GFL inverters, which operate as current sources and can actively inject or absorb negative-sequence current, GFM inverters typically behave as voltage sources that oppose negative-sequence voltage, often resulting in the absorption of such current. Whether a GFM sinks or sources negative-sequence current depends on the control strategy and the system conditions during unbalanced faults.

Several respondents correctly highlighted that negative-sequence current provision must respect total apparent current limits. That is, any negative-sequence component must fit within the current envelope once positive-sequence current and any active/reactive current injection are accounted for. Overloading capabilities may offer some margin, but prioritisation remains essential, particularly as many compliance obligations and grid support capabilities depend primarily on positive-sequence current.

In line with the discussion on positive-sequence k-factors, the use of explicit thresholds or deadbands for negative-sequence current injection was opposed. A more appropriate approach would treat negative-sequence response as a continuous function of voltage imbalance, avoiding on/off-type behaviour due to mode triggering.

AEMO supports the point that maintaining phase voltages within limits is important, particularly in very weak networks or distribution systems. This is consistent with the "control objective" defined in Package 1, which focuses on minimising per-phase voltage deviation during both balanced and unbalanced faults. However, this should not be the sole control objective, especially if it compromises protection effectiveness. Any negative-sequence response strategy must balance voltage control, protection support, and total current capability, and should be fit-for-purpose rather than one-size-fits-all.

### Specific considerations for distribution networks

Several DNSPs provided feedback on unique challenges associated with connecting GFM plant to the distribution network. AEMO notes that many of the concerns raised, such as the impact of long-duration faults, auto-reclose events, and operation under strong network conditions. It is important to emphasise that challenges related to strong grid conditions and auto-reclose operations are not specific to the distribution network and are equally relevant to transmission-connected Schedule 5.2 GFM plant.

AEMO also acknowledges comments regarding limited communications infrastructure in some parts of the distribution network. It is reasonable to expect that Schedule 5.2 GFM plant should be capable of short-term autonomous operation under conditions of limited or delayed communications. However, this is not unique to

GFM and is typically addressed through appropriate plant-level control design. As such, it does not warrant separate treatment in access standards.

Finally, the point raised regarding the limited representation of distribution networks in wide-area phasor-domain models is also noted. While some areas may require EMT-based studies to assess performance, such modelling considerations are outside the scope of this approach paper.

## D.5 Performance during exceptional operating states

### D.5.1 Factors for seamless steady-state switchover between GFM and GFL modes

#### NSP feedback

**Questioning the need for mode switching.** One respondent questioned the necessity of switching from GFM to GFL modes, suggesting that plants should be properly tuned to handle all credible operating scenarios without requiring a mode change. It was further suggested that, at a minimum, any automatic switchover from GFL to GFM mode should be carefully evaluated to ensure appropriateness. Some reluctance was expressed to approve automatic control mode changes without clear justification and robust safeguards to prevent unintended consequences.

**Key factors for seamless transition.** Several key factors were identified as critical for ensuring seamless transition between GFM and GFL modes. Detecting islanding conditions reliably is fundamental to managing GFM behaviour during network transitions. The speed of the mode transition was also highlighted, with emphasis on how quickly the system can switch between modes without compromising performance. Respondents discussed the importance of the trigger mechanism — specifically, whether the switchover is initiated manually or automatically, and under what conditions — as well as the need to minimise disturbances and maintain stable operation throughout the transition.

**Technical and process considerations.** Respondents noted that inverter controls should include built-in functionalities that enable switching between two sets of control parameters tailored for GFM and GFL operation. The connection process should comprehensively document all settings, procedures, and limitations relevant to both modes, ensuring transparency and proper configuration during commissioning and ongoing operation.

**Practical considerations.** From a practical standpoint, expected mode transition times were reported to range from approximately one to thirty minutes, depending on the specific technology and configuration. Respondents also suggested that a minimum system strength, expressed as an SCR of about two, should serve as a recommended threshold for switching from GFL to GFM mode as system strength declines. This threshold provides a practical benchmark for determining when a transition is warranted.

#### OEM feedback

**Divergent views on the necessity of switching.** Varying views were raised on this point. Some respondents acknowledged the benefits of a steady state switch over between GFL and GFM and confirmed that similar requirements exist in other jurisdictions. However, others questioned the necessity of such a requirement, arguing that GFM should be tuned to operate effectively across all conditions without the need to switch to GFL. Additionally, some noted that transitioning between modes could introduce unnecessary complexity and may not align with how GFM is intended to function.

**General position on GFM-GFL switching based on the survey.** Most respondents do not recommend switching between GFM and GFL due to potential instability and unpredictable performance. It was discussed that automatic transitions are generally not provided due to high uncertainty, and manual transitions (as referenced in RfG 2.0 draft) should be defined based on NSP requirements. Some OEMs do not see a compelling reason to implement this feature, as GFM should be capable of operating in both strong and weak grids without requiring mode switching.

**Recommended conditions for seamless switching (if implemented).** Switching should only occur in a steady-state condition to allow internal control to reset and prevent transient glitches. Seamless transition is possible only if the operating point is feasible in both GFM and GFL modes.

**Concerns about mode switching and the definition of GFM.** Some respondents argue that a converter ceases to be truly GFM if it switches to GFL during FRT. However, this may reflect a misunderstanding of the question's intent, which is to explore mode switching during steady-state operation, particularly in scenarios where NSPs anticipate low system strength, or where the system has entered a low system strength condition following a fault. Switching between modes introduces non-linear responses, which could lead to unexpected behaviours and instability.

### AEMO's response

AEMO agrees with the position that mode switching between GFM and GFL should not be necessary under normal steady-state conditions, and that Schedule 5.2 GFM plant should be tuned to operate acceptably across all credible system conditions without requiring a transition to GFL. Automatic mode switching, particularly without clear justification and appropriate safeguards, introduces unnecessary complexity and risk and should be approached with caution.

While some responses highlighted potential benefits of steady state switching under specific scenarios (e.g., in very low system strength conditions), these were counterbalanced by concerns regarding non-linear control responses, potential instability, and the practical burden of managing multiple modes. This includes more complex connection studies, expanded commissioning procedures, and the need to define and test separate control settings, placing additional demands on both OEMs and NSPs.

Recognising these challenges, we support a focus on achieving a technically robust and stable GFM response that performs acceptably under a wide range of system conditions, while acknowledging its inherent limitations. This trade-off allows for system-wide resilience without the need for mode switching, simplifying integration and reducing operational risk.

At present, AEMO does not foresee a need or requirement to change between GFL and GFM performance operationally, nor was this raised as a desire from survey respondents. Therefore, this has not been considered as an objective of this approach paper. Nonetheless, it is acknowledged that if this position were to evolve in the future, any proposal for operational switching would require careful consideration of system needs, appropriate safeguards, and the broader implications for modelling, commissioning, and compliance frameworks.

## D.5.2 Islanding

### NSP feedback

**Consideration for islanding operation.** It was suggested that GFM projects should be assessed for their ability to operate under islanded network conditions, particularly in locations where islanding is considered an acceptable operating state. Respondents proposed that the provision of key stability services, including inertia, system strength, and support for islanded operation, should be included as success criteria for evaluating the

performance of GFM plants. Additionally, a question was raised regarding how islanding should be explicitly incorporated into AEMO's technical requirements.

**Response time.** It was suggested that the response time of GFM plants should be fast enough to maintain stability in an islanded grid, although no specific value was universally agreed upon. One respondent proposed a response time of approximately 100 ms, while others did not provide specific recommendations or indicated they needed more time to consider the issue. Another suggestion was that, given the typical reclose time in distribution networks ranges from 3 to 15 seconds, the GFM plants' response should be designed to occur within this timeframe.

#### **Limitations in the network for GFM in islanding operation**

**Protection system requirements.** A comprehensive network protection assessment is necessary before permitting islanded operation. Many distribution networks rely on over-current protection, which requires sufficient current injection from the inverter to ensure reliable fault clearance. Protection settings may also need to be adjusted for islanded conditions, as demonstrated in the Energy Storage for Commercial Renewable Integration (ESCRI) BESS at Dalrymple case study.

**Fault level considerations.** Adequate fault level must be maintained to ensure the proper operation of protection devices when operating in islanded mode. Compliance with electricity supply quality standards, such as S5.2.5.2, which governs the quality of the generated voltage waveform, and S5.2.5.6, which addresses the ability to withstand high harmonics, flickers, and voltage unbalances, must also be upheld during islanded operation.

**Measurement and monitoring challenges.** The lack of measurement devices in some parts of the network could hinder effective islanding operations and fault detection. Ensuring sufficient visibility and monitoring of the network is therefore essential to support reliable and safe islanded operation.

**Need for further investigation.** Some stakeholders indicated that they require additional time to fully assess the implications of GFM technology for islanded operation. They emphasised the importance of thoroughly evaluating potential changes to other access standards, which are likely necessary to enhance the stability and performance of GFM inverters in islanded configurations.

**Potential changes to other access standards.** Changes to existing access standards are expected to be necessary to better support islanded operation of GFM inverters. These adjustments would help ensure that the technology can deliver stable and compliant performance under such conditions.

**Reliance on third-party assets.** Concerns were raised about the risks of relying on third-party assets to restore and sustain an island unless the system has been explicitly designed and coordinated for that purpose. Clear responsibilities and technical provisions are needed to address this issue effectively.

**Voltage regulation at the connection point after islanding.** NSPs will need to assess each islanding case individually to ensure compliance with the S5.2.5.1 voltage requirements. Some respondents suggested that the appropriate voltage limits for islanded operation should align with NER S5.1.4, which specifies a range of 95% to 105% of target voltage, rather than the proposed 0.9 to 1.1 p.u. range. The ability to sustain voltage stability during islanded operation also depends on whether the BESS or other GFM technology was explicitly designed for such conditions, particularly if the plants' rating or available headroom are insufficient to balance active and reactive power within the island. Without these design provisions, it is unlikely that plants could maintain voltage and manage the generation-load balance for an extended period. Respondents also noted that it is difficult to generalise expectations, as performance will depend heavily on the specific design and capabilities of the GFM system.

## OEM feedback

**Hardware requirements.** Respondents confirmed that no additional hardware modifications are required to deliver this capability. Moreover, the ability of plants to maintain continuous operation during islanding is primarily determined by the GFM converter itself and does not depend on the functionality of the PPC.

**Response time.** It was highlighted that most GFM inverters can respond to intentional islanding conditions within 100–250 ms, although the actual response time is highly dependent on control tuning and prevailing system conditions. In the case of unintentional islanding, the transient response is typically under one second.

**Prioritising grid support capabilities during non-islanded conditions.** However, while islanding was noted as an interesting and valuable capability of GFM technology, respondents suggested that too much emphasis has been placed on this function. They noted that the primary goal of GFM should be to provide adequate support to the grid to prevent islanding events in the first place, rather than focusing on sustaining operation once islanded. Unlike synchronous generators, where islanding capability is inherent, the emphasis for GFM should remain on strengthening grid stability to avoid entering an islanded state.

**Impact on protection.** Protection settings may also need to be reviewed and adjusted to prevent unnecessary tripping of GFM inverters during islanding events, which could include softening access standards to account for credible contingencies.

**Need for further studies.** Some respondents indicated they were not yet in a position to comment fully on GFM performance in islanded conditions, suggesting that further study may be required.

**Technology relevance.** It was noted that not all technologies are applicable in this context; for example, STATCOM and Enhanced STATCOM are not relevant to discussions of sustained islanding capability.

## AEMO's response

Key challenges raised by NSPs regarding the viability of islanding include the compatibility of GFM inverters with existing protection systems and the need to maintain sufficient fault levels and voltage regulation. Furthermore, as noted by NSPs, islanding capability is highly context-dependent and requires detailed assessment to determine whether stability, protection, and operational integrity can be maintained under credible contingencies. In particular, successful islanding may also depend on the ability of third-party assets to operate under islanded conditions, especially where they form part of the islanded network initiated by Schedule 5.2 GFM plant. In light of these considerations, AEMO agrees that while Schedule 5.2 GFM plant may have the technical capability to support islanded operation, this alone does not ensure secure or reliable outcomes.

It is also noted that synchronous generators are not currently subject to equivalent requirements for demonstrating islanding capability. In some jurisdictions, survival following the loss of the last synchronous machine has been proposed as a technical requirement. In the NEM context, this may be a useful screening condition; however, it does not guarantee that a resulting island will operate securely or sustainably.

OEMs indicated that no significant hardware changes are required to enable islanding in GFM inverters, as this capability is primarily determined by control system tuning. However, they cautioned against placing undue emphasis on islanding, emphasising that the primary role of GFM should remain focused on enhancing system strength and helping to prevent island formation.

OEMs also noted, consistent with NSP feedback, that successful islanded operation depends on the coordination between GFM inverter settings and the protection settings of plants and the surrounding network. Assessing, confirming, and mitigating these interactions requires more detailed studies than those typically undertaken during GPS negotiations for GFL or synchronous plants.

### D.5.3 System restoration

#### NSP feedback

It was discussed that SRAS is currently provided by synchronous generators, and that GFM black start capability should be considered as these providers withdraw from the market. System restoration capability has not historically been included in the GPS and may therefore need to be addressed outside the GPS framework. The need for GFM system restoration capability is expected to grow as traditional generators retire; however, significant technical improvements from OEMs will be required to achieve this.

#### OEM feedback

Respondents confirmed that the development and implementation of well-defined access standards for GFM will not hinder the future provision of black start capability. They indicated that GFM can support black start recovery without requiring additional hardware modifications, provided that an external auxiliary power supply is available to support critical components within the plants (referred to as restoration support services in the NER). Protection settings can also be adjusted as needed to meet black start requirements, with operators ensuring sufficient energy reserves, particularly for non-zero SoC conditions.

#### AEMO's response

AEMO included questions on the system restoration capability of Schedule 5.2 GFM plant in the OEM and NSP surveys, not because black start is being considered as part of access standards, but to better understand the interaction between access requirements and future restoration capability. The intent is to ensure that the development of access standards does not inadvertently compromise the ability of Schedule 5.2 GFM plant to support system restoration at a later stage.

With OEMs confirming that GFM technology can support black start without hardware modifications, there is growing confidence that this capability can be developed and delivered as a system service. However, despite this confirmation, the need for an external auxiliary power supply, potential modifications to protection systems, the requirement for significantly more detailed studies (and the associated impact on connection timeframes), and the need to maintain sufficient SoC, with implications for participation in other market services, have led AEMO to conclude that system restoration capability should not be treated as an access standard at this stage.

## D.6 Technology definition and classification

### D.6.1 Definition and classification of GFM

#### NSP feedback

**Concerns about emulating synchronous machines.** One response disagrees with the approach of making GFM inverters emulate synchronous machines, arguing that better control system designs should be available that do not necessarily replicate synchronous machine behaviour. Concern was specifically raised on whether swing equations are the right control approach for GFMs.

A key challenge noted is that GFMs are classified as asynchronous generating systems under the NER, yet they attempt to function similarly to synchronous generators. This may create challenges in aligning technical requirements and access standards.

**Agreement on the need to modify access standards for GFM performance optimisation.** There is agreement that modifications to access standards are necessary to ensure that good performance can be achieved without

noticeable increases in costs. However, respondents pointed out that limitations in current GFM implementations stem from the way the swing equation has been applied and how the voltage source behaviour of the converters has been approximated.

One respondent highlighted that there are already precedents for the differentiated treatment of GFM technologies, as seen in the GB Grid Code, highlighting both the feasibility and the benefits of this approach.

**Balance between technical feasibility and performance requirements.** While it is acknowledged that GFM technology may not be able to fully replicate the best performance of synchronous generation, there are genuine technical and economic reasons for this. Respondents also highlighted that AEMO faces a fine balance in “teasing out” optimal GFM performance without imposing excessive cost burdens on operators.

**Agreement that PLL inclusion should not be a defining factor.** Multiple responses agreed that GFM vs. GFL definitions should not be based on internal control features such as the presence of a PLL, swing equation control, or FRT mode logic. Instead, performance outcomes measured at the terminals should form the basis for classification and technical requirements.

**Preference for minimising distinct requirements across technologies.** There was general agreement on modifying the standard, but a strong preference for avoiding too many separate requirements for GFM, GFL, and synchronous machines. It was suggested that if GFMs aim to replicate the response of synchronous machines, then a more unified set of performance standards might be preferable rather than maintaining three distinct sets of requirements.

It was also noted that while GFM may provide a better response than synchronous generators, respondents questioned whether adding extra requirements for GFM (beyond what is required for synchronous generators) is justified unless similar requirements are imposed on synchronous plants.

If there are specific performance requirements for GFM that are desirable but not available in other technologies, AEMO or NSPs could provide guidance on these behaviours outside the NER. For example, the SRAS (System Restart Ancillary Services) capability is negotiated separately with each provider and not included as an NER access standard.

**Alternative classification terminologies for GFM.** It was suggested that GFM could be categorised as “Grid-Forming Asynchronous” or “Voltage Source Asynchronous” to better reflect its characteristics. Another approach proposed defining “synchronous” and “asynchronous” plants explicitly in Schedule 5 or Chapter 10 of the NER, which could improve readability and simplify references to generating systems and integrated resource systems in Schedule 5. Another respondent highlighted that not all synchronous generators and condensers exhibit grid-forming capabilities. Compliance with S5.2.5.15 requirements was noted as an important factor in classification. The ability to operate in an electrical island was suggested as a distinguishing feature of GFM.

GFM plants should be capable of delivering power to the load without relying on system strength services provided by synchronous generation. However, the network impedance between GFM plants and the load must remain sufficiently low to enable practical active power transfer.

## OEM feedback

**Core characteristics and definitions of GFM technology.** GFM technology was described by most respondents as having the following core characteristics:

- Constant internal voltage phasor, providing resistance to fast changes in voltage magnitude, phase angle, and frequency.

- Ability to independently establish voltage amplitude and frequency without relying on external grid conditions.

Additionally, the following was suggested by one respondent to add that the resistive apparent impedance be between 0 and 1 kΩ except between 45 and 55 Hz, and can withstand low system strength conditions, including a rapid reduction in the system strength.

One respondent proposed that GFM should be defined as any converter capable of forming the grid within its available energy, whether or not it is a power-generating unit. This ensures grid-forming status is not limited to generators with energy storage.

There were differing views on whether GFM access standards should be aligned with those of synchronous machines. Even among those supporting alignment, only selective aspects, such as removing rise time requirements for reactive current injection, were recommended, while other provisions were considered inappropriate.

Lastly, one OEM suggested that GFM technologies be classified into two tiers, Tier 1 involving reactive power response (voltage magnitude resistance), and Tier 2 including active power response (phase angle resistance).

**Synchronisation and PLL considerations.** Most respondents confirmed that their GFM plants use power synchronisation control rather than relying on PLLs, which are essential for GFL inverters. There was strong opposition to defining the presence or absence of a PLL as a requirement in the NER. This is because PLLs may be used for secondary functions such as monitoring grid conditions, enhancing stability, or facilitating transitions between GFM and GFL modes.

Instead of prescribing specific implementations, respondents suggested that access standards should focus on defining performance-based synchronisation requirements, for example, defining acceptable phase angle and RoCoF response. Different synchronisation schemes can be employed, such as power or energy synchronisation. Respondents indicated that mandating a specific synchronisation method in detail could limit available solutions and lead to suboptimal system performance.

It was also highlighted that synchronisation methodologies are often dependent on OEM-specific designs, which may involve proprietary control strategies that cannot be disclosed to third parties. This further supports the need for a performance-based approach rather than prescriptive technical specifications.

## AEMO's response

AEMO acknowledges the range of feedback received on the definition and classification of GFM inverters. There is strong support for a performance-based approach to classification, one that avoids prescriptive control system definitions and instead focuses on outcomes observable at the connection point under relevant operating conditions. AEMO agrees that the classification of inverters as GFM or GFL should not be based on internal design features such as the presence or absence of a PLL or the use of swing equation control. The use of a PLL may be acceptable, provided Schedule 5.2 GFM plant can meet the definition and deliver the expected performance requirements. Whether or how a PLL is used remains the responsibility of the OEM and should not form the basis for regulatory differentiation. The same applies to the use or otherwise of swing equation control. While a deficient implementation may cause adverse impacts in some instances, technical requirements cannot practically encourage or discourage the use of a particular design.

In terms of defining GFM capability, AEMO supports the core characteristics put forward by respondents, particularly the definition of GFM technology as having a constant internal voltage phasor and the ability to independently establish voltage amplitude and frequency, irrespective of external grid conditions. These

characteristics are consistent with the widely adopted “voltage source behaviour” concept, which remains the most practical and accepted basis for defining GFM operation.

AEMO acknowledges additional criteria proposed by some respondents, including:

- Capability to withstand low system strength, and
- Capability to form the grid within its available energy to allow consideration of plants without dedicated energy storage.

The ability to operate in an electrical island and to deliver power to loads without relying on system strength services from synchronous generation was also suggested.

One respondent further suggested that resistive apparent impedance in the range of 0 to 1 kΩ (excluding 45–55 Ω) should be considered a defining property. While we recognise this as a potentially useful concept, we believe the application of passivity in this context requires further investigation, particularly regarding the suitability and standardisation of assessment methods for power system applications.

AEMO agrees with respondents who expressed concern about maintaining three fully distinct sets of technical requirements for synchronous generators, GFM inverters, and GFL inverters. Performance should remain the focus; what the power system needs, not how the technology delivers it. The responsibility for internal implementation rests with the OEM, through the design and tuning of appropriate controls. However, this still recognises that the provision of a given capability may be significantly more technically and economically efficient in one technology than another and does not imply that all technologies should be required to deliver identical capabilities.

AEMO also acknowledges the challenge that GFM inverters share similarities and differences with each of the synchronous generators and GFL plants. This can complicate the alignment of technical requirements and access standards. While certain aspects of synchronous generator behaviour remain useful benchmarks, GFM inverters should not be expected to emulate synchronous machines in every respect. Doing so risks importing the limitations of synchronous machines and could obscure the potential of GFM technologies to deliver superior performance in areas such as fast dynamic response. That said, there are also physical and economic constraints in GFM design, particularly with respect to current limitations, which means some synchronous generator behaviours cannot be practically replicated. Forcing equivalence may not be consistent with the NEO if it imposes undue cost without a clear system-wide benefit.

In this context, AEMO does not support the use of terminology that classifies GFM inverters as “synchronous,” as proposed by some respondents. Despite similarities in performance objectives, GFM technologies remain asynchronous Schedule 5.2 plant under the NER Schedule 5.2. This approach provides a more accurate basis for recognising both the capabilities and limitations of GFM technologies.

Finally, AEMO acknowledges the strong recommendation from several respondents to develop fit-for-purpose access standards for GFM technologies, rather than relying solely on the existing negotiation framework used for GFL inverters. Our objective is not only to capture the additional capabilities that GFM inverters can offer, but also to correctly reflect their technical limitations. GFM should not be assumed to be a superior technology to GFL in all respects. At the same time, the absence of clearly defined requirements for GFM could result in lower-quality access standards being accepted, standards that neither leverage the strengths nor acknowledge the limitations of GFM, and that may fail to align with broader system needs. Developing specific, well-calibrated performance expectations for asynchronous Schedule 5.2 plant implementing GFM technology is essential to realising their potential while managing integration risks.

## D.6.2 Application of technical requirements to hybrid plants

### NSP feedback

The application of GFM technical requirements in hybrid AC-coupled plants should be determined on a case-by-case basis as part of the GPS negotiation process. It may not be practical for non-GFM technologies (especially pre-existing legacy systems) to meet the same technical requirements as GFM, such as in cases where a BESS is added to an existing solar farm. Some respondents suggested that GFM requirements should only apply to the GFM portion, while others noted that plant-wide performance standards should be set for specific technical clauses where necessary.

### AEMO's response

Hybrid plants that combine GFM and GFL technologies present a range of technical and compliance challenges that cannot be addressed through a one-size-fits-all approach. However, there is a growing need for greater clarity and consistency in how GFM technical requirements are applied at the connection point.

**Increasing prevalence of hybrid configurations.** Several practical hybrid configurations are now emerging across the NEM and globally, with diverse technology mixes and coupling arrangements. These include both wind-based and solar-based hybrid configurations as shown in **Error! Reference source not found.4**.

**Table 4 Wind-based and solar-based hybrid configurations**

Hybrid Type	Configuration	Notes
<b>Wind-based hybrids (AC-coupled)</b>	GFM AC standalone BESS + GFL wind turbine generators (WTGs)	Very common, e.g., GFM BESS retrofitted to an existing wind farm with GFL inverters.
	GFM AC standalone BESS + GFM WTGs	Full GFM capability, but often different vendors/controllers.
	GFL AC standalone BESS + GFM WTGs	Less common; may limit full system-level benefits.
	GFM WTGs + GFL WTGs	Emerging in mixed-fleet retrofits or where partial upgrades are occurring.
<b>Solar-based hybrids</b>	GFM AC standalone BESS + GFL PV	Most common; often deployed to provide system strength at weak solar farm locations.
	GFM DC-coupled BESS + GFL PV	Increasing interest, particularly for cost and land-use efficiency. However, DC coupling can limit independent dynamic control, especially during disturbance conditions.
	GFL BESS + GFM PV	Uncommon; may emerge as GFM PV inverter offerings mature, but not typical today.

Hybrid Type	Configuration	Notes
	GFM PV + GFL PV	Theoretical; not adopted in practice due to deployment complexity and current market offerings.

These different arrangements have important implications for system performance, controllability, and the appropriate application of access standards.

**Plant-wide vs component-level compliance.** There are two principal approaches to applying GFM-related access standards:

- Plant-wide application: Applying GFM requirements at the connection point, irrespective of whether all subcomponents are GFM-capable.
- Component-level application: Applying GFM requirements only to the GFM portion, with separate performance assessments for the GFL assets.

Each has merits and limitations. While plant-wide application promotes system-level consistency, it may impose impractical obligations on GFL components. Conversely, component-level application allows greater flexibility but introduces fragmentation in compliance and operational behaviour.

**Need for a functional performance-based approach.** Rather than defaulting to either extreme, a hybridised performance-based framework may offer a more technically robust and practically implementable solution:

- Connection point-level GPS should define the aggregate behaviours required of the plants (e.g. RoCoF withstand, fast fault current support, post-fault voltage recovery) where such performance aspects can be expected from both the GFL and GFM. This will exclude aspects such as phase angle jump suppression and inertia provision.
- Subcomponent-level GPS (e.g. for GFM BESS and GFL PV or WTGs) can then demonstrate how these behaviours are contributed. Additional GFM-specific requirements would apply at the subcomponent level to the portion of the plants providing GFM capability.

**Practical considerations.** In practice, the latter approach may necessitate:

- A three-tiered GPS structure: one each for the GFM subsystem, GFL subsystem, and the plant-level connection point.
- Coordinated control strategies and harmonised tripping logic, ensuring that the GFL portion supports, or at least does not inhibit, the GFM functionality.

While this enables a more nuanced and technically appropriate application of performance requirements, it also introduces greater complexity in terms of GPS preparation, compliance assessment, and negotiation. The need for multiple GPS documents and corresponding studies may increase the time and effort required during the connection process.

## Next steps

Given the diversity of hybrid configurations and the technical, commercial, and operational implications of different compliance approaches, this issue requires further investigation. AEMO welcomes stakeholder

feedback on the proposed performance-based framework, including specific challenges or opportunities observed in recent or proposed hybrid plants developments. In particular, views are sought on how GPS structures, modelling and studies could evolve to ensure effective integration and performance assessment of mixed technology plants.