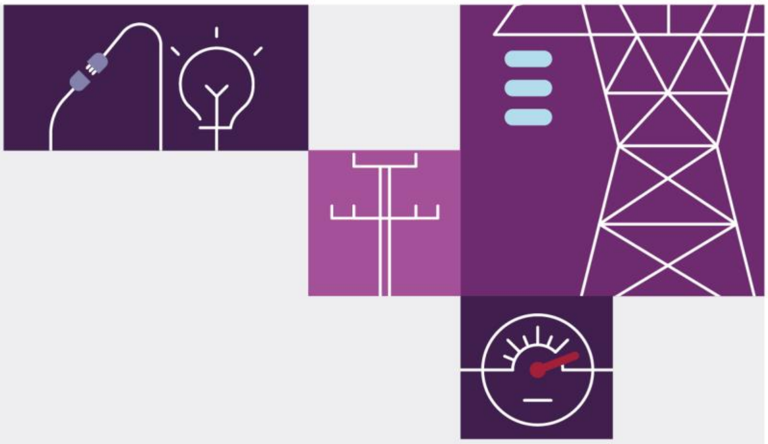
Quantifying Synthetic Inertia of a Grid-forming Battery Energy Storage System – Technical Note

September 2024

A report for the National Electricity Market



Important notice

Purpose

The purpose of this publication is to provide technical information to the industry. This publication outlines a methodology to quantify the synthetic inertia from a grid-forming battery energy storage system. It also outlines various factors and power system conditions that affect inertial contribution from a grid-forming battery energy storage system. This publication is generally based on information available to AEMO as at 1 September 2024 unless otherwise indicated.

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Version control

Version	Release	Changes
1.0	September 2024	Initial version

AEMO acknowledges the Traditional Owners of country throughout Australia and recognises their continuing connection to land, waters and culture. We pay respect to Elders past and present.

Executive summary

As the energy transition progresses, the National Electricity Market (NEM) is moving towards periods of 100% instantaneous penetration of renewables. Much of the renewable generation will be provided by inverter-based resource (IBR) generation. Operating a power system at or near 100% IBR generation introduces new considerations for managing power system security and reliability.

This report summarises the preliminary analysis carried out to quantify the synthetic inertia of a grid-forming (GFM) battery energy storage system (BESS). In this context, the term ‘synthetic inertia’ is used in a general sense to represent the magnitude of synthetic inertial response as quantified by the methodology described below. This activity was identified in the AEMO Engineering Roadmap to 100% Renewables – FY2024 Priority Actions Report[1].

Unlike synchronous inertial response, which is the inertial response from stored kinetic energy in the rotating mass of a machine that is electro-magnetically coupled to the power system, synthetic inertial response from a GFM BESS is dependent on the control system logic, inverter design and configuration. Synthetic inertial response following a frequency disturbance is considered as a valuable capability for a GFM inverter, as outlined in Voluntary Specification for Grid-forming Inverters[2].

The Voluntary Specification for Grid-forming Inverters splits capabilities of grid-forming inverters into ‘core’ and ‘additional’ capabilities. Core GFM inverter capabilities are expected to be achievable with no or minimal modification to plant hardware and operational processes when compared with a grid-following design, requiring changes mainly to the software and control algorithms of the plant. Further to the core capabilities, some GFM inverters might be capable of providing additional capabilities that could necessitate material hardware upgrades or changes to operational practices to provide a larger energy buffer.

This report presents a methodology to quantify the synthetic inertia of a GFM BESS. The proposed methodology is based on the power system swing equation and derives synthetic inertia of a GFM BESS at various operating points. The analysis also considers the impact of contingency size and resultant rate of change of frequency (RoCoF) on the synthetic inertia provided by a GFM BESS. The report highlights the confounding impact of fast frequency response (FFR) on determining synthetic inertia of a GFM BESS based on the proposed approach.

The key findings from this analysis are outlined below.

- **Operating point of GFM BESS** – the synthetic inertia of a GFM BESS is likely to vary based on its operating point. When a GFM BESS is operating at lower (closer to zero active power) pre-disturbance operating points, it would have sufficient headroom to provide synthetic inertial response. When a GFM BESS is operating at higher (closer to its limit) pre-disturbance operating points, the synthetic inertial response provided by the GFM BESS may start to reduce due to lower available headroom before the BESS reaches its current limit.
- **Contingency size and RoCoF** – a larger contingency size or higher RoCoF in conjunction with higher operating points can increase the likelihood of a GFM BESS reaching its current limit, and thus reducing the inertial contribution from the GFM BESS. Therefore, the contingency size and the RoCoF should be factored in when quantifying synthetic inertia of a GFM BESS.

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[1] See https://www.aemo.com.au/-/media/files/initiatives/engineering-framework/2023/nem-engineering-roadmap-fy2024--priority-actions.pdf.

[2] See https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf.

- **FFR** – the FFR provided by a GFM BESS acts based on the measurement of frequency change. Generally, the FFR is fast, with response time in a few hundreds of milliseconds (ms). Therefore, FFR can have a confounding impact on the quantification of synthetic inertia provided by a GFM BESS. This confounding impact would vary based on the operating point of a GFM BESS, the size of the contingency, and thus the RoCoF the GFM BESS is exposed to. Therefore, it is recommended that FFR (or any equivalent frequency support based on the frequency measurements) should be disabled when determining synthetic inertia of a GFM BESS.

The analysis presented in this report provides guidance on quantifying the synthetic inertia of a GFM BESS and highlights factors that should be considered while determining synthetic inertia of a GFM BESS. This report does not seek to propose any new requirements on GFM inverters. AEMO intends to commence a review in Q4 2024 of the NEM technical requirements for connection relating to GFM inverters. This will investigate whether any changes are needed to better specify the required capabilities of these devices.

This analysis is not proposing a direct replacement of synchronous inertia with synthetic inertia. Further work is required to understand the interrelationship and interchangeability between synthetic inertia and synchronous inertia, and the split between synthetic inertia and synchronous inertia required in the NEM to operate the power system in a secure operating state.

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1 Introduction

1.1 Context and background

The Engineering Roadmap[3] is a body of work that provides a technical base to inform industry prioritisation of the steps necessary for a secure, reliable, and affordable transition through key milestones in the transition of the National Electricity Market (NEM), identifying the critical engineering actions required to manage the technical envelope of the power system as renewable penetration increases.

A priority focus area of the Engineering Roadmap is to define potential system security needs that emerging technologies could supply to provide long-range investment visibility.

One associated activity is to investigate the ability of grid-forming (GFM) battery energy storage systems (BESS) to provide synthetic inertial response.

AEMO began Engineering Roadmap work in this area with an explanation of inertia in the NEM[4], then identified synthetic inertial response as a technical capability[5] that all grid-forming inverters could likely achieve[6], then developed a test framework to quantitatively demonstrate this capability[7]. This paper follows on from these prior initiatives to develop a common view on quantifying synthetic inertia from a GFM BESS.

Defining and specifying synthetic inertia

Synthetic inertia is an emerging area of power system engineering, with the terminology around its desired performance, measurement, and quantification still evolving. This report uses the term ‘synthetic inertia’ in a general sense to represent the magnitude of synthetic inertial response as quantified by the methodology described below. Other characteristics of synthetic inertial response may also need to be specified and quantified for the purposes of defining a GFM BESS’s contribution to power system inertia. As a starting point, this report assumes that plant providing synthetic inertia meet the simulation tests defined in AEMO’s *Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework*.

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[3] AEMO. Engineering Roadmap to 100% Renewables, at https://www.aemo.com.au/initiatives/major-programs/engineering-roadmap.

[4] AEMO. Inertia in the NEM explained, March 2023, at https://aemo.com.au/initiatives/major-programs/engineering-roadmap/engineering-roadmap-execution-reports.

[5] This refers to core capability as described in the voluntary specification. It is expected that a grid-forming inverter could readily achieve this capability with no or minimal modification to plant hardware and operational processes when compared with a grid-following design, requiring changes mainly to the software and control algorithms of the plant. AEMO intends to commence a review in Q4 2024 of the NEM technical requirements for connection relating to GFM inverters. This will investigate whether any changes are needed to better specify the required capabilities of these devices.

[6] AEMO. Voluntary Specification for Grid-forming Inverters, May 2023, at https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E.

[7] AEMO. Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework, January 2024, at https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf?la=en&hash=7778A2249D8C29A95A2FADCD9AAA509D.

1.2 Document purpose

This report details a methodology that AEMO developed to quantify the inertia contribution from a GFM BESS. This simulation-based methodology, one of many methodologies being discussed in the industry, aims to measure and quantify the synthetic inertia of a GFM BESS.

The report considers how factors including pre-disturbance operating point, rate of change of frequency (RoCoF) and fast frequency response (FFR) enablement, affect the size of the inertial contribution. This information could inform specifications for procuring synthetic inertia from GFM BESS.

1.3 Structure of this document

Section 2 of this document discusses the methodology in detail with numerical examples being presented in Appendix A1. Section 3 introduces the form of capability curve under various system conditions, and highlights the impact of key contributing factors in quantifying the synthetic inertia from a GFM BESS.

1.4 Next steps

This methodology is a starting point for quantifying the synthetic inertia of a GFM BESS. While this is not a consultation, AEMO welcomes any feedback from industry participants and original equipment manufacturers (OEMs) that would help inform ongoing work in this space.

Stakeholders wishing to provide feedback can send this to FutureEnergy@aemo.com.au.

AEMO is planning to continue work in this area by examining the inertial contribution from different GFM BESS projects that are being connected to the NEM.

2 Quantifying synthetic inertia

This section presents a methodology to quantify the synthetic inertia from a GFM BESS. It extends the approach presented in a recent CIGRE publication that outlined a concept for determining the inertia contribution from a GFM BESS[8]. The approach presented in this report is also similar to the standard load rejection tests historically used to measure synchronous machine inertia constant[9].

2.1 Methodology

The measurement of the inertia contribution is based on the swing equation (with damping ignored[10]), as shown in equation (1)[11] below:

$$\frac{2 \times I}{\omega_s} = \frac{P_{mech} - P_{elec}}{d\omega/dt} \tag{1}$$

where

- I is inertia in megawatt-seconds (MWs),
- ω_s is synchronous speed in radian per second,
- $Pmech$ and $Pelec$ are the mechanical power into and electrical power out of the plant(s) under consideration respectively, both in megawatts (MW).

Rearranging equation (1), the equivalent inertia can be calculated as shown in equation (2) below:

$$I_{total} = \sum_{n=1}^{N} (MW.s_n) = \frac{\Delta P_{MW} \times f}{2 \times RoCoF} \tag{2}$$

where

- I_{total} is the total inertia contribution of the system in MWs,
- N is the total number of plants in the system providing inertia,
- ΔP_{MW} is the applied active power disturbance to the system in MW,
- f is the nominal frequency of the system in hertz (Hz),
- $RoCoF$ is the rate of change of frequency in hertz per second (Hz/s).

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[8] Determining Inertia contribution from grid-forming battery energy storage systems, Nilesh Modi, Ahvand Jalali, Jayanth Ramamurthy, Andrew Groom, Jane Yu, 4 – 7 September 2023, CIGRE Cairns Symposium 2023.

[9] Generator testing requirements, Transpower, NZ, at https://static.transpower.co.nz/public/bulk-upload/documents/GL-EA-010%20Generator%20Testing%20Requirements.pdf.

[10] Note that, unlike synchronous generators, depending on the specific implementation, damping may be essential for stable operation of GFM BESS, and thus its implication on inertia contribution from GFM BESS may require further investigations in the future. However, the proposed methodology remains practically robust for determining synthetic inertia from the system perspective.

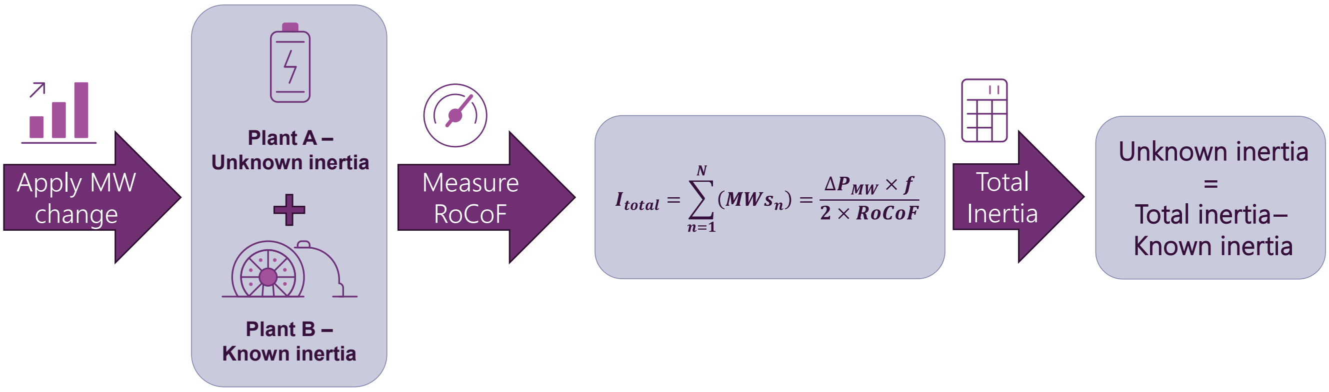
[11] P.M. Anderson, A. A. Fouad, Power System Control and Stability, 2003, Wiley-IEEE Press, pp. 33 – 40.

Figure 1 shows a conceptual view of the methodology that has been developed based on the above mathematical representation.

It comprises Plant A (whose synthetic inertia or inertial contribution is to be determined) and Plant B (whose inertia is known[12]). When an active power imbalance is applied to the system comprised of Plant A and Plant B, the frequency of the system will change. This will result in a RoCoF, which depends on the size of the disturbance and the inertial contribution from Plant A and Plant B. This RoCoF and the known amount of active power disturbance is then used to calculate the total inertia of the system (comprised of Plant A and Plant B). As the inertia of Plant B is known, the inertia of Plant A can be determined by subtracting the Plant B inertia from the total calculated inertia.

It should be noted that this methodology emulates near real-world conditions for providing inertial response. That is, an active power contingency (e.g. load or generation trip) in the system leads to changes in the frequency, RoCoF, and voltage. Following a contingency, a plant capable of providing inertial response will contribute to total system inertia in conjunction with other inertial responses in the system. In a simulation domain, it is possible to apply change in the frequency without necessarily creating an active power contingency. This can be achieved via a controlled voltage source. The synthetic inertia of a GFM BESS can then be quantified by measuring the synthetic inertial response from this plant to certain RoCoF values. Although different in nature, in theory, both methodologies should result in a similar quantification for synthetic inertia from a GFM BESS to similar resultant RoCoF values in the system. The frequency measurement in the power system simulation tools can often be complex, and thus utmost care should be taken by user when calculating RoCoF to quantify synthetic inertia.

Figure 1 Quantification of inertia contribution steps



2.2 Test system

Figure 2 further illustrates the implementation of the methodology used for this analysis, in a simulation test setup. A known amount of power imbalance (megawatt change or contingency) is created by opening the breaker at time of t_0 in the test system of Figure 2. Note that depending on the flow across the transmission line, the applied contingency would lead to an under-frequency or over-frequency event. Frequency measurement is then used to calculate the RoCoF over a 500 milliseconds (ms) rolling window[13]. These values will be plugged back into

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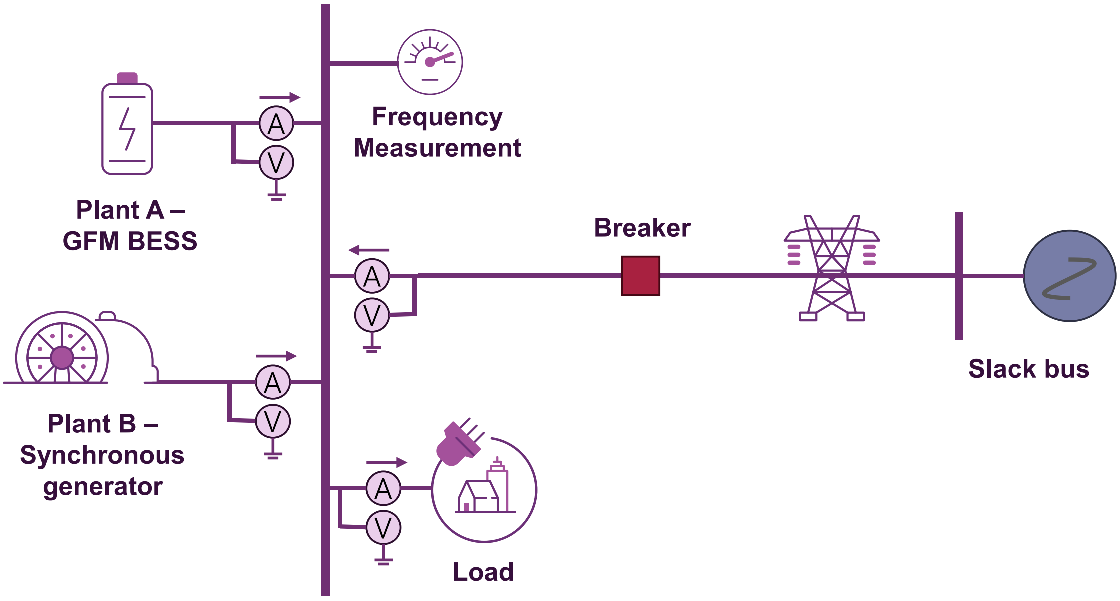
[12] This could be a synchronous generator whose inertia (MWs) is normally known from the design datasheet or power system model.

[13] The time window used here is an example only.

equation (2) for calculation of total inertia (I_{total}). As the inertia from Plant B is already known and tested based on the available data sheet, the unknown inertia of Plant A can be determined by subtracting Plant B inertia from the total calculated inertia.

Figure 2 Schematic representation of the test system



Test assumptions and inputs

The following assumptions are implicit in the test that was used to determine the synthetic inertia from GFM BESS:

- Model quality of Plant A should be in accordance with AEMO requirements[14].
- The inertia of Plant B[15] is known.
- Since the 'bare-bone' inertial responses of the plants are of interest, frequency control loops of both plants (A and B) are disabled[16].
- Load is constant power and static load (that is, it is not sensitive to voltage and frequency changes).
- Model should meet existing requirements under Schedule 5.2 of the National Electricity Rules (NER).
- The resultant RoCoF[17] of the overall system in test examples is up to 2 Hz/s[18].
- Plant B is approximately twice the size of Plant A to achieve desirable dispatch, RoCoF and operating conditions.

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[14] AEMO. Power System Modelling Guideline, July 2024, at https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-security-market-frameworks-review/2023/power_systems_model_guidelines_2023_published_.pdf.

[15] During this work a synchronous machine was used to represent Plant B. It is operating away from any limits (such as Pmin and Pmax) pre- and post-disturbance. Its initial terminal voltage is closer to 1.0 per unit (pu). Although during the work site-specific parameters for automatic voltage control (AVR) and Power System Stabiliser (PSS) have been used, a generic parameter setup is not expected to impact the proposed methodology.

[16] For synchronous generator model, the governor should be disabled. For IBR, frequency control response (such as FFR) should be disabled.

[17] Measured over 500 ms window.

[18] 2 Hz/s is used as an example only.

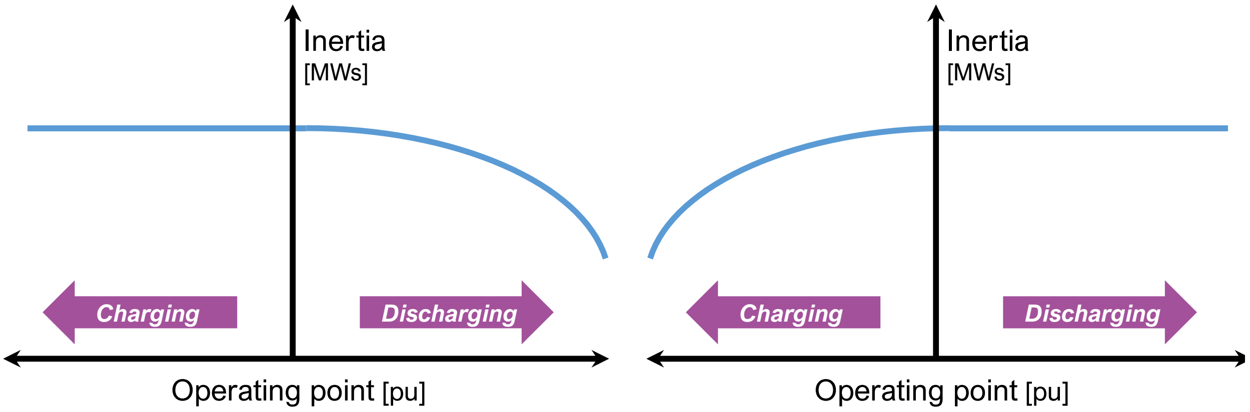
It is important to note that by disabling the frequency control of Plant A and Plant B, and load relief, there is no mechanism to arrent and recover the frequency change following a contingency. Users should consider this point when determining the synthetic inertia using the methodology proposed in this document.

3 Synthetic inertia from GFM BESS

This section provides a summary of analysis carried out to quantify the synthetic inertia of a GFM BESS using the methodology outlined in Section 2. Appendix A1 provides detailed simulation results including the quantification of synthetic inertia for two GFM BESS projects, inter-relationship between FFR and synthetic inertia, the impact of the operating point, contingency size and RoCoF.

Figure 3 shows a typical synthetic inertia capability curve for a GFM BESS. It is of particular note that the synthetic inertial contribution from a GFM BESS varies depending on various factors such as operating point, contingency size, and overload capability. The synthetic inertia capability curve may be asymmetric depending on the operating point, magnitude and the direction of frequency event, available headroom and charging and discharging capacity. The following subsections outline key aspects that can affect the level of synthetic inertia provided by a GFM BESS.

Figure 3 A typical inertia capability curve



Under-frequency events

Over-frequency events

Note: in reality, there would be a family of three-dimensional curves showing relationship between operating point, synthetic inertia and contingency size (or RoCoF).

3.1 Pre-disturbance operating point

The pre-disturbance operating point impacts the amount of synthetic inertia provided by the GFM BESS, as shown below in Figure 4. This can be due to the plant's available headroom or energy buffer, types, and implementation of limits specific to the GFM BESS inverters.

In summary, the following are the impacts of the pre-disturbance operating point on the synthetic inertia provided by a GFM BESS (Appendix A1.2 has further details and example simulation results):

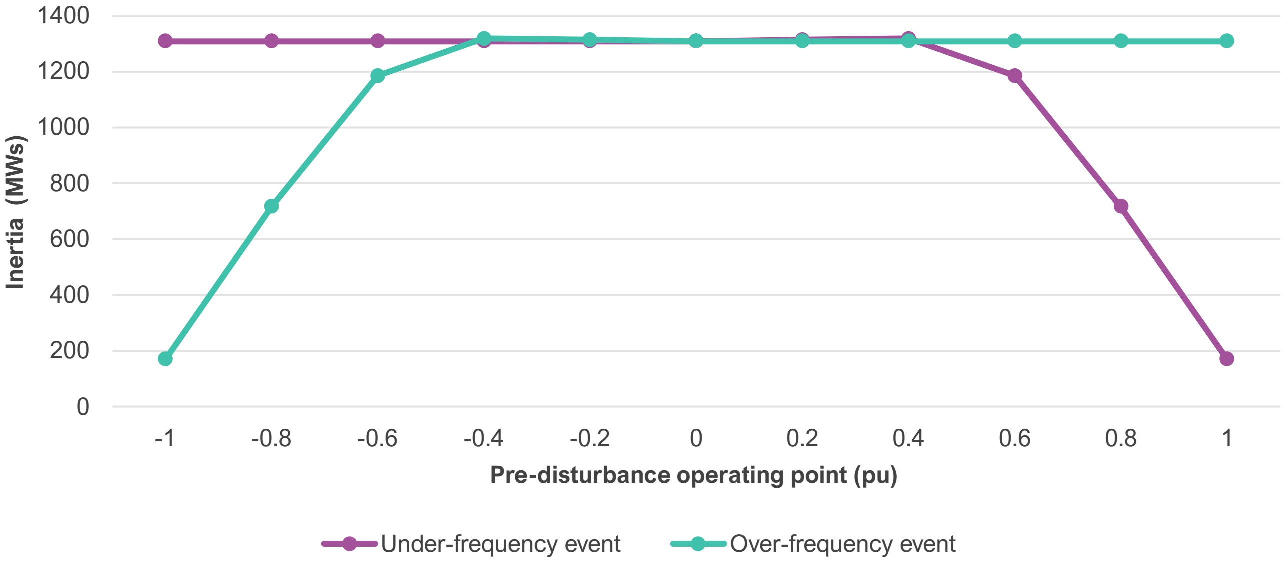
- When a GFM BESS is operating at lower (closer to zero active power) pre-disturbance operating points, it may have sufficient headroom to change its active power in response to a change in the frequency.
- When a GFM BESS is operating at higher (closer to its limit) pre-disturbance operating points, the synthetic inertia provided by the GFM BESS starts to reduce, due to lower available headroom before the BESS hits its

current limit. As an example, when a GFM BESS is discharging at 0.8 pu (with respect to MW base), it has less headroom to provide inertial response for an under-frequency event compared to an operating point of 0.5 pu. However, when a GFM BESS is charging at the same operating point (- 0.8 pu), it has more headroom to provide inertial response for the same under-frequency event.

- Furthermore, an additional capability, also known as overload capability, enables a GFM BESS to operate temporarily at a current output greater than its continuously rated capacity. The extent to which different operating points can affect the synthetic inertia provided by a GFM BESS thus depends on the inverter overload capability, with lower overload capability being associated with a higher likelihood of a limited inertia contribution at higher pre-disturbance operating points.
- When a GFM BESS is operating at or near its active power limit, its inertia contribution may be substantially limited compared to lower pre-disturbance operating points. This is because the inertial response of a GFM BESS at higher operating points is constrained by inverter limits.

Figure 4 shows a typical synthetic inertia capability curve of a GFM BESS at different operating point for a fixed contingency size. In reality, there would be a family of three-dimensional curves showing relationship between operating point, synthetic inertia and contingency size (or RoCoF). For avoidance of doubt, results shown in Figure 4 are only applicable for a contingency size considered.

Figure 4 Synthetic inertia of a GFM BESS at different operating points for a fixed contingency size



3.2 Contingency size and rate of change of frequency

The contingency size (and resultant RoCoF) is identified as a key contributing factor in quantifying synthetic inertia provided by the GFM BESS. This is primarily because, other things being equal, larger contingency results in larger RoCoF, which results in a higher magnitude of response from the GFM BESS[19]. This can result in a higher

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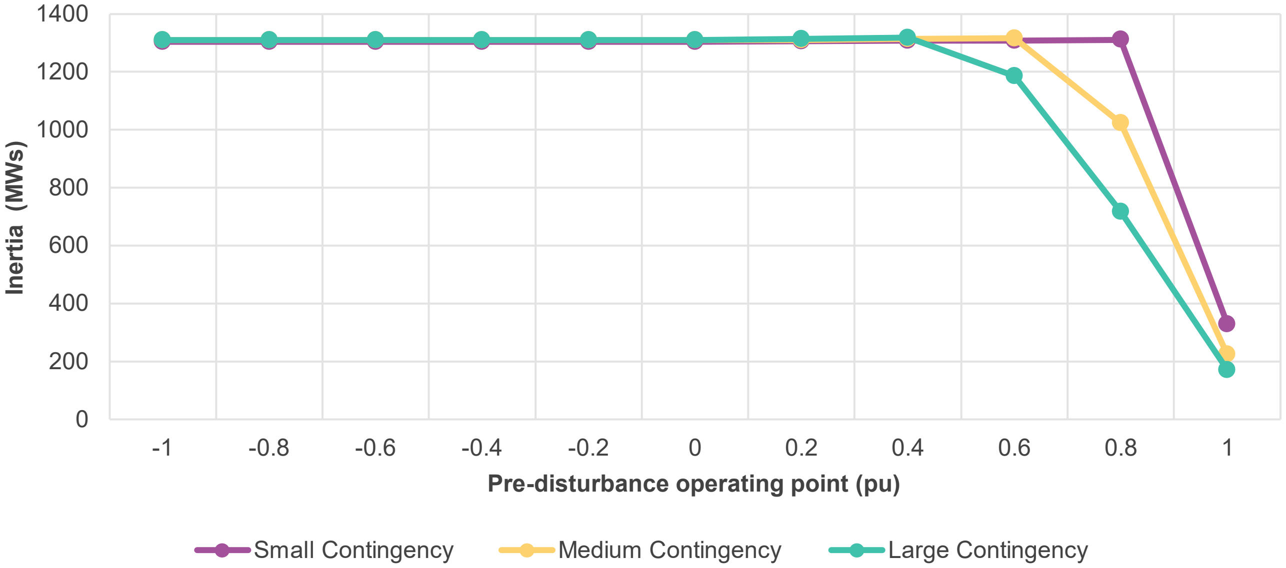
[19] It has been assumed that a GFM BESS use basic principles of swing equation or virtual synchronous machine logic. Most GFM BESS currently make use of a swing equation approach or its extension in their control system.

likelihood of hitting the current limit. Figure 5 shows the impact of contingency size/RoCoF on quantification of synthetic inertia from a GFM BESS.

The impact of contingency size on quantification of synthetic inertia is summarised below (further details and example simulation results are in Appendix A1.3):

- At lower operating points, a large contingency size (which would generally result in high RoCoF) may lead to a noticeable reduction in the ability of a GFM BESS to provide a synthetic inertial response. On the other hand, at higher operating points, a small contingency size (which would generally result in low RoCoF) may also result in a limited synthetic inertial contribution from a GFM BESS. Therefore, a larger contingency size/higher RoCoF in conjunction with higher operating points can increase the likelihood of hitting the current limit, and thus reduce the inertial contribution from a GFM BESS.
- The contingency size and the resultant RoCoF[20] should be factored in when quantifying synthetic inertia from a GFM BESS.

Figure 5 Impact of contingency size (or RoCoF) on synthetic inertia from a GFM BESS – under-frequency event



Note: the resultant RoCoF values for small, medium, and large contingency size are 0.6 to 0.9 Hz/s, 0.9 to 1.38 Hz/s and 1.2 to 2 Hz/s respectively. During this work, the contingency size has been used as a disturbance. The impact of contingency size would result in RoCoF which would depend on the inertia of the overall system and GFM BESS operating points. Applying a constant RoCoF would require applying a number of contingency sizes to achieve a desired RoCoF and would not materially provide different outcomes.

3.3 Fast frequency response

Ideally, the quantification of synthetic inertia should discount any response provided through FFR or any other frequency control mechanism. The FFR is a response based on the measurement of frequency, while inertial response is inherent and independent of the activation signal received from the measurement of the frequency. With advancement in fast acting control systems, the FFR from a BESS can be achieved in a few hundreds of milliseconds. The FFR and synthetic inertial response are technically two different characteristics and may overlap

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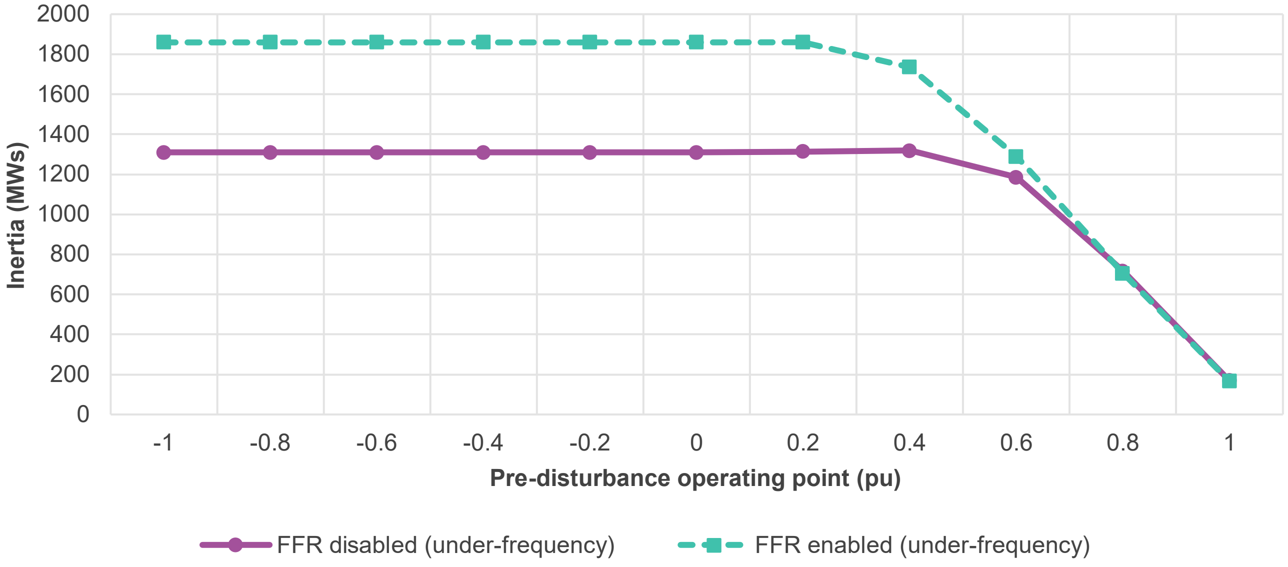
[20] Note that the impact of the RoCoF on the size of the response from a GFM BESS may depend on the inertia setting and relevant control implementation.

in the timeframe in which synthetic inertia contribution is determined. The GFM BESS with FFR is more effective in arresting frequency, because without FFR, a GFM BESS by itself (without any frequency control capability in the system) can only slow the RoCoF, and cannot arrest the frequency. Therefore, to recognise 'bare-bone' synthetic inertia, it is important that FFR is excluded when quantifying the inertia contribution from a GFM BESS. This can be achieved by disabling the frequency response from a GFM BESS. Figure 6 shows the confounding impact of FFR on quantification of synthetic inertia from a GFM BESS.

The confounding impact of FFR on quantification of synthetic inertia provided by a GFM BESS is discussed below (further details and example simulation results are in Appendix A1.4):

- The FFR has a confounding impact on the quantification of synthetic inertia provided by a GFM BESS, particularly when the pre-disturbance operating point is away from its current limit. The impact of FFR on synthetic inertia provided by a GFM BESS appears to be insignificant when the GFM BESS is operating at or near its active power limit before the contingency event.
- When quantifying the synthetic inertia provided by the GFM BESS, FFR (or any equivalent frequency support based on frequency measurements) should be disabled to calculate the 'bare-bone' inertial response.

Figure 6 Confounding impact of FFR on determining synthetic inertia from a GFM BESS – under-frequency event



A1. Quantifying synthetic inertia from GFM BESS – example results

This appendix provides example results of the analysis carried out to quantify the synthetic inertia from GFM BESS based on the methodology outlined in Section 2.

AEMO considered two GFM BESS projects (Project A and Project B) while carrying out this analysis, using a simulation test setup as shown earlier in Figure 2 that comprised:

- Plant A (GFM BESS) whose synthetic inertia is unknown.
- Plant B (synchronous generator) whose inertia is known.
- A slack generator and associated loads for creating required flow across the transmission line to apply different contingency sizes, and various operating points of Plant A (GFM BESS).

During this analysis, AEMO examined the impacts of pre-disturbance operating points, different contingency sizes, and FFR on quantification of the synthetic inertia of a GFM BESS. The positive operating points are associated with discharging mode and negative operating points are related to charging mode. During this analysis, AEMO used as-provided project specific models, so did not examine the potential impact of factors such as DC-side power/voltage constraints, parameter tuning and an inverter hard limiter.

A1.1 Summary of test steps

Table 1 provides high-level guidance on the test setup, initial checks, and approach for the simulation. The measured values are then replaced in equation (2) solving for the inertia contribution from a GFM BESS.

Table 1 Test bench setup in the simulation

Initial setup
a. Set up the simulation case as shown in Figure 2.
b. Set up generation from Plant A, Plant B and load such that desired contingency (active power change) is flowing through the transmission line.
c. Disable the control loops in the model which acts on the measurement of frequency and provides frequency control.
Test Sequence
1. Run the simulation until a steady state is achieved.
2. Open the breaker at t = t_0.
3. Measure the RoCoF* in the system.
Simulation checks
a. Plants' active power outputs match desired dispatched levels.
b. Frequency should be 1 pu.
c. Voltages across the system is as expected.
d. There should not be oscillations in the system.
e. Reactive power output from all devices should be within limits.

Determining synthetic inertia
a. Calculate the total inertia in the system based on the applied contingency and measured RoCoF.
b. Subtract the known inertia of Plant B from the total calculate inertia to obtain the inertia contribution from Plant A.

* During this work, a 500 ms rolling window was used to calculate RoCoF.

A1.2 Pre-disturbance operating point

One potential impact of the pre-disturbance operating point is the possibility of limiting the available headroom to provide inertial response, resulting in a reduced inertia contribution from a GFM BESS. AEMO therefore carried out an analysis to calculate the inertia contribution of a GFM BESS for two different projects, namely Project A and Project B, for under-frequency and over-frequency tests. The FFR was disabled in this test to avoid any confounding impact of it and to isolate the inertial response from frequency support systems based on frequency measurements.

During this analysis, AEMO studied various pre-disturbance operating points for both charging and discharging modes. Figure 7 below shows the quantification of synthetic inertia of GFM BESS for projects A and B at different operating points.

As Figure 7 shows, for a contingency size leading to an under-frequency event, when operating in charging mode or low active power setpoints, the synthetic inertial contribution of the GFM BESS remains almost constant. However, with an increase in pre-disturbance operating points in discharging mode, the synthetic inertial contribution of the GFM BESS starts to decline. For operating points near the active power limit, this contribution can be substantially limited.

This trend is observed to be consistent in both over- and under-frequency contingency tests. For a contingency size leading to an over-frequency event, the inertia contribution in discharging mode or at low operating points remains unchanged, while higher operating points in charging mode leads to a substantial reduction in the inertia contribution of the GFM BESS.

When a GFM BESS is dispatched at higher pre-disturbance active power setpoints, its inertia contribution may be substantially limited (if the post-disturbance operating point moves towards the limit) compared to lower pre-disturbance operating points. This is because the inertial response of GFM BESS at higher operating points is constrained by inverter limits. As the active power setpoint increases, the inertia contribution of the GFM BESS starts to reduce due to lower available headroom before the plant hits its limits.

Furthermore, an additional overload capability enables GFM BESS to operate temporarily at a current output greater than continuously rated levels. This explains the provision of some inertial response even when a GFM BESS is dispatched at 1 pu setpoint, as shown in Figure 7. For the same contingency size (and other system conditions remaining unchanged), the synthetic inertia of Project A is substantially less than Project B when operating closer to its limit[21].

The extent to which different operating points can impact the inertia contribution of a GFM BESS may also depend on the inverter overload capability, with lower overload capability being associated with a higher likelihood of limited inertia contribution at higher pre-disturbance operating points. Hence, with higher pre-disturbance

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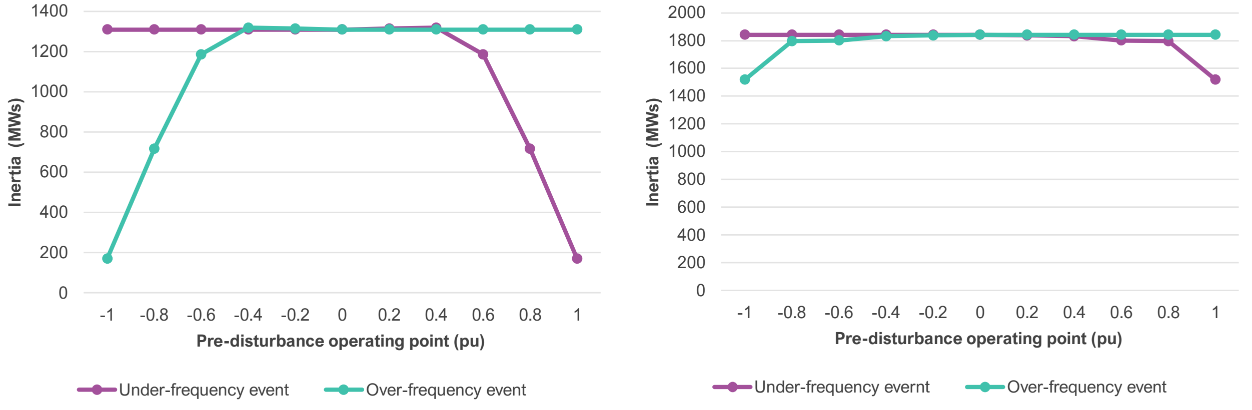
[21] To simplify the presentation of results, one of the projects has been modified to achieve similar charge and discharge ratings (that is, to achieve symmetry across the operating points).

operating points, it is more likely that the inverter's limit is reached when providing inertial response, thus resulting in a limited synthetic inertia contribution from the GFM BESS.

It should be noted that the size of both tested projects is largely similar, so the difference in the inertia contribution of these GFM BESS projects is largely driven by a wide range of factors, such as hardware technology, inertia settings, control algorithms, and overload capability.

Figure 7 Synthetic inertia from GFM BESS projects A and B at different pre-disturbance operating points for a fixed contingency size



Project A Project B

A1.3 Contingency size and rate of change of frequency

This section aims to investigate the impact of contingency size (leading to RoCoF) on the synthetic inertia from GFM BESS projects. To investigate the impact of contingency size, three scenarios are considered with different contingency sizes, namely large (1 pu with respect to plant's MW base), medium (0.75 pu with respect to plant's MW base), and small contingencies (0.5 pu with respect to plant's MW base)[22]. For completeness, this study also includes different operating points at both charging and discharging modes of operation.

The numerical results for synthetic inertia contribution from GFM BESS projects A and B for different contingency sizes are shown Figure 8 and Figure 9 for under-frequency and over-frequency disturbances, respectively. As these figures show, in a scenario with a small contingency, the inertia contribution from a GFM BESS starts to decline only for dispatch points near its operating limit, whereas with an increase in contingency size, the inertia level starts to decline at lower operating points. This is because the magnitude of response is greater for larger contingency sizes, resulting in a higher likelihood of hitting the current limit at lower active power setpoints compared to smaller contingencies. On the other hand, at higher operating points, a small contingency may also reduce the inertia contribution from the GFM BESS. A larger contingency size in conjunction with higher operating points can increase the likelihood of hitting the current limit, thus reducing the inertia contribution from the GFM BESS. Therefore, contingency size and the resultant RoCoF should be factored in when quantifying the inertia contribution from a GFM BESS.

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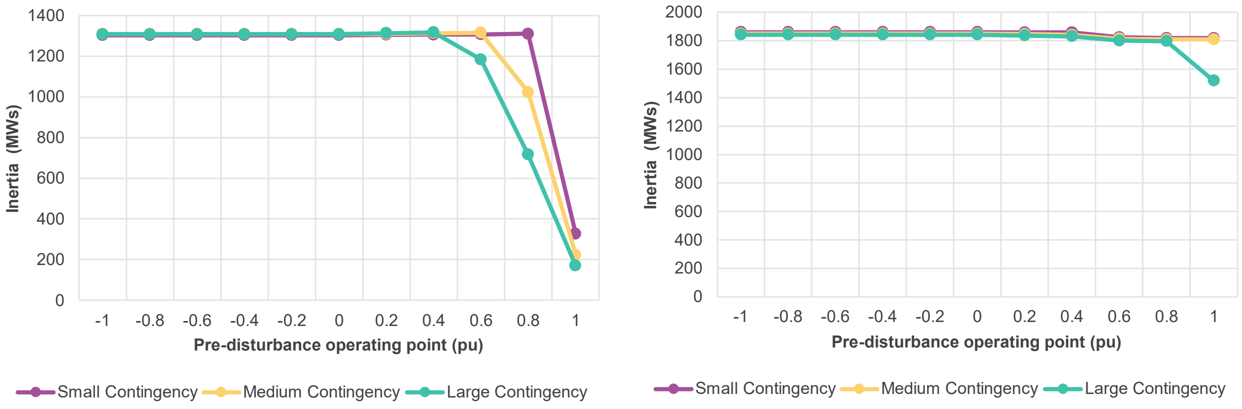
[22] As outlined in this report, the method uses contingency size as an input to create RoCoF and therefore different contingency sizes have been considered instead of RoCoF. Applying a constant RoCoF would require iterations of applying number of contingency sizes to achieve a desired RoCoF and would not materially provide different outcomes.

It was also noted that to certain extent, the impact of contingency size on the synthetic inertia contribution varies between two projects. That is, all things being equal, large contingency size at higher operating points results in more reduction in the inertia contribution in Project A compared to Project B. For instance, as shown in Figure 8, for a large contingency size, when Project A is dispatched at 1 pu, its inertia contribution reduces to less than 200 MWs, which is some 87% lower than the inertia contribution at low active power setpoints. However, for Project B, when dispatched at 1 pu, the inertia contribution reduces to approximately 1,500 MWs, which is only around 18% lower than the inertia contribution at low active power setpoints. This may be associated with the difference in overload capability of inverters, control design and inverter specifications in these two projects[23].

Figure 8 **Synthetic inertia contribution from GFM BESS projects A and B for different contingency sizes leading to under-frequency event**

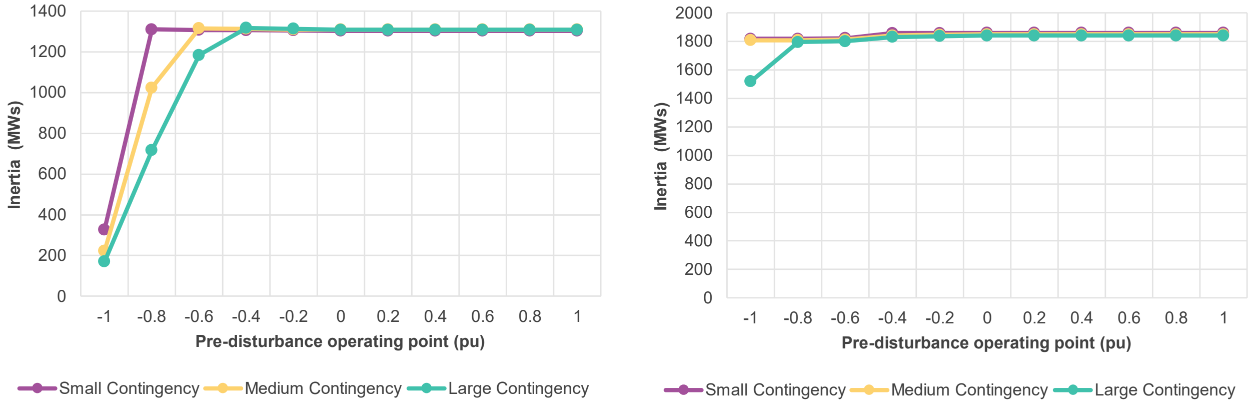


Project A

Project B

For Project A, the resultant RoCoF values for small, medium, and large contingency size are 0.6 to 0.9 Hz/s, 0.9 to 1.38 Hz/s and 1.2 to 2 Hz/s respectively. For Project B, the resultant RoCoF values for small, medium, and large contingency size are 0.53, 0.78 and 1.15 Hz/s respectively.

Figure 9 **Inertia contribution from GFM BESS projects A and B for different contingency sizes leading to over-frequency event**



Project A

Project B

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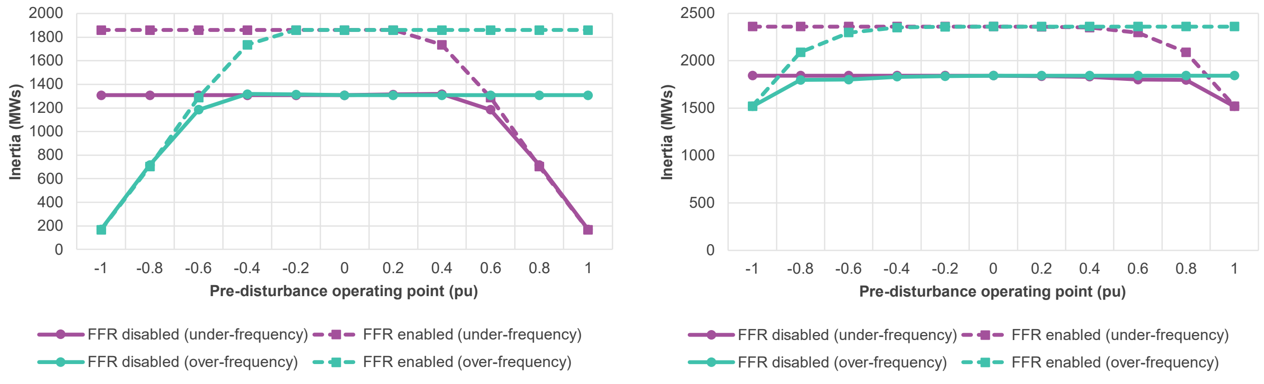
[23] Note that, in general, the difference in numerical values of the inertia contribution between different GFM BESS projects may also depend on a wide range of factors, such as the size of the plant, hardware technology, inertia settings, and control algorithms.

A1.4 Fast frequency response

This section analyses the impact of FFR on the quantification of synthetic inertia from a GFM BESS. Figure 10 shows the inertia contribution from a GFM BESS with and without FFR for under-frequency and over-frequency events. The inertia contribution in FFR-enabled mode is the equivalent inertia level calculated based on the measured RoCoF value in the system, and should not be interpreted as 'bare-bone' synthetic inertia, as it includes droop response to frequency deviations. As Figure 10 shows, generally the calculated synthetic inertia of a GFM BESS is higher when FFR is enabled[24]. The impact of FFR on the calculation of synthetic inertia from a GFM BESS is negligible when the operating point is closer to its active power limit and following a contingency the operating point moves towards the limit.

This highlights the importance of disabling FFR for quantifying the synthetic inertia of GFM BESS. Therefore, when quantifying the synthetic inertia of GFM BESS, FFR (or any equivalent frequency support based on frequency measurements) needs to be disabled to calculate 'bare-bone' inertia.

Figure 10 Confounding impact of FFR on inertial contribution from GFM BESS



Project A

Project B

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[24] It should be appreciated that in this analysis, the entire response from GFM BESS with FFR enabled in the rolling window of RoCoF measurement is accounted for as equivalent inertia contribution, while the FFR response may need to be distinguished and assessed separately to obtain the inertia contribution alone.

Abbreviations

Term	Definition
BESS	battery energy storage system
DC	direct current
FFR	fast frequency response
GFM	grid-forming
Hz	hertz
Hz/s	hertz per second
IBR	inverter-based resources
ms	milliseconds
MW	megawatts
MWs	megawatt-seconds
NEM	National Electricity Market
NER	National Electricity Rules
pu	per unit
RoCoF	rate of change of frequency