Advice on the maturity of grid forming inverter solutions for system strength

Transgrid

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1 Introduction

Transgrid has engaged Aurecon to provide advice on the maturity of grid-forming (GFM) inverters in meeting system strength requirements with focus on battery energy storage systems (BESS) and STATCOMs. This review comprises the following:

- Comparison of GFM inverters and synchronous generators
- Comparison of GFM and grid-following (GFL) inverters, and a hybrid of GFL inverters and synchronous condensers (SynCon)
- Provide a literature review on where GFM solutions have been deployed or are committed/contracted to be deployed globally, what services they are being deployed for and, if they are being deployed in response to the needs of a grid operator, has there been any limits placed on the quantity of services that come from grid forming solutions.
- Determine whether Transgrid should consider GFM, solutions to be a *credible* option from 2 December 2025 to provide a) fault current to meet minimum power system security requirements and/or b) stable voltage waveform support for new connecting renewables (efficient level). If not from 2 December 2025, when. Document the justification for this.
- Determine whether annual caps or 'hold points' on the quantity of grid forming solutions that can make up a network need should be applied to meet a) minimum fault levels or b) to support stable voltage waveforms are appropriate (e.g. no more than 20% of the efficient level provision for the first 2 years), and if so, recommend caps from FY25 onwards (noting the RIT-T analysis continues until 2045). Assess whether there should also be 'de-ratings' on the capability of GFM solutions.
- Advise what factors Transgrid should look for to allow GFM solutions to step up to the next system strength 'hold point', or what would justifying staying at an existing hold point.

2 International use cases for TSO/ISO initiated GFM inverters

2.1.1 BESS

There are not many known experiences of TSO or ISO driven GFM BESS worldwide in large interconnected power systems. The best example to date relates to National Grid ESO's procurement rounds. In 2022, National Grid ESO awarded long-term stability contracts through the Stability Pathfinder Phase 2 tender (SP2), to manage insufficient short circuit level (SCL) and inertia in various locations across Scotland, driven by growing wind generation capacity in this region. ESO awarded ten contracts to four providers worth a total of £323 million and procured 11.55 GVA of SCL and 6.75 GVAs of inertia. This will be provided by a combination of GFM BESS and SynCons.

ESO published details of the tender outcome and a summary of this information is shown in Table 2-1. More detailed project information, such as rated MW and power conversion systems (PCS) oversize, has not been disclosed.

Table 2-1: Summary of successful bidder in Stability Pathfinder Phase 2 (Source: National Grid ESO)

Developer	Technology	Substation	Max SCL[1] (MVA)	Inertia[1] (MWs)
Zenobē Energy	GFM BESS	Blackhillock 275 kV Kilmarnock South 400 kV Eccles 400 kV	84 249 936	333 1,341 2,686
Statkraft UK LTD	GFM BESS	Coylton 275 kV Neilston 132 kV	125 79	0 0
TINZ	SynCons	Beatrice 400 kV	1,918	549
WP Grid Services	SynCons	Gretna 400 kV Rothienorman 400 kV Thurso South 275 kV Neilston 400 kV	1,334 1,037 591 540	470 470 454 454

[1] Max SCL and inertia are adjusted by effectiveness and availability factors in the tender assessment process. The effectiveness factor is similar to NEM's System Strength Locational Factor (SSLF) accounting for the electrical distance between the pre-defined system strength nodes and the location at which the solution will be installed. This means that the most effective solutions will be those closest to the system strength node and located at the same voltage level.

To evaluate SCL provision in the various network locations, ESO has defined the fault current as that observed 100 ms after the fault. It has also specified eight representative fault locations in the grid and provided the retained voltage at each substation for a fault at each of the eight requirement nodes. This is similar to the concept of SSN in NEM's System Strength Requirements.

Kilmarnock South BESS is designed to provide 480 MVA of short circuit level (SCL) for the local fault and maintain the highest possible SCL for the remote faults at eight different nodes. The maximum remote fault is designed to achieve about 90% of local fault SCL contribution, where the retained voltage at the point of connection is 0.26 pu.

Both SynCons and GFM can provide a SCL that positively contributes to system stability. However, the overload limitations of semiconducting switching devices means that IBRs often provide a lower fault current contribution when compared to the SynCons. A key challenge for GFM BESS was to provide an equivalent, or better, SCL contribution than the SynCon. The inverter OEM has developed the current booster function by optimizing the control parameters for LVRT mode and current rating for pre-fault condition. This results in a higher short-term overload capability, when compared to the conventional inverter.

Plant performance was evaluated by simulating the SCL support during a fault at the required, retained grid voltage.

A recent IEEE PES Power and Energy Magazine article[1] compares the response of the modified GFM BESS against that of a typical SynCon. As expected, the SynCon provides a high peak current, which decays rapidly within the first cycle. The GFM provides a smaller peak; however, the response decays less since it is fully controlled. These results are obtained from electromagnetic transient (EMT) simulations, indicating the GFM BESS's capability to provide fault current more than 2 pu, as measured at 100 ms after the fault for the prescribed retained voltage.

An important differentiator between the response of GFM BESS and SynCon is the non-linear relationship between the fault current magnitude and the retained voltage. More importantly, the contribution ceases at around 0.65 pu retained voltage. Another point not shown here is the current magnitude for a very low retained voltage. Some GFM designs may not inject any currents if there is very low or no retained voltage to protect the semiconducting switching devices. The same behaviour can be observed in GFL inverters. However, such low retained voltages, e.g., below 10-15%, are generally localised and will occur during solid close-in faults. This means that while such a low voltage can result in current cessation in a couple of GFM plant, a system-wide impact among many GFM BESS is unlikely.

2.1.2 STATCOM

GFM STATCOM is a relatively newer technology compared to GFM BESS with less proven track record. However, it is gaining strong momentum in Europe and in particular among the four German TSOs who are considering a standardised +/- 300 Mvar design. A key reason for pursuing GFM STATCOMs is that they do not generate or consume MW, hence can be owned and operated by a network owner rather than a generation owner. The key objective is to provide inertia and suppress RoCoF under cascaded tripping and islanding conditions. However, it is noted that a standard STATCOM has much less storage than a BESS, therefore not as GFM capable as a BESS. Several design improvements have been pursued by the OEMs to provide improved storage, e.g., with the use of super capacitors. These STATCOMs with additional storage are sometimes referred to as E-STATOM. A further shortcoming of STATCOMs compared to the BESS is that there are not any already assessed and approved dynamic models for STATCOMs especially recognising the more extensive modelling requirement in Australia which often means that unless a model has been assessed against the Australian requirements and improvements have been made in advance, there is a strong possibility that it will not meet the requirement potentially adding to the project timeframe.

A different application of GFM STATCOMs compared to those pursued by German TSOs is Fingrid's initiative to install a GFM STATCOM and a SynCon in a remote part of their network with high penetration of IBR, similar to CWO REZ. This application is more similar to Transgrid's system strength procurement.

In summary, while GFM STATCOM has a great prospect, with an understanding that Transgrid needs to make an immediate decision based on the best information in hand, it is recommended not to consider GFM STATCOM until already approved models meeting Australian requirements become available.

3 Potential technical side effects

All inverter-based resources, GFL or GFM, will need to maintain their total current within safe levels to protect semiconducting switching devices. As discussed in Appendix A, depending on the design, GFM may or may not have a direct current limiter. For those with a direct current limiter, the inverter can act like a GFL inverter when the current limit is reached for example during fault conditions. Practical examples of such designs are known where the inverter will effectively switchover from the GFM to GFL during fault conditions, where the GFM capability might be most necessary. Even if an indirect current limiter is applied, in many cases GFM stability is degraded when operating at or above the rated current. Whilst it is proven that GFM Inverters can provide several grid support functions, it is important to note that a well performing GFM inverter from a stability standpoint is that operated at all times below the rated current. This may not make

[1] B. Badrzadeh et al., "Grid-Forming Inverters: Project Demonstrations and Pilots," in IEEE Power and Energy Magazine, vol. 22, no. 2, pp. 66-77, March-April 2024.

GFM inverters very attractive for meeting the minimum fault level requirements. However, it is suggested as the optimal way of utilising GFM's suite of capabilities rather than focusing on one capability whilst performance might be compromised in other aspects.

A general limitation of GFM inverters with regard to system stability is degraded performance under high system strength conditions. Noting the limitation of GFL inverters under low system strength conditions, this might seem counterintuitive, however, it can be readily explained by differentiating between current sources and voltage sources. GFL Inverters do not have the ability to form a voltage source and as such require connection to a relatively strong voltage source. The best performance can be achieved when connecting to an ideal voltage source. These devices come with excellent current control capability and do not require connection to a current source. The opposite generally applies to the GFM since they can form their own voltage source, but do not have the same tight current control exercised in the GFL, or if it is implemented it can adversely impact other aspects of system stability as discussed in the previous paragraph. This means that GFM inverters are most susceptible under strong grid voltage with a low impedance[2]. Such instabilities are not experienced in synchronous machines under high system strength conditions as the concept of loose/tight converter current control does not apply. Note that system instability with GFM inverters can still be experienced under low system strength conditions. However, most these instabilities are attributed to exceeding the maximum power transfer capability from a steady-state standpoint rather than inverter control susceptibilities.

Since GFM inverters are primarily aimed for low system strength conditions, the impact of this limitation might not be immediately pronounced. However, as several GFMs start to connect in currently strong part of the network, e.g., Hunter Valley, even if those nearby synchronous generators were to be withdrawn, there is still a possibility that high concentration of several large GFM BESS will result in similarly high system strength conditions which could adversely impact GFM's stability.

The last known limitation of inverters in general, is the possibility of very little or no injection under very low or very high, i.e., close to 90% residual voltages (as discussed in Chapter 2). Furthermore, fault current contribution can vary depending on steady-state operating conditions, making it more difficult to correctly account for GFM's fault current contribution for all conceivable operating conditions in fault current calculation engines. This is further discussed in Chapter 4.

4 Potential risks for Transgrid and AEMO

Table 4-1 presents a summary of key risks involved, recommended actions to better assess and address those risks and a materiality rating. Of the five risks presented, it is recommended that correct operation of protection systems remains a significant unknown with commensurate significant activities to be undertaken before sufficient confidence can be gained. It should be noted that the intent of this exercise is well above and beyond the provision of sufficient fault current for correct operation of overcurrent relays or fuses. There are several relay types who make a decision based on calculation of dynamic impedance or the amount of sequence components. The former is a challenge for synchronous or IBR dominated power systems if the system strength changes drastically for different operating conditions, e.g., from minimum demand to peak demand. The latter is not a concern for synchronous dominated power systems as the response of a synchronous machine to sequence components is inherent. In an IBR dominated power system, comprising GFL or GFM, the amount of positive- and negative-sequence currents injected depends on the response of control system and the availability of the total current. This cannot be assessed with sufficient accuracy using commercial fault current calculations or protection coordination tools. The use of an integrated EMT model accounting for dynamic models of the IBR, network, loads and importantly protection systems which likely be impacted will be a key step to identify any residual concerns and gain confidence in overall system security after making the necessary modifications where required. This will be effectively an enhanced wide-area PSCAD model with dynamic models of the necessary relays included. Examples of relays of importance from a dynamic perspective include impedance-based relays such as distance, out-of-step and loss-of-excitation

[2] Y. Li, Y. Gu and T. C. Green, "Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory," in IEEE Transactions on Power Systems, vol. 37, no. 6, pp. 4541-4554, Nov. 2022.

relays, and relays sometimes using negative-sequence current for decision making, such as differential, directional and overcurrent protection.

With regard to correct representation of GFM for static fault current calculation studies, it is understood that Transgrid has developed a process whereby fault current calculations using PSCAD dynamic models are fed into an RMS fault current calculation tool such as PowerFactory or PSS/E, effectively as a set of currents and voltages in a look-up table format. Whilst this approach is a step ahead and addresses some of the deficiencies of the built-in engines, there still remains some uncertainties as the GFM fault current contribution depends on the retained voltages, and the initial active and reactive power dispatch which is not straightforward to account for them all simultaneously. Furthermore, whilst these responses are based on OEM models, as discussed previously even for the same OEM, the response could vary to a large extent depending on which grid support functions are prioritised and the access standards aimed for, i.e., automatic vs negotiated. Notwithstanding this and without a detailed review of Transgrid's methodology it is our view that it is definitely a step forward relative to what is available in the industry. The above discussions aim to shed lights on the extent of the complexity and to raise cautions on full reliance on existing or improved methodologies for operational decision making.

Table 4-1: Summary of key risks

Correct operation of protection systems	▪ Very little or no studies with integrated wide-area dynamic and protection system models	
Magnitude and duration of fault current	▪ GFM can provide fault current for a longer duration. ▪ Installing GFM BESS of 2-3 times more MVA than that of SynCons might still be more cost effective	
Voltage change due to reactive plant switching	▪ Can be assessed with a very simple SMIB set-up	
Considerations for distributed IBR stability	▪ The same problem, if not more severe, will apply if using synchronous machines	
Lack of accurate GFM models/solutions in commercial simulation tools	▪ Power system analysis tools do not include correct models for GFM to perform fault current calculations. ▪ Responses could vary among OEMs	

5 Impact on revenue stacking

Key consideration when assessing the impact of a desired grid support function on revenue stacking is the current limited nature of GFM inverters as discussed in Chapter 3. GFM can provide many different capabilities, however, each require the use of some of the limited current available. Whilst GFM inverters provided by some OEMs can provide fault current contribution of up to 2 pu and even above, this comes at a cost, and the most widely used GFM inverters come with a capability which is at or just slightly above the inverter rated current. A prudent planning principle is therefore to assume that GFM inverters can only contribute up to their rated current. Furthermore, as discussed in Chapter 3, such an operation below the rated current even if GFM has a higher capability will assist in avoiding adverse effects on other aspects of GFM performance.

With this in mind, it is important to note that not all GFM capabilities can be provided at the same time because most these capabilities will rely on a portion of the total current, active or reactive as shown in Figure 5-1. This figure focuses on medium system strength conditions. The capabilities highlighted in green are those which are essential either to meet the generator performance standards (GPS) compliance or most required by the power system to which the GFM is connected. Those highlighted in orange are desirable but only to the extent that their provision does not compromise those highlighted in green. Those highlighted in red are not default capabilities and often come at a significant cost where a commensurate benefit may not be achieved.

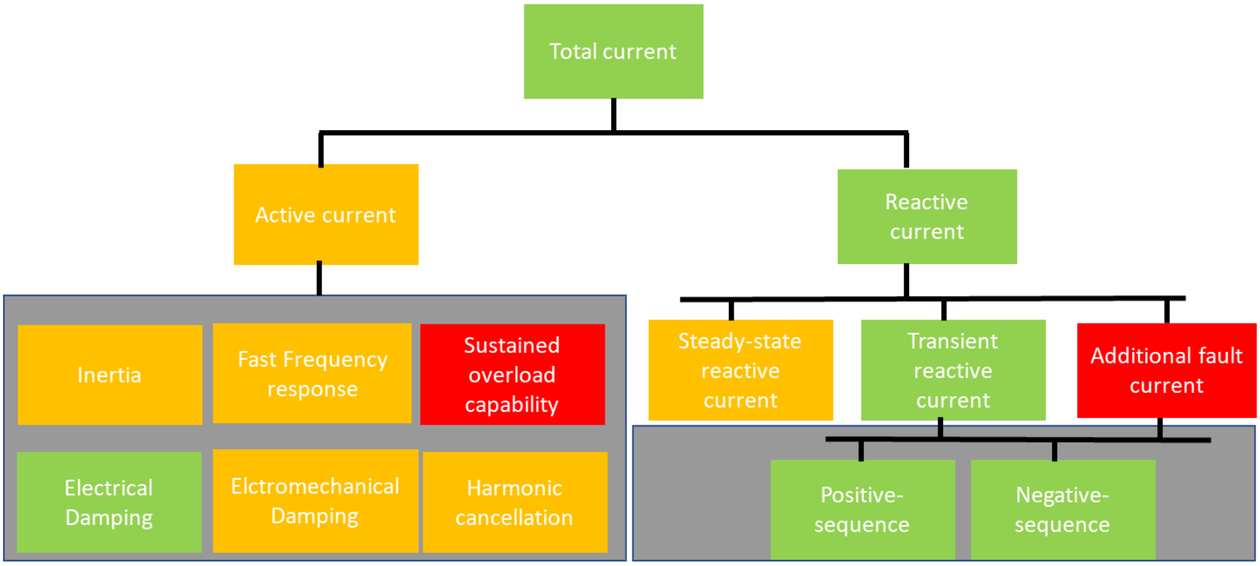

Figure 5-1 Fault current contribution of GFM BESS and SynCon (Source Babak Badrzadeh)

A ''switchover'' between the capabilities can be achieved, however, it means a more complex design, modelling and compliance studies. The aspects where the conflict in priorities due to the limited current is most likely to arise is the provision of FFR/inertia when there is a combined voltage and frequency disturbance.

Since BESS is the most widely used GFM technology this will also mean two further limitations:

- Limited time it can maintain sufficient charge and be ready to respond to the next event.
- A life cycle of ~1000 deep charges and discharges (this may vary from ~500 to ~3000)
  - Providing a large fault current will mean larger changes in both active and reactive current even under conditions such changes are not desired from a lifetime perspective, e.g., a rapid change in active current from zero to full discharge to provide a large current.

6 Recommendation on GFM's role in meeting System Strength Requirements

6.1 Minimum level

6.1.1 Discussion

Noting the risks discussed and as the impact and mitigation measures are not currently known deterministically, it is recommended to exclude GFM BESS and STATCOM from meeting the minimum level. This position can be re-assessed once those risks are assessed and mitigation measures are implemented (if required).

It should also be noted that using the GFM for the baseline level will likely result in thermal plant to withdraw from those dispatch intervals and the resultant long timeframe to come back online, therefore likely loss of other benefits of those thermal plant.

Lastly, it is noted that the use of a constraint is not option. This coupled with the impractically of fast dispatch of synchronous generators to address a dynamic instability, infers the need to gain sufficient confidence in GFM BESS response under those conditions before relying on them to contribute to the minimum level even at a partial capacity.

6.1.2 Timeframe and percentage of deployment for minimum level

Table 6-1 presents different scenarios as function of GFM percentage deployment, the likely timeframe for implementation and associated risks for meeting the minimum level. Risks considered include:

- Power system security
  - A Fundamental principle in power system protection is for protection systems to operate where they should and do not operate where they should not. An inability to meet these criteria could result in involvement form protective relays in non-faulted part of the network, and disconnection of a larger number of elements than actually required. This could cause system insecurity in particular where the unintended disconnections include major generation or critical transmission lines.
- Safety
  - A further concern with an inability to detect a fault is that faulted elements will remain energised with a concern on health and safety.
- Ongoing compliance
  - Should a notable mismatch be identified between the real system measurements and simulation which do not currently account for the behaviour of the protection systems or even possibly the fault current contribution itself, this could impact both the plant owner and the system strength service provider (SSSP). This might mean that the plant owner will be non-compliant with respect to their agreed GPS whereas the SSSP/TNSP could become non-compliant with their ability to maintain system standards. Furthermore, system operation with minimum number of any types of units, including synchronous machines, requires deliberation and evidence gathering before it can be fully operationalised. For example, the full role out of the four synchronous condensers in South Australia nearly took two years before AEMO and ElectraNet gained the necessary confidence and this was with a much simpler synchronous condenser technology. Including GFM in the minimum level might mean that these plants will not be even able to meet their agreed GPS due to the potential interactions with other control systems including those of other GFMs. While such issues may be understood and overcome by detailed studies and control system tuning, the time required for a system-wide and coordinated response would likely be in the order of 2-3 years than 2-3 months.
- Quality of supply
  - Synchronous machines do not generally inject harmonics, flickers and voltage unbalances into the power system. Furthermore, they act like a sink for some harmonics including some of the significant ones such as the second harmonic. A replacement of some synchronous machines with grid-forming inverters will substitute non-emitting synchronous sources with emitting GFM. Whilst GFM has the capability to cancel out certain harmonics, the impact on the total current available and the resultant trade-off with other important capabilities each requiring a part of the same total current should be carefully considered.

These timeframes are in Financial Year, i.e., 2033 GFM % starts on 1 July 2032, and relate to estimated timeframe for the necessary activities within that period:

- 2027: to complete an integrated dynamic and protection modelling in PSCAD, and identify areas of potential concern

- 2030: to develop solutions for the problems identified in 2027 and uncover any other residual risks
- 2033: to develop solutions for all problems identified including potentially developing new relay types do not currently exist.

The percentages indicated in the table correspond to the maximum cap on GFM's contribution to the total solution. Note that the use of the 50% uptake in different time horizons is provided as an example to convey the key message on relative risks involved. With the information in hand such a percentage cannot be determined with any accuracy, and using different percentages will not change the key message which is the risk rating in each period.

Table 6-1: Percentage deployment of GFM to meet minimum fault level requirements and associated risks

Risk level	2024 GFM %	2027 GFM %	2030 GFM %	2033 GFM %
Very high risk	50	50	0	0
High risk	0	50	50	0
Moderate risk	0	0	50	50
Low risk	0	0	0	100

Transgrid is recommended to adopt the low-risk approach for the immediate procurement.

6.2 Efficient level

Assuming that the minimum level is provided by synchronous generators and condensers only, GFM can have a key role in meeting the efficient level. This is indeed akin to the current inertia requirements. Furthermore, it is noted that the use of a constraint, whilst undesired, is a practical last resort option which can ensure that the power system will return to a secure operating state.

Another differentiator with the minimum level is that individual component and wide-area power system models already exist to assess whether the GFL, GFM and the overall power system can maintain stability if the additional hosting capacity is provided by the GFM only or to a substantial extent. This can be assessed with individual and wide-area EMT models, and does not rely on less established fault current calculation methods for the GFM. Furthermore, since correct operation of the protection system is ensured via the minimum level, integration of dynamic models of protection systems is not essential.

Several public domain publications exist including separate works conducted by AEMO and Powerlink demonstrating equally good or better contribution of GFM BESS in releasing hosting capacity of GFL IBR compared to a SynCon. There is also prior experience of commercial procurement for a very similar application set out in VicGrid's Renewable Energy Zones Development Plan in 2021.

7 The merit of introducing operational transition points

The use of operational transition points can be considered as a gradual way of increasing the deployment of GFM, reducing the number of online synchronous machines or a combination. This will allow gaining sufficient confidence during the commissioning, R2 testing and ongoing operation of a limited number of GFM before a widespread role out.

This section assesses the merit of introducing such operational transition points for each of the minimum and efficient levels. It is recommended that for the efficient level there are much less unknowns and risks that must be overcome before GFM can be considered at a substantial scale. Furthermore, from an economical perspective GFM inverters with a noticeably higher total MVA rating compared to that of SynCons might cost the same or even lower. A transition point of GFM inverters contributing up to a maximum cap of 50% of the solution for the total efficient level is recommended. This recommendation accounts for the fact that to date GFM have not been used at any scale for meeting the efficient level, and aims at striking a balance between a sizeable deployment of GFM, minimising the risk of known and unknown unknowns, and avoiding the frequent curtailment of GFL IBR in practice. Secure and reliable power system operation with higher percentages of GFM may be possible once determined by further studies and system-wide testing at a range of system strength conditions. The proposed approach and associated ‘’safety net’’ will ensure that the trajectory will be continually upward giving the industry the necessary confidence for planning and investment without bearing a large risk, for example associated with the short-notice curtailment, that could pertain to a 100% GFM contribution from the beginning.

This complementary use of GFM and SynCon, whilst more expensive than using 100% GFM, would be prudent to maximise the collective technical capability of the two devices. For example, SynCons can be used for their inertia contribution whereas GFM can be prioritised for the faster speed of response to disturbances, and comparable system strength enhancement capability.

For the minimum level, it is recommended that any such transition points should be milestone based rather than relying on specific IBR, whether GFL or GFM, penetration levels. These milestones were set out in Chapter 6. Furthermore, it would be prudent to consider large-scale trails for various system operating conditions as far as practically possible, ideally in high, medium and low system strength part of the network, and close, mid-distant and far from the respective system strength node.

Appendix A: Technology review

This section briefly introduces GFM controls and then presents a comparison of GFM inverters and synchronous generators.

Potential GFM controls

Figure 7-1 shows a consolidated view of the suite of control functions for a GFM inverter. This is to highlight all conceivable capabilities, however, it does not suggest that all GFM inverters will or should have all these capabilities for all applications. The required capabilities could differ from one make/application to another. The use of largely independent control loops allows selecting/deselecting the required capabilities consistent with the specific project and power system needs.

Of control loops presented, voltage control is the fundamental building block of all GFM makes. All other control loops are optional and even when implemented they may be placed differently to that shown in Figure 7-1. A detailed description of each control loop is outside the focus of this report. However, particular attention should be made to the inner current control loop implemented by some OEMs. This will play a key part in determining the GFM fault current contribution being the key focus of this report and will be discussed later in this report.

As shown in the figure the inertia provision can be substituted or augmented by either of the fast frequency response (FFR) or frequency containment functions whereby:

- FFR involves a change in active power output of the inverter proportional to a drift in the frequency from its nominal value, e.g., 100% change in BESS output for a 1 Hz change in the frequency. An end-to-end response time of a few hundred milliseconds is achievable (typically ~200 ms or slower), making it approximately an order of magnitude faster than the turbine-governor control for synchronous generators.
- Frequency containment is the near instantaneous increase in inverter's active power output once the frequency hits a certain threshold.

Both the FFR and frequency containment can be provided by a GFL or GFM inverter.

Not all the three services can be maximised at the same time and the provision of one capability could adversely impact others as the total active power provided is limited by the current capability of the inverter. Deliberation is therefore required to prioritise the order by which these three capabilities will be provided noting that the provision of inertia is not mandatory nor inherent for a GFM inverter, and can be reduced or removed altogether if required.

Experience from Australia's National Electricity Market (NEM) indicates that at present FFR is equally if not more valuable relative to inertia in general[3]. This is because such a response cannot be provided by a synchronous generator, and it offers significant saving in the amount of frequency control required otherwise. This FFR is particularly important when operating in a permanent or sustained electrical island. The need for virtual inertia may become more important as more synchronous generators will retire in the future, however, an assessment of system needs is always required considering the flexibility a GFM inverter provides compared to a synchronous generator.

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[3] [1] B. Badrzadeh, N. Modi, N. Crooks, A. Jalali, "Sustained islanding operation of a normally interconnected power system with a high share of inverter-based resources – South Australian experience", CIGRE Science & Engineering Journal, CSE No 21, June 2021.
[2] A. Jalali, E. Farahani, M. Delac, N. Modi, "Impact of Grid-Forming Inverters on Frequency Control of a Grid with High Share of Inverter-Based Resources", CIGRE Science & Engineering Journal, CSE No.31, December 2023.

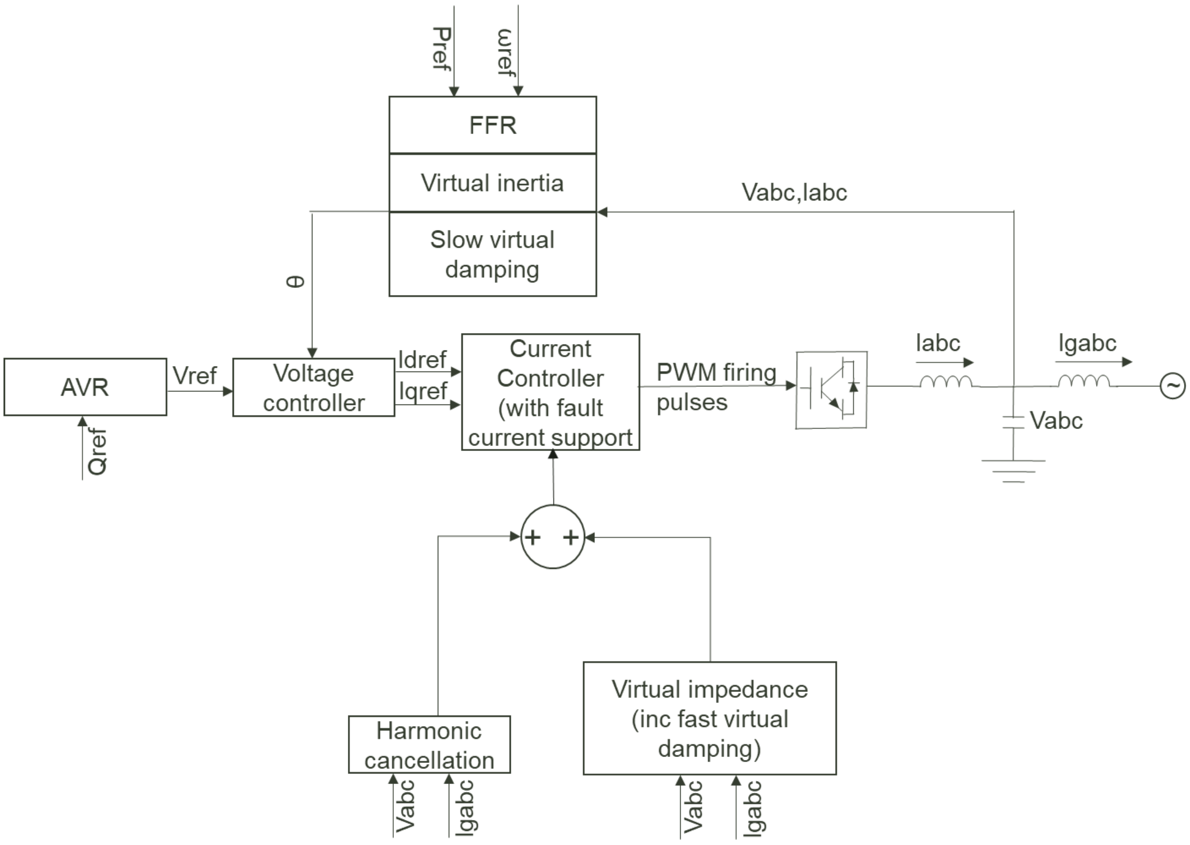

Figure 7-1 Comprehensive GFM inverter control features

GFM inverters vs synchronous generators

Table 7-1 provides a comparison of synchronous generators and GFM inverters from a grid-support perspective. GFL inverters are excluded from this comparison due to their limited range of grid-support capabilities.

In summary, it can be observed that GFM inverters can provide similar or even better grid-support compared to synchronous generators in all aspects where the response is determined by the control system design and tuning. The key two aspects where gird-forming inverters may fall short of synchronous generators are:

- Fault current contribution
- Black start capability
- Overload capability

This is because these aspects are dependent on both the control system response, and the hardware design. A comparable fault current contribution/overload capability to that of a synchronous generator, and an equally good if not superior black start performance can be achieved by the GFM BESS. However, this may come at the cost of additional semiconducting switching devices, or the need for a BESS with high MWh capability. The need for both these characteristics can be largely reduced with judicious choice of restoration path energising synchronous generators and GFL inverters along the way[4]. Lastly, note that not all synchronous generators are blackstart capable.

Other notable differences between a GFM inverter and synchronous generator include:

- Controllable and adjustable response of the GFM inverters as opposed to a fixed response. For example, the virtual inertia provided by a GFM inverter can be tailored to meet the needs of the power system to which it is connected, and can vary by a wide range.

[4] G-PST Topic 5 Stage 2: The role of inverter-based resources during system restoration, July 2023, available at: https://www.csiro.au/en/research/technology-space/energy/G-PST-Research-Roadmap/Final-Reports

- Unlike a synchronous generator where most capabilities are provided largely as an inherent bundle without the opportunity to add or remove any, each GFM BESS project can be designed based on specific needs of the power system to which it is connected to include some or all of the grid-support capabilities.

For applications where a GFM inverter is intended to replace the need for a local SynCon for system strength support, power system modelling is required to determine their relative MVA size to achieve the same performance. However, as discussed above the highly controllable response of GFM inverters provides an advantage. Additionally, the following two benefits are noted for this application of GFM inverters:

- Unlike a SynCon, a GFM BESS can charge/discharge whilst assisting other nearby inverter-based resources (IBRs) to operate stably. This will allow participation in the energy and ancillary services markets subject to energy availability and total current limitations.
- Typically, GFM BESS have a shorter construction and commissioning time allowing faster connection of GFL IBRs.

Care should be exercised when emulating the response of a synchronous generator as it might mean that a GFM inverter might inherit some of the inherent susceptibilities of a synchronous generator, e.g., rotor angle instability for light and remote synchronous generators, that would not pertain to a GFM inverter if it is not controlled to exactly replicate the behaviour of a synchronous generator.

Table 7-1: Comparison of synchronous generators and GFM inverters from a grid-support standpoint

Attribute	Synchronous generator	GFM inverter
Inertia	Inherent and constant between 1-10 s	Controlled and variable between 0-10 s and more subject to the availability of the total current[5]
Contingency frequency control response time	Typically 1-6 s[6]	Typically a few cycles
Frequency containment	With inherent inertia and slow contingency frequency response	Fast and nearly instantaneous increase in active power output once the frequency hits a pre-defined threshold
RoCoF suppression	With inherent inertia	A combination of emulated inertia and FFR
Fault current provision (excluding peak current)	2-3 pu[7]	Typically 1-1.5 pu (with several OEMs quoting 1 pu). The capability can increase to 2 pu or slightly above, and there are some practical examples of such provisions[8]. However, this will mean that the product will be significantly more expensive.

[5] A higher inertia can be delivered if required subject to the current limitations of the inverter also recognising that this might impact the provision of other capabilities in particular FFR.
[6] The timeframe quoted is for the controlled aspects of the response provided by the turbine-governor. The uncontrolled and inherent inertia response which is much faster will also provide some contribution in responding to the frequency event.
[7] Quoted at the high-voltage side of the unit transformer.
[8] Note that these values are generally quoted at unit terminals since the contribution at the connection point could vary significantly depending on the balance of plant design. However, the frame of reference in this report as well as for compliance assessment is the connection point. Practical experiences of GFM BESS, including ESCRI project, exists who have been able to maintain a similarly high fault current contribution between the unit terminals and the connection point, and this can be achieved with judicious design of balance of plant. However, it cannot be taken for granted in particular noting two levels of transformers in a typical BESS project compared to one level only for a synchronous condenser.

Negative-sequence fault current control	Inherent	Controlled
Zero-sequence fault current control	Dependent on neutral grounding method and the grounding impedance	Via wye-grounded/delta transformers
Damping of low frequency electromechanical oscillations	With PSS	With slow damping or virtual impedance control loop
Damping of low frequency electrical oscillations	No direct mechanism	With fast current control loop
Blackstart capability	▪ Possible with the use of trip-to-house-load or a small cranking machine, e.g., a diesel unit. ▪ Storage is not a major concern	▪ Storage is a major consideration
System strength susceptibility	The risk of angular instability for light synchronous generators in remote areas	▪ Similar risks if the response of a synchronous generator is closely emulated without considering the side-effects. However, the risks/instabilities pertaining to conventional GFL inverters do not apply. ▪ An advantage compared to a synchronous generator is that the balance between the input and output power can be very quickly re-established following a disturbance as no mechanical components are involved. Also a higher inertia than that of a synchronous generator can be programmed with some GFM designs if required.
System strength enhancement	Possible	Possible
Harmonic behaviour	Sink for harmonics	▪ Source for harmonics, but deliberate control is possible to reduce/cancel out its own harmonics or harmonics present in the network. ▪ Note that this feature does not impact the dynamic response at the fundamental frequency and sub-synchronous frequencies. However, care is required to limit the total current used for this purpose such that the overload/fault current capability of the inverter is not reduced substantially.

Islanding operation	Possible with the use of isochronous control for the black start/anchor generator, and frequency droop for other generators.	Several GFM designs can withstand the loss of main creating an island without any synchronous generators. Different control system modes and settings are usually invoked during islanding conditions. Compliance with statutory clauses for the grid-connected mode is not generally possible under islanding conditions.
Ease of modelling, testing and operation in multi-plant configurations	Established principles as synchronous machines do not involve in any adverse interactions amongst each other or with other plant	Less established processes and principles due to the possibility of adverse control interactions between the nearby GFL and GFM, as well as among GFMs

Appendix B: GFL vs GFM vs GFL + SynCon

Table 7-2 provides a high-level comparison of the GFL and GFM with the hybrid of GFL and SynCon. Despite several performance differences, the hardware used by a given OEM for their GFL and GFM is generally similar or the same unless certain capabilities such as additional fault current provision are sought from the GFM. The key difference between the two inverter types is the way by which they are controlled.

Notable differences between a GFM and SynCon include:

- Controllable and adjustable response of the GFM as opposed to a fixed response. For example, the virtual inertia provided by a GFM can be tailored to meet the needs of the power system to which it is connected, and can vary by a wide range.
- Unlike a SynCon where most capabilities are provided largely as an inherent bundle without the opportunity to add or remove any, a GFM BESS can provide some or all of it possible grid-support capabilities depending on the system needs and the priority of the services required.
- Typically, GFM BESS have a shorter construction and commissioning time allowing faster connection of GFL IBRs.

GFM can provide a comparable grid-support response relative to the hybrid option in several aspects where the response is determined by the control system design and tuning. However, it is noted that the hybrid option will have the highest installed MVA capacity of all options considered, and therefore has the highest steady-state and dynamic reactive power capability.

Table 7-2: High-level comparison of GFL and GFM, and hybrid of GFL and SynCons

Attribute	GFL	GFM	GFL + SynCon
Low system strength susceptibility	Several demonstrated experiences, however, OEM capabilities have been evolving.	■ Relatively much less susceptibility compared to GFL. ■ Risk of angular instability if the response of a synchronous generator is closely emulated without considering the side-effects. ■ Coupling between voltage and frequency under low system strength conditions will mean that the provision of FFR could result in a voltage collapse.	The use of the SynCons provides the flexibility for tuning control system parameters of the BESS without the need for trade-offs with other technical requirements.
Background system strength enhancement	Limited experience	Comparable. A GFM can sometimes provide an even better system strength support subject to control system tuning. However, this may come at the expense of adversely impacting compliance with technical requirements.	
Independent islanding operation	Not possible	Possible with several GFM OEMs	Likely possible but more challenging than that of a synchronous generator with a governor control and the switchover between the droop and isochronous control. This will also be more challenging than that provided by the GFM.
System restart	Not possible	Possible if sufficient storage (MW and MWh) is available	Likely possible with a combination of SynCons and GFL BESS
Fault current support (for successful operation of protection systems)	Limited to at or slightly above the nominal current, e.g., 1.0-1.5 pu.	Limited to slightly above the nominal current, e.g., up to 1.5 pu, with some OEMs providing higher capability of up to 2 pu with the use of oversized inverters	Will provide the highest fault current due to having the largest MVA size, and higher pu fault current contribution of SynCons compared to GFM (SynCons are expected to provide a fault current contribution of 2-3 pu).

General overload capability	Very little or no capability	Other than 2-3 OEMs with specialised GFM designs, for most other OEMs the GFL and GFM are comparable in this regard.	Similar to the GFL option except that SynCons will have good overload capability with regard to the reactive power.
Fault ride-through (FRT) capability	The rise and settling time and K-factor have been generally the key challenges. However, the new rules have made the compliance much easier.	Not all GFM design have been programmed to use the concept of K-factor. Compliance can therefore be sometimes challenging.	Best performance compared to the other two options due to the use of the largest total installed MVA capacity.
Negative-sequence fault current control	Offered by most OEMs, however, limited by the total current capability of the inverters	The same as for GFL option except that a potentially higher total inverter current would provide more flexibility and slightly a higher contribution.	Inherent response of SynCons which are a sink for the negative-sequence current.
Inertia	Not provided	▪ Can be provided with all except one OEMs surveyed who utilise swing equation-based implementation to emulate the response of a synchronous machine. ▪ Controllable within a wide range with some OEMs quoting 0-100 s. (The upper range is much higher than that of a synchronous machine). However, provision of a such a high inertia can adversely impact compliance with technical requirements.	Inherent and constant inertia of SynCon ranging between 1-10 s. The use of a round rotor machine will generally limit the inertia to below 2 s. This can be increased, e.g., around 6 s, if a salient pole machine is used. The use of a flywheel provides a higher inertia as sometimes used for round rotor machines.
Fast frequency response	Default capability	Default capability. However, care is required on how much of the total current available will be allocated to other grid support services such as inertia, and how much is left to provide the FFR. A case-by-case prioritisation of various possible grid support opportunities is required.	The same as that with the GFL option as the SynCons do not impact FFR.
RoCoF suppression	Limited with FFR only	A combination of virtual inertia and FFR	A combination of physical inertia and FFR

Network harmonic cancellation	Possible but no commercial products were found as it is less straightforward to implement than that with GFM.	▪ Possible with a few OEMs already providing commercial products. Similar to a GFL, a GFM is a source for harmonics, but deliberate control is possible to reduce/cancel out its own harmonics or harmonics present in the network. ▪ Care is required to limit the total current used for this purpose such that it does not adversely impact other aspects of technical requirements.	The same as that for GFL option, except that the SynCons will provide inherent control of the second harmonic.
The need for harmonic filters	To be determined on a case-by-case basis.	The capability to supress certain harmonics is already available, however, has not been offered in any of the commercial projects to date.	The same as that for the GFL option
Active damping of low-frequency electrical oscillations	Limited experience	Possible with fast current control loop, however, this approach is not adopted by many OEMs.	The inherent response of SynCons will achieve a similar response to that provided by controlled response of GFM
Active damping of low-frequency electromechanical oscillations	Possible but there is no demonstrated experience	Possible but there is no demonstrated experience. The use of the GFM will unlikely provide any added benefits.	SynCons with a Power System Stabiliser (PSS) have been proposed by multiple OEMs and implemented in Europe.
Steady-state reactive power capability	No appreciable difference exists between the two technologies		This option will have the highest MVA installed capacity of all options, and therefore the highest Mvar generation/absorption capability

Complexity	Electrical control is well-understood by the OEMs. However, complexity arises in the event of adverse interactions with third party assets such as other IBRs	▪ No appreciable complexity if a GFM with minimal grid support functions is chosen. ▪ Proceeding with multiple grid support functions and the need for additional modelling and studies will make it slightly more involved. However, considering the likely benefits the moderate complexity is warranted.	▪ A more complex voltage control strategy coordinating the response of the GFL and SynCons. ▪ Additional time for modelling and grid-connection studies due to the use of two types of equipment.
PSS/E model maturity	Mature	Several OEMs do not have reliable and accurate PSS/E models	Mature for both the GFL and SynCons
PSCAD model maturity	Mature	Often available and mature. Addition of new features could impact model re-development; however, the risk is limited for established OEMs who develop their PSCAD model directly from the actual plant control code. However, there will still be some risks if proposing novel grid support opportunities or when there is a need for several parameter changes within the control system.	Mature for both the GFL and SynCons

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