Transgrid

People. Power. Possibilities.

# Transgrid's technical performance and power system modelling requirements for stable voltage waveform support services from grid-forming BESS

Supplementary to the 'Meeting system strength requirements in NSW' Project Assessment Draft Report (PADR)

Date of issue: 17 June 2024

# Contents

# 1. Acronyms

Key terms and definitions relating to the work instruction.

| Term | Definition |
|---|---|
| AAS | Automatic Access Standard |
| AEMC | Australian Energy Market Commission |
| AEMO | Australian Energy Market Operator |
| BESS | Battery Energy Storage System |
| BOP | Balance of plant |
| CUO | Continuous Uninterrupted Operation |
| DMAT | Dynamic Model Acceptance Test |
| FFR | Fast Frequency Response |
| FRT | Fault Ride Through |
| HiL | Hardware in Loop |
| LVRT | Low Voltage Ride Through |
| IBR | Inverter-based resource |
| GFL | Grid Following |
| GFM | Grid Forming |
| GFMI | Grid Forming Inverter |
| GPS | Generator Performance Standard |
| MMIB | Multi Machine Infinite Buss |
| NER | National Electricity Rules |
| NREL | National Renewable Energy Laboratory |
| NSW | New South Wales |
| OEM | Original Equipment Manufacturer |
| PFR | Primary Frequency Response |
| PLL | Phase locked loop |
| POC | Point of connection |
| POD | Power Oscillation Damper |
| Proponent | A prospective supplier of SVWSS |
| PSCAD | Power Systems Computer Aided Design |
| PSS | Power System Stabiliser |
| PV | Photovoltaic |
| RL | Resistive and Inductive |
| RMS | Root Mean Squared |
| ROCOF | Rate of change of frequency |
| ROCOV | Rate of change of voltage |
| RUG | Releasable User Guide |
| SCR | Short Circuit Ratio |
| SMIB | Single Machine Infinite Bus |
| SOC | State of Charge |
| SRAS | System Restart Ancillary Service |
| SSS | System Strength Service |
| SVWSS | Stable Voltage Waveform Support Service |
| SSSP | System Strength Service Provider (Transgrid) |
| TOV | Temporary Overvoltage |
| Voluntary Specification | AEMO's Voluntary Grid-forming Inverter Specification - May 2023 [1] |

# 2. Scope of This Document

This specification provides guidance to Proponents and grid-forming inverter Original Equipment Manufacturers (OEMs) on Transgrid's technical performance and power system modelling requirements for a grid-forming (GFM) battery energy storage system (BESS) that provides a stable voltage waveform support service (SVWSS) to the NSW power system.
In this regard, this document:

- provides a general explanation of relevant system strength concepts and conceptual definition of a GFM BESS;
- describe Transgrid's expectations and compliance requirements from this technology; and
- describe methods of assessments for these expectations and their relevance to the SVWSS.

This document also points to the scope of works which the proponent must assume as deliverable of the contractual agreement that will be made between Transgrid and the proponent who is intending to utilise GFM BESS for the purpose of stable voltage waveform service support.

# 3. Collaboration with the Industry

The provision of a "stable voltage waveform support service" is new, provided by a relatively novel technology, grid-forming batteries. Transgrid has developed this document based on best available knowledge and information and is now seeking industry engagement to help refine it. As such, this document should be considered in draft form, and we seek your feedback during our system strength PADR consultation period (until 2 August 2024, contract systemstrength@transgrid.com.au).

We would appreciate your feedback on specific areas of this document that you think is unclear, could be improved or could pose problems for proponent projects or the grid. This feedback will be taken into consideration for a final specification document which will be used when entering into contracts between a grid-forming battery proponent and Transgrid for a stable voltage waveform support service.

# 4. Relationship with AEMO Voluntary Grid-forming Inverter Specification

It is important to note that this document is not a general grid-forming inverter specification, and it does not supersede or replace AEMO's Voluntary Grid-forming Inverter Specification - May 2023 (Voluntary Specification) [1] or Core Requirements Test Framework (January 2024) [2].

Those documents specify the 'core' and 'additional' technical capabilities that power electronic devices should have to be categorised as grid-forming inverters, and a methodology for testing compliance with the 'core' capabilities. Whereas this document specifies the performance requirements for a stable voltage waveform support service (SVWSS) in NSW provided by grid-forming (GFM) BESS.

Some of the capabilities described in the Voluntary Specification are essential for provision of SVWSS, but compliance with the Voluntary Specification does not guarantee that a GFM BESS is able to provide SVWSS, or any minimum quantity of SVWSS.

The tests described in this document are designed to demonstrate and quantify provision of system strength support in the context of specific present and future system strength requirements in Transgrid's transmission network, and are necessarily different to the tests in the Core Requirements Test Framework, which are designed to demonstrate grid-forming behaviour in a generic context.

We encourage proponents to voluntarily perform all the tests in the Core Requirement Test Framework to check the robustness of their technology; however, undertaking those tests does not replace performing the tests in this specification.

*Table 1 Summary Table of Transgrid Requirement vs AEMO's Voluntary Specification Requirements*

| **Voluntary Specification Requirement** | | **Required for provision of SVWSS in Transgrid's network** |
|---|---|---|
| Core capabilities | 2.3.1 Voltage source behaviour – response to voltage magnitude and phase changes | Required.<br>• It is critical for the system strength solution not only be able to respond to the voltage disturbance but also be able to operate in different conditions of the voltage.<br>• In addition to the Voluntary Specification [1], Transgrid expects the battery remains grid forming even when operating at the limit; however, it is accepted that the response from battery as a voltage source is only provided up to the current limits. Reaching the current limit thresholds must not be a reason to switch the control mode to grid following current controller including during steady state and Fault Ride Through. |
| Core capabilities | 2.3.2 Frequency domain response | Not required.<br>The Voluntary Specification [1] and Test Requirements Framework [2] propose to use this to illustrate GFMI performance based on the impedance scan of generator; however, Transgrid has not adopted this approach in its business-as-usual network planning processes. Transgrid instead requires oscillation damping performance to be evaluated via wide-area PSCAD™ and Small Signal studies, to ensure that all control interactions are accounted for, and confirm that the network need (stable voltage waveforms at IBR connection points) can be met.<br>This eliminates the need for the impedance scan test for SVWSS. |
| Core capabilities | 2.3.3 Inertial response | Not required (but desirable for possible future inertia procurement).<br>• Once the new inertia framework commences on 1 December 2024, Transgrid may seek to |

| Voluntary Specification Requirement | | Required for provision of SVWSS in Transgrid's network |
|---|---|---|
| | | procure SVWSS and inertia as a combined service. In the meantime, Transgrid is not procuring inertia, so inertia is required for SVWSS only to the extent it is necessary or helpful to maintain stable voltage waveforms.<br>• While Transgrid acknowledges the advantages of this inertial response, it is understood that it may be possible that some technologies can provide a suitable level of system strength service without necessarily Inertia type response.<br>• This feature is however mandatory for those types of technologies that depend on this for their grid forming controls. |
| Core capabilities | 2.3.4 Surviving the loss of the last synchronous connection | Required. |
| Core capabilities | 2.3.5 Weak grid operation and system strength support | Required. |
| Core capabilities | 2.3.6 Oscillation damping | Required.<br><br>• SVWSS is in-line with core capability 2.3.6 of the Voluntary Specification [1]; however, Transgrid will require adequately damped response, especially for low order oscillations, be proven in small signal platforms that can capture the BESS's contribution as well as overall network stability damping for different operating condition.<br>• Transgrid also relies on PSCAD™ wide area studies post disturbance to ensure the effectiveness of the battery providing SVWSS to IBRs. |
| Additional capabilities | 2.4.1 Headroom and energy buffer | May be required, depending on the nature of the technology (not compulsory if technology meets all of its requirement without overload). |
| Additional capabilities | 2.4.2 Current capacity above continuous rating | Desirable. |
| Additional capabilities | 2.4.3 Black start capability | Not required (unless contracted for black start services). |
| Additional capabilities | 2.4.4 Power quality improvement | Desirable. |

# 5. Stable Voltage Waveform and Definition of Grid-Forming

In this document, GFM BESS, is referred to as a battery technology equipped with inverters that operates as voltage source synchronised with the grid frequency and inherently provides power to the grid based on the load angle and voltage magnitude. The stable operation of GFM BESS, in the same manner as conventional synchronous generators, must not be dependent on the system strength of the system. In fact, it increases the system strength of the nearby power system (e.g. voltage waveform stability), by generating a robust voltage waveform at its own terminal comprising the magnitude and angle at the synchronised 50 Hz frequency.

This performance must be continuously and inherently provided by the GFM BESS unless it is explicitly raised and agreed with Transgrid otherwise. This inherent behaviour must be consistent with the requirements described in sections 5, 6, and 8 of this document.

To best follow the reasoning behind the requirement in this document, some background on system strength which is relevant to the GFM BESS requirement is discussed in this section.

To assist with system strength in the power system and potential cause of instability, Stable Voltage Waveform requirements comprise of four criterion including Voltage magnitude, voltage angle, voltage distortion and voltage oscillation, as explained below:

*Table 2 Stable Voltage Waveform Criteria, as defined in the System Strength Requirements Methodology [3]*

| Ref | Criterion | Definition |
|---|---|---|
| 1 | Voltage magnitude | The positive-sequence RMS voltage magnitude at a connection point does not violate the limits in the operational guides for the relevant network. |
| 2 | Change in voltage phase angle | Change in the steady-state RMS voltage phase angle at a connection point should not be excessive following the injection or absorption of active power at a connection point. |
| 3 | Voltage waveform distortion | The three-phase instantaneous voltage waveform distortion at a connection point should not exceed acceptable planning levels of voltage waveform distortion for pre- and post-contingent conditions. |
| 4 | Voltage oscillations | Any undamped steady-state RMS voltage oscillations anywhere in the power system should not exceed an acceptable planning threshold as agreed with AEMO. |

Among these criteria, the expectation is the GFM BESS could assist with:

1. Voltage magnitude
2. Voltage phase angle
4. Voltage oscillations

It is also expected that GFM BESS does not amplify any harmonic emission, voltage fluctuation and material distortion to the voltage waveform unless agreed otherwise with Transgrid under the agreed performance standard. Being capable of absorbing harmonic current to reduce the harmonic voltage emissions by the GFM BESS will be taken as advantage for competing for system strength contract.

# 6. Grid Forming BESS Characteristics to Support Voltage Waveform

GFM BESS, which is a voltage source generator, must generate and control its own terminal voltage waveform while being synchronised with the grid. GFM BESS must also have an inherent response to voltage magnitude and voltage angle change at its own terminal. In this section, some key expectations of these characteristics are described.

## 6.1. Voltage Magnitude

1. Support to magnitude of Voltage:
    a. This requirement is in-line with one of the core capability raised in Voluntary Specification [1].
    b. The GFM BESS must be able to provide 50 Hz voltage at its terminals including steady state and FRT as a voltage source and provide reactive power for Voltage Magnitude support and to compensate for the voltage drop according to the agreed droop characteristics.
        i. For this purpose, BESS must provide the amount of reactive power within the normal voltage operating range [0.9 pu – 1.1 pu], which has been agreed under the Generator Performance Standard regardless of generator's participation in other ancillary services. This amount of Reactive Power capability is expected to meet or exceed AAS of NER S5.2.5.1 (i.e. minimum 0.395 of rated power)..
    c. Overload capacity from the inverters and BESS is desirable but not compulsory.
    d. If there is any temperature derating in normal (i.e. below 50 degrees) ambient temperature, the BESS capability will be assessed accordingly and the derated Reactive Power will be used as the guaranteed capability.

2. Support to rate of change of Voltage:
    a. While this function is desirable but not compulsory subject to being effective in controlling rapid voltage changes.

3. During FRT, the GFM BESS:
    a. Must remain as the voltage source so that SVWSS is continuously provided. This means, if a fault occurs nearby the GFM BESS which is associated with a frequency drop (e.g. a fault that immediately trips a synchronous generator), the GFM BESS must continue operating as a voltage source while providing SVWSS. This will be one of the performed tests in our PSCAD™ studies.
    b. It is expected that when the inverters reach their current limits, they continue to function as voltage source while the inverter controller may have internal current logic to protect the damage to the inverter due to excessive current flow.
    c. The proponent, must provide, in the RUG and the models, the equivalent of sub-transient, transient and steady-state reactance for accurate [4]representation of inverters for fault level and short circuit studies.
    d. The inverter must be cable of negative sequence current injection, so that at the request of Transgrid, in the event of excessive over-voltages, it can be enabled to help with the over-voltages.
    e. Fault current contribution and the overload capacity must be stated in Amps so that it is comparable with other proposed projects, regardless of their per unit base.

f. The technology must ride through the frequency disturbances as per Automatic Access Standard requirement and respond to at least 4 Hz/s of ROCOF accordingly.
    i. The evidence of this must be presented in the connection study report.

4. If the priority of inverter current components has an effect in providing the voltage source behaviour described in this document, the proponent may request this current component priority to change depending on the outcome of System Wide Power System simulations.

5. The technologies must be able to ride through concurrent voltage and frequency disturbances required for Automatic Access Standard. For example, if the fault leads to the loss of generation loss which leads to under-frequency, the technology must satisfy both requirements and not only one in isolation. Please refer to the table section 7 for the relevant tests.

6. SCR dependency:
    a. Subject to the energy reserve availability, the technology should be able to operate in the absence of grid supply under continuous operating conditions with no reliance on the system strength from the grid (e.g. fault level support from conventional synchronous generators). This means, the GFM BESS, subject to energy reserve availability, must be able to operate in conditions equivalent to black start, and still provide the SVWSS.
        i. It is advantageous if, subject to contractual agreements made, the GFM BESS can provide Black Start Services. Further information may be sought in [1].

7. Generating a stable voltage waveform should be the actual outcome of the technology rather than a behaviour which the controller dynamically switches to on the detection of a disturbance.

8. While the operating envelope of the GFM BESS for Active and Reactive Power, subject to the type of contract for SVWSS, may not be symmetrical across the origin in S5.2.5.1 capability curve, Transgrid only counts for the symmetrical range of operating envelope under SVWSS.

## 6.2. Voltage Phase Angle

9. Support to ROCOF:
    a. Control methodologies that emulate synchronous machine behaviour are highly desirable, but not mandatory, i.e. other grid-forming control methodologies (e.g. droop control) are also acceptable if they function as effective for SVWSS from voltage phase angle stability. It is, however, understood that the most commonly used control mode to develop grid forming battery is emulation of a synchronous machine.
    b. Unlike AEMO's Voluntary Specification [1], Transgrid does not need inertial response as a core requirement for GFM technologies for SVWSS (though it is desired), unless the technology needs this response to be able to provide the Grid Forming function. Transgrid understands that there may be technologies and control modes that may provide the same level of effectiveness in SVWSS without inertial response.
    c. If synchronous machine behaviour is emulated, it must be implemented using the standard form of the swing equation (Eq.1). The implementation of filtering must not to compromise the classic swing equation or change the order of the control system. Once the control design is completed, the OEM back calculate the implemented swing equation from the block diagram and change it to the below formations of these equations (Eq 1 and Eq 2) to see if inertia and damping have any unexpected non-linearity.

$$\frac{2H}{\omega_0}\frac{d^2\theta}{dt^2} = \Delta P \qquad Eq\ 1$$

$$H = \frac{\omega_0\ \Delta P}{2\frac{d^2\theta}{dt^2}} \qquad Eq\ 2$$

d. It is expected that the back calculated constant inertia from the block diagram of the GFM BESS, (through reformation of the implemented swing equation to Eq 2 and excluding the effect of frequency and PSS), the linear relationship between $\Delta P$ and ROCOF will be found.

e. If the damping part of the swing equation is implemented, the other components in the control system (e.g. filters) must be designed such that the damping factor remains as the only coefficient of $\frac{d\theta}{dt}$ = after reformation of the control block diagram from S-domain to a classic time domain differential equation (Eq.3).

$$\frac{2H}{\omega_0}\frac{d^2\theta}{dt^2} = \Delta P - D\ \frac{d\theta}{dt} \qquad Eq3$$

Note 1: This linear inertial response described in point c. to e. would be mandatory for GFM BESS to have an inertia service contract with Transgrid; however, it is only desired for SVWSS if the existence of any non-linearity does not compromise SVWSS . Non-linear inertial response is acceptable for SVWSS, provided that the non-linearity is accurately reflected in the models, and modelling confirms that the non-linearity does not have any adverse effects on SVWSS. For example, if GFM BESS presents an inertia constant of 3 MWs/MVA at ROCOF of 1 Hz/s but it presents and inertia constant of 4 MWs/MVA at the ROCOF of 2 Hz/s, it is acceptable for SVWSS. However, this may not be acceptable for future inertia service agreements.

Note 2: The inertia constant, damping factor, and other key parameters that affect the inertial response may need to be retuned in the detailed design phase following the completion of system level studies and consultation with AEMO. If the GFM BESS has already completed the design, Transgrid still may request a parameter change or a further optimisation to the proponent as a part of SVWSS.

Note 3: Should a virtual impedance be implemented for the control purposes, the value and reasoning for the tuning must be communicated to Transgrid.

Note 4: To prove the linearity of the active power response versus ROCOF, which shows the linear estimated inertia, modelling results must be presented with and without other functions which may impact the estimated inertia such as Power System Stabiliser (PSS), Battery Management System (BMS) or Power Oscillation Damper (POD).

f. All relevant limitations for ROCOF ride-through and/or response must be described in the design document, accurately reflected in the relevant modelling platforms, and demonstrated in the connection study report. For example:

(a) ROCOF limits
(b) ROCOV limits
(c) Rate of change of phase angle limits
(d) State of charge of BESS

(e) Limitations impacted by overall state of charge management system (e.g. BMS or charge or discharge cycle management)
(f) Number of frequency events, at what state of charge
(g) Active power import/export limits
(h) Ambient conditions

g. The BESS must have ride through capability for ROCOF as per Automatic Access Standard under S5.2.5.3 while maintaining all other features of the GFM function.

10. Support to Power Frequency including PFR and FFR must still be provided by the GFM BESS as per the agreed performance, NER, and enablement instruction, without being interrupted by the response to the ROCOF. The validation of the inertial response and frequency response will need to be individually tested by disabling of the one at the time both in simulation and commissioning.

11. For the BESS which provides an inertia service in addition to SVWSS, in-line with requirement in section 6.2 and equations 1-3, the inertial response of the grid forming to the ROCOF must be linear for all ROCOF rates when inertia service is provided and desired for SVWSS. For example, the inertia of the battery cannot represent an inertia of 2 for ROCOF of 0.1 Hz/s while it has inertia of 8 at the ROCOF of 1 Hz/s.
    a. The validation method of inertial response must be agreed between the Proponent and Transgrid during the assessment.

12. When the battery operates in synthetic inertial mode and frequency control mode (e.g. PFR or FFR), it must provide the same inertial response as it would with frequency control disabled. This is needed so that the inherent response from the BESS is not dependent on the frequency control elements such as deadband and droop. Refer to the corresponding test in section 7.

## 6.3. Voltage waveform Distortion

13. Contribution of harmonic emissions must be presented in PowerFactory models with full detailed (all BOP and collector groups to be modelled) of the passive elements of the generating system.

14. Harmonic Assessment and requirements are as per NER S5.2.5.2 of the Generator Performance Standard and Transgrid's Harmonic Assessment Requirement Guide [5].

## 6.4. Voltage Oscillation

15. While GFM BESS must comply with all adequately damped requirement of NER under schedule 5.2, it must provide damping response and anti-phase oscillations for all inter-area and intra-area modes of network.
    a. SVWSS BESS must be equipped with Power System stabiliser (PSS) or Power Oscillation Damping (POD) Capability to stabilise the small signal active power and speed/frequency oscillations. Number of Washout filters and lead/lag compensator must be agreed with or be advised by Transgrid. Transgrid can accept other methodologies for providing power oscillation damping subject to the method being as effective as conventional PSS or POD, and the tuning of the control mode, during the detailed design phase, being available to Transgrid for optimisation of Network oscillation including interconnectors. The effectiveness of this capability must be presented in the small signal modelling.

b. Where required by Transgrid during the detailed design phase, further tuning or implementation of damping control logic may be needed and must also be implemented for the corresponding control loops.
c. Primary Assessment Tool:
   i. Small Signal Studies will be used to illustrate the stability related features of the BESS against all modes of the system, including, but not limited to, the critical modes of the network such as interconnector modes.
   ii. PSCAD™ studies will also be used to show the improvement of post fault oscillation damping for nearby buses as well as actively lowering the peak-to-peak oscillations of the system voltage.
   iii. PSCAD™ studies will also be used to show the improvement to fictitious oscillations using an intentionally malfunctioning control system in a neighbouring generator.

## 6.5. Other General Requirements

These capabilities will be assessed at the connection point of the transmission network and must account for saturation of the control systems and the impact of the BOP including the capacitor banks and saturation curves of the transformer, which may reduce the SVWSS capability in extreme cases. These details, such as saturation curve of the transformers must be provided in the datasheet and be modelled in PSCAD™ model platform.

16. The grid forming characteristics of the GFM BESS including response of the BESS inertial response and voltage waveform stability should not be dependent on the PLL performance in steady state or FRT.
    a. If the technology uses PLL for other purposes:
       i. The Proponent must provide the details of what the PLL is being used, in the relevant design document.
       ii. The Proponent must provide technical evidence, including modelling real-time response analysis, that the performance of PLL will not be compromised for delivering its function under any system strength condition both in transient and in steady-state response.

17. It is Transgrid's preference that the technology which provides SVWSS is independent of the headroom and energy buffer for the whole operating range of the battery. If some features of the GFM BESS for providing SVWSS are dependent on the headroom available, Transgrid will accept some headroom on Active Power as defined in the following, while headroom on the agreed reactive power (reactive current) is not acceptable under any conditions.

    The headroom for Active Power must be selected in such a way that generator would not reach its maximum active power (whether continuous rating limit or optional overload limit), for a 1.0 Hz/s event as the highest ROCOF for a credible contingency in Frequency Operating Standard [6]. As the response from the battery is considered to be dependent on the swing equation modelling, the required headroom can be back-calculated from the swing equation which is a function of constant inertia for the highest ROCOF identified in [6], being 1.0 Hz/s for Mainland. The AEMC may revise this value of ROCOF in the Frequency Operating Standard, and if so, then the amount of headroom will need to be amended by the Proponent accordingly.

18. System Restart / Black Start Support (not required)

1) Black start support is not required for SVWSS.
2) If a SVWSS BESS is also contracted to provide black start support:
   a) The BESS should have the capabilities described in Voluntary Specification [1] additional capability 2.4.3 Black start capability.
   b) The SVWSS BESS must have sufficient capability (e.g. energy reserve availability) to provide both services simultaneously during black start conditions.
   c) Black start support (known as System Restart Ancillary Services / SRAS) is procured by AEMO (not Transgrid), so the Proponent will need to coordinate with both AEMO and Transgrid to ensure the technical requirements and contracts for both services do not conflict with each other.

# 7. PSCAD™ SMIB, MMIB and Wide Area Validation Studies

This section describes the compulsory tests to demonstrate and quantify the capability of a SVWSS BESS to help meet a system strength need on Transgrid's transmission network. The compulsory tests include:

1. Single machine infinite bus (SMIB) tests, to be undertaken by the Proponent. These tests will demonstrate the capability of the SVWSS BESS to provide system strength support in a generic context.
2. NEM wide-area tests, to be undertaken by Transgrid. These tests will demonstrate and quantify the capability of the SVWSS BESS to help meet specific system strength requirements on Transgrid's transmission network.

The SMIB studies undertaken by the Proponent, and the NEM Wide studies, undertaken by Transgrid, are compulsory for validating the capability of the proposed GFM BESS.

Transgrid also recommends the proponent to develop a Multiple Machine Infinite Bus (MMIB) case, which is marginally unstable due to lack of system strength (which includes a weak SMIB and a grid-following IBR), which can be shown to become stable following the addition of a GFM BESS. This will also enable the proponent to be able to undertake the tests indicated as optional in Table 3 or to repeat the tests described for Wide Area, but in a less complicated environment.

**Simulation Notes:**

1. All the tests to be performed at P=0, Pmin and Pmax unless noted otherwise.
2. If SCR is not noted in the test description, the test must be performed under a Short Circuit Ratio (SCR) of 1.2 and SCR of 20 at the POC for SMIB modelling.
3. SMIB studies must be done by the proponent and the results to be presented in a report format (and raw data if requested). It is also recommended that proponent, performs the same or similar tests in a MMIB environment to represent the best performance and effectiveness of GFM technology. In the optional MMIB models, the tests do not need to be limited to the requested tests by Transgrid and can go beyond this.
4. All the wide area tests will be done by Transgrid.

*Table 3 Minimum Tests Required to be Performed by GFM BESS proponent and Transgrid*

| Test No | Description | Purpose of the test | Reference to SVW criteria[3] | SMIB (or MMIB) | Wide Area |
|---|---|---|---|---|---|
| 1 | Cause 3% Voltage drop through a remote fault | • Monitor the response to a small signal voltage disturbance up to 3% (without hitting the limiters).<br>• Correct droop characteristic at the POC and voltage control at the inverter, Fast rise time and adequately damped response are expected. It is also expected that voltage profile of nearby buses will improve by adding BESS. | 1,2,4 | Y | Y |
| 2 | Cause a 5% Voltage drop through a remote fault | • Monitor the response to a small signal voltage disturbance up to 5% while likely to hit some limiters.<br>• Correct droop characteristic at the POC and voltage control at the inverter, Fast rise time and adequately damped response are expected. It is also expected that voltage profile of nearby buses will improve by adding BESS. | 1,2,4 | Y | y |
| 3 | Cause 10% Voltage drop through a remote fault | • Monitor the response to a voltage disturbance up to 10% while likely to see all the steady state limiters are reached.<br>• Correct droop characteristic at the POC and voltage control at the inverter, Fast rise time and adequately damped response are expected. It is also expected that voltage profile of nearby buses will improve by adding BESS. | 1,2,4 | Y | Y |
| 4 | Creating Voltage oscillation in the grid by: making a fictitious GFL generator co-located at the same controlled bus of Battery oscillating its reactive power at certain frequency ($Q = Asin(\omega t)$)<br>Size of 2% voltage (peak to peak) at BESS to be applied at [0.1-0.9] Hz with 0.1 Hz step. | Monitor the oscillation rejection capability of the BESS mainly but not limited to voltage as voltage oscillation will cause other quantities to oscillate.<br>It is expected that peak-to-peak of same mode oscillation is improved by adding the BESS (voltage overlays to be provided for with and without BESS). | 4 | Proposed test (or DMAT test 190) | Proposed test |
| 5 | Creating Voltage oscillation in the grid by: making a fictitious GFL generator co-located at the same controlled bus[2] of Battery oscillating its reactive power at certain frequency ($Q = Asin(\omega t)$) | Monitor the oscillation rejection capability of the BESS in medium frequency mainly but not limited to voltage as voltage oscillation will cause other quantities to oscillate.<br>It is expected that peak-to-peak oscillation is improved by adding the BESS (voltage overlays to be provided for with and without BESS). | 4 | Proposed test (or DMAT test 191) | Proposed test |

| Test No | Description | Purpose of the test | Reference to SVW criteria[3] | SMIB (or MMIB) | Wide Area |
|---|---|---|---|---|---|
| | Size of 2% voltage (peak to peak) at BESS to be applied at [1- 9] Hz with 1 Hz step. | | | | |
| 6 | Creating Voltage oscillation in the grid by: making a fictitious GFL generator co-located at the same controlled bus[2] of Battery oscillating its reactive power at certain frequency ($Q = Asin(\omega t)$) Size of 2% voltage (peak to peak) at BESS to be applied at [10 - 49] Hz inclusive, with 10 Hz step. | Monitor the oscillation rejection capability of the BESS in high frequency mainly but not limited to voltage as voltage oscillation will cause other quantities to oscillate. It is expected that peak-to-peak oscillation is improved by adding the BESS (voltage overlays to be provided for with and without BESS). | 4 | Proposed test (or DMAT test 192) | Proposed test |
| 7 | Create a frequency event either through a fictitious generator/load or using infinite machine. The event must be selected that the pre and post fault voltage angle be within 20 degrees without the participation of BESS to the effect of the support can be identified. ROCOF to change from 0.1 to 0.9 Hz/s with 0.1 Hz/s increment. Test to be done once with all the frequency control functions enabled and once with frequency controls disabled. | Standard tests to show the response to ROCOF, frequency change, compliance to PFR and FFR without compromising voltage support and remaining compliant to CUO. Test results must illustrate the overlay of voltage angle and voltage magnitude of the POC with and without GFM BESS being in service to show its effectiveness. For all the tests with and without frequency control enabled, $\Delta P$ provided for the inertial response (distinct to frequency $\Delta P$) should be plotted versus ROCOF to illustrate the linear relationship between them. | 2,4 | Y | Y |
| 8 | Create a frequency event either through a fictitious generator/load or using infinite machine. The event must be selected that the pre and post fault voltage angle be within 20 degrees without the participation of BESS to the effect of the support can be identified. | Standard tests to show the response to ROCOF, frequency change, compliance to PFR and FFR without compromising voltage support and remaining compliant to CUO. Test results must illustrate the overlay of voltage angle and voltage magnitude of the POC with and without GFM BESS being in service to show its effectiveness. For all the tests with and without frequency control enabled, $\Delta P$ provided for the inertial response (distinct to frequency $\Delta P$) should be plotted versus ROCOF to illustrate the linear relationship between them. | 2,4 | Y | Y |

| Test No | Description | Purpose of the test | Reference to SVW criteria[3] | SMIB (or MMIB) | Wide Area |
|---|---|---|---|---|---|
| | ROCOF to change from 1 to 6.0 Hz/s with 0.5 Hz/s increment.<br>Test to be done once with all the frequency control functions enabled and once with frequency controls disabled. | | | | |
| 9 | Repeat the tests 7 and 8 only for 0.1 and 6 Hz with both inertial response and frequency response disabled. | The purpose of the tests is to overlay the active power and see the effectiveness of inertial response on the active power versus the potential active power response that may be provided by the phase jump angle.<br>The overlay must be provided within the sub-cycle of the response to the event.<br>The measurement in the model must exclude all the unnecessary filtering to avoid the effect of them on the active power measurement. | 2,4 | Y | Y |
| 10 | Local 3Ph-G fault to be applied at BESS controlled bus<br><br>The test must be performed in extremely weak (SCR of 2) and extremely strong (SCR of 50) grid conditions, so that current limiters are tested in both conditions. | This test is proposed to check the performance of BESS during the fault and post fault from voltage magnitude and angle perspective. Some key features such as response time at the occurrence of the fault, phase current and voltage at and post fault using instantaneous and RMS positive sequence (voltage and current) and maintaining angle support (ΔΘ) will be compared with and without BESS.<br>It is also expected to see the voltage source behaviour of the GFM when current limiters are reached. | 1,2,4 | Y | Y |
| 11 | Local 2Ph-G fault to be applied at BESS controlled bus<br><br>The test must be performed in weak and strong grid conditions (SCR of 2 for weak conditions and SCR of 20 for strong conditions) | This test is proposed to check the performance of BESS during the fault and post fault from voltage magnitude and angle perspective. Some key features such as response time at the occurrence of the fault, voltage of healthy phase at and post fault using instantaneous and RMS values, positive sequence and negative sequence (if configured), maintaining angle support (ΔΘ) will be compared with and without BESS. | 1,2,4 | Y | Y |
| 12 | Local 1Ph-G fault to be applied at BESS controlled bus<br><br>The test must be performed in weak and strong grid conditions (SCR of 2 for weak conditions and SCR of 20 for strong conditions) | This test is proposed to check the performance of BESS during the fault and post fault from voltage magnitude and angle perspective. Some key features such as response time at the occurrence of the fault, voltage of healthy phase at and post fault using instantaneous and RMS values, positive sequence and negative sequence (if configured), maintaining angle support (ΔΘ) will be compared with and without BESS. | 1,2,4 | Y | Y |
| 13 | Apply multiple faults that are concurrent with | This test is expected to show that concurrently applying voltage and frequency disturbances, does | 1,2,4 | Y | N |

| Test No | Description | Purpose of the test | Reference to SVW criteria[3] | SMIB (or MMIB) | Wide Area |
|---|---|---|---|---|---|
| | a frequency event of 1 Hz/s to the extent that shows the ride through capability of GFM BESS. Test must be repeated for both charging and discharging modes. If there is any condition for pre-disturbance which might become a limiting factor, the test must include the enablement and disablement of the feature to illustrate the limiting factor. The test must be performed in extremely weak (SCR of 2) and extremely strong (SCR of 50) grid conditions, so that current limiters are tested in both conditions. | not change any desired performance of the BESS as the voltage source (e.g. continue to operate as voltage source and does not switch to current source grid following mode). As a result, both voltage and voltage angle/frequency support are provided. It is also expected that post fault behaviour of active power satisfies the expected performance against the frequency drop. | | | |
| 14 | Apply a fault which immediately trips one fictitious synchronous machine local to the BESS. Test must be repeated for both charging and discharging modes. If there is any condition for pre-disturbance which might become a limiting factor, the test must include the enablement and disablement of the feature to illustrate the limiting factor. | In addition to the above three tests, test is expected to show that concurrently applying voltage and frequency disturbances, does not change any desired performance of the BESS. As a result, both voltage and voltage angle/frequency support is provided. It is also expected that post fault behaviour of active power satisfies the frequency drop (active power drop post disturbance). | 1,2,4 | Y, alternative is Test 4 in Core Requirements Test Framework [2] noting the acceptance criteria limited to SVWSS reviewing the results. | Y |
| 15 | Load Rejection and imposing extreme over-voltage as a result of charge of the line remaining on the grid until the other end of line opens | Performance of BESS for TOV and immediate reactive power absorption. The advantage will be given to the products which can provide support to voltage control sub-cycle. | 1,2,4 | Y | Y |

| Test No | Description | Purpose of the test | Reference to SVW criteria[3] | SMIB (or MMIB) | Wide Area |
|---|---|---|---|---|---|
| 16 | If contracted for Black Start Service, Energising a range of RL loads in island mode operation of BESS (in the absence of grid) | The main purpose of this test is to show the independency of operation to the SCR and not necessarily controlling the 50 Hz frequency while responding to sudden load change while load is being resistive. However, it is expected that the outer control loop would manage the frequency while inertial response is provided by the programmed swing equation. Should there be any mode change in the control system to provide a response for this test due to the complete lack of Infinite Bus Machine, the OEM must provide the reasoning to Transgrid. | 1,2,4 | Y | N |
| 17 | Creating small voltage disturbances in an unbalanced network condition (by adding a RL load to one phase of the line between POC and the network bus) within normal voltage operating band.<br>An RL Load can be selected to cause 0.5% and 1% voltage drop across a single phase of the POC. | The intention is to see the voltage behaviour to voltage angle and voltage magnitude changes that happen asymmetrically across the three phases. | 1,2,4 | Y | N |

*Table 4 Minimum Measured Quantities for Requested Tests*

| Quantity | SMIB | Optional Multi-Bus Multi Generator Model |
|---|---|---|
| Active and Reactive power POC and Inverter Terminal. | Yes | Yes |
| Frequency and Voltage angle POC and Inverter Terminal. | Yes | Yes |
| Voltage and Current RMS and instantaneous Voltage waveform for POC and Inverter terminal. | Yes | Yes |
| Neighbouring GFL Generator, P, Q, POC voltage magnitude and angle with and without GFM BESS for the same event. | N/A | YES |

| Quantity | SMIB | Optional Multi-Bus Multi Generator Model |
|---|---|---|
| Estimated Inertia, ROCOF* of the event and MW variation used for the inertia estimation. | Yes | Yes |

# 8. Modelling package of GFM BESS

## 8.1 General Requirements

The Proponent must submit the GFM BESS modelling package which includes all the following platforms in the latest model versions that are acceptable by AEMO and Transgrid. As the model version may be upgraded between the time of developing this document, while all the models must be compatible with the noted platforms below and [4, 7], the supplier must discuss the latest acceptable version prior the modelling work commencement:

1. PSS®E 34.7 and the latest acceptable version by AEMO (Source code format to be Fortran base as requested by AEMO).
2. PSCAD™ V4.6 and PSCAD™ V5 compatible with Intel Fortran Compiler 2021 compliant with DMAT [7]
3. SSAT V22.3 compatible with [4]
   a. For SSAT, models must be developed as per block diagrams and not as per impedance/admittance calculations using PSCAD™ model across limited number of operating point.
4. PowerFactory model (including static and dynamic models).

All the models provided to Transgrid, must also comply with the following requirements:

1. The modelling package must follow AEMO R1 check list while some key requirements of the submission are listed below.
2. Should there be multiple GFM BESS located at the same location, the modelling package must be submitted individually for each BESS unless agreed otherwise with Transgrid.
   a. It must be noted that, to optimise the damping or other characteristics of aggregated performance of multiple GFM BESS, during the detailed design phase, during the detailed design phase, Transgrid may request different tuning for GFM BESS even though they are connected to the same network bus.
3. For any model change throughout the due diligence process, reduced or full DMAT and compliance studies may require to be repeated.
4. The models must be submitted with a Releasable User Guide which must be updated with each update of the model. RUG must be a standalone document without needing to refer to any other OEM document.
5. The dynamic models must be benchmarked against each other as per [4, 7].
6. Both the model's and the real BESS's dynamic and static parameters must also be submitted in a format of a mapping sheet with the used scaling (if any).
7. The encryption of the models must follow [4, 7]
8. The RMS block diagram must be provided to Transgrid which will be used for modelling the GFM BESS in an internal small signal modelling platform for benchmarking purposes with SSAT. Block diagrams are to be submitted as an independent document and not a part of RUGs while RUGs include brief version of block diagram.
9. For the selection of BESS Inertia, stator inductance and damping factor while all the requirements in the GPS and in this document must be met, the default of the objective function for all the parameter tunning should be the damping and general system strength support.
10. All the protection logics that may impact the availability of the whole generating system, including BOP and the inverters, must be modelled in both PSS®E and PSCAD models that represent the correct tripping thresholds of the GFM BESS.

   a. If, as result of implementing swing equation in the control system, GFM BESS may experience mathematical pole slipping conditions that leads to oscillations, the OEM must advise on it and either avoid this condition or address the issue by preventing this from happening completely.

11. All the RMS block diagrams of the PPC and inverters must be available to Transgrid including inner current controller and PLL (if it is being used).
    a. NDAs can be put in place for confidential parts of the controllers.
12. Upon the request, HiL and its overlays with PSCAD™ simulations may be provided to Transgrid.
13. If the GFM BESS technology cannot operate in an islanded condition (the absence of grid), extreme high level fault condition or extreme low level fault condition such as black start, the dynamic models must reflect this. For example, if in reality, the operation in conditions of test 16 cannot be supported by the GFM BESS, the models must also indicate this inability.

### 8.2 Compliance

A GFM BESS that provides SVWSS to Transgrid must comply with the requirements outlined in this document and must remain compliant with all the National Electricity Rules(NER) clauses and the agreed Generator Performance Standard (GPS) clauses. Should the Proponent suspect any contradictory expectation between the requirement in this document and NER, it must be immediately raised with Transgrid.

It must also be noted that providing SVWSS cannot be used as a reason to be used as a reason to:

- Cause any non-compliance or non-conformance with respect to NER and the agreed Generator Performance Standard.
- Negotiate a lower access standard than it would, using the implemented GFM technology without providing SVWSS.
- Receive exemption to go through 5.3.9 process or to propose a negotiated access standard less onerous than the existing agreed performance standard, when applying to alter a generating system under NER 5.3.9. Transgrid does not have any discretion to grant an exemption to this rule[1].

Additionally, it is expected to meet Transgrid's requirement of SVWSS using Grid Forming BESS, the requirements captured in this document are also met.

## 9. Commissioning and R2 Model Validation

From the grid performance and compliance, the commissioning and R2 model validation includes four main following stages:

1. Agreement on the proposed test plan, which includes Hold Point testing as well as R2 model validation. The test plan must follow the structure captured in [8] but be populated for specific project by working with Transgrid and AEMO.
   - While number of Hold Point tests to be agreed depending on the specifics of individual projects, the minimum considered test points are three.
   - In addition to the standard test procedure, the proponent must propose and perform some additional tests during Hold Point testing to specifically illustrate the independency of the inverters to the system strength of the network. For example, Transgrid would like to observe the inverters

[1] NER 5.3.4A(b)(1A): energy-rules.aemc.gov.au/ner/current/5.3.4A

operating in stable manner in the first Hold Point when the High Voltage side of the generator is electrically disconnected from the grid. However, as this may have some unmanageable complexity in the BOP design of the generator, Transgrid is open to accept the alternatives proposed by the proponent.

    - In the cases that the proponent has completed all the R1, Hold Point Testing and R2 model validation as per standard practice, all the modelling tests in this document will still need to be done; however, for the commissioning aspect only the additional tests which are directly targeting the Grid Forming features of the technology as well as the ongoing Compliance Monitoring described under item 4 of this section will be applicable.

2. Scheduling and undertaking the GPS compliance assessment and performing Hold Point testing. This includes the submitting the Hold Point report which includes model overlays with PSS®E or PSCAD™.
    - Moving from each Hold Point requires receiving approval from Transgrid and AEMO based on the Hold Point Test report.
    - Minimum of 2 business days must be considered for review period by Transgrid. Transgrid will attempt to also work with AEMO for achieving the approval from AEMO in this period; however, this will depend on the availability of resource on AEMO's side and the quality of the presented reports and results.

3. R2 Model validation: this phase starts from the approval of the final Hold Point and the Proponent has maximum of 3 months to submit R2 package.
    - It is worth noting R2 model validation report is only one component of R2 package. R2 package must include the latest version (changed or unchanged) of any document to Transgrid. This includes RUGs, drawings, VCS, etc.

4. Ongoing Compliance Monitoring apart from ongoing compliance monitoring report to Australian Energy Regulator and any network incident that has been captured in R2 model validation report, the generator must submit a yearly compliance report to Transgrid, including PSSE and PSCAD overlays, for minimum of three nearby faults, per year, for the first five years of the SVWSS contract term. If the initial contract term is less than five years, this requirement extends into the subsequent contract term(s). It must be noted that the generator must find the time of these network events and faults independent to Transgrid's assistance.

It must be noted that should there be any material difference between the model representation and the real response of the machine identified in the Hold Point Testing or R2 model validation, the model supplier must perform enough modelling works to ensure the pre-commissioning modelling works remain valid for the compliance and planning purposes.

If the project involves multiple GFM BESS at the same connection point, depending on the timing of the unit's commissioning, each unit may require its own test plan. It must also be noted that test results from one unit cannot be presented for another unit at the same connection point or elsewhere in the network even with supposedly identical unit.

# 10. References


[1] AEMO, "Voluntary Grid-forming Inverter Specification," May 2023. [Online]. Available: http://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf.

[2] AEMO, "Core Requirements Test Framework," January 2024. [Online]. Available: https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf.

[3] AEMO, " System Strength Requirements Methodology - Chapter 5 Stable Voltage Waveforms," [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-strength-requirements/system-strength-requirements-methodology.pdf.

[4] AEMO, "Power System Model Guideline," 2023. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-security-market-frameworks-review/2023/power_systems_model_guidelines_2023_published_.pdf.

[5] Transgrid, "Harmonic Assessment Requirements Guide Version 2.0," Nov 2023.

[6] AEMC, "Frequency Operating Standard," April 2023. [Online]. Available: https://www.aemc.gov.au/sites/default/files/2023-04/FOS%20-%20CLEAN.pdf.

[7] AEMO, "Dynamic Model Acceptance Test Guideline published by," November 2021. [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/network_connections/model-acceptance-test-guideline-nov-2021.pdf.

[8] AEMO, "GPS COMPLIANCE ASSESSMENT AND R2 MODEL VALIDATION TEST PLAN TEMPLATE," May 2016. [Online]. Available: https://aemo.com.au/-/media/Files/Electricity/NEM/Network_Connections/Transmission-and-Distribution/Generating-System-Test-Plan-Template-for-Conventional-Synchronous-Machines.pdf.

[9] NREL, "Grid Impedance Scan Tool (GIST)," April 2023. [Online]. Available: https://www.nrel.gov/docs/fy23osti/86112.pdf.