Grid Forming BESS

Fault Current Contribution Study Scope

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Executive Summary

The Australian Energy Market Operator (AEMO) has initiated a work package to investigate the capability of grid forming (GFM) inverters to contribute to system security services, specifically their potential contributions towards helping meet minimum levels of system strength. At present, GFM inverters are effectively excluded from supporting the requirements, as their fault current contributions are not formally recognised. Synchronous machines are therefore the only practical solution available at the present time to satisfy system security criteria. This reflects a lack of confidence and limited industry wide understanding of GFM inverter capabilities.

AEMO is seeking to build a clearer understanding of both the capabilities and limitations of GFM inverters, with the objective of including this technology in future system strength assessments if it is deemed to be capable. Amplitude has been engaged to develop a *Scope of Study* that sets out an investigative framework for identifying and assessing the capabilities of GFM inverters.

This report has explored the potential contributions of GFM inverters to system strength, with a particular focus on fault current contributions to support network protection operation. While it is widely recognised that GFM inverters possess this capability, published literature highlights limitations and variability in their fault response characteristics, especially for unbalanced conditions, which need to be carefully considered. These limitations pose challenges for conventional protection schemes and necessitate detailed EMT studies and iterative tuning to validate their performance. In short, there are additional issues beyond a simple assessment of fault current magnitude that require attention.

To address these challenges, the report proposes a *Scope of Study* that includes simulation-based, hybrid, and hardware-in-the-loop (HIL) investigative methods to examine GFM inverter characteristics and impacts on network protection. The approach provides a structured pathway to validate and better define the fault current response that can be reasonably expected across the range of technical solutions available, as well as any associated issues. By considering the different tuning strategies of various original equipment manufacturers (OEM) and systematically evaluating different fault scenarios, the study aims to determine whether some or all GFM inverters can be credibly included in minimum system strength assessments going forward.

The *Scope of Study* describes the following key tasks that should be undertaken collaboratively between AEMO, OEMs, and industry stakeholders:

1. Cooperate with OEMs to define and validate GFM inverter performance requirements.

   Engage with OEMs to access detailed inverter models and support tuning activities, particularly for fault ride-through (FRT) and current boost functions that influence fault current contributions. Examine available evidence of measured FRT behaviours that might be available for already in-service equipment.

2. Adopt EMT-based assessment frameworks for fault and protection studies.

   Promote the use of EMT models and tools for fault current and protection analysis noting that RMS platforms are inadequate for assessing the performance of inverter-based resources (IBR) during unbalanced network disturbances, as well as for high penetration scenarios.

3. Look to utilise HIL test methods to validate protection relay operation.

   Where practical to do so, conduct HIL testing to validate protection relay performance under realistic network fault conditions which include varying levels of contribution from GFM and grid following (GFL) inverters. Where HIL testing is deemed not possible, revert to PSCAD as the next best alternative.

4. Standardise fault current requirements.

   Develop and adopt standards that define the fault current characteristics required of GFM inverters to enable them to be considered in minimum system strength assessments. This would help promote consistency across OEMs and assist with future protection design activities.

5. Conduct wide-area network studies.

   Use validated GFM inverter models in National Electricity Market (NEM) wide EMT studies to evaluate their impact on minimum system strength related issues across regions, using recommended fault scenarios to validate their benefits.

These recommendations form the foundation of the proposed assessment framework that can support the future integration of GFM inverters into system strength planning.

1. Introduction

1.1. Objectives

The Australian Energy Market Operator (AEMO) has initiated a work package to assess the capability of grid forming (GFM) inverters to contribute to system security services, specifically their potential contributions towards helping to meet minimum levels of system strength. A key consideration in determining the required minimum system strength at a system strength node (SSN) is the impact on network protection, both in the transmission network, as well as for downstream distribution networks. Looking ahead, as large thermal generators continue to retire, a major challenge will be the progressive reduction in system strength, resulting in changes to fault current characteristics that are observed by protection relays.

At present, GFM inverters are effectively excluded from contributing to the minimum system strength requirements as their contributions are not formally recognised. Synchronous machines are the only accepted source of fault current contributing to system strength. This reflects the present lack of confidence and limited industry wide understanding of GFM inverter capabilities.

Through this work package, AEMO is seeking to build a clearer understanding of both the capabilities and limitations of GFM inverters, with the objective of being able to include such devices in all aspect of system strength planning if they are assessed as capable.

AEMO has engaged Amplitude to develop a *Scope of Study* that sets out an investigative framework for identifying and assessing the capabilities of GFM inverters. It is anticipated that AEMO will then initiate a second stage of work, in which this *Scope of Study* will be applied to determine the potential role of GFM inverters in contributing to minimum system strength.

1.2. Deployment and recent advances of GFM inverters

The deployment of inverter-based resources (IBR) is now well established, particularly for solar and wind farm connections. In such applications, the inverters typically operate using a grid following (GFL) topology, which synchronises to the grid via a phase-locked-loop (PLL). The grid voltage phase angle is used as the reference. GFL inverters exchange active and reactive power with the grid by adjusting the reference point through direct current control. Consequently, being able to reliably track the grid voltage phase angle is critical to their operation, both in pseudo steady state operation as well as during network disturbances. The nearby presence of synchronous machines greatly assists the performance of GFL inverters by helping maintain a more stable voltage reference, reducing the risk of PLL and inverter maloperation.

While GFL technology is already widely deployed in Battery Energy Storage Systems (BESS), solar and wind farms, static compensators (STATCOM), and high voltage direct current (HVDC) systems, the use of GFM is still somewhat limited. To date, BESS installations have been the most readily available commercial application, noting however that original equipment manufacturers (OEM) are trialling GFM across a variety of other platforms. It should be noted that GFM inverters depend on the availability of stored energy to deliver their distinctive capabilities which include inertial response and fast frequency support.

Another factor driving the wider deployment of GFM inverters is their proven ability to operate in networks exhibiting a low short circuit ratio (SCR). They have been demonstrated to function effectively and reliably with SCR as low as ≈1.2 and are also able to support the correct operation of nearby GFL inverters. Consequently, their use in standalone energy storage installations, as well as hybrid configurations alongside other IBR generation, offers a practical and cost-efficient alternative to conventional system strength remediation. GFM inverters are already an accepted solution for helping meet the 'efficient level of system strength' as referred to in AEMO's *System Strength Requirements Methodology*[1]*.*

While many OEMs are now offering GFM solutions, there can be notable differences in the hardware design and control algorithms which can vary their overall response. Differences can directly influence the shape and characteristics of the current waveforms injected during fault events, and in turn affect their ability to contribute to minimum system strength requirements. It is such uncertainties that have so far precluded GFM inverters being considered for this role.

2. Background research

2.1. Literature review

This section presents an overview of several investigations that have been carried out to examine the impacts of IBR fault current characteristics, including those coming from GFM inverters, on network protection systems. Although published work on this topic is limited, the identified references have provided valuable insight.

2.1.1. Sandia National Laboratories

Sandia National Laboratories, in collaboration with several IBR and relay manufacturers, transmission system operators, and consultants, conducted a study to investigate the practical issues encountered when protection relays detect fault current from IBRs during unbalanced fault conditions [1].

The study was motivated by concerns including:

a. The lack of adequate IBR models in commercial short-circuits analysis tools.

b. At least two relay maloperations in North America attributed to unexpected IBR responses during unbalanced network faults.

c. The absence of standardisation on the topic.

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[1] Available online at: www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-strength-requirements/system-strength-requirements-methodology.pdf

Findings indicated that the unbalanced fault current characteristic of some IBRs was insufficient to ensure reliable operation of conventional protection relays when 'typical settings' were applied.

Outcomes were observed to vary across IBR manufacturers, indicating that alternate, but uniform protection relay setting practices may also not ensure system security.

The authors noted that the positive-sequence current contribution for balanced faults is relatively well understood and RMS platforms can model this behaviour with reasonable precision. However, simulation of unbalanced fault conditions involving negative sequence components lack accuracy and understanding, necessitating the use of EMT studies with detailed inverter models, which became a primary focus of the research.

A summary of the key research findings is as follows:

a. When a 'strong test grid[2]' was connected to the IBR equipment being examined, all relays operated as expected for all simulated faults.

b. During weak grid operating conditions, the following occurred:

   - Relay operation varied depending on the OEM model of the IBR that was used.
   - Using the IBR of OEM 1, the relays did not trip as expected for ground faults. However, the relay pickup indicated that detection and tripping would have been possible with alternative elements or settings. For line-to-line faults, the relays failed to operate due to transient impacts on the elements.
   - Using the IBR of OEM 2, the only fault that did not result in a relay trip was the balanced fault. In other cases, tripping was initiated by unexpected relay elements.
   - The negative-sequence current magnitudes from the IBRs were often too low, necessitating overly sensitive relay settings.
   - Variations in the frequency of the negative-sequence current and voltage, and resulting phase angle variations, prevented directional relay elements from operating reliably.
   - Some IBR models exhibited delayed fault current injection, resulting in protection trips occurring beyond expected time windows.
   - The relays did not always correctly identify the faulty phase (noting the potential implications for single pole auto-reclose (SPAR) schemes and momentary open pole operating conditions).
   - When the frequency of the current waveform was determined by the local IBR controller and voltage frequency determined by the remote synchronous generators, the resulting frequency difference caused reverse-directional and distance elements to operate unreliably.
   - Overall, 16 of the 32 tests conducted showed unexpected relay behaviour.

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[2] A strong grid being one where a significant contribution of 'system strength' comes from traditional synchronous machines.

It is worth noting that as of Version 234, the National Electricity Rules (NER) does not have specific requirements for negative-sequence current injection. In practice, this characteristic is typically tuned on a project-by-project basis according to the requirements of the local network service provider (NSP), with the focus being management of potential over-voltages on healthy phases during unbalanced fault events. Often only a ratio of negative to positive-sequence current is requested but rarely evaluated. This lack of regulation leaves negative-sequence fault current behaviour highly variable across IBR plants.

Examples of alternate approaches included German VDE Standards AR-N-4120 and AR-N-4130 which now define requirements for both positive and negative-sequence current injections for unbalanced faults.

The Sandia report recommended standardising IBR responses to unbalanced fault conditions and including EMT studies in interconnection assessments to evaluate the adequacy of network protection. It was noted that developing a consistent and standardised IBR fault current characteristic would also simplify future protection scheme selection and design, and the development of new relay setting practices.

2.1.2. Aurecon

Transgrid engaged Aurecon to provide advice on the ability of GFM inverters to help meet system strength requirements, with a specific focus on BESS and STATCOM applications [2]. The primary objective was to determine whether GFM inverters could be credibly considered for addressing one or both system strength criteria.

The authors provided descriptions of known examples where the fault current contributions from GFM inverters were increased by adjusting the relevant FRT settings. However, the authors noted that "*inverters operating at currents higher than rated might face stability issues or might have to switch from GFM to GFL for direct control of current during the fault when GFM features are most needed*". This suggested that deliberately tuning GFM inverters to maximise fault current support could have implications on other performance characteristics and that trade-offs may be necessary if such a strategy was widely pursued.

The authors also cited many of the same issues described in Section 2.1.1 in not supporting the immediate inclusion of GFM inverters in minimum system strength assessments. Issues mentioned included negative sequence current limitations, ability to detect and respond to shallow faults, and general lack of evidence / confidence in GFM inverter performance under a wide range of real-world operating conditions (inclusive of network disturbances).

The report recommended that Transgrid postpone the inclusion of GFM inverters in minimum system strength calculations until 2033 to allow time for all uncertainties and risks to be properly investigated and resolved. Nevertheless, the report recommend including GFM inverters in efficient level calculations due to their proven benefits of increasing IBR hosting capacity, while relying on synchronous machines to meet the minimum system strength requirements.

2.1.3. Investigations of GFM inverters operating in distribution and islanded networks

The challenges and potential solutions for protection relay fault detection when relying solely on GFM inverters has also been explored in distribution system applications [3]. In this conference paper, a BESS plant using GFM inverters was operated in two modes, being grid-tied and islanded. The main finding was that protective relays using inverse-time overcurrent elements (ANSI 51) must distinguish between the network operating modes to correctly detect and trip for downstream fault events. An adaptive protection method was subsequently proposed whereby voltage-based protection is activated when the BESS plant is operated in islanded mode. HIL test methods were implemented to validate the proposed approach using physical protection relays.

The authors identified hardware limitations, such as silicon limits, thermal limits (cooling system), and battery constraints, as well software limitations, including inverter-level protection limits, as key factors contributing to the low fault current contribution from the GFM inverters in the BESS plant.

Similar to [3], another study documented in [4] investigated a novel protection scheme for detecting faults supplied by GFM inverters BESS plant in an islanded microgrid. The authors proposed a superimposed phase-current scheme with a voltage-restraint element. This approach uses differential overcurrent logic by subtracting the current waveform at the present time from the same waveform delayed by four cycles. To avoid false tripping due to load step changes, a voltage-restraint quantity is applied, calculated from the phase voltage magnitude using FFT and activated if this voltage falls below 0.8 p.u.

Another example of similar work undertaken by Quanta Technologies involved investigating islanded operation of 2 x 2.5 MW GFM BESS units supplying a 1.8 MW load [5]. Both islanded and grid-connected modes were tested, with a wide range of disturbance events considered in each mode including motor starting, transformer energisation, load rejection, capacitor switching, and various fault types (single line to ground, line to line, three phase to ground). For balanced faults, the relays performed as expected, with multiple elements operating correctly. While the results of other fault cases were not detailed in the presentation material, the conclusions indicated that several of the originally designed protection schemes (and settings) required modification between grid-connected and islanded mode to ensure reliable relay performance when solely relying on the GFM BESS units.

While transmission and distribution network protection vary significantly in terms of their complexity and network security implications, the investigations described above maintain a common theme. The fault current contributions from GFM BESS need to be carefully considered and conventional protection solutions are unlikely to be adequate without some form of modification.

2.2. Key observations and learnings

The main findings from the literature review can be summarised as follows:

a. The body of published research on the subject remains limited. As proposed by AEMO, further detailed investigations are required before consideration can be given to substituting GFM inverters in place of synchronous machines to meet minimum system strength requirements.

b. Concerns related to protection relay malfunction are more significant for the detection of unbalanced faults relying on negative-sequence current injection from IBRs, rather than for balanced faults. The reduced fault current magnitude that is available from IBR will clearly impact the latter, however there are other technical aspects which are equally critical.

c. RMS simulation platforms commonly used by protection engineers are inadequate for protection design under high IBR penetration. EMT studies are necessary as IBR fault current contributions depend heavily on control settings rather than being well-represented by a simplified 'voltage source behind an impedance'. This is not an insignificant shift in requirements, noting that in addition to the many well-known issues, e.g. simulation speed and complexity, many protection engineers may not be familiar with EMT analysis.

d. The magnitude of positive- and negative-sequence fault currents from IBRs varies significantly across OEM designs. Even where variations are less pronounced, fault current magnitudes may still be too small for reliable detection of certain types of fault events by protection relays.

e. Shallow faults are likely to present a specific challenge, as the fault current contribution of IBR depends on the pre-fault steady-state operating conditions. For some inverter designs or tuning approaches, current injection may not be triggered unless the observed fault is severe enough. This is another notable difference when comparing to a synchronous machine.

f. Previous research has already demonstrated a high risk of protection relay malfunction when relying on traditional setting and design practices under high IBR penetration scenarios. While some researchers have proposed modified protection schemes, retrofitting such changes across the installed base of relays within the NEM would be impractical.

g. There is no standardised approach for the design of FRT performance in GFM inverters leading to different behaviours across OEM products. Even if future standards are introduced, a large already installed base of IBR equipment will remain in operation.

h. IBR, whether GFL or GFM, are thermally limited, with fault current injection typically constrained at levels close to rated current. For BESS applications, GFM inverters may include a modest current overhead (typically 10% to 15%), but this capacity must be shared between multiple functions including delivery of inertia, fast frequency response (FFR) and fault current support. Prioritising additional fault current may compromise other services, particularly inertial response which represents a unique and valuable feature of GFMs. 'Trade-offs' may need to be considered.

i. Several prior investigations have utilised real-time digital simulator (RTDS) platforms to implement HIL testing of physical protection relays. In some cases, offline playback of recorded waveforms (into protection relays) from digitally simulated fault scenarios can also be worthwhile. These approaches provide the most reliable insight of actual relay performance. Designing meaningful tests that are not impractically burdensome on computing hardware requirements is a challenge to be addressed.

j. Across literature, both within Australia and internationally, there is broad consensus that network security would be at risk if existing protection relays remain unchanged while synchronous generators were replaced with IBRs, including GFMs. It is foreseeable that some changes will be required to both relay and inverter settings going forward, particularly the design and tuning of inverter FRT performance. A foreseeable challenge is identifying which locations in the NEM are likely to be impacted by increasing IBR penetration (coupled with loss of synchronous machine support). Such areas become the prime candidates for initial protection review investigations.

2.3. Discussions with OEMs

A technical questionnaire was issued to the three OEMs to gain further insight of potential issues and possible solutions from an equipment design perspective. The cooperation of SMA, Power Electronics (PE) and Tesla is greatly appreciated, particularly SMA, which engaged in multiple discussions and meetings to provide valuable input.

The following section summarises key information relevant to the scope of work but deliberately excludes highly specific technical details provided by each OEM about their equipment. The objective of this overview is to identify key themes which will be relevant to any providers of GFM converters, including those not part of the survey.

Major OEMs operating in Australia have adopted very different approaches to GFM FRT design. Examples include:

a. Virtual impedance implementations with user-defined positive and negative-sequence impedances, yielding outcomes not directly comparable to GFL 'K-factor' behaviour.

b. Inverters without a defined FRT state, where 'Iq' injection is based solely on the voltage difference between the inverter terminals and the defined point of connection (POC).

c. Configurable user options such as switching to GFL during FRT events, remaining in GFM mode, or remaining in GFM but limiting Id and Iq (a hybrid method).

Beside the difference in fault current magnitude that can be delivered, these design variations also effect the characteristics of the fault current waveforms, including rise and settling times. In some cases, rise times can be so slow that target fault current levels are never reached before fault clearance, further complicating protection relay operation.

To highlight the design freedoms available to each OEM, Table 1 describes the basic design differences across the range of GFM inverter designs currently available from those surveyed.

Tesla GFM inverters have been commercially available for over two years and are among the earliest models introduced to the Australian market. Several plants have already been commissioned within the NEM. It is understood that new BESS projects using both the SMA and PE GFM designs are currently progressing through the NER connection application process, with projects expected to be completed and online in the foreseeable future.

Table 1 - Summary of GFM inverter features applicable to fault current contributions.

Characteristics	SMA	PE	TESLA
Inertia reserve	30% for up to 5 sec.	Minimum 10%, tuneable via (Is_limit). Reduces maximum current that can be provided on a continuous basis.	20% for up to 10 seconds.
Distinct tuneable FRT function?	Yes, via virtual impedance (VI).	Yes, via VISMA hybrid model parameterisation.	No – operated in virtual synchronous machine mode.
Fault current limiting method	Adjustable virtual impedance (VI) or dynamic boost via current boost function (if available and activated).	Dynamic FRT Id/Iq (K-factor based); slow limiter (Is_limit), fast limiter (Is_limit2). Steady-state fault current at (Is_limit).	Droop-based steady-state current limiters. Default settings is 1.2 pu for 10 sec at inverter terminals.
Tuneable positive/negative sequence fault current?	Yes, via separate virtual impedances (for deep faults) and voltage droop gains (for shallow faults).	Yes, through K-factors in VISMA hybrid model.	No direct control of negative sequence; delivered as an inherent response from synchronous machine mode.
Peak fault current	Initial peak set by IGBT hardware limits, typically 1.4 p.u.	Up to (Is_limit2), typically 1.6 p.u.	1.2 p.u for 10 sec default. Higher values can be considered on request for research purposes.
Maximum steady-state current (@ inverter terminals)	1.3 p.u	0.9 p.u (providing headroom of 10% to provide inertial response).	1.2 p.u
Maximum achievable fault current with tuning	Higher magnitudes with increased number of inverters. With current boost function, the magnitude will be a function of time (thermal energy considerations).	0.9 p.u (at inverter); higher at POC with increased number of inverters.	1.2 p.u for 10 sec; higher at POC with additional inverters. Higher values can be considered on request for research purposes.
Does the current model support these tunings and studies?	Yes – via "current boost" function and an increased number of inverters.	Yes – Primarily via increased number of inverters.	Yes – via I^2t Overload Current setting.

The following summary captures the common high-level issues which were explored as part of the survey.

a. It is important to define the type of response that is needed (desirable) from GFM inverters. OEMs have flexibility to tune the FRT characteristics of their equipment to deliver different outcomes recognising that trade-offs may be required, i.e. it may not be possible to satisfy all requirements without considering options beyond just controller tuning.

b. Engagement with OEMs is important to help identify what options might exist including increasing the number of inverters installed to provide the additional fault response capabilities that are being sought.

c. OEMs are acutely aware of the network challenges that come with high IBR penetration scenarios, including protection impacts. As evidence of this, SMA has introduced its 'Current Boost' function as described in [6], while PE now offers VISMA Hybrid mode which provides a substantial amount of FRT tuning flexibility compared to previous designs.

d. It is important to avoid using the inverters full thermal headroom during the initial fault for several key reasons including:

   - Additional capability may be required to deliver other critical GFM function such a providing inertial response to a frequency disturbance which follows a transmission fault event.
   - Being able to sustain the delivery of fault current beyond primary protection clearance times. Consideration needs to be given to how inverters can support circuit breaker failure (CBF), zone two and three distance protection schemes, and any other backup schemes which may have a deliberately delayed clearing times.
   - Ensuring that sufficient response capability exists to support the occurrence of multiple fault events in succession, e.g. failed auto-reclose. Auto-reclose deadtimes become a consideration as this provides an opportunity to dissipate thermal energy before the converter needs to respond to the next disturbance.

e. Simply maximising the initial fault current response via tuning may therefore be counterproductive. It is critical that the full gamut of fault events are properly considered to ensure that all protection schemes (across all operating times) are adequately supported. Aggressive tuning also needs to consider converter stability across a wide range of network operating conditions.

f. Tuning of GFM inverters should consider the response of the plant to both shallow and deep faults as the control functions that are initiated in each of the inverter designs can be quite different.

Unsurprisingly, many of the high-level issues discussed were consistent with those coming out of the literature review.

3. Assessing Fault Current From GFM Inverters

This section outlines the scope of study for evaluating the fault current contribution of GFM inverters. The goal is to determine whether such equipment can reliably support protection system operation and be considered in minimum system strength calculations.

3.1. Assessment methodology

Three distinct methods are proposed to assess fault current contributions and protection relay responses, each offering different levels of reliability and complexity:

a. Simulation-Based Assessment: This desktop-based method uses PSCAD to simulate fault scenarios and evaluate inverter and relay behaviour. It is suitable for initial studies but requires accurate modelling of protection relay logic. Custom relay functions may be needed, and validation with relay manufacturers is recommended to ensure model fidelity.

b. Hybrid Assessment: Fault waveforms generated in PSCAD are recorded and replayed through physical relay hardware using waveform playback systems. This method allows direct observation of relay responses to simulated fault conditions. While effective for individual relay testing, it does not capture coordination between multiple relays and breakers.

c. Closed-Loop HIL Assessment: Real-time digital simulators can be used to directly interface with relay hardware in a closed loop simulation environment. Commercially available platforms suitable for this purpose include RTDS, OPAL-RT, Typhoon, and dSPACE. While OPAL-RT and dSPACE are based on MATLAB/Simulink environments, RTDS and Typhoon utilise their own dedicated electromagnetic transient (EMT) simulation software.

   This method provides the highest fidelity and captures full system interactions, including relay coordination, time grading, and directional logic. It also accounts for real-world effects such as measurement inaccuracies and communication delays. This method is recommended for critical validation studies.

   There are however several significant considerations for implementing closed-loop HIL assessments:

   - The extent of the network which is to be represented in the digital twin environment will likely be limited. While it is understood that AEMO has a relatively complete model of the NEM available in PSCAD, it is unlikely that development of an equivalent will be possible in the short to medium term for HIL assessments.
   - At this point in time, proponents are only required to provide AEMO and the connecting NSP with validated models for use in PSS/E and PSCAD software. Transferring the models to an alternate software platform can be time consuming. While there may be a possibility of accessing real time digital simulator models directly from manufacturers of GFM inverters, consideration will need to be given to how to represent other surrounding plant relevant for the study.

3.2. Test cases and scenarios

Two representative network configurations can be used to support the assessment:

a. A 'theoretical base case' featuring a network with mixed system strength and a single GFM inverter-based BESS. Switching between a strong and weak connection point could be achieved through the switching of a single transmission line.

b. An IBR-dominated case with multiple GFM inverter-based BESS units and a weak voltage source representing the interconnecting AC network. To increase the credibility of the results, simulating the proposed connection arrangements for a large Renewable Energy Zone (REZ) could also be appropriate, e.g. Central West Orana in NSW. For this particular example, proposed synchronous condensers within the REZ could be substituted with GFM BESS to understand that difference on local protection schemes and pre-existing schemes in the 500 kV network to which the REZ connects.

Each configuration would be subjected to a range of fault scenarios, including balanced and unbalanced faults, and applied at various locations with varying fault impedances (to explore the issues associated with deep and shallow voltage disturbances). Different protection operating scenarios would also need to be examined, e.g. CBF, backup line protection and auto-reclose events.

These scenarios are designed to test the detectability and reliability of protection relay operations under realistic grid conditions.

3.3. Tuning strategy

The tuning process ensures that fault currents injected by GFM inverters are sufficient in magnitude, duration, and frequency tracking to allow the applied faults to be reliably detected and cleared by protection relays. The process includes the following steps:

a. Initial configuration: Define inverter quantities and settings to achieve GFM BESS fault current levels of 1.3 p.u, 1.5 p.u, 1.8 p.u, and 2.0 p.u at the point of connection (POC). Ensure consistent fault current magnitude across all test cases.

b. Simulation and testing: Apply fault scenarios using PSCAD simulations. Evaluate relay responses for both shallow and deep faults, and for balanced and unbalanced fault types. Ensure compliance with protection timing and performance criteria (including directionality calculations). It is assumed that PSCAD protection relay models can be developed that faithfully implement the critical protection elements typically enabled by NSPs in the NEM.

c. Failure identification and root cause analysis: Document cases where relays fail to trip, trip incorrectly, or exhibit delayed operation. Investigate root causes and adjust inverter parameters accordingly to identify possible remediations.

d. Incremental fault current adjustment: Increase fault current levels if failures persist. Re-tune inverter parameters and repeat testing until reliable protection operation is achieved or no further tuning options exist.

e. Robustness validation: Where possible, confirm that tuned inverter models maintain performance across all fault scenarios. Document final FRT configurations and other relevant parameters at which protection systems would operate successfully.

f. Application to weak system configuration: Apply tuned inverter models to a system dominated by inverter-based resources. Validate that protection systems continue to operate reliably. If issues arise, conduct further tuning and update criteria to ensure robustness across system configurations.

3.4. Expected outcomes

This initial scope of study provides a structured and iterative approach to assess and then tailor the fault current contributions coming from GFM inverters. In undertaking this first stage of work, the objective is to:

a. Become familiar with tuning and other design options that can be used to 'mould' the fault current response of GFM BESS in a way that supports reliable protection relay operation. Depending on the OEM being assessed, the number of variables available to be modified will be different.

b. Recreate some (or all) of the 'potential failure mechanisms' discussed in Section 2.1 to gain confidence in the veracity of models to identify issues already known to industry. There is no point claiming success if the input data sets do not provide for the opportunity to fail.

By demonstrating the range of solutions that can enable an isolated test system to operate securely, there can be confidence to carry forward the same solutions for eventual testing in a wider area system model.

4. Framework for Wide-Area Studies

Following the successful assessment and tuning of GFM BESS inverters in Section 3, the next phase involves applying the validated models to a wide-area study across a broader section of the NEM. This stage aims to determine whether GFM inverters can credibly contribute to minimum system strength requirements when subjected to the dynamic complexities of a larger network.

4.1. Assessment methodology

The localised studies provide confidence that GFM inverters can be made deliver protection-quality fault current under a range of network and disturbance conditions, and that it is possible to confidently detect failure events. These results form the foundation for evaluating their impact at a system-wide level. The wide-area study builds on this by progressively replacing synchronous machines with tuned GFM inverter models (expected to be a combination of existing and new BESS installations) and assessing whether the resulting fault current characteristics remain adequate for reliable protection operation.

The wide-area study is proposed to be conducted using the PSCAD model of the NEM. The validated inverter models can be integrated into this environment without further retuning. This also provides reliable access to all network, synchronous machine and IBR models that are already in commercial operation, as well as those committed. If larger GFM capacities are required, multiple identical inverter plants can be added at the same connection points used for new plant. If smaller capacities are needed, inverter counts can be reduced proportionally if desired.

The study should proceed in two stages:

Stage 1: Progressive replacement of synchronous machines close to system strength nodes.

a. Begin with one NEM region and select SSNs in priority order starting with areas of the network that already have a high IBR penetration.

b. Identify synchronous generators contributing to the fault level requirements at each SSN.

c. Replace each synchronous machine with a GFM inverter-based BESS of equivalent size in the same geographical location (or near to if existing or committed plant is already available) and apply the previously tuned plant characteristics.

d. Evaluate fault level adequacy using the four criteria used for system strength planning: voltage change due to reactive switching, fault ride-through performance, protection system operation, and regional islanding capability.

e. If minimum three phase fault levels fall short considering the contribution from GFM BESS, increase inverter capacity or add parallel plants until Rule based requirements are satisfied. Please note that this study does not aim to validate or prove the adequacy of the minimum or efficient three phase fault levels defined by AEMO and *system strength service providers* in each region but simply uses the figures for assessing the overall adequacy of grid-forming dispatch based on existing approaches.

f. Document the ratio of GFM inverter capacity to replaced synchronous machine capacity.

Stage 2: Fault response validation

a. Apply balanced and unbalanced faults near each SSN as well as areas of the network now significantly more remote from dispatched synchronous machines (whether these be generators or synchronous condensers). It is anticipated potential issues may present here rather than at network nodes that are still close to synchronous machine support.

b. If detailed relay models are unavailable in PSCAD and cannot be reliably developed in a reasonable time frame, record fault waveforms and replay them through physical relay hardware using the hybrid method. In either case, an understanding of the types of relays currently in service across the NEM will be needed, along with typical protection settings.

c. Given the number of potential permutations, it is recommended that protection relays at the highest voltage present in each region be assessed first, i.e. 500 kV in Victoria and New South Wales etc. If issues present themselves quickly in network locations such as around planned REZ developments, this will provide an early indication of potential fatal flaws.

d. Remember to consider the critical failure mechanisms described in literature when undertaking the assessments:

   - Balance fault current magnitude – what is the effective equivalent fault level magnitude provided by the GFM BESS at its *connection point.* Are there any risks of converter instabilities due to aggressive tuning approaches?
   - Positive and negative sequence contributions to unbalanced faults. Are healthy phase over voltages adequately managed?
   - Frequency of injected fault current (frequency tracking) to avoid issues as described in [1].
   - Shallow fault coverage. Are the controls of the plant sufficiently tuned to deliver the right outcome for a wide range of fault impedances? This will require NSPs to describe their existing protection setting philosophies.
   - Post-fault thermal margin. Do the GFM BESS provide enough fault current capability over the periods of time relevant to all aspects of network protection, e.g. primary, secondary and backup. Does the thermal limitations of GFM BESS run the risk of emergency operating conditions spiralling out of control?
   - The impacts on inertial response, and any other services that GFM BESS are great at providing, if too much focus is attributed to fault current provision. What are the trade-offs that need to be considered.

e. Repeat tests across different fault types and depths to confirm protection robustness.

f. Use findings to further refine tuning criteria developed in Stage 1 (as necessary).

4.2. Expected outcome

This scope of study will provide valuable insight on the fault current contributions coming from GFM inverters, and that they are not only technically viable at the local level to meet system security expectations, but also scalable across the broader NEM. It provides a robust basis for examining whether GFM inverters can be included in all aspects of system strength planning, or if there were fatal flaws that would prevent such a move until other changes can be implemented, e.g. wholesale change of protection setting philosophies across existing network or for areas that can be reliably identified to be at highest risk.

5. Conclusions

This report has explored the role of GFM inverters in contributing to minimum system strength, with a particular focus on fault current and ensuring reliable operation of protection systems. While it is widely recognised that GFM inverters possess capabilities that can assist, published literature highlights limitations and variability in their fault current characteristics—especially under unbalanced fault conditions—which may constrain their overall contribution to system requirements. These limitations pose challenges for conventional protection schemes and necessitate detailed EMT studies and iterative tuning to validate their performance.

To address these challenges, the report proposes a comprehensive *Scope of Study* that includes simulation-based, hybrid, and HIL assessment methods. These approaches provide a structured pathway to validate and refine the fault current characteristics provided by GFM inverters. By considering the different tuning strategies of various OEMs and systematically evaluating different fault scenarios, the study aims to determine whether some or all GFM inverters can be credibly included in minimum system strength assessments going forward.

The *Scope of Study* will include the following key tasks undertaken collaboratively between AEMO, OEMs, and industry stakeholders:

1. Cooperate with OEMs to define and validate GFM inverter performance requirements.

   Engage with OEMs to access detailed inverter models and support tuning activities, particularly for fault ride-through (FRT) and current boost functions that influence fault current contributions. Examine available evidence of measured FRT behaviours that might be available for already in-service equipment.

2. Adopt EMT-based assessment frameworks for fault and protection studies.

   Promote the use of EMT models and tools for fault current and protection analysis noting that RMS platforms are inadequate for assessing the performance of IBR during unbalanced network disturbances, as well as for high penetration scenarios.

3. Look to utilise HIL test methods to validate protection relay operation.

   Where practical to do so, conduct HIL testing to validate protection relay performance under realistic network fault conditions which include varying levels of contribution from GFM and GFL inverters. Where HIL testing is deemed not possible, revert to PSCAD as the next best alternative.

4. Standardise fault current requirements.

   Develop and adopt standards that define the fault current characteristics required of GFM inverters to enable them to be considered in minimum system strength assessments. This would help promote consistency across OEMs and assist with future protection design activities.

5. Conduct wide-area network studies.

   Use validated GFM inverter models in NEM-wide EMT studies to evaluate their impact on minimum system strength related issues across regions, using recommended fault scenarios to validate their benefits.

These recommendations form the foundation of the proposed assessment framework that can support the future integration of GFM inverters into system strength planning.

6. References

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