The Role of Inverter-Based Resources During System Restoration

Report

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Executive summary

This report is prepared as part of topic 5 of Australia's Global Power System Transformation (G-PST) Research Roadmap, with the intent of understanding and expanding system restoration capabilities in the National Electricity Market (NEM). This work was divided into two stages:

- Stage 1: Assessment of capabilities and limitations of various black start options using simplified, but realistic network models. Development of high-level functional specifications for the use of IBR during system restoration based on results obtained from several hundreds of PSCAD™/EMTDC™ simulation studies.
- Stage 2: Use of wider power system models to investigate system restoration needs in a Renewable Energy Zone (REZ), and the REZ's interaction with the wider power system during the restart process.

The first stage focusses on investigating the performance and capabilities of various possible black start capable generator technologies, both synchronous and asynchronous, in power systems with a high share of inverter-based resources. Technology types investigated include: a grid-forming battery energy storage systems (BESS), a thermal synchronous generator, and a combination of a grid-following BESS and a nearby transmission connected synchronous condenser. Specific emphasis was given to identifying trends impacting black start and restoration support service capability both from individual plant and network perspectives. The response of each option is assessed with the use of detailed vendor-specific electromagnetic transient (EMT) simulation models.

Studies were performed utilising the PSCAD™/EMTDC™ time-domain based power system simulation software, investigating the ability of each candidate black start option in energising network transformers and transmission lines; restarting large induction motor-based loads; and restarting grid-following inverter-based resources (IBR). Detailed vendor-specific EMT simulation models of each black-start technology type were utilised, as well as for analysis of restarting different types of grid-following inverters including wind farms, solar farms, and grid-following BESS.

Distance and differential line protection relays were also included in the overall simulation model to assess the potential maloperation of these relays under low fault level conditions during early stages of system restoration when subject to a network fault. Models of key protective relays for synchronous generators such as loss-of-excitation (LOE), out-of-step (OOS) and V/Hz relays were not included due to the use of generic synchronous generator models and the need for developing the design and settings of these relays which was out of scope of this project. Furthermore, it was noted that the core objective of this work was to assess the capabilities and limitations of IBR for system restoration rather than those associated with synchronous generators.

Studies conducted simulate an indicative step-by-step network energisation process for each candidate black start option. The impact of various contingencies that might occur in the early stages of system restoration such as fault occurrences, generation reduction due to resource variability, and load disconnection, were then studied for each step. These studies demonstrate that all three options can provide viable black start contribution.

Despite providing a lower fault current contribution to that of a synchronous generator, the grid-forming BESS was identified as the most capable black start option. This stems from its faster response to voltage and, in particular, to frequency disturbances, and the inherent ability to act as a generator or as a load. The latter is important as it will provide the flexibility to energise additional grid-following inverters which could otherwise be limited due to the load scarcity, especially in network locations with a high penetration of distributed photovoltaics operating before a blackout.

From the three options investigated, the combined grid-following BESS and synchronous condenser was shown to be the least capable in terms of energising other network assets and grid-following inverters. This primarily stems from the fact that neither the grid-following BESS nor the synchronous condenser in isolation can restart the power system, and collectively provide the required voltage and frequency control. Additionally, the required system strength or the short circuit ratio (SCR) for stable operation of the grid-following inverters need to be provided by the synchronous condenser first. Overall, whilst less capable than the other two options, this is still a viable option, which can largely utilise existing network and generation assets, due to its technology maturity relative to large grid-forming inverters. Note that the excitation system type used for the synchronous condenser is an AC exciter. A comparative analysis of the potential impact of static vs AC exciter on the black start performance of the combined grid-following BESS and synchronous condenser was out of scope of this project. This may be revisited in the second stage subject to access to vendor-specific models of synchronous condensers with different types of excitation systems.

The fault ride-through aspect, which is one of the aspects requiring most attention for grid connection studies and generator performance standard negotiation, was also investigated indirectly since most disturbances applied were network faults. It was observed that none of the unstable cases were caused by the instability of the black start unit(s) itself. Note that the key mechanism for transient instability of synchronous generators is the exceedance of critical rotor angle, often caused by exceeding the critical clearing time. Fault durations applied for these studies were the primary protection clearance times which are well below the critical clearing time of synchronous generators. The use of a more extensive network model for the second stage would provide an opportunity to assess the impact of longer duration network faults, in particular those associated with a circuit breaker failure. Also note that these aspects do not pertain to IBR unless a GFM is designed to emulate the rotor angle response of synchronous machines.

The studies conducted demonstrate the insignificant impact of inherent parameters of the black-start synchronous generator such as fault current, inertia, and damping. The grid-forming BESS used emulate the latter two aspects of the response with its control systems, however, the variation of these parameters did not noticeably alter the response and the overall black start capability in the power island studied.

The key metric where the grid-forming BESS outperforms the other two options is the Generator Restart Size Ratio (the ratio of the MVA capacity of a grid-following inverter plant that can be stably restarted by a given MVA capacity of a black starter device). This ratio was also determined to be dependent on the SCR withstand capability of the grid-following inverters being restarted, whereby the lower the SCR threshold which can be withstood by the plant whilst connected to the grid resulted in a higher permissible Generator Restart Size Ratio. In this regard, differences were observed in the overall black start performance depending on the use of grid-following BESS, solar or wind farms. These differences primarily stem from site-specific control system tuning conducted on each of these plants, rather than superior capability of one IBR technology against another. As such these outcomes should not be generalized without due caution.

The second stage of the project focusses on system restart capabilities, needs, constraints and reliance to the wider power system when looking at a larger and more practical power system. The North Queensland power system model were used thanks to AEMO. In addition to re-assessing the impact of the GFM BESS, synchronous generator and combined synchronous condenser and grid-following BESS as black starters, the following points were also investigated with detailed PSCAD™/EMTDC™ simulation studies.

- Whether the NQREZ can restart itself and synchronise to the transmission network south of it
- Whether the NQREZ can restart the downstream network in the event of a more widespread blackout
- Advantages and disadvantages of having a local SRAS source within the NQREZ as opposed to investing in SRAS sources in the downstream network
- The impact of various variables including
  - Network topology accounting for various restoration paths and maximum viable distance between the black starter and the asset to be restored.
  - Presence or absence of other network assets such as generating units with low or no minimum stabilising load requirements such as hydro units and other reactive support plant in the wider network.
  - Key control parameters of the GFM black starter such as virtual inertia and maximum fault current contribution.
  - Synchronous condenser inertia and excitation system variables.

Similar to the work conducted in stage 1, the capabilities and limitations of the three prospective black start options were considered. The use of the wide-area EMT model provided an opportunity to proceed with a larger number of energisation sequences, in turn permitting the restoration of a larger power system, better stress testing of the black start sources involved, and giving more insight into various failure mechanisms. Some of these failure mechanisms could not be observed in stage 1 due to the use of a smaller number of switching events which provided fewer opportunities to stress test the equipment involved. Examples include plant disconnection due to the operation of generator or network protection systems, excessive temporary or transient over-voltages due to the cable charging of long transmission lines, and excessive harmonic voltage distortions in the network. Failure mechanisms common to both stage 1 and 2 were:

i) plant instability and consequent disconnection,

ii) frequency collapse, and;

iii) sustained low frequency oscillations.

Consistent with the observations in stage 1, the GFM BESS provided superior performance compared to both the synchronous generator alone and the combined GFL BESS and SynCon. The combination of GFL BESS and SynCon exhibited the poorest performance, failing in many scenarios. A key factor influencing this behaviour was the electrical distance between the GFL BESS and SynCon. Once this distance was reduced and in particular when it was removed meaning that when they were co-located, this option provided a better response albeit still the most inferior option of the three. Bespoke tuning of the SynCon excitation system and GFL BESS inverter control could potentially improve the performance.

Regardless of the primary black start technology used, the key limiting factor to a successful energisation path was reactive power capability. The use of several existing line and substation reactors was necessary to minimise reactive power loading on the black start source. Furthermore, it was important to ensure that the dynamic control was enabled. Where line reactors were not used, and the reactive power capability of the black start provider was exceeded, sustained over-voltages and unexpected generator performance, exhibited as oscillations and generating unit response not following targets or supporting voltage, were commonly observed. Long transmission lines in the North Queensland REZ investigated create significant excess reactive power and more densely configured REZ in other regions may be less prone to this limitation due to a lower line charging associated with shorter transmission lines. The provision of static or preferably dynamic reactive support is therefore essential if restoration paths are further away from the load centres due to the use of IBRs as opposed to synchronous generators. The dynamic reactive support can be provided by IBRs with a capability to deliver full reactive power at no load. The use of existing network static var compensators (SVCs) could be another viable option (see Section 3.5). Ensuring the availability of any such critical plant is best to be dealt by the restoration support services framework.

The responses of the GFM BESS and synchronous generator were also compared when subject to a wide range of network faults. It was observed that the GFM BESS was able to ride-through all faults applied whereas the synchronous generator tripped in one scenario due to the operation of its negative-sequence current and V/Hz relays. Note that the V/Hz relay operated on stage 3 at fault clearance where the voltage was 1.12 pu and the frequency dropped to 49.45 Hz. Although the frequency nadir seems reasonable, caution should be exercised since PSCAD™/EMTDC™ frequency calculations can be sometimes erroneous during the fault inception and clearance. However, this does not impact the overall conclusions since the synchronous generator would have tripped in any case due to the operation of negative-sequence current relay.

List of Acronyms

BESS	Batter Energy Storage Systems
BS	Black Starter
DER	Distributed Energy Resources
FACTS	Flexible AC Transmission Systems
GFL	Grid-Following
GFM	Grid-Forming
G-PST	Global Power System Transformation
IBR	Inverter-Based Resources
PLL	Phase-Locked Loop
PSS	Power System Stabiliser
PV	Solar Photovoltaic
REZ	Renewable Energy Zone
SCR	Short Circuit Ratio
SF	Solar Farm
SG	Synchronous Generator
SMIB	Single-Machine, Infinite-Bus
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SynCon	Synchronous Condenser
TOV	Temporary over-voltage
WF	Wind Farm

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1 Introduction

1.1 Purpose of this report

This report is prepared as part of topic 5 of Australia's Global Power System Transformation (G-PST) Research Roadmap. It includes two stages:

- Stage 1: Assessment of capabilities and limitations of various black start options using simplified, but realistic network models. Development of high-level functional specifications for the use of IBR during system restoration based on results obtained from several hundreds of PSCAD™/EMTDC™ simulation studies.
- Stage 2: Use of wider power system models to investigate system restoration needs in a Renewable Energy Zone (REZ), and the REZ's interaction with the wider power system during the restart process.

1.2 Background information

Synchronous machines, comprising synchronous generators and condensers, have the advantage of creating their own voltage source without, generally, requiring additional energised network, fault level or standard system normal characteristics to operate stably. This ability to create their own internal reference and act as a voltage source is valid regardless of whether the synchronous machine has black start capability.

Most IBRs such as solar photovoltaic (PV), wind, and battery energy storage systems (BESS) operate as grid-following inverters (GFL). With this control philosophy, a phase-locked-loop (PLL) or similar control system monitors the terminal voltage and automatically adapts inverter switching to ensure output power remains in synchronism with the grid. Unlike synchronous machines, grid-following inverters need sufficient grid voltage waveform stability, typically provided by synchronous machines, to operate stably. This requirement is often expressed as the minimum SCR at which inverters remain stable and is often used as a simplified proxy of system strength. Inverters would not likely remain stable if the SCR available at the network drops below the minimum SCR at which at an inverter is designed for with original control system parameters. For this reason, grid-following inverters are not frequently used during the early stages of system restoration until more synchronous generators or condensers are brought online or the black start island has been synchronized to a larger grid.

Also note that the strength of the power system and the number of nearby synchronous machines and interconnecting lines are not the only factors that determines stability. Design and tuning of control systems deployed in IBR have an equally important role to play. This will become especially important during system restoration where non-standard control system modes may be required, and where there is currently a lack of sufficient information on what changes from standard operation would potentially be required for robust functionality during restoration conditions. Changes to either control system settings or switchover to different control modes are the most likely options. This is because system normal settings could be too aggressive during system restoration, and that coordinated control system philosophies when there are several machines in the network will not be useful when there is only one independent source in the power system.

A further impact of changing generation mix is that a synchronous machine typically provides approximately two to three times higher fault current contribution compared to an IBR of the same rated power output[1]. The reason for this difference is that the contribution of synchronous machine is inherent and non-limited whereas an IBR is designed to limit the fault current to protect the semiconducting switching elements used in the inverters. IBR can be designed to provide higher fault currents, and there are practical examples of some IBR providing more than 2 pu fault current[2]. However, this comes at a cost and as such it is not a common practice, in particular for grid-following inverters.

[1] This is quoted at the transmission network voltage accounting for the sub-transient reactance of the synchronous machine and the transformer impedance which is collectively in the order of 35-60%.

[2] S. Cherevatskiy et al, ''Grid-forming energy storage addresses challenges of grids with high penetration of renewables (A case study), CIGRE Session 48, Paris, August 2020.

Existing system restart pathways have been developed to expedite access to large non-black start synchronous generators. Long distances between areas of IBR concentration and major synchronous generators and load centres means that IBRs are not often picked up at early stages of system restoration even if there was a desire to do so. However, transitioning to a power system with significantly less or no synchronous generators, would challenge this approach.

2 Stage 1

2.1 Modelling and study methodology

2.1.1 Simplified power island model

A simplified but representative and realistic PSCAD model was developed for black start studies. Note that the rest of the network is assumed to be entirely disconnected. The advantage of this simplified model is that it allows identifying the positive or negative contribution of each power system element on issues observed without being potentially impacted by other nearby plants.

Vendor-specific PSCAD models of the IBR were used by signing mutual NDA between those OEMs and Aurecon. These includes models of wind farms, solar farms and grid-forming and grid-following BESS. A representative model of a synchronous generator was developed based on known transfer function block diagrams of the excitation system and governor. Generic models were used for synchronous condensers and protection relays and were parametrised to match the specific system used for the studies.

Black start technology types investigated include:

- Grid-forming BESS (two different site-specific OEM EMT models were investigated)
- Synchronous generator (gas turbine)
- Grid-following BESS along with a synchronous condenser (utilising AC1C rotating exciter model).

Additionally, this simplified network model consists of:

- Grid-following solar and wind farms, and BESS
- Distance and differential protection
  - A distance protection relay was used for the transmission line between the BS and the induction motor load, and a differential relay was employed across the BS grid transformer, connected to a breaker located on HV side.
- Transmission lines, represented as frequency dependent geometric line modes, and two-winding transformers
- Loads, comprising static and induction motor-based loads
  - Note that the induction motors used are small, approximately 2% of the MVA size of the largest transformer to be energised.

It is worth mentioning that GFLs, transformers, transmission lines, and loads are all energisation targets. Note that a PSCAD model of distributed energy resources (DER) was not available from AEMO at this stage. Stage 2 studies can include the DER PSCAD model subject to the availability.

The block diagram of the island is shown in Figure 2-1.

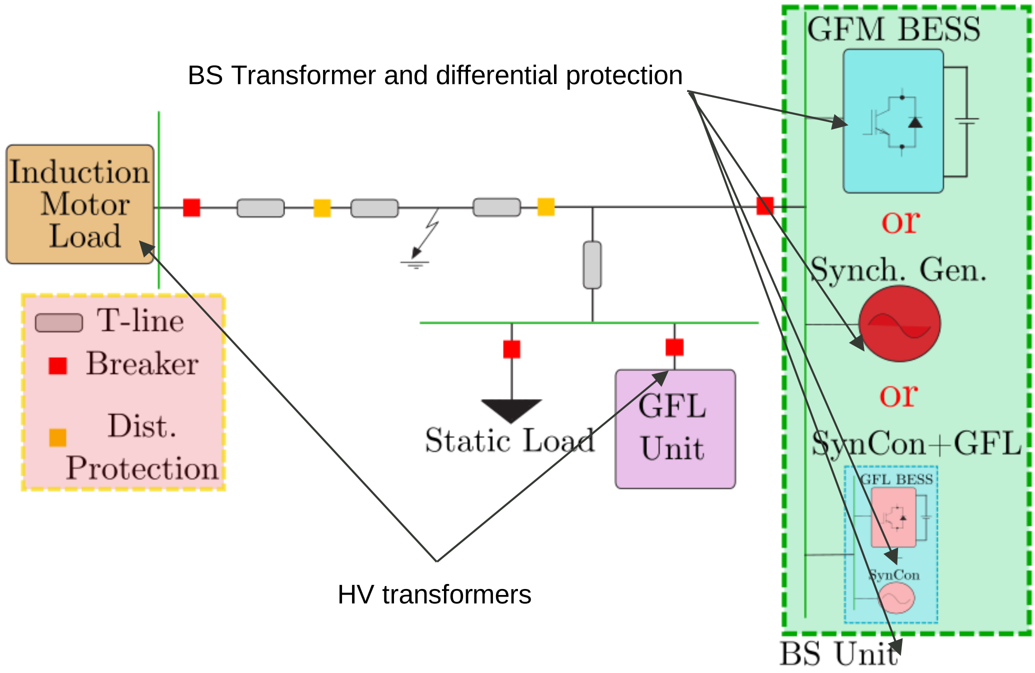

Figure 2-1: Island under study block diagram.

As it is seen in Figure 2-1, the black starter (BS) is either a GFM BESS, SG, or SynCon plus GFL BESS throughout this report. Also, Table 2-1 summarises the list of events and respective timing. Note that point-on-wave energisation studies were not conducted at this stage.

Table 2-1: The list and timing of the events.

Time (s)	List of events	Description/Purpose
0.1	Black start device energisation	The BS gets connected to the island.
2.0	10 MW Local static load energised and connected	Providing some amount of load to maintain generation and consumption balance in all scenarios.
2.5	Induction motor load energised	The impact of induction motor loads on the system stability and dynamics is investigated.
4.0	10 MW Local load energised and connected	Providing some amount of load to maintain generation and consumption balance in all scenarios.
6.0	10 MW Local load energised and connected	Providing some amount of load to maintain generation and consumption balance in all scenarios.
8.0	10 MW Local load energised and connected	Providing some amount of load to maintain generation and consumption balance in all scenarios.
9.0	Grid-following device commissioned	The impact of a GFL plant commission on the system stability is investigated. Depending on its type, it can inject or absorb active power into the grid.
12.0	10 MW Local load energised and connected	Providing some amount of load to maintain generation and consumption balance in all scenarios.
25	Fault application	The impact fault occurrence in the grid is investigated. Also, the effects of protection schemes are studied.
40	Large transformer energization	The impact of a very large transmission level transformer on the system performance and stability is observed.
45.0	Simulation complete	N/A

With this model the following aspects were then studied:

2.1.2 Study objectives

2.1.2.1 Phase 1

The following aspects were assessed in phase 1 of the investigation based on numerous PSCAD studies.

- Determine the criteria on when each IBR can be introduced during system restoration, e.g., short circuit ratio, total MW dispatch, number of inverters
- Determine the extent to which existing simulation models provided for connection studies can adequately represent the IBR response during system restoration[3]
- The ratio of MVA rating of GFM IBR to the MVA rating of the largest transformer or non-black start plant to be energised by the IBR, and how it is compared to that with a synchronous generator black starter
- The risk of harmonic resonances with the surrounding network in an IBR dominated power system during system restoration due to the presence of low-order high-impedance resonance frequencies.

2.1.2.2 Phase 2

The following aspects were also analysed based on numerous PSCAD studies. Note that most tests were developed such that they will concurrently address the objectives of phase 1 and 2.

- The extent to which a grid-forming inverter needs to emulate some, or all the following characteristics provided by synchronous generators. The following attributes were investigated in the PSCAD models received, to determine both the minimum required for stable operation and to determine trends where further tuning can optimise performance further:
  - Minimum provision of fault current (or short-term overload capability)
  - Virtual inertia
  - Virtual impedance (damping factor)
  - Voltage regulation capabilities
- Technology differentiators among grid-following wind, solar and BESS as a restoration support service
- High-level specification of both the grid-forming and grid-following BESS
- The trade-off between achieving system normal and black start performance objectives, in particular with regard to NER clauses S5.2.5.5 and S5.2.5.13.

The original proposal also included an assessment of the impact of the following two performance aspects of grid-forming inverters. However, this could not be assessed as the OEM models provided did not have these aspects as adjustable settings.

- Certain sequence of fault current, i.e., the ratio of negative-to positive-sequence
- Harmonic cancellation

2.1.3 Blackstart scenarios and sensitivity studies

The base case model parameters are available in Table 2-2. Note that any value that is not specified in the body of the report in all sections is set based on this table. Also, Table 2-3, presents the list of scenarios and the corresponding sensitivity tests.

[3] This focuses on the adequacy of simulation models, e.g., inclusion of the necessary control systems, rather than the model accuracy and validation against site measurements. It is noted that there is limited opportunity for the latter as very little R2 testing experience exists for actual grid-forming BESS projects against actual network faults. Furthermore, we are not aware of any network wide system restoration testing including an IBR that could potentially be used to validate the models and simulation results used in this report.

Table 2-2: Base case model parameters' values

Base case parameter	Default value	Sensitivity range	Sensitivity step size	Units
GFM inertia constant (2xH)	5	0 – 100		s
Transmission line length	50	0 – 300		km
GFL plant capacity	0.8	0.4 – 2.0	0.4	pu
GFL plant transformer capacity	0.8	N/A	N/A	pu
GFM capacity	1.0	0.4 – 1.0, 2.0	0.2	pu
GFM transformer capacity	1.2	N/A	N/A	pu
GFM Max. overload current	1.0	1.0 – 2.0	0.25	pu
GFM damping factor	10	0.1-10	N/A	N/A
Fault impedance	0	N/A	N/A	Ω
Fault type	Two-phase to ground	N/A	N/A	N/A
Fault duration	100	N/A	N/A	ms
HV voltage level (275 kV)	275	N/A	N/A	kV
Induction motor capacity	8.2	N/A	N/A	MVA
Induction motor power factor	0.85	N/A	N/A	N/A
SG inertia constant	5	1-20	N/A	N/A

- Note that in all tests, the base MVA (S_{base}) is assumed to be 250 MVA.

Note that if the GFL is a battery, the tests are conducted both for charging and discharging modes.

Table 2-3: List of scenarios and sensitivity tests

Scenario No.	Black starter	Generator to be picked up	Sensitivity investigated
1	GFM BESS	GFL BESS	▪ GFM inertia constant (2xH) ▪ GFM damping factor ▪ GFM max. overload current (note that only one of the OEM models received provide access to this setting). ▪ Transmission line length ▪ GFL to GFM MVA ratio ▪ BESS charging vs discharging
2	GFM BESS	GFL Solar	▪ GFM inertia constant (2xH) ▪ GFM damping factor ▪ GFM max. overload current ▪ Transmission line length ▪ GFL to GFM MVA ratio
3	GFM BESS	GFL Wind	▪ GFM inertia constant (2xH) ▪ GFM damping factor ▪ GFM max. overload current ▪ GFL and GFM MVA ratio ▪ Transmission line length

4	Synchronous generator	GFL BESS	- Transmission line length - GFL to SG MVA ratio - SG inertia constant - BESS charging vs discharging
5	Synchronous generator	GFL Solar	- Transmission line length impact - GFL to SG MVA ratio - SG inertia constant
6	Synchronous generator	GFL Wind	- Transmission line length impact - GFL to SG MVA ratio - SG inertia constant
7	Synchronous condenser + GFL BESS	GFL BESS	- BESS charging vs discharging - GFL to BS's GFL BESS MVA ratio - GFL online inverters to BS's GFL MVA
8	Synchronous condenser + GFL BESS	GFL Solar	- GFL to BS's GFL MVA ratio - GFL online inverters to BS's GFL MVA ratio - GFL MW dispatch to BS's GFL MVA ratio (GFL higher installed MVA)
9	Synchronous condenser + GFL BESS	GFL Wind	- GFL to BS's GFL MVA ratio - GFL online inverters to BS's GFL MVA ratio - GFL MW dispatch to BS's GFL MVA ratio (GFL higher installed MVA)

2.1.4 Grid connected scenarios and sensitivities

2.1.4.1 Dynamic Model Acceptance Testing

To address the final bullet point under Phase 2, a partial set of tests set out in AEMO's Dynamic Model Acceptance Testing (DMAT) Guidelines were carried out on the GFM BESS that is being used as the black starter both for when the Islanded mode of it is activated and deactivated. The list of tests performed are presented below:

- Balanced fault,
- Unbalanced fault,
- Voltage reference changes,
- Grid voltage step changes,
- Grid frequency changes,
- Grid voltage dips,
- Grid voltage ramp changes,
- Grid voltage oscillations,
- Phase angle jumps.

The purpose of these tests is to monitor any possible performance differences between the islanded mode and grid connected mode of the GFM BESS with the black start capability.

2.1.4.2 Impact of System Strength on GFL BESS, Solar farm, and Wind Farm

Studies are conducted to assess the SCR withstand capability of each of the GFL plants used in this project, i.e., wind farms, solar farms, and BESS. The objective is to determine if there is a relationship between the SCR withstand capability of the GFL plants and achieving more successful and stable outcomes during system restoration.

2.2 GFM BESS as the BS

To establish the baseline capability a grid-forming BESS is first used as a black starter. This part includes Scenarios 1, 2, and 3.

Note that GFM technologies commonly have two control modes; islanded and grid-connected modes. The islanded mode of operation is used for the GFM BESS for all studies conducted in this report except a few studies discussed in Chapter 6 which assesses the potential differences between the grid connected and islanded mode.

2.2.1 Scenario 1: GFM BESS Picking-up GFL BESS

In this scenario, a GFM BESS is used as the BS for energizing a GFL BESS, induction motor load, transmission lines, a transmission level large transformer, and some static load. To verify the performance of the GFM as a BS in this scenario, some tests according to Table 2-3 are performed in PSCAD.

2.2.1.1 GFM Inertia Constant

In this section, the impact of GFM inertia constant is investigated. In this scenario, all parameters except the GFM inertia are as shown in Table 2-2. The inertia constant of the GFM is set to 0, 5, 20, 50, and 100 seconds. Results obtained from simulation studies indicate that the GFM inertia constant has an insignificant impact. No instability or unreasonable performance is observed as the inertia constant is varied. Note that tests for Scenario 1 are performed for both the charging and discharging modes of the GFL BESS. Table 2-4 summarizes the impact of GFM inertia constant on the system stability.

Note that a simulation case is considered stable if none of the following conditions is observed:

- No load or generation tripping
- No inadvertent operation of the protection systems
- Voltages and frequencies are maintained within +/-15%
- No sustained or growing oscillations

Table 2-4: GFM inertia constant impact on the system stability.

GFM inertia constant	Island
0	Stable
5	Stable
20	Stable
50	Stable
100	Stable

Key finding:

- The GFM inertia constant does not have an appreciable impact on the system stability and performance.

2.2.1.2 GFM Damping Factor

In this section, the impact of GFM damping factor on the system stability and performance is investigated. For this purpose, the damping factor is set to 0.1, 1, and 10. It is observed that this parameter does not impact the ability of the GFM to pick up the load and create the grid. Also, the dynamic performance of the GFM during and immediately after the fault is not impacted while the damping factor is altered. Table 2-5 presents the summary of the simulation results with different damping factors.

Table 2-5: GFM damping factor impact on the system stability.

GFM damping factor	Island
0.1	Stable
1	Stable
10	Stable

Key finding:

- The GFM damping factor does not have an appreciable impact on the system stability and performance within the range if considered inertia constants and given the other assumed system parameters.

2.2.1.3 GFM Fault Current Provision

In this section, the impact of the GFM fault current capability on system stability is investigated by varying this parameter from 1 pu to 2 pu in steps of 0.25 pu. It is observed that this parameter does not impact the system stability of the system. The only difference observed is that a higher fault current capability results in a lower voltage drop during the faults. Table 2-6 summarizes the simulation results of the corresponding tests.

Table 2-6: GFM max fault current impact on the system stability.

GFM Max Fault Current (pu)	Island
1	Stable
1.25	Stable
1.5	Stable
1.75	Stable
2	Stable

Key finding:

- No material impact is observed on GFL and overall system stability with varying levels of fault current contribution from the GFM.

2.2.1.4 Transmission Line Length

In this section, the impact of transmission line length on system stability is investigated. For this purpose, the transmission line length is varied from 10 km to 300 km. Table 2-7 illustrates the impact of transmission line length on system stability. It is observed that with all transmission line lengths from 10 km to 300 km the GFL BESS can be picked up. The Table also shows line charging associated with each transmission line length. It was observed that the total reactive absorption required is within the capability of the in-service generation. However, a longer transmission line also means a lower SCR at the GFL plant connection point attributing to their instability upon restoration by the black start unit.

Table 2-7: Transmission line length impact on the GFL BESS stability while the BS is a GFM.

Line length (km)	GFL BESS	Line Charging (MVar)
10	Stable	2.142
50	Stable	10.623
100	Stable	21.327
200	Stable	43.131
300	Unstable	65.958

The simulation results of the last scenario are shown in Figure 2-2. When the transmission line length equalled 300 km, the GFL BESS could not be picked up due to the high voltage resulted from high line charging at its PoC. Also, it is observed that the GFM BESS can initially pick up the rest of the loads in the system; however, after the large transformer gets energized at t = 40 s, the provided active power by the GFM BESS deteriorates as well.

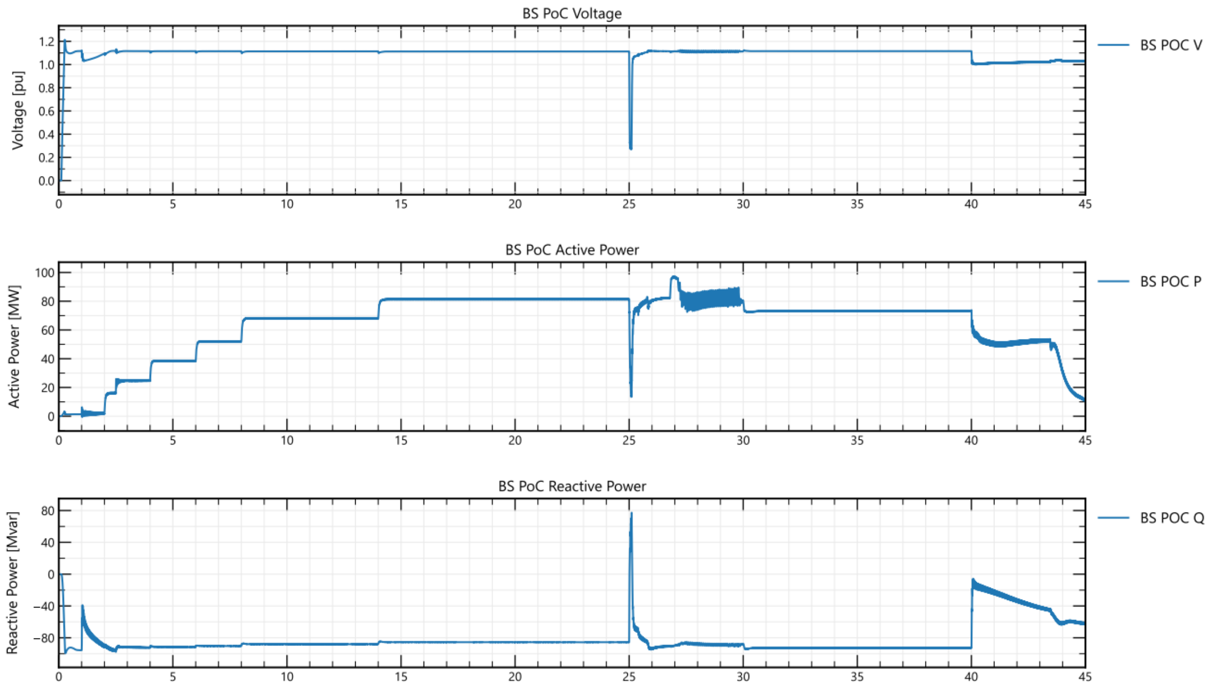

Figure 2-2: The voltage, active power, and reactive power of the GFM BESS at its PoC while the transmission line is 300 km.

Key finding:

- Longer transmission lines impose the higher risk of GFL plant instability and potential tripping.

2.2.1.5 GFL to GFM MVA Ratio

In this section, the impact of GFL to GFM MVA ratio impact is investigated. This is to find a threshold for the relative size of the GFL BESS which can be successfully picked up with the GFM. These tests were developed such that first the GFM MVA is kept constant and the GFL MVA is changed, and then the other way round. The aim here is to find a general trend and not exact numbers as they are highly dependent on other factors such as control loops used, capacity, and transmission line length. Note that simulation studies conducted focus on a few samples to assess whether a trend exists rather than covering all possible combinations.

Table 2-8, Table 2-9, and Table 2-10 show the results of different combination of GFL and GFM MVA ratings. It is observed that for higher GFL/BS MVA ratios, in majority of the cases the GFL plant could not be picked up. However, the absolute MVA of each unit is important as well. In particular, smaller MVA capacity of the GFL and BS makes GFL plant restoration more difficult.

Furthermore, it can be seen that in one instance the charging or discharging mode of the BESS impacts system stability.

Table 2-8: The impact of GFM MVA variation from 0.4 pu to 2 pu while the GFL MVA is kept at 0.8 pu.

GFL BESS	GFM (GFL charges)	GFM (GFL discharges)	Ratio (GFL/BS)
0.8 pu	0.4 pu	0.4 pu	2
0.8 pu	0.6 pu	0.6 pu	1.33
0.8 pu	0.8 pu	0.8 pu	1
0.8 pu	1 pu	1 pu	0.8
0.8 pu	1.6 pu	1.6 pu	0.5
0.8 pu	2 pu	2 pu	0.4

Table 2-9: The impact of GFL MVA variation from 0.4 pu to 0.7 pu while the GFM MVA is kept at 0.5 pu.

GFL BESS	GFM (GFL charges)	GFM (GFL discharges)	Ratio (GFL/BS)
0.4 pu	0.5 pu	0.5 pu	0.8
0.5 pu	0.5 pu	0.5 pu	1
0.6 pu	0.5 pu	0.5 pu	1.2
0.7 pu	0.5 pu	0.5 pu	1.4

Table 2-10: The impact of GFL MVA increase from 0.4 pu to 2 pu while the GFM MVA is kept at 0.4 pu.

GFL BESS	GFM (GFL charges)	GFM (GFL discharges)	Ratio (GFL/BS)
0.4 pu	0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	0.4 pu	2
1.2 pu	0.4 pu	0.4 pu	3
1.6 pu	0.4 pu	0.4 pu	4
2 pu	0.4 pu	0.4 pu	5

Key finding:

- A GFL/GFM ratio of 0.8 or lower is required to ensure consistently stable operation. However, for certain operating conditions some successful scenarios with ratios of up to 1 were identified. In particular, larger MVA sizes of the GFM will improve the restoration performance.

2.2.2 Scenario 2: GFM BESS Picking-up GFL Solar Farm

In this section, the GFM BESS is acting as the BS and a GFL solar farm is picked up.

2.2.2.1 GFM Inertia Constant

In this section, the impact of GFM inertia constant on GFL solar farm is investigated. For this purpose, the GFM inertia in varied from 0 to 100 seconds. The results of these tests are summarized in Table 2-11. It is observed that like Scenario 1, this variable does not play a role in stability or otherwise of the solar farm.

Table 2-11: The impact of GFM inertia constant on system stability.

Inertia Constant	GFM
0	Stable
5	Stable
20	Stable
50	Stable
100	Stable

Key finding:

- GFM inertia constant has no material impact on system stability during system restart and GFL pick up.

2.2.2.2 GFM Damping Factor

In this section, the impact of GFM damping factor on the system and solar farm stability and performance is investigated. For this purpose, the damping factor is set to 0.1, 1, and 10. It is observed that this parameter does not impact the ability of the GFM BESS to pick up the load and form the grid. Also, the dynamic performance of the GFM is not impacted while the damping factor is altered. Table 2-12 shows the simulation results for these tests. It is observed that all damping factors tested will result in a stable operation.

Table 2-12: The impact of GFM damping factor on system stability.

GFM damping factor	Island
0.1	Stable
1	Stable
10	Stable

Key finding:

- The GFM damping factor does not have an appreciate impact on the system stability and performance.

2.2.2.3 GFM Fault Current Provision

In this section, the impact of GFM fault current provision on the solar farm stability is investigated by varying this parameter from 1 pu to 2 pu with steps of 0.25 pu. It is observed that this variable does not impact the system stability of the system. The only difference observed is the less voltage drop during faults while the max overload current is set to a higher value. Table 2-13 summarizes the simulation results of the corresponding tests.

Table 2-13: GFM max fault current impact on the system stability.

GFM Max Fault Current (pu)	Island
1	Stable
1.25	Stable
1.5	Stable
1.75	Stable
2	Stable

Key finding:

- The maximum fault current provision by the GFM BESS does not have any appreciable impacts on the stability of the restored system and the ability of the GFM to pick up the solar farm.

2.2.2.4 GFL Solar farm MVA to GFM BESS MVA Ratio

In this section, the impact of GFL SF MVA to GFM BESS MVA ratio is investigated. For this purpose, the SF and BESS MVAs are varied to for different combinations and ratios. Table 2-14, Table 2-15, and Table 2-16 summarize the simulation results of these tests.

Table 2-14: The impact of GFM MVA variation from 0.4 pu to 2 pu while the GFL MVA is kept at 0.8 pu.

GFL SF	GFM BESS	Ratio (GFL/BS)
0.8 pu	0.4 pu	2
0.8 pu	0.6 pu	1.33
0.8 pu	0.8 pu	1
0.8 pu	1 pu	0.8
0.8 pu	1.6 pu	0.5
0.8 pu	2 pu	0.4

Table 2-15: The impact of GFL MVA variation from 0.4 pu to 0.7 pu while the GFM MVA is kept at 0.5 pu.

GFL SF	GFM BESS	Ratio (GFL/BS)
0.4 pu	0.5 pu	0.8
0.5 pu	0.5 pu	1
0.6 pu	0.5 pu	1.2
0.7 pu	0.5 pu	1.4

Table 2-16: Constant BS (0.4 pu) while GFL MVA varies from 0.4 pu to 2 pu.

GFL Solar farm	GFM BESS	Ratio (GFL/BS)
0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	2
1.2 pu	0.4 pu	3

1.6 pu	0.4 pu	4
2 pu	0.4 pu	5

Key finding:

- The GFM BESS can pick up a GFL solar farm of up to three times and the corresponding transformer up to 2.5 times of the BESS MVA capacity. It can also be found that the smaller MVA sizes of the GFM provide better capability compared to that achieved with the use of GFL BESS in the previous section.

2.2.2.5 Transmission Line Length

In this section, the impact of transmission line length between the GFM BESS and the GFL SF is investigated. To this end, the transmission line length is varied from 10 km to 300 km. The simulation results are summarized in Table 2-17.

Table 2-17: Transmission line length impact.

Line length (km)	GFL SF	Cable Charging (MVar)
10	Stable	2.142
50	Stable	10.623
100	Stable	21.327
200	Stable	43.131
300	Unstable	65.958

Key finding:

- Very long transmission lines will result in GFL plant instability, likely due to increasing the apparent impedance and reducing the SCR seen by the GFL plant.

2.2.3 Scenario 3: GFM BESS Picking-up GFL Wind Farm

In this section, the GFM BESS is the BS unit, and it is supposed to pick up a GFL wind farm (WF). Similar sensitivity tests are conducted on this combination as well.

2.2.3.1 GFM BESS Inertia Constant

In this section, the impact of GFM inertia impact constant is being investigated. To this end, the GFM inertia is being varied from 0 to 100. The simulation results summary is provided in Table 2-18.

Table 2-18: The impact of GFM BESS inertia constant on the system stability.

Inertia	GFM
0	Stable
5	Stable
20	Stable
50	Stable
100	Stable

Key finding:

- The GFM inertia constant does not appreciable impact the system stability. Indeed, the GFL WF could be successfully picked up even with an inertia constant of 0s.

2.2.3.2 GFM BESS Damping Factor

In this section, the impact of GFM damping factor on the system and WF stability and performance is investigated. For this purpose, the damping factor is set to 0.1, 1, and 10. It is observed that this parameter does not impact the ability of the GFM to pick up the load and create the grid. Also, the dynamic performance of the GFM is not impacted while the damping factor is altered. Table 2-19 shows the simulation results of these tests. It is observed that all tested damping factors result in stable operations.

Table 2-19: GFM damping factor impact on the system stability.

GFM damping factor	Island
0.1	Stable
1	Stable
10	Stable

Key finding:

- The GFM damping factor is not influential on the system stability and performance.

2.2.3.3 GFM BESS Fault Current Contribution

In this section, the impact of GFM fault current contribution is investigated on the system stability by varying this parameter from 1 pu to 2 pu with steps of 0.25 pu. It is observed that this variable does not impact the system stability of the system. The only difference observed is the less voltage drop during faults while the max overload current is set to a higher value. Table 2-20 summarizes the simulation results of this part.

Table 2-20: GFM max fault current impact on the system stability.

GFM Max Fault Current (pu)	Island
1	Stable
1.25	Stable
1.5	Stable
1.75	Stable
2	Stable

Key finding:

- No material impact is observed on the GFL and overall system stability with varying levels of fault current contribution from the GFM.

2.2.3.4 Transmission Line Length

In this section, the impact of transmission line length between the GFM BESS and the GFL WF is investigated. To this end, the transmission line length is varied from 10 km to 300 km. The simulation results are summarized in Table 2-21.

Table 2-21: Transmission line length impact.

Line length (km)	GFL BESS	Line Charging (MVar)
10	Stable	2.142
50	Stable	10.623
100	Stable	21.327
200	Stable	43.131
300	Stable	65.958

Key finding:

- The WF could be stably picked up using the GFM BESS for all transmission line lengths studied.

2.2.3.5 GFL WF MVA to GFM BESS MVA Ratio

In this section, the impact of relative size of GFL WF and GFM BESS on the system stability is investigated. Hence, similar to the previous scenarios, different combinations of GFL WF and GFM BESS MVAs are studied. Table 2-22, Table 2-23, and Table 2-24 illustrate the simulations results corresponding to this study.

Unlike the GFL BESS and SF, the GFL WF remains stable for all sensitivity studies conducted. However, this only applies to the specific models used in the project and importantly associated control system tuning on each, and the relative performance cannot be generalised.

Note that to be consistent with the rest of the report, the WF MVA was increased up to 2 pu without identifying the exact threshold at which the instability will occur. Also note that this threshold could differ significantly from one application to another as it is subject to many factors such as wind turbine control system design and system strength.

Table 2-22: The impact of GFM BESS MVA variation from 0.4 pu to 2 pu while the GFL WF MVA is kept at 0.8 pu.

GFL WF	GFM BESS	Ratio (GFL/BS)
0.8 pu	0.4 pu	2
0.8 pu	0.6 pu	1.33
0.8 pu	0.8 pu	1
0.8 pu	1 pu	0.8
0.8 pu	1.6 pu	0.5
0.8 pu	2 pu	0.4

Table 2-23: The impact of GFL WF MVA variation from 0.4 pu to 0.7 pu while the GFM BESS MVA is kept at 0.5 pu.

GFL WF	GFM BESS	Ratio (GFL/BS)
0.4 pu	0.5 pu	0.888
0.5 pu	0.5 pu	1
0.6 pu	0.5 pu	1.2
0.7 pu	0.5 pu	1.4

Table 2-24: The impact of GFL WF MVA variation from 0.4 pu to 2 pu while the GFL WF MVA is kept at 0.4 pu.

GFL WF	GFM BESS	Ratio (GFL/BS)
0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	2
1.2 pu	0.4 pu	3
1.6 pu	0.4 pu	4
2 pu	0.4 pu	5

Key finding:

- The MVA ratio of the GFL WF to that of the GFM BESS is the greatest with the use of the grid-following wind farm compared to the grid-following solar farm or BESS. Further tests are conducted to better understand the underlying reason as will be discussed in Section 6.

2.3 The use of a Synchronous Generator as a Black Starter

In this section, a SG is used as a BS unit. This part includes Scenarios 4, 5, and 6. Note that throughout this section, the exciter employed in the SG is type AC1C. It is worth mentioning that although the exciter type and settings could be influential on the results provided in this section, the type of the exciter is not considered as one of the studied sensitivities.

2.3.1 Scenario 4: Synchronous Generator Picking-up GFL BESS

In this scenario, a SG is used as the BS, powering up the same island shown in Figure 2-1. Sensitivity tests are performed based on Table 2-3.

2.3.1.1 Transmission Line Length

In this section, the impact of transmission line length on the on the system stability is being investigated. For this purpose, the transmission line length is varied from 10 km to 300 km. Table 2-25 illustrates the impact of transmission line length on the system stability.

For longer transmission lines, the GFL BESS could be picked up except for the 300 km line length.

Table 2-25: The impact of transmission line length on the GFL BESS stability when the BS is an SG.

Line length (km)	SG (GFL charges)	SG (GFL discharges)	Cable Charging (MVar)
10	Stable	Stable	2.142
50	Stable	Stable	10.623
100	Stable	Stable	21.327
200	Stable	Stable	43.131
300	Unstable	Unstable	65.958

Key finding:

- The SG has a comparable capability to that of the GFM BESS in energising long transmission lines.

2.3.1.2 Synchronous Generator Inertia

In this section, the impact of SG's inertia on the GFL BESS stability is investigated. For this purpose, the SG's inertia is changed from 1 to 20. Table 2-26 summarizes the results of the corresponding studies. It is observed that while the SG inertia is low, the island frequency cannot be maintained as the inertia and Rate-of-Change-of-frequency (RoCoF) are inter-related.

Table 2-26: The synchronous generator inertia impact of the GFL BESS stability.

Inertia	SG
1	Unstable
5	Stable
10	Stable
20	Stable

Key finding:

- The impact of lower inertia constants on the success or otherwise of the black start synchronous generator is greater than that for GFM BS. Also, these results indicate the need for large gas turbines, hydro units or trip-to-house-load technologies as the main synchronous black starters rather than small diesel or reciprocating engines.

2.3.1.3 GFL BESS to SG MVA Ratio

In this test, the impact of GFL BESS to SG MVA ratio is investigated. The aim of this part is to find a threshold for the relative size of the GFL BESS that is being picked up via the SG Table 2-27, Table 2-28, and Table 2-29 summarize the simulation results of the system for different combination of GFL BESS and SG MVAs.

Table 2-27: The impact of SG MVA variation from 0.4 pu to 2 pu while the GFL MVA is kept at 0.8 pu.

GFL BESS	SG (GFL charges)	SG (GFL discharges)	Ratio (GFL/BS)
0.8 pu	0.4 pu	0.4 pu	2
0.8 pu	0.6 pu	0.6 pu	1.33
0.8 pu	0.8 pu	0.8 pu	1
0.8 pu	1 pu	1 pu	0.8
0.8 pu	1.6 pu	1.6	0.5
0.8 pu	2 pu	2 pu	0.4

Table 2-28: The impact of GFL BESS MVA variation from 0.4 pu to 0.7 pu while the SG MVA is kept at 0.5 pu.

GFL BESS	SG (GFL charges)	SG (GFL discharges)	Ratio (GFL/BS)
0.4 pu	0.5 pu	0.5 pu	0.8
0.5 pu	0.5 pu	0.5 pu	1
0.6 pu	0.5 pu	0.5 pu	1.2
0.7 pu	0.5 pu	0.5 pu	1.4

Table 2-29: The impact of GFL MVA increase from 0.4 pu to 2 pu while the SG MVA is kept at 0.4 pu.

GFL BESS	SG (GFL charges)	SG (GFL discharges)	Ratio (GFL/BS)
0.4 pu	0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	0.4 pu	2
1.2 pu	0.4 pu	0.4 pu	3
1.6 pu	0.4 pu	0.4 pu	4
2 pu	0.4 pu	0.4 pu	5

Key finding:

- As the GFL/SG ratio increases, the risk of GFL plant tripping increases. It is observed that these results are relatively inferior compared to when the BS is a GFM.

2.3.2 Scenario 5: Synchronous Generator Picking-up GFL Solar Farm

In this section, the BS unit is supposed to be the SG, which is used for picking-up the GFL SF. Tests were performed based on Table 2-3.

2.3.2.1 Transmission Line Length

In this section, the impact of the transmission line between the SG and the GFL SF length in investigated. For this purpose, the transmission line length between the BS and the GFL SF is varied from 10 km to 300 km. Table 2-30 illustrates the simulation results of these tests.

Table 2-30: Transmission line length impact of the system stability while a SG is picking-up a GFL SF.

Line length (km)	SG
10	Stable
50	Stable
100	Stable
200	Stable
300	Stable

Key finding:

- A black start synchronous generators provides greater stability when energising longer transmission lines and picking up a GFL SF compared to GFM BESS as a black start unit. This behaviour differs from that observed for the GFL BESS, indicating that the GFL technology and control system tuning could play an important role in the stability of the restored path.

2.3.2.2 SG Inertia Constant

In this section, the impact of SG inertia on the system stability and ability of the BS for picking up the GFL SF is investigated. Table 2-31 shows the simulation results of the system while the SG inertia constant is varied from 1 to 20.

Table 2-31: The impact of SG inertia on the system stability.

Inertia	SG
1	Stable
5	Stable
10	Stable
20	Stable

Key finding:

- SG inertia has no material impact on the stability during system restart and GFL SF pick up. This is an improved performance compared to the use of a GFL BESS discussed previously, indicating that the GFL technology and control system tuning could play an important role in the stability of the restored path.

2.3.2.3 GFL SF MVA to SG MVA Ratio

In this section, the impact of GFL SF MVA to SG MVA ratio impact on the stability of the system is investigated. The aim here is to find what is the relative size of the largest WF that could be picked up via a SG. For this purpose, similar to the previous scenarios, various combinations of GFL SF and SG MVAs are tested. Table 2-32, Table 2-33, and Table 2-34 summarize the simulation outcomes of these tests.

Table 2-32: The SG MVA variation from 0.4 pu to 2 pu while the GFL SF MVA is kept at 0.8 pu.

GFL SFSFSF	SG	Ratio (GFL/BS)

0.8 pu	0.4 pu	2
0.8 pu	0.6 pu	1.33
0.8 pu	0.8 pu	1
0.8 pu	1 pu	0.8
0.8 pu	1.6	0.5
0.8 pu	2 pu	0.4

Table 2-33: The GFL SF MVA variation from 0.4 pu to 0.4 pu while the SG MVA is kept at 0.8 pu.

GFL SF	SG	Ratio (GFL/BS)
0.4 pu	0.5 pu	0.8
0.5 pu	0.5 pu	1
0.6 pu	0.5 pu	1.2
0.7 pu	0.5 pu	1.4

Table 2-34: The GFL SF MVA variation from 0.4 pu to 2 pu while the SG MVA is kept at 0.4 pu.

GFL Solar farm	SG	Ratio (GFL/BS)
0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	2
1.2 pu	0.4 pu	3
1.6 pu	0.4 pu	4
2 pu	0.4 pu	5

Key finding:

- A higher GFL/SG ratio imposes higher risk of instability and GFL plant tripping.

2.3.3 Scenario 6: Synchronous Generator Picking-up GFL Wind Farm

In this scenario, the BS unit is the SG, which is supposed to pick up the GFL WF. In this scenario, the sensitivity tests are performed based on Table 2-3.

2.3.3.1 Transmission Line Length

In this section, the impact of transmission line length on the ability of the SG in picking-up the GFL WF is investigated. Table 2-35 summarizes the simulation results of this part. It is observed that there is no example of WF tripping throughout the tests.

Table 2-35: Transmission line length impact on the GFL WF stability.

Line length (km)	SG
10	Stable

50	Stable
100	Stable
200	Stable
300	Stable

Key findings:

- The SG can pick-up the WF for transmission lines between 10 km to 300 km successfully.

2.3.3.2 SG Inertia Constant

This part illustrates the impact of SG inertia impact on the GFL WF stability. For this purpose, the SG inertia constant is increased from 1 to 20. Table 2-36 shows the summary of the simulation results of this part. It is observed that the SG with the lowest inertia cannot maintain the grid frequency, and hence, leading to instability. On the other hand, SGs with higher inertias can maintain the frequency, and therefore, the stability of the whole island.

Table 2-36: SG inertia impact on the GFL WF stability.

Inertia	SG
1	Unstable
5	Stable
10	Stable
20	Stable

Key finding:

- Similar to the previous tests, it is observed that the low SG inertia leads to instability and inability of the SG to pick-up the WF.

2.3.3.3 GFL WF MVA to SG MVA Ratio

In this section, the maximum relative size of the GFL WF that could be picked up by the SG is identified. To do so, different combinations of GFL WF and SG MVAs are used. The simulation results of the corresponding tests are summarized in Table 2-37, Table 2-38, and Table 2-39. Note that a successful scenario is to successfully initialise the GFL WF and have subsequent stable operation.

Table 2-37: The impact of SG MVA variation from 0.4 pu o 2 pu while the GFL WF MVA is kept at 0.8 pu.

GFL WF	SG	Ratio (GFL/BS)
0.8 pu	0.4 pu	2
0.8 pu	0.6 pu	1.33
0.8 pu	0.8 pu	1
0.8 pu	1 pu	0.8
0.8 pu	1.6	0.5

0.8 pu	2 pu	0.4

Table 2-38: The impact of GFL WF MVA variation from 0.4 pu o 2 pu while the SG MVA is kept at 0.5 pu.

GFL WF	SG	Ratio (GFL/BS)
0.4 pu	0.5 pu	0.8
0.5 pu	0.5 pu	1
0.6 pu	0.5 pu	1.2
0.7 pu	0.5 pu	1.4

Table 2-39: The impact of GFL WF MVA variation from 0.4 pu o 2 pu while the SG MVA is kept at 0.8 pu.

GFL WF	SG	Ratio (GFL/BS)
0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	2
1.2 pu	0.4 pu	3
1.6 pu	0.4 pu	4
2 pu	0.4 pu	5

Key finding:

- As the GFL/SG ratio increases, the risk of GFL plant instability and consequent tripping increases.

2.4 SynCon + GFL BESS Usage as the BS

In this section, the combination of SynCon and GFL BESS is used as the BS. This part includes scenarios 7, 8, and 9. Due to use of generic SynCon model optimal tuning could not be achieved within the project timeframe. Therefore, GFL protection settings were relaxed to facilitate this scenario. Without wider protection settings or refined tuning no stable scenario was observed with SynCon+ GFL. All results outlined in this section have wider than standard protection settings and are indicative of the requirement for greater voltage and frequency withstand capability or additional plant tuning. Table 2-40 compares the standard and widened reconnection frequency limit of the protection setting.

Table 2-40: The re-connection frequency limits of the widened and standard protection setting.

Protection setting	Higher limit (Hz)	Lower Limit (Hz)
Standard	55	45
Widened	60	40

2.4.1 Scenario 7: SynCon + GFL BESS Picking-up GFL BESS

As discussed in the introduction, GFM inverters might not be widely available in weaker parts of the grid which typically attract high IBR concentration, where there are not often many if any black start synchronous generators. It was therefore considered prudent to assess the capability of alternative technologies. In this section, it is shown that the combination of GFL inverters and SynCons could be used as a BS unit. These studies focused on GFL BESS only due to its superior and more demonstrated frequency control capability compared to WFs and SFs.

Note that in contrast to SGs and GFM inverters where one device provides both the voltage and frequency control, in the hybrid SynCon and GFL BESS option, the SynCon is responsible for creating the grid and maintaining the voltage while the GFL BESS regulates the frequency (it has some impact on the voltage regulation as well, however, the SynCon is the primary voltage regulator).

2.4.1.1 GFL BESS to SynCon + GFL BESS MVA Ratio

In this section, the impact of GFL BESS MVA to SynCon+GFL BESS MVA ratio is investigated. The MVA ratio is calculated as the GFL BESS MVA divided by the cumulative MVA of the SynCon and GFL BESS participating in the BS. However, this ratio has different implications from the GFL BESS to SG or GFM MVA ratios as the component responsible for providing the short circuit current is merely the SynCon. Table 2-41, Table 2-42, and Table 2-43 summarize the results of these tests for different combinations of GFL BESS, SynCon and BS's GFL BESS MVAs. It is worth mentioning that these simulation studies were performed for both when the GFL BESS charges and discharges.

Note that the last row of Table 2-42 is performed to show that increasing the SynCon size can stabilise the grid while the BS's GFL BESS MVA is increased. This demonstrates the positive impact of the SynCon MVA on system stability during the restoration.

Table 2-41: The impact of SynCon MVA on the system stability (both for BESS charging and discharging).

GFL BESS	SynCon	BS GFL BESS	GFL/BS MVA ratio
0.8 pu	0.2 pu	1 pu	0.67
0.8 pu	0.4 pu	1 pu	0.57
0.8 pu	0.6 pu	1 pu	0.5
0.8 pu	0.8 pu	1 pu	0.44
0.8 pu	1 pu	1 pu	0.4

Table 2-42: The impact of BS's GFL BESS MVA on the system stability (both when the GFL BESS charges and discharges).

GFL BESS	SynCon		BS GFL BESS		GFL/BS MVA ratio
0.8 pu	0.6 pu		0.4 pu		0.8
0.8 pu	0.6 pu		0.8 pu		4/7
0.8 pu	0.6 pu		1.2 pu		4/9
0.8 pu	0.6 pu (BESS charging)	0.6 pu (BESS discharging)	1.6 pu (BESS charging)	1.6 pu (BESS discharging)	4/11
0.8 pu	0.6 pu		2 pu		4/13
0.8 pu	0.8 pu*		2 pu		2/7

*This test is done to verify that an increase in the SynCon MVA can make the system stable.

Table 2-43: The impact of GFL BESS MVA on the system stability (both when the GFL BESS charges and discharges).

GFL BESS	SynCon		GFL BESS		GFL/BS MVA ratio
0.4 pu	0.6 pu		1 pu		0.25
0.8 pu	0.6 pu		1 pu		0.5
1.2 pu	0.6 pu		1 pu		0.75
1.6 pu	0.6 pu		1 pu		1
2 pu	0.6 pu (BESS discharging)	0.6 pu (BESS charging)	1 pu (BESS discharging)	1 pu (BESS charging)	1.25
2.4 pu	0.6 pu (BESS discharging)	0.6 pu (BESS charging)	1 pu (BESS discharging)	1 pu (BESS charging)	1.5

Key finding:

- The total required MVA capacity of the combined black starter is greater than that for the other two options. However, looking at from the perspective of the SynCon characteristics alone, the required MVA rating of the synchronous condenser is equal or less than that of the black start synchronous generator to achieve comparable performance.

2.4.1.2 SynCon Inertia

This part investigates the SynCon inertia impact on the GFL BESS operation and overall system stability. Table 2-44 summarizes the simulation results. It is observed that low SynCon inertia can lead to instabilities.

Figure 2-3 shows the simulation results when the SynCon inertia is set to 1. It is observed that the stability of the restored system is lost, and the voltage cannot be maintained within the steady-state band. The tests were conducted for both charging and discharging mode of the GFL BESS.

Table 2-44: SynCon inertia impact while the GFL BESS MVA is 0.8 pu and BS's GFL BESS MVA is 1 pu (both when the GFL BESS charges and discharges).

SynCon inertia
1

5
15
20

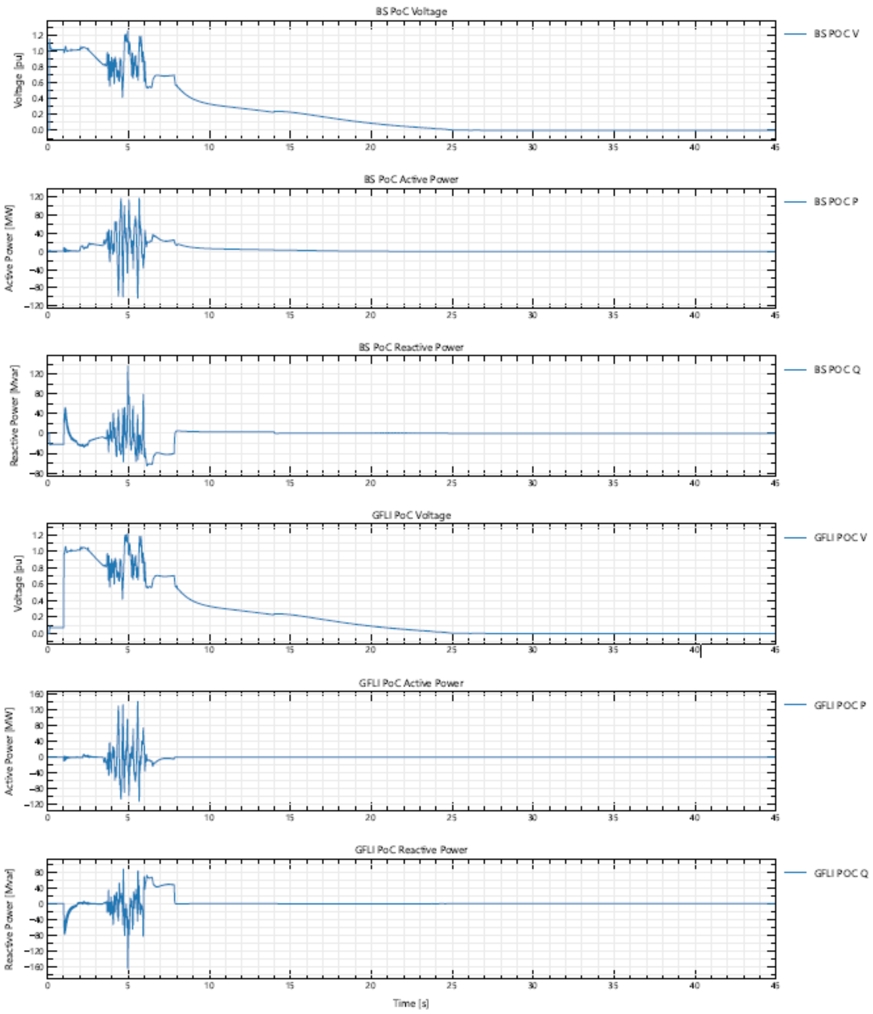

Figure 2-3: Simulation results with SynCon inertia set to 1 s.

Key finding:

- Low inertia SynCons are more exposed to the risk of instability, potentially necessitating the need for SynCons with flywheels.

2.4.1.3 Transmission Line Length

These tests aim to find the transmission line between the BS and the GFL BESS impact on the GFL BESS stability. Table 2-45 shows the summary of the simulations. It is observed that if the transmission line is longer than a particular threshold, the system becomes unstable. In these tests, the 200 km transmission line and above lead to instability.

Table 2-45: The transmission line length impact on the stability (both when the GFL BESS charges and discharges).

Transmission line length (km)
10

50
100
200
300

Key finding:

- Long transmission lines may cause instability and loss of synchronism. The line length at which instability occurs is below that observed for BESS and SG black starters.

2.4.2 Scenario 8: SynCon + GFL BESS Picking-up GFL Solar Farm

In this section, the BS unit is a SynCon + GFL BESS, which is used for powering up the island and picking-up the GFL Solar farm. Similar to Scenario 2, the aim here is to understand the strengths and weaknesses of this combination as a BS unit in picking-up a GFL SF. Similar tests were therefore carried out to those discussed in Scenario 2.

2.4.2.1 GFL SF to SynCon + GFL BESS MVA Ratio

In this section, the impact of MVA rating of the GFL SF, and the ratio of MVA rating of the GFL SF to be picked up to the MVA capacity of the black start source is investigated. Table 2-46 to Table 2-48 summarize the simulation results conducted for this part. In these tests, different combinations of GFL BESS, GFL SF, and SynCon MVA are investigated.

Table 2-46:The impact of SynCon MVA variation from 0.2 pu to 1 pu on the system stability while the GFL SF and BESS MVAs are kept at 0.8 pu and 1 pu, respectively.

GFL SF	SynCon	GFL BESS	GFL/BS MVA ratio
0.8 pu	0.2 pu	1 pu	2/3
0.8 pu	0.4 pu	1 pu	4/7
0.8 pu	0.6 pu	1 pu	0.5
0.8 pu	0.8 pu	1 pu	4/9
0.8 pu	1 pu	1 pu	0.4

Table 2-47: The impact of GFL BESS MVA variation from 0.4 pu to 2 pu on the system stability while the GFL SF and BESS MVAs are kept at 0.8 pu and 0.6 pu, respectively.

<table>
<tr><th>GFL SF</th><th colspan="2">SynCon</th><th colspan="2">GFL BESS</th><th>GFL/BS MVA ratio</th></tr>
<tr><td>0.8 pu</td><td colspan="2">0.6 pu</td><td colspan="2">0.4 pu</td><td>0.8</td></tr>
<tr><td>0.8 pu</td><td colspan="2">0.6 pu</td><td colspan="2">0.8 pu</td><td>4/7</td></tr>
<tr><td>0.8 pu</td><td colspan="2">0.6 pu</td><td colspan="2">1.2 pu</td><td>4/9</td></tr>
<tr><td>0.8 pu</td><td>0.6 pu (GFL BESS discharging)</td><td>0.6 pu (GFL BESS charging)</td><td>1.6 pu (GFL BESS discharging)</td><td>1.6 pu (GFL BESS charging)</td><td>4/11</td></tr>
<tr><td>0.8 pu</td><td colspan="2">0.6 pu</td><td colspan="2">2 pu</td><td>4/13</td></tr>
<tr><td>0.8 pu</td><td colspan="2">0.8 pu*</td><td colspan="2">2 pu</td><td>2/7</td></tr>
</table>

*This test is done to verify the positive impact of SynCon MVA increase.

Table 2-48: The impact of GFL SF MVA variation from 0.4 pu to 2.4 pu on the system stability while the GFL BESS and SynCon MVAs are kept at 1 pu and 0.6 pu, respectively.

GFL SF	SynCon	GFL BESS	GFL/BS MVA ratio
0.4 pu	0.6 pu	1 pu	0.25
0.8 pu	0.6 pu	1 pu	0.5
1.2 pu	0.6 pu	1 pu	0.75
1.6 pu	0.6 pu	1 pu	1
2 pu	0.6 pu	1 pu	1.25
2.4 pu	0.6 pu	1 pu	1.5

Key finding:

- If the GFL/BS MVA ratio increases, the risk of instability increases as well.

2.4.2.2 SynCon Inertia

In this section, the impact of SynCon inertia on system stability is investigated. To this end, the SynCon inertia is increased from 1 to 20. Table 2-49 summarizes the simulation results conducted for this part.

Table 2-49: The impact of SynCon inertia on the GFL SF stability.

SynCon inertia
1
5
15
20

Key finding:

- Low inertia for the SynCon increases the risk of instability and GFL SF tripping. These results indicate the need for SynCons with flywheels.

2.4.2.3 Transmission line length

In this section, the impact of transmission line length on the GFL SF stability is investigated. For this purpose, the transmission line length is increased from 10 km to 300 km. Table 2-50 shows the summary of simulations of this part.

Table 2-50: Transmission line length impact on the GFL SF stability.

Transmission line length (km)
10

50
100
200
300

Key finding:

- Longer transmission lines can lead to instability due to increasing the apparent impedance, hence reducing the SCR seen by the GFL plant.

2.4.3 Scenario 9: SynCon + GFL BESS Picking-up GFL Wind Farm

In this section, the BS unit is a combination of a SynCon and GFL BESS aiming to pick up a GFL wind farm. Similar to Scenario 3, the aim here is to understand the strengths and weaknesses of this combination as a BS unit in picking-up a GFL WF. Similar tests are therefore carried out to those discussed under Scenario 3.

2.4.3.1 GFL WF to SynCon + GFL BESS MVA Ratio Impact

In this section, the GFL WF to the cumulative SynCon and GFL BESS MVAs ratio impact on the system stability and WF pick up is investigated. Therefore, different combination of these units MVAs as illustrated in Table 2-51, Table 2-52, and Table 2-53 are tested.

Table 2-51: The impact of SynCon MVA variation from 0.2 pu to 1 pu on the system stability while the GFL WF and BESS MVAs are kept at 0.8 pu and 1 pu, respectively.

GFL WF	SynCon	GFL BESS	GFL/BS MVA ratio
0.8 pu	0.2 pu	1 pu	2/3
0.8 pu	0.4 pu	1 pu	4/7
0.8 pu	0.6 pu	1 pu	0.5
0.8 pu	0.8 pu	1 pu	4/9
0.8 pu	1 pu	1 pu	0.4

Table 2-52: The impact of GFL BESS MVA variation from 0.4 pu to 2 pu on the system stability while the GFL WF and SynCon MVAs are kept at 0.8 pu and 0.6 pu, respectively.

GFL WF	SynCon	GFL BESS	GFL/BS MVA ratio
0.8 pu	0.6 pu	0.4 pu	0.8
0.8 pu	0.6 pu	0.8 pu	4/7
0.8 pu	0.6 pu	1.2 pu	4/9
0.8 pu	0.6 pu	1.6 pu	0.4
0.8 pu	0.6 pu	2 pu	4/11
0.8 pu	0.8 pu*	2 pu	2/7

*This test is done to verify a larger SynCon can stabilize the system.

Table 2-53: The impact of GFL WF MVA variation from 0.4 pu to 2.4 pu on the system stability while the GFL BESS and SynCon MVAs are kept at 1 pu and 0.6 pu, respectively.

GFL WF	SynCon	GFL BESS	GFL/BS MVA ratio
0.4 pu	0.6 pu	1 pu	0.25
0.8 pu	0.6 pu	1 pu	0.5
1.2 pu	0.6 pu	1 pu	0.75
1.6 pu	0.6 pu	1 pu	1
2 pu	0.6 pu	1 pu	1.25
2.4 pu	0.6 pu	1 pu	1.5

Key finding:

- In addition to the MVA ratio of BS/GFL, the MVA ratio of the SynCon to the accompanying BESS, and more importantly the absolute MVA size of the SynCon play a part in this scenario.

2.4.3.2 SynCon Inertia

This part illustrates the impact of SynCon inertia on system stability including that of the GFL WF. Similar to previous tests, SynCon inertia is varied from 1 to 20 to analyse the system sensitivity to this parameter.

Table 2-54: The impact of SynCon inertia on the GFL WF stability.

SynCon inertia
1
5
15
20

Key finding:

- Low inertia for the SynCon increases the risk of instability and GFL SF tripping. These results indicate the need for SynCons with flywheels.

Transmission line length

In this section, the impact of transmission line length on the GFL WF stability is investigated. For this purpose, the transmission line length is increased from 10 km to 300 km. Table 2-55 shows the summary of simulations of this part.

Table 2-55: Transmission line length impact on the GFL SF stability.

Transmission line length (km)
10
50
100
200

300

Key finding:

- Very long transmission lines can cause instability and GFL unit tripping as they increase the risk of loss of synchronism.

2.5 Sensitivity Analysis

In this section, a few sensitivity studies were conducted as detailed below:

- Comparison of GFM BESS from another OEM with the original GFM BESS used for the studies reported in sections 1, 2, and 3
- A partial DMAT[4] on the GFM BESS under grid-connected and islanded modes to investigate to what extent the model used for standard grid-connection studies differ from the model required for the system restoration
- Assessing the critical SCRs (the minimum SCR required for successful initialisation and subsequent stable operation) for GFL WF, SF, and BESS used in this report
- Assessing the impact of widening the protection settings for the GFL units on the critical SCR and low-SCR withstand capability.

2.5.1 GFM BESSs Comparison

To understand the extent to which the conclusions drawn from simulation studies for GFM BESS, several shortlisted studies were conducted with using a different GFM BESS model from another OEM.

In the rest of this section, the simulation results for the second GFM BESS, named as GFM 2, is presented, and compared with the initial GFM BESS (GFM 1).

2.5.1.1 Picking up the GFL BESS

In this section, selected tests from scenario 1 were repeated with GFM 2 as the BS unit instead of GFM 1. The tests are conducted will assess the impact of transmission line length, GFL BESS to GFM BESS MVAs ratio, and GFM BESS inertia.

Transmission Line Length

In this section, the transmission line between the BS and the GFL BESS is varied from 10 km to 300 km. Table 2-56 shows the simulation results of the system for these tests. Also, this table provides a comparison between GFM 1 and GFM 2. It is observed that the GFM 2 can pick up the GFL BESS located in 300 km distance and below. However, this limit is 200 km for GFM 1.

Table 2-56: The impact if transmission line length between the GFM BESS and the GFL BESS on the GFL BESS stability.

Transmission line length	GFM 1	GFM 2
10 km	Stable	Stable
50 km	Stable	Stable
100 km	Stable	Stable
200 km	Stable	Stable
300 km	Stable	Stable

GFL BESS to GFM BESS MVA Ratio

In this section, the impact of GFL BESS MVA to the alternative GFM BESS MVA ratio is investigated. Table 2-57 and Table 2-58 show simulation results for some example scenarios with different GFL/GFM MVA ratios. It is observed that for having a stable system with no unit tripping, the maximum GFL/BS MVA ratio should be

[4] model-acceptance-test-guideline-nov-2021.pdf (aemo.com.au)

0.8 and 1 for GFM 1 and 2, respectively. Both GFMs show the same trend, i.e., if the GFL MVA to GFM MVA ratio exceeds a certain amount, the GFL could not be picked up anymore.

Table 2-57: The impact of GFL BESS MVA variation from 0.4 pu to 2 pu while the GFM BESS MVA is kept at 1 pu. This table shows the results both for GFM 1 and GFM 2.

<table>
<tr><th>GFL BESS MVA</th><th colspan="2">GFM 1 MVA</th><th>GFM 2 MVA</th><th>GFL/GFM ratio</th></tr>
<tr><td>0.4 pu</td><td colspan="2">1 pu</td><td>1 pu</td><td>0.4</td></tr>
<tr><td>0.8 pu</td><td colspan="2">1 pu</td><td>1 pu</td><td>0.8</td></tr>
<tr><td>1.2 pu</td><td colspan="2">1 pu</td><td>1 pu</td><td>1.2</td></tr>
<tr><td>2 pu</td><td>1 pu
GFL discharging</td><td>1 pu
GFL Charging</td><td>1 pu</td><td>2</td></tr>
</table>

Table 2-58: The impact of GFL BESS MVA variation from 0.4 pu to 2 pu while the GFM BESS MVA is kept at 0.4 pu. This table shows the results both for GFM 1 and GFM 2.

<table>
<tr><th rowspan="2">GFL BESS MVA</th><th rowspan="2" colspan="2">GFM 1 MVA</th><th colspan="2">GFM 2 MVA</th><th rowspan="2">GFL/GFM ratio</th></tr>
<tr><th>GFL BESS Discharging</th><th>GFL BESS Charging</th></tr>
<tr><td>0.4 pu</td><td>0.4 pu
GFL Charging</td><td>0.4 pu
GFL Discharging</td><td>0.4 pu</td><td>0.4 pu</td><td>1</td></tr>
<tr><td>0.8 pu</td><td colspan="2">0.4 pu</td><td>0.4 pu</td><td>0.4 pu</td><td>2</td></tr>
<tr><td>1.2 pu</td><td colspan="2">0.4 pu</td><td>0.4 pu</td><td>0.4 pu</td><td>3</td></tr>
<tr><td>1.6 pu</td><td colspan="2">0.4 pu</td><td>0.4 pu</td><td>0.4 pu</td><td>4</td></tr>
<tr><td>2 pu</td><td colspan="2">0.4 pu</td><td>0.4 pu</td><td>0.4 pu</td><td>5</td></tr>
</table>

Key finding:

- Regardless of the control system design and tuning, if the GFL BESS to GFM BESS MVA ratio exceeds a particular minimum threshold that the GFL BESS cannot be picked up.

GFM BESS Inertia Constant

In this section, the inertia constant impact is investigated for GFM 2 and compared with the results for GFM 1. Table 2-59 summarizes the simulation results performed for this purpose. It is observed that similar to GFM 1, no material impact on the GFL BESS stability is exhibited. As an example, Figure 2-4 shows the output active power of GFMs 1 and 2 at their PoCs in the scenario in which both GFMs inertia constant is set to 100. It is observed that while the magnitude of the transients at t = 25 s are slightly different (which occurs due to a sever fault), during load changes and normal conditions the outputs are similar, and there is no material difference between them.

Table 2-59: The inertia constant impact of GFM 1 and 2 on the system and GFL BESS stability.

GFM 1	GFM 2
0	0
5	5
20	20
50	50
100	100

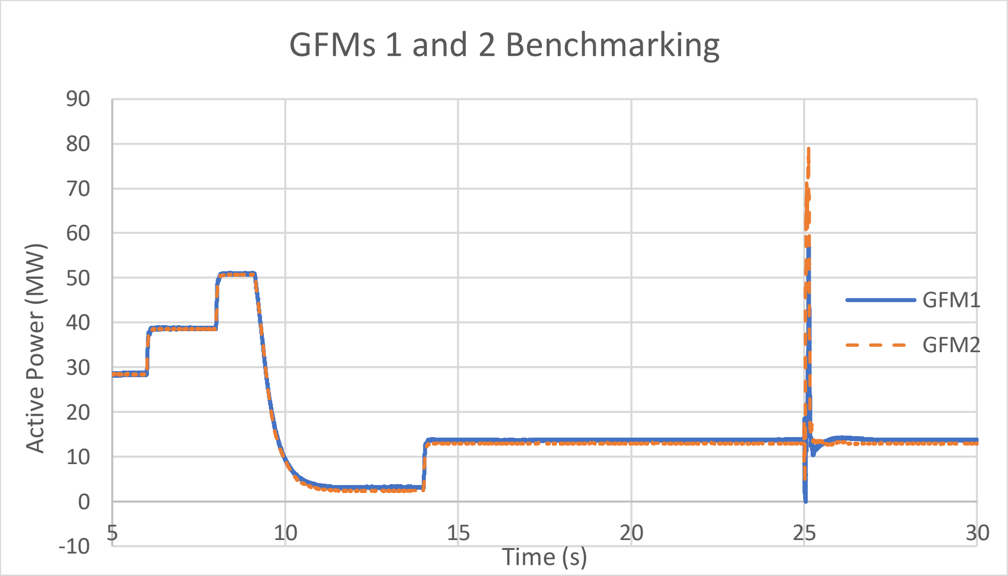

Figure 2-4: The output active power of GFM1 and GFM2 at their PoCs when their inertia constant is set to 100.

Key finding:

- No material impact is observed on the GFL BESS stability for different inertia constants for GFM BESS.

2.5.1.2 Picking-up the GFL Solar Farm

In this section, some tests of scenario 2 are done again with having GFM 2 as the BS unit instead of GFM 1. The tests are conducted are transmission line length impact, GFL SF to GFM BESS MVAs ratio, and GFM BESS inertia impact.

Transmission Line Length

In this section, the transmission line between the BS and the GFL SF is varied from 10 km to 300 km. Table 2-60 shows the simulation results of the system for these tests. Also, this table provides a comparison between GFM 1 and GFM 2. It is observed that there is no difference between the performance of GFM 1 and 2.

Table 2-60: The impact if transmission line length between the GFM BESS and the GFL SF on the GFL SF stability.

Transmission line length	GFM 1	GFM 2
10 km	Stable	Stable
50 km	Stable	Stable
100 km	Stable	Stable
200 km	Stable	Stable
300 km	Stable	Stable

GFL Solar Farm to GFM BESS MVA Ratio

In this section, the impact of GFL BESS MVA to the alternative GFM BESS MVA ratio is investigated. Table 2-61 and Table 2-62 show the simulation results for some combinations of GFL SF MVAs and GFM BESS MVAs. It is observed that for having a stable system with no unit tripping, the maximum GFL/BS MVA ratio should be 1.2 and 2 for GFM 1 and 2, respectively. Closer inspection of the failed cases indicates slightly different small-signal behaviour between the two GFM makes, and their ability to suppress of small-signal oscillations caused by operating GFL plant under low SCR conditions. Control system design and tuning of the GFM will therefore play a key part here.

Table 2-61: The impact of GFL SF MVA variation from 0.4 pu to 2 pu while the GFM BESS MVA is kept at 1 pu. This table shows the results both for GFM 1 and GFM 2.

GFL solar farm MVA	GFM 1 MVA	GFM 2 MVA	GFL/GFM ratio
0.4 pu	1 pu	1 pu	0.4
0.8 pu	1 pu	1 pu	0.8
1.2 pu	1 pu	1 pu	1.2
2 pu	1 pu	1 pu	2

Table 2-62: The impact of GFL SF MVA variation from 0.4 pu to 2 pu while the GFM BESS MVA is kept at 0.4 pu. This table shows the results both for GFM 1 and GFM 2.

GFL solar farm MVA	GFM 1 MVA	GFM 2 MVA	GFL/GFM ratio
0.4 pu	0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	0.4 pu	2
1.2 pu	0.4 pu	0.4 pu	3
1.6 pu	0.4 pu	0.4 pu	4
2 pu	0.4 pu	0.4 pu	5

Key finding:

- Regardless of the control system design and tuning of the GFM, if the ratio of GFL BESS to GFM BESS MVA exceeds a certain amount, which varies depending on the tunings, the GFL BESS cannot be restarted.

Picking-up the GFL Wind Farm

In this section, selected tests from scenario 3 were repeated with GFM 2 as the BS unit instead of GFM 1. The tests conducted will investigate the impact of transmission line length, GFL SF to GFM BESS MVAs ratio, and GFM BESS inertia.

Transmission Line Length

In this section, the transmission line between the BS and the GFL BESS is varied from 10 km to 300 km. Table 2-63 shows the simulation results of the system for these tests for GFM 1 and GFM 2. As shown consistent results can be obtained.

Table 2-63: The impact of the transmission line length between the GFM BESS and the GFL BESS on the GFL WF stability.

Transmission line length	GFM 1	GFM 2
10 km	Stable	Stable
50 km	Stable	Stable
100 km	Stable	Stable
200 km	Stable	Stable
300 km	Stable	Stable

Key finding:

- Consistent results are obtained with both GFM makes.

GFL Wind Farm to GFM BESS MVA Ratio

In this section, the impact of GFL WF MVA to different GFM BESS MVA ratio is investigated. Table 2-64 and Table 2-65 show the simulation results for some combinations of GFL BESS MVAs and GFM BESS MVAs. It is observed that except for when both the GFL WF and GFM 2's MVA are 0.4 pu, in all scenarios both GFM BESSs could pick up the GFL WF successfully.

Table 2-64: The impact of GFL WF MVA variation from 0.4 pu to 2 pu while the GFM BESS MVA is kept at 1 pu. This table shows the results both for GFM 1 and GFM 2.

GFL wind farm MVA	GFM 1 MVA	GFM 2 MVA	GFL/GFM ratio
0.4 pu	1 pu	1 pu	0.4
0.8 pu	1 pu	1 pu	0.8
1.2 pu	1 pu	1 pu	1.2
2 pu	1 pu	1 pu	2

Table 2-65: The impact of GFL WF MVA variation from 0.4 pu to 2 pu while the GFM BESS MVA is kept at 0.4 pu. This table shows the results both for GFM 1 and GFM 2.

GFL wind farm MVA	GFM 1 MVA	GFM 2 MVA	GFL/GFM ratio
0.4 pu	0.4 pu	0.4 pu	1
0.8 pu	0.4 pu	0.4 pu	2
1.2 pu	0.4 pu	0.4 pu	3
1.6 pu	0.4 pu	0.4 pu	4
2 pu	0.4 pu	0.4 pu	5

Key finding:

- Both GFMs could pick up the GFL WF successfully even for higher GFL WF/GFM MVA ratio.

GFM BESS Inertia Constant

In this section, the inertia constant of the energisation source impact is investigated for GFM 2 and compared with the results for GFM 1. Table 2-66 summarizes the simulation results performed for this purpose. These results indicate that system instability is not impacted by the choice of the inertia constant for either GFM design.

Table 2-66: The inertia constant impact of GFM 1 and 2 on the system and GFL BESS stability.

GFM 1	GFM 2
0	0
5	5
20	20
50	50
100	100

Key finding:

- The variations of the inertia constant for the GFM shows no impact on system stability.

2.5.2 Assessing the Potential Trade-off between System Normal and Black Start Performance

In this section, the trade-off between system normal and black start performance objectives, in particular with regard to NER clauses S5.2.5.5 and S5.2.5.13, is investigated. For this purpose, a set of partial DMAT tests are conducted on the GFM BESS employed for the system restart. Note that DMAT tests are conducted on a SMIB model of the under-study generator connected to an infinite bus, i.e., the diagram shown in Figure 2-1 is not used in this part.

To investigate the impact of GFM Islanded/Grid-connected mode activation impact and differences, similar DMAT tests are conducted once when the GFM Islanded mode is activated and once when it is set to Grid-connected. It is observed that this difference does not impact the performance/stability of the GFM BESS in any of the performed tests. Below, some examples of the simulations performed are provided, and the results of when the GFM is set to islanded mode and when it is set to grid-connected mode are overlayed in same figure.

Balanced fault occurrence

Figure 2-5 shows the active and reactive power of the GFM in islanded and grid-connected modes when subject to a three-phase fault at the point of connection. It is observed that although there is a slight difference during the transients, the stability of the system is not impacted by the setting.

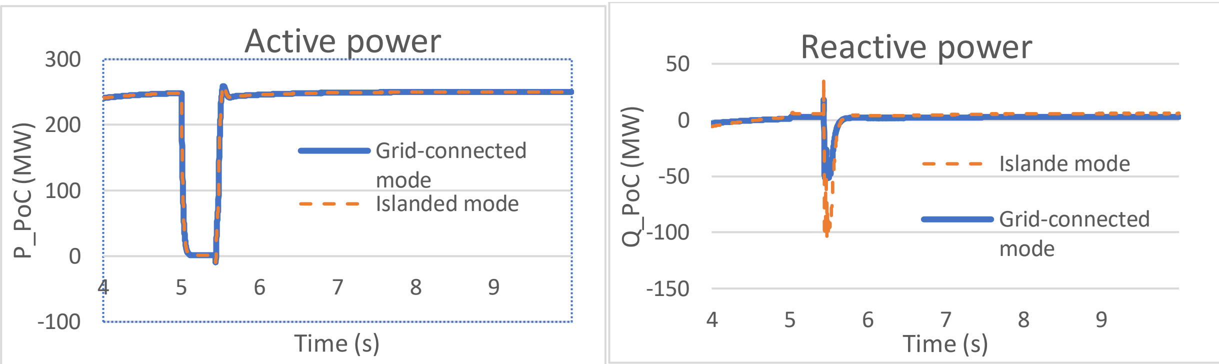

Figure 2-5: Active and reactive power comparison in the presence of a balanced fault while the GFM is in islanded and grid-connected modes.

PoC Voltage Reference Step Change

In this test, the GFM BS is subject to Voltage Reference Step Change under islanded and grid-connected modes. The PoC voltage of the GFM is shown d in Figure 2-6. It is observed that the voltages are identical in both modes. Also, Figure 2-7 shows the active and reactive power of the GFM in both cases. It can be seen that the outputs of the inverters are identical.

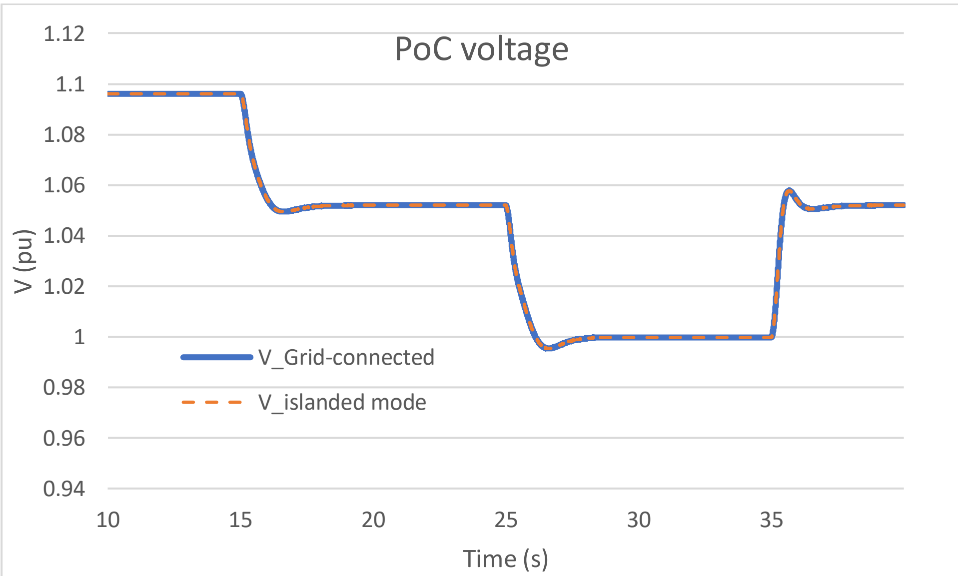

Figure 2-6: PoC voltage of the GFM while the inverter is working in islanded and grid-connected modes.

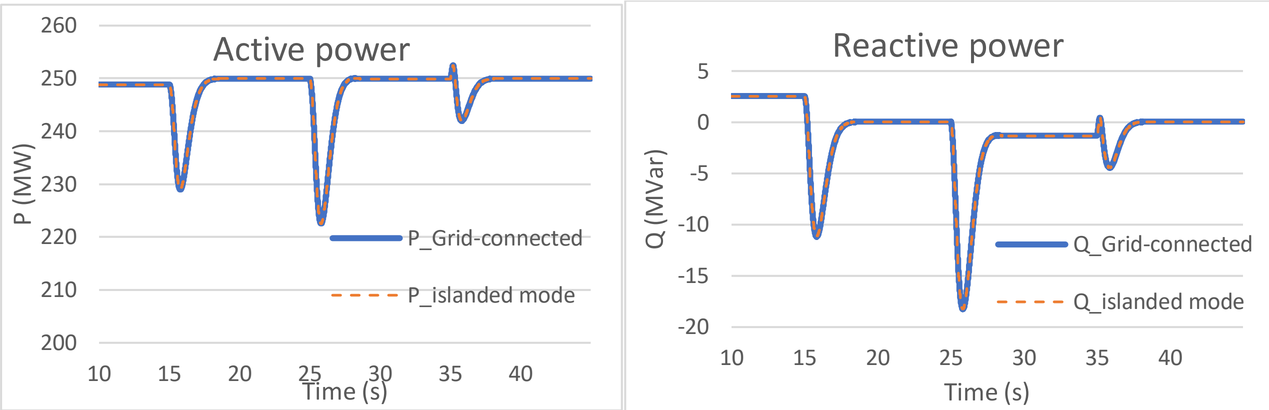

Figure 2-7: Active and reactive power comparison in the presence of multiple PoC voltage reference step changes, and while the GFM is in islanded and grid-connected modes.

Key finding:

- Very little performance differences are observed between the grid connected and islanded modes of operation.

2.5.3 Impact of System Strength on GFL BESS, Solar farm, and Wind Farm

This section investigates the impact of SCR withstand capability of the three GFL types used for this project on the ability of black start units to successfully energize them during restoration conditions. For this purpose, a SMIB test system in which the GFL plant is connected to the equivalent grid was developed, and the grid SCR is decreased from 3 to 1 with steps of 0.1. The base MVA is set to 250 MVA, and the GFL plant injects/absorbs 50 MW into/from the grid. Table 2-67 shows the critical SCR at which each GFL plant trips and could not be picked up. This critical SCR is the SCR until which the GFL plant remains stable.

Based on the nine scenarios conducted in this project, the high-level observation is that the GFL WF have the most stable operation among the three GFL plants studied. The aim of these tests was to confirm that one critical factor for the superior performance of the GFL WF is its better withstand capability (the ability of the IBR to remain stably connected to the grid under conditions of low SCR without either tripping protection settings or losing synchronism) against very low SCR conditions. Such conditions can be attributed to very early stages of system restoration.

Table 2-67: The critical SCR for each GFL plant.

Plant	Critical SCR
GFL BESS	2.9*
GFL solar farm	2.8
GFL wind farm	1**

*The BESS becomes unstable at SCR 2.9 both for charging and discharging.

**The wind farm is stable for all SCRs between 3 and 1. The actual critical SCR might be lower than 1.

Key finding:

- The higher the withstand capability of the GFL plant under low SCR conditions, the more stable it will be when picked up by the BS in early stages of system restoration. Note that the outcome that a wind farm is more stable than a BESS or solar farm is based on specific examples used here without any tuning conducted and cannot be unconditionally generalised.

2.5.4 GFL Protection Widening

During system restoration wider ranges of voltage and frequency are generally permitted compared to those applied for continuous uninterrupted operation.

This section investigates the impact of widening the GFL plant voltage and frequency protections from the standpoint of enhancing system stability. For this purpose, a set of simulations have been done with the protection settings used in Section 5. Also, the SCR variation tests are done with the new protection settings. This part briefly summarizes the results of these tests.

2.5.4.1 Critical SCR

If a more relaxed voltage protection setting is applied for the GFL plants, it is observed that the critical SCR decreases considerably for these units. Table 2-68 shows the critical SCR for GFL plants with the modified voltage protection. It is observed that the GFL can withstand a considerably lower SCR.

Table 2-68: Critical SCR for GFL plants with Loose voltage protection settings.

Plant	Critical SCR
GFL BESS	1.6
GFL solar farm	1.6
GFL wind farm	1*

*The wind farm does not trip throughout the simulations.

Similar trend is observed when the transmission line between the BS and the GFL plant is increased. For instance, as illustrated in Table 2-7, the GFL BESS could not be picked up via the GFM BESS if the transmission line is 300 km. However, with the protection settings in Section 5, the GFL BESS can be successfully picked up. Figure 2-8 shows the simulation results of Case study # 16 while the voltage protection setting is widened. It is observed that in contrast to the initial model with standard protection setting, the GFL BESS can be picked up successfully at 9 seconds.

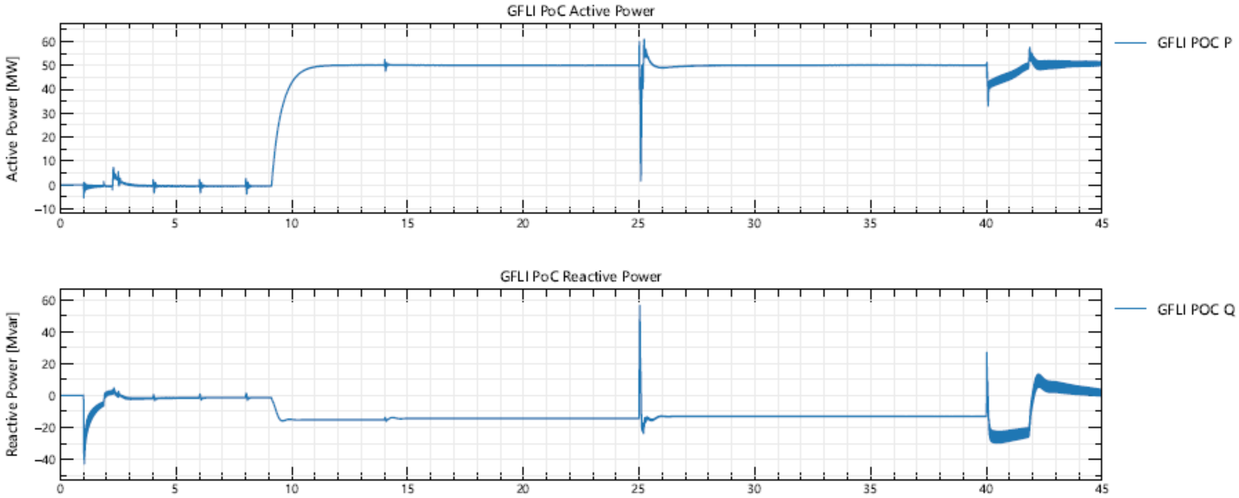

Figure 2-8: The GFL BESS (the energisation target) output active and reactive power while picked up via the GFM BESS, the transmission line length is 300 km, and loose voltage protection setting is implemented.

Key finding:

- Wider than normal voltage and frequency protection settings improves the SCR withstand capability of the GFL plants, hence increasing the likelihood of successful GFL plant pick up and overall system stability during the restoration process.

2.6 Summary

This section provides a short summary of the key finding for each of the main points included in Aurecon's proposal.

2.6.1 Phase 1

- Determine the criteria on when each IBR can be introduced during system restoration, e.g., short circuit ratio, total MW dispatch, number of inverters
  - Minimum SCR withstand capability of the GFL plant to be restarted is the key determining factor.
- Determine the extent to which existing simulation models provided for connection studies can accurately represent the IBR response during system restoration
  - The GFM models provided did not have soft energisation or harmonic cancellation capabilities. It is understood that the latter can be included by some OEMs as a project specific feature, however, the former seems to be a missing feature in most if not all available models.
- The ratio of MVA rating of GFM IBR to the MVA rating of the largest transformer or non-blackstart plant to be energised by the IBR, and how it is compared to that with a synchronous generator black starter
  - It is observed that the GFM/GFL ratio that can be successfully picked up is typically greater than the SG/GFL ratio. This ratio, however, depends on the minimum SCR withstand capability of the GFL plant and the MVA size of the GFM and GFL. It was observed that there is generally a minimum MVA for the black start unit, whether GFM or SynCon, below which successful energisation cannot be achieved regardless of the MVA ratio mentioned above.
- The risk of harmonic resonances with the surrounding network in an IBR dominated power system during system restoration due to the presence of low-order high-impedance resonance frequencies.
  - Studies indicated that for longer transmission lines, the harmonic impedance has more resonance points with larger picks and lower frequencies. However, none of the failed cases reported could be attributed to the excitation of a resonance frequency, and as such no discussion was included in this regard as they do not provide any added value in uncovering the capabilities and limitations of GFL and GFM IBR during system restoration.

2.6.2 Phase 2

- The extent to which a grid-forming inverter needs to emulate some, or all of the following characteristics provided by synchronous generators or providing additional non-standard functions not available to all grid-forming inverters by default. The following attributes were investigated:
  - Certain amount of fault current:
    - No sensitivity was observed to fault current variations between 1 and 2 pu
  - Virtual inertia:
    - No sensitivity was observed to the variation of the inertia constant between 0 and 100 s
  - Virtual impedance (damping factor):
    - No sensitivity was observed.
  - Voltage regulation capabilities
    - Only one of the two GFM makes was based on the so-called virtual synchronous machine capability which includes an AVR-like function being an essential component of a synchronous machine. The presence or absence of the AVR did not contribute to any performance differences between the two GFM makes.

- The original proposal also included an assessment of the impact of the following two performance aspects of grid-forming inverters. However, this could not be assessed as the OEM models provided did not have these aspects as adjustable settings.

    iv) Certain sequence of fault current, i.e., the ratio of negative-to positive-sequence

    v) Harmonic cancellation

- Technology differentiators between grid-following wind, solar and BESS as a restoration support service
  - The minimum SCR withstand capability of the GFL plant was determined as the most critical factor. Despite providing a superior frequency control, in some instances the GFL BESS exhibited inferior performance to those of the solar and wind farms.
- High-level specification of both the grid-forming and grid-following BESS
  - GFM BS performance does not depend on its inertia, the respective damping or fault current contribution. Although this work only looked at the GFM BESS, its excellent frequency control and the ability to act as a load or generator are convenient advantages that may not be available should grid-forming capability be implemented in other IBRs. Wider voltage and in particular frequency protection bands during system restoration were also identified to improve the black start performance.
  - The main attribute that would make a grid-following inverter attractive for participation during system restoration is the minimum SCR withstand capability.
- The trade-off between system normal and black start performance objectives, in particular with regard to NER clauses S5.2.5.5 and S5.2.5.13.
  - No material difference was observed between the two modes.

3 Stage 2

3.1 Objectives

The use of a wide-area EMT model makes system restoration studies take significantly longer to run compared to the studies conducted in stage 1 with a simplified network model. As such judicious decision was made on the most critical and informative studies to be repeated in stage 2 rather than comprehensively conducting all studies completed in stage 1. These shortlisted studies were chosen to allow answering the following key questions for the black start GFM BESS in a remote part of the network:

- Can the GFM BESS energise network sections between its connection point and that of a synchronous generator and energise the synchronous generator's auxiliary load?
  - This was analysed with the GFM BESS alone, including when it had already picked up other generation and network elements.
  - Also this tested both
    - vi) at the early stages of restoration picking up smaller and closer hydro units, and;
    - vii) later on aiming to pick up larger and more distant coal fired stations.
- Can the GFM BESS energise a large transmission level transformer without additional support?
- Can the GFM BESS energise and provide stabilising support to a GFL plant?
- Does a synchronous generator or GFM BESS offer better resilience to network faults during a system restoration process?

Furthermore, the following questions were investigated for the combined SynCon and GFL BESS:

- Can a combined SynCon and a GFL BESS be used as a primary system restart provider?
- Can a synchronous generator outside the REZ be used to energise to and black start the REZ?

To answer the key questions outlined above, selected system restart scenarios were studied with key results documented in Section 3.4. The step-by-step energisation sequence is presented in Appendix A.

3.2 Additional details required for generator and network modelling for black start studies

3.2.1 Synchronous generator

3.2.1.1 Alternator

For synchronous generator modelling, built-in PSCAD models with two q-axis damper windings, and distribution of saturation on both the d- and q-axis are suitable.

3.2.1.2 Synchronous generator control and protection systems

The following shall be generally represented for (where possible the use of vendor-specific models is preferred to generic models).

- System-normal control loops such as AVR and PSS.
  - Also for PSS the logic indicating how the PSS will be engaged/disengaged depending on the loading level.
- Limiters, such as under and over-excitation limiters, or V/Hz limiters

- All possible operating modes for the governor including isochronous and droop control, and automatic switchover between these modes .
- Protection functions, such as under- and over-excitation protection, out-of-step (OOS) and loss-of-excitation (LOE) protection.

3.2.2 Inverter-based resource

IBR should be accurately modeled to perform the different type of studies required to verify a system restoration plan. IBR models should accurately represent all relevant regulation, control and protection functions. Key functional requirements are provided below.

- The model should include plant scale output controls as well as the inverter (inner) control loops that derive the firing pulses for inverter switches (even if average switch modelling is used where the semiconductor switching devices are not modelled explicitly).
- The input signal measuring and filtering modules should be the actual signal processing algorithms and filters in the physical implementation. Signal processing and communication delays must be represented in the model.
- Voltage and frequency protection settings.
- Fault ride-through activation and deactivation settings.
- Any other control functions that are activated during restoration conditions that may not apply during normal operating conditions.

3.2.3 Transformers

A transformer model can be divided into two parts: representation of windings, and representation of the iron core. The first part is linear, the second one is nonlinear, and both are frequency dependent. Each part plays a different role, depending on the study for which the transformer model is required. For EMT black start studies, the transformer winding can be adequately represented to only the same level of details as a phasor-domain model, where the frequency dependency of the winding is neglected.

The three main features associated with the iron core are saturation, hysteresis, and (frequency dependent) eddy current losses. In general, the hysteresis loops of modern transformers have a negligible influence on the magnitude of the magnetising current. The information necessary for modelling hysteresis characteristics is not generally provided, and it is therefore excluded from the transformer modelling for black start studies. Eddy current losses can be neglected for frequencies of up to 2-3 kHz, hence can also be excluded from the transformer model required for black start studies. However, transformer saturation characteristics play a significant part in black start studies.

Saturation characteristics can be incorporated from test data/manufacturer's curves, or by estimating the key parameters from transformer geometry. The former approach is a simple and convenient way of determining worst case inrush currents at the design phase. This is because, with this approach, the frequency dependency of the losses is neglected. The latter approach provides a marginal accuracy improvement, however, the information required for this type of modelling is often only available to the transformer manufacturer.

3.2.4 Overhead transmission lines

Transmission lines are nonlinear in nature due to frequency dependency in both conductors (the skin effect) and in the ground (or earth return) path. Two main alternative approaches exist to represent transmission lines in EMT programs. The simplest method is to use a pi-section. The second and more detailed method is to use a distributed transmission line model. The pi-section model is a lumped parameter model based on series RL elements and parallel CG elements. This model can be adopted to study the transient behaviour when the end-to-end length of the line is shorter than a couple of km, (or when studies need to be run to represent several tens of seconds and a distributed line model would be too computationally intensive to solve). This model can also be used when tower geometry is unknown.

The distributed transmission line models are based on the principle of traveling waves. Relative to the PI models, distributed parameter models are more accurate but more computationally intensive.

A Bergeron distributed transmission line model is a distributed-parameter model with no frequency dependence and valid for some single specified frequency, whereas a frequency-dependent distributed parameter model (including both Mode and Phase models) is fitted for some given frequency range, and is hence more accurate. The parameters of the Bergeron model are constant with frequency, and thus may be used when no frequency dependency is to be represented. However, this model may be quite sensitive to the model frequency specified by the user.

With the extent of data available for network planning studies and phasor-domain load flow cases, either a PI model or a Bergeron model can be readily developed (the latter model would need to be converted from the PI model via the phasor-domain using? an EMT conversion tool). These models are generally appropriate for short lines if harmonic resonance is not a matter of concern. With either a pi- or Bergeron model, the line impedances need to be explicitly entered in the model. Note that for black start studies, the negative- and zero-sequence impedances, and mutual impedances of the double circuit lines are critically significant, and need to be entered in the EMT model should either of the PI or Bergeron models be used. The mutual impedances of the lines are important whether energising one or both circuits on the same tower. Indeed, energising a single circuit could be a more critical case due to the induced voltages and currents on the un-energised circuit.

Of the three distributed line models, including Bergeron, frequency-dependent (Mode) and frequency-dependent (Phase) models, the latter is the most accurate and should be used whenever harmonic resonance needs to be investigated. The use of frequency-dependent (phase) model is envisaged for all transmission lines involved in the system restoration if tower geometry is given.

With frequency-dependent models of the line, the sequence impedances are not often required in the model but instead can be calculated automatically through a line-constant routine, based on given tower geometry and conductor data.

The following information is generally sought:

- Transmission line conductor diameter and resistance per unit length (can also be selected from a user-defined list for standard/commonly used conductors).
- Total length of each transmission line.
- Phase transformation data and distances between phases.
- Spacing between conductors in a phase bundle.
- Spacing between phases.
- Shield wire diameter and resistance per-unit length.
- Height of each conductor and shield wire at the tower and sag to midspan, or average height of each conductor and shield wire above ground.
- Tower dimensions.
- Ground resistivity.
- Line transposition (if applicable)

Note that the transmission lines were pre-arranged to be energised at the worst-case theoretical voltage phase angle. As such point-on-wave line energisation studies were not conducted.

3.2.5 Surge arrester

The primary reason for inclusion of surge arrester behaviour in black start studies is that system restoration can impose excessive TOV lasting for several seconds. Such TOV can compromise the insulation of the surge arrester. Modelling surge arresters for voltages in the range 1.0-1.3 pu, and assessment of TOV resulting from switching transients is critical. Surge arrester models will need to be included in system restoration studies to ensure that TOVs due to component energisation will not cause inadvertent damage to the surge arresters, and to identify alternate restoration path if there is a risk of adversely impacting surge arresters with the original restoration path.

Surge arresters exhibit a nonlinear voltage versus current (V-I) characteristic such that they have an extremely high resistance during normal system operation and a relatively low resistance during transient over-voltages.

The commonly used frequency-independent surge arrester model is appropriate for simulations involving low frequency transients and most switching frequencies in order of a few kHz. This is because the frequency dependency will only become relevant at very high frequency over-voltages associated with lightning strikes or transients associated with gas insulated substations (GIS).

3.3 Wide-area modelling methodology

3.3.1 Network modelling

A North Queensland network model was used for this investigation. Two wide-area EMT models were provided to Aurecon thanks to AEMO under non-disclosure agreement. These include the wide-area system intact EMT model generally used for system strength studies and other operational and planning investigations by AEMO and NSPs. Another wide-area EMT model was also received, intended for black start studies conducted by AEMO. This model represents a smaller portion of the network, but each component is represented with a greater level of detail commensurate with the details required for black start studies. The latter model does not include any IBRs or dynamic reactive support plant, and smaller synchronous generators are typically neglected. Furthermore, this model does not represent all substations and transmission lines in the North Queensland power system, as it is recognised that not all these sections are involved in early phases of system restoration or even during the system build-up.

Lastly, for black start studies, the commonly used bus-branch representation of the substation should be replaced with the more detailed breaker-node modelling, to show which specific breakers are closed in a substation during the restoration process, and which substation they are connecting to at the other end of the line.

3.3.2 Synchronous generator modelling

Dynamic models of existing synchronous generators that are suitable for black start studies were sourced from AEMO. These models account for different (control) operating modes, such as droop and isochronous modes for the governor, and for large fans and pumps used in power station auxiliaries. Mode switchover during the restoration process represented for these generators where necessary, for example switching from the isochronous mode to droop mode when other generators are brought online, or by engaging the power system stabiliser (PSS) when generator loading increases above a certain level.

Models of synchronous generators that are non-critical from a system restoration perspective were treated with the same level of detail as those used for system intact studies.

3.3.3 IBR modelling

3.3.3.1 GFM inverter modelling

A known connection point in the Far North Queensland power system with a proposed large GFM BESS was considered as a prospective black starter. Models of GFM BESS provided under NDA with two OEMs were used for this purpose with identical settings used as those applied in stage 1. Note that these models do not necessarily reflect the same manufacturer, or settings applied for an actual GFM BESS connection in the same part of the network. This is because a key objective of this work was to assess the impact of different GFM manufacturers and parameters on system restoration, recognising that those parameters and operating modes could differ significantly from those applied during the system intact.

Table 3-1 summarises the base case settings of key parameters for the GFM BESS with further sensitivity studies conducted to assess the impact of each of these variables.

Note that the model provided is an average switch model, rather than a fully switched model which would include a detailed representation of pulse width modulation (PWM) switching of semiconducting switching devices. As such, caution should be exercised on the accuracy of results, greater accuracy could be obtained from harmonic studies.

Table 3-1: GFM internal default settings.

Variable	Value	Units
Plant base	349	MVA
Rated active power	300	MW
Damping constant	8	
Inertia constant	4	s
Maximum overload current	1	pu
Voltage droop	0.0	%
Voltage deadband on nominal voltage	0.0	%
Governor frequency droop	2.517	%
Governor frequency deadband on nominal frequency	0.03	%

3.3.3.2 GFL inverter modelling

A proposed GFL BESS in close proximity to the prospective GFM BESS was considered as the first GFL IBR to be picked up by the GFM black starter. Consistent with the approach adopted for the GFM BESS, the detailed EMT models sourced from OEMs for stage 1 were used. Minor changes were applied to the originally sourced model, in particular to its voltage and frequency droop settings, to avoid an excessive response when operating together with the GFM BESS. Table 3-2, summarises the base case settings of key parameters for the GFL BESS with further sensitivity studies conducted to assess the impact of each of these variables.

The same limitations mentioned for GFM models regarding their suitability for harmonic studies apply here, due to the use of average switched models as an industry standard for most IBR models.

Table 3-2: GFL internal default settings.

Variable	Value	Units
Plant base	163.8	MVA
Rated active power	100	MW
Voltage droop on active power base	4.0	%
Voltage droop dead band on nominal voltage	0.0	%
Frequency droop on active power base	2.4	%
Frequency deadband on nominal frequency	0.03	%

3.3.4 SynCon modelling

To ensure a like-for-like comparison between the performance of the GFM BESS and combined GFL BESS and SynCon, a SynCon was placed at the same location as the GFM BESS. SynCon parameters and settings are consistent with those used in stage 1. This means that the SynCon did not have a PSS function. The SynCon is equipped with an external start-up device, such as a diesel generator or a pony motor, to energise the SynCon and allow reaching the nominal speed. Consistent with industry standard system restoration studies, this phase of the restoration was not simulated and was assumed to be always successful. It was noted that the SynCon performance is highly dependent on its excitation system parameters. A more detailed investigation, and tuning using small-signal stability analysis tools, is one of the suggested focus areas for the 2023-24 research on topic 5.

3.4 Results

3.4.1 Study Summary

Table 3-3, provides a summary of each system restoration scenario studied, including the following key information:

- Study ID: a reference and link to the respective scenario described in Appendix A.
- Primary black start source: the generating unit or combination of devices used to initiate the restoration process and energise the network.
- Restarted elements: any key network elements such as large transformers, additional generating units or significant loads.
- Failure mechanism(s): Key mechanism where the attempted restart path was not viable with the particular black start source considered.
- Comments: additional noteworthy details on the energisation sequence performed or results observed

Studies with the same ID number but different ID letter correspond to variations of the same black start source and key restarted elements. Please refer to Appendix A for a detailed description of energisation steps and timing performed in each study.

Table 3-3: System restoration study summary

Study ID	Black start source	Restarted elements	Failure Mechanism(s)	Comments
A1a	GFM BESS	Coal generator 1	Over-voltage	Over-voltage occurred due to excessive line charging and insufficient reactive power capability of the GFM BESS.
A1b	GFM BESS	Coal generator 1	Over-voltage	The same as above
A1c	GFM BESS	Coal generator 1	Sustained low frequency oscillations Harmonic voltage distortion	GFM BESS exhibited a small (2-3 MW) magnitude of oscillations with a dominant frequency of approximately 0.3 Hz when Coal generator 1 auxiliaries were energised.
A1d	GFM BESS	Coal generator 1	Harmonic voltage distortion	The same as above also, Sustained low order (2nd to 10th) harmonic voltage distortion exceeded the permissible limits when Coal generator 1 auxiliaries were energised. The extent to which these harmonic orders are associated with network resonance frequencies or caused by the GFM control system was not investigated. However, as a rule of thumb harmonics above the 5th order are outside the bandwidth of the converter control system and cannot be caused by the GFM.
A1e	GFM BESS	Coal generator 1	Harmonic voltage distortion	Many low order harmonic voltages (2nd to 25th) exceeded the permissible limits when Coal generator 1 auxiliaries were energised.
A1f	GFM BESS	275/132 kV transformer, Hydro generator 1, Hydro generator 2, Coal generator 1	Over-voltage	Sustained over-voltage of 1.15 pu observed during energisation of transmission lines to connect Coal generator 1. GFM BESS lacked sufficient reactive power capability to suppress voltage. Additional synchronous generating units were too remote to provide sufficient support.

A1g	GFM BESS	275/132 kV transformer, Hydro generator 2, Coal generator 1	Harmonic voltage distortion	Transformer energisation resulted in over-voltage of approximately 1.2 pu for 10 s. Hydro generator 2 appeared to mis-operate and boost voltage until following a subsequent switching event it returned to normal operation. GFM BESS had insufficient reactive power capability to compensate for Hydro generator 2 response. Harmonic distortion spiked and exceeded limits following energisation of Coal generator 1.
A2a	GFM BESS	Coal generator 2	Over-voltage	Over-voltage occurred due to excessive line charging and insufficient reactive power capability of the GFM BESS. Over-voltage also coincided with a frequency drop due to the coupling between the voltage and frequency under very low system strength conditions pertaining to system restoration.
A2b	GFM BESS	Coal generator 2	Harmonic voltage distortion	Sustained low order (2nd to 10th) harmonic voltage distortion exceeded the permissible limits when Coal generator 1 auxiliaries were energised.
A3a	GFM BESS	Coal generator 3	Over-voltage	Over-voltage occurred due to excessive line charging and insufficient reactive power capability of the GFM BESS. Over-voltage also coincided with a frequency drop due to the coupling between the voltage and frequency under very low system strength conditions pertaining to system restoration.
A3b	GFM BESS	Coal generator 3		No concerning performance observed with studied system restart scenario.
A3c	GFM BESS	275/132 kV transformer, Hydro generator 1, Coal generator 3		Transformer energisation resulted in over-voltage of approximately 1.2 pu for 5 s and a coincident over-frequency condition. Harmonic distortion spiked on transformer energisation but settled to within acceptable limits. This means that harmonics generated by transformer energisation excited a network resonance frequency, hence creating an over-voltage as opposed to an under-voltage where the latter is more often experienced during transformer energisation. GFM BESS appeared to respond to over-frequency and step out of over-voltage condition. Plant response normal following this.
A3d	GFM BESS	275/132 kV transformer Hydro generator 2 Coal generator 3		Transformer energisation resulted in over-voltage of approximately 1.2 pu for 5 s. Hydro generator 2 appeared to mis-operate and boost voltage until following a subsequent switching event it returned to normal operation. GFM BESS had insufficient reactive power capability to compensate for Hydro generator 2 response. Harmonic distortion spiked on transformer energisation but settled to within acceptable limits.
A4a	GFM BESS	275/132 kV transformer, Hydro generator 2	Harmonic voltage distortion	Sustained low order (2nd to 6th) harmonic voltage distortion and total harmonic distortion exceeded the permissible limits following connection of Hydro generator 2.
A4b	GFM BESS	275/132 kV transformer, GFL BESS, Hydro generator 2	Harmonic voltage distortion	Total harmonic distortion observed above planning limits, but individual harmonics spiked and returned to within limits through the simulation. No other concerning response.
A5a	GFM BESS	275/132 kV transformer, Hydro generator 1	Harmonic voltage distortion	Total harmonic distortion and 2nd harmonic order voltage distortion exceeded the permissible limits. Harmonic distortion for all harmonic orders spiked following transformer energisation and was observed to recover at the end of the simulation. Further analysis through a longer run duration may have shown harmonics settling to within limits.

A6a	GFL BESS+ SynCon	Coal generator 1	Unit tripping	GFL BESS tripped on energisation due to over-voltage. Frequency dropped to below 47 Hz before GFL BESS was energised and SynCon would have tripped on protection prior to this (SynCon protection was not modelled).
A6b	GFL BESS+ SynCon	Coal generator 1	Sustained low-frequency oscillations Harmonic voltage distortion	GFL BESS peak instantaneous voltage protection increased to prevent trip on energisation. SynCon located at the same substation as the GFL BESS and able to successfully energise and support network restart. Low frequency active power oscillations in the order of 2-3MW and increasing in frequency from 0.1Hz to 0.3Hz as additional lines were energised. Total harmonic distortion and low order (2nd to 6th) harmonic order voltage distortion exceeded the permissible limits.
A6c	GFL BESS+ SynCon	Coal generator 1	Under-frequency Unit tripping (over-voltage)	GFL BESS tripped on energisation due to over-voltage. Frequency dropped to below 47 Hz before GFL BESS was energised and SynCon would have tripped on protection prior to this.
A6d	GFL BESS+ SynCon	Coal generator 1	Unit tripping (over-voltage)	GFL BESS tripped due to over-voltage when attempting to energise a transmission line. Active power response was unstable, moving from Pmin to Pmax with a step change type response and driving frequency up to 54 Hz prior to trip.
A6e	GFL BESS+ SynCon	Coal generator 1	Sustained low-frequency oscillations	GFL BESS frequency control had a step-wise response and active power swings in the order of 0.25 pu, interacting with SynCon. This behaviour stabilised when Coal generator 1 auxiliary loads were energised. Frequency prior to energisation of GFL BESS reached 47 Hz and SynCon protection may have tripped if modelled. (Note that compared to the two previous examples where the SynCon would have clearly tripped, a high-level assessment of the response of protection systems using primary measurements was not possible in this example).
A7a	Coal generator 3	GFL BESS	Sustained low-frequency oscillations Harmonic voltage distortion	Low frequency active power oscillations were observed on Coal generator 3 response in the order of 1-2 MW. The frequency oscillations changed from approximately 0.8 Hz to 0.1 Hz as additional network elements were energised but had a sustained magnitude. Total harmonic voltage distortion exceeded the permissible levels, but individual harmonics did not appear to have a sustained exceedance of limits. Note that some protection elements triggered on energisation of the Coal generator 3 and its auxiliaries. This was ignored as it is assumed this restart component is tested and proven on-site and what was observed is a modelling artifact.
A7b	Coal generator 3	GFL BESS	Sustained low-frequency oscillations Harmonic voltage distortion	Low frequency active power oscillations were observed on Coal generator 3 response in the order of 1-2 MW. The frequency of oscillations changed from approximately 0.8 Hz to 0.1 Hz as additional network elements were energised but had a sustained magnitude. A sustained high frequency oscillation was observed at GFL BESS and drove measured voltage harmonic distortion well above planning limits. It is noted that some protection elements triggered on energisation of the Coal generator 3 and it's auxiliary. This was ignored as it is assumed this restart component is tested and proven on-site and is a modelling artifact.

A7c	Coal generator 3	GFL BESS	Sustained low-frequency oscillations Harmonic voltage distortion	Low frequency active power oscillations were observed on Coal generator 3 response in the order of 1-2 MW but damped out upon energisation of GFL BESS. Total harmonic voltage distortion, and 4th harmonic significantly exceeded the permissible levels. It is noted that some protection elements triggered on energisation of the Coal generator 3 and it's auxiliary. This was ignored as it is assumed this restart component is tested and proven on-site and is a modelling artifact.

3.4.2 Typical failure mechanisms

The main failure mechanisms observed in this report are described below, categorised into critical failure mechanisms and ones which can potentially be managed with further analysis and minor changes to restart procedures including settings changes or minor re-sequencing. The latter are among the key proposed focus areas for 2023-24 research.

- Critical failure mechanisms:
  - **Unit tripping:** The most straightforward and critical mechanism for assessing the viability of a system restart scenario is whether or not the primary system restart source, or any other restored generating systems, would trip or behave unstably. Other scenarios resulting in a unit tripping are an expected or inadvertent operation of generator or transformer protection systems. In the simulation models used, the activation of a trip signal for the relays modelled will not result in the operation of relevant circuit breakers. As such the generator or transformer will remain connected in the dynamic simulation although in reality the plant would have tripped. All these cases are considered an unsuccessful restoration outcome. Most common failure mechanisms due to protection tripping were observed to be under- and over- frequency and voltage protection. It is noted that for some generating systems, a greater capability than that required by the Automatic Access Standard of the National Electricity Rules (NER) clause S5.2.5.3 and S5.2.5.4, can change the outcome. Relaxing voltage protection settings, especially instantaneous voltage protection by increasing tripping threshold of the magnitude of short-duration peak voltage, was observed to provide a more robust restoration process, and facilitated energisation of a GFL inverter in some cases where it would otherwise trip.

Figure 3-1: Example of unit tripping due to under-voltage

- **Frequency collapse:** Although usually detected through the above (under-voltage) failure mechanism, the frequency collapse was classified as a separate critical factor. This must be specifically considered in the interpretation of simulation scenarios where detailed generator protection models are not available. In these instances, an analysis of the rate of change of frequency (RoCoF) and frequency magnitude were performed instead to understand if a unit tripping could occur based on typically permitted ranges of these two quantities. A particular scenario where a frequency collapse was observed is when the combination of a SynCon and GFL BESS are used as the black starter. In this scenario if the BESS is not yet restarted, is disconnected, or does not have enough active power margin to respond to a frequency event, a frequency collapse would occur as the SynCon does not have any mechanisms (beyond inertia) to control the frequency. One of the key considerations when using this combination as a black starter is to ensure that either the SynCon and GFL BESS are co-located or otherwise that the GFL BESS is not subject to any higher likelihood of disconnection due to contingencies compared to the SynCon.

Figure 3-2: Example of frequency collapse

- Areas of potential concern:
  - **Harmonic voltage distortion:** although it is acceptable for network harmonic voltage distortion to momentarily exceed the permissible limits, i.e., the computability levels set out in AS 61000-3-6 (for instance, when a network step change occurs due to a generating unit or transmission line being energised), sustained harmonic voltage distortions are an area of concern.

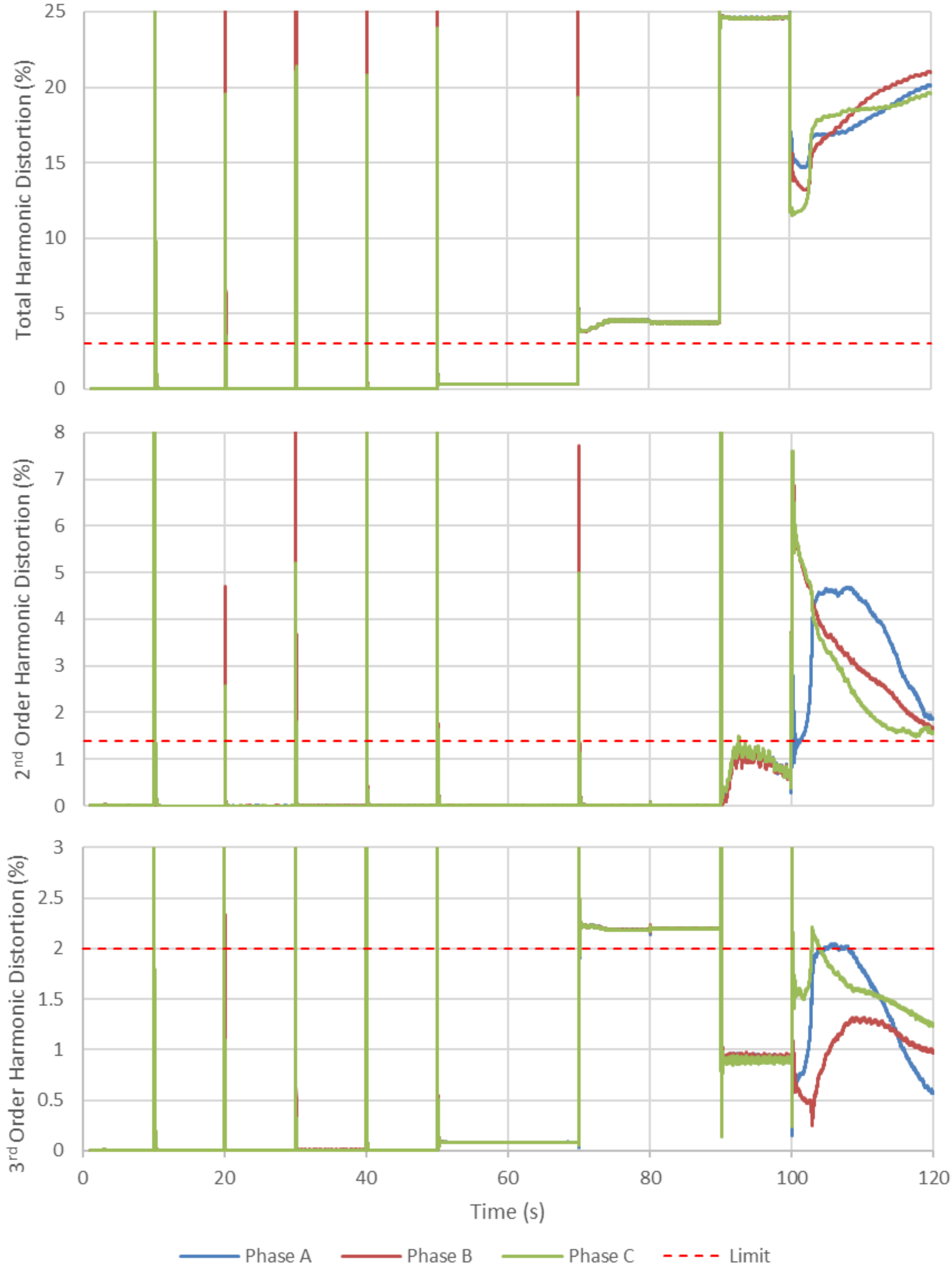

Figure 3-3: Example of harmonic voltage distortion (particularly THD) exceeding limits

- **Sustained low-frequency oscillations:** Sustained oscillations in either voltage or frequency, and indirectly active and reactive power, were observed for several scenarios studied. Note that unlike the harmonic voltage distortion, these oscillations are generally sub-synchronous, i.e., below the network fundamental frequency. While none resulted in any plant tripping, such oscillations were considered unacceptable due to exceeding flicker compatibility requirements set out in the NER and the potential adverse impact on loads reconnected. The following are also noted in relation to these low-frequency oscillations.
  - Sustained oscillations may be damped to below the acceptable levels by energising an additional network element or generating system. It is therefore advisable to continue with at least one extra energisation before considering a case unsuccessful. In particular, it is noted that energising network elements with resistive behaviour such as non-inverter-based loads could provide the necessary damping.
  - These sustained oscillations are sometimes associated with the sensitivities of inverter control system, in particular under very low system strength conditions pertaining to system restoration and might therefore be addressed by judicious control system tuning. This is one of the proposed focus areas for 2023-24 research, however, it is contingent on better access to control system parameters such that their impact can be investigated.

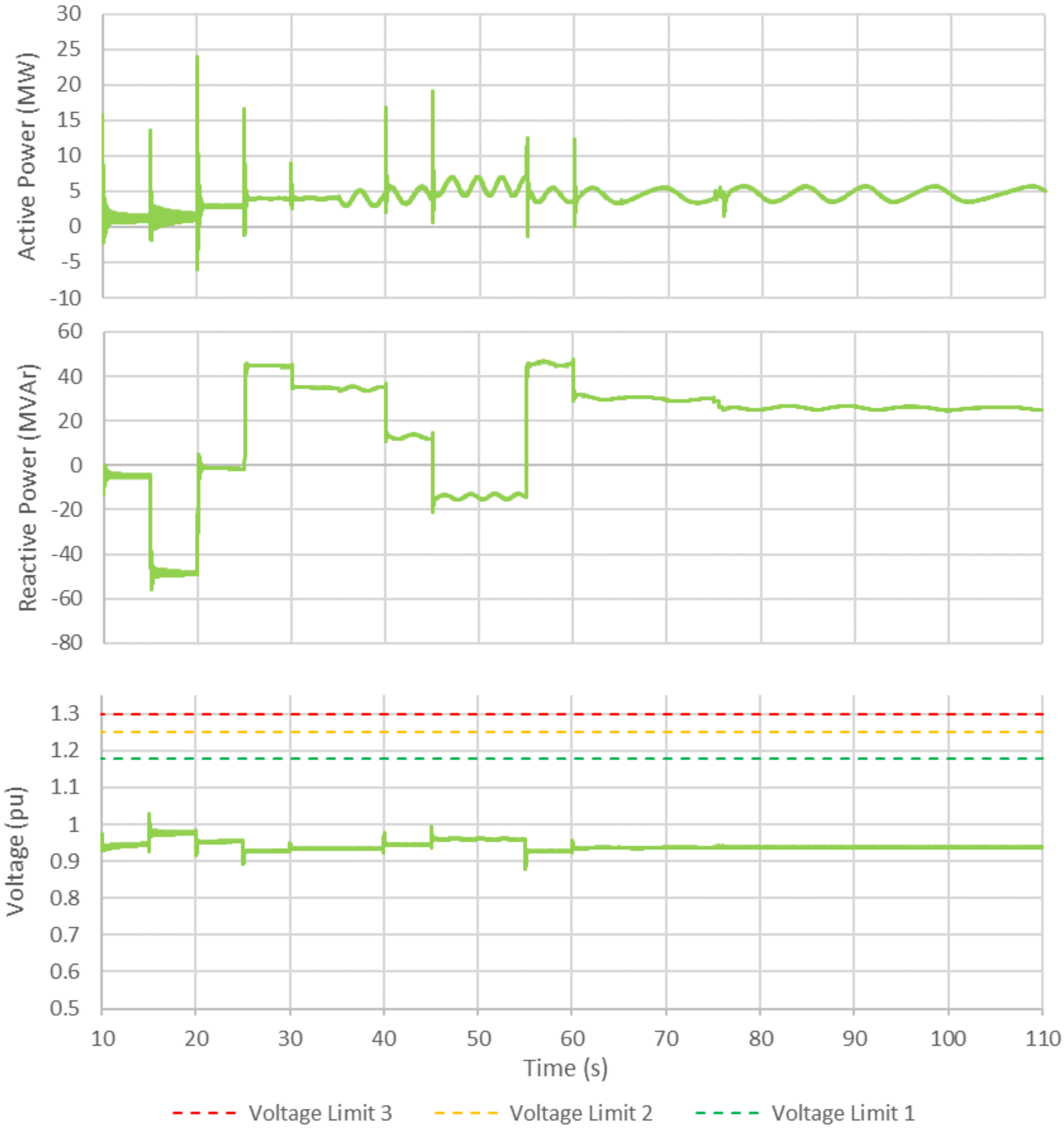

Figure 3-4: Example of sustained low frequency oscillations

3.4.3 Observations for each black start source considered

3.4.3.1 GFM BESS

The use of a grid-forming inverter located within a REZ to energise elements of a REZ and to energise network outside a REZ was studied. The GFM BESS response was typically very fast and stable. Energisation of transmission level transformers, generating auxiliary loads, and generating units, introduced transients that were settled by the GFM BESS within 5 s. Reactive power capability limitations were the key driver of unsuccessful system restart scenarios, with over-voltage observed when GFM BESS exceeded -0.5 pu reactive power generation. The reactive power capability was the limiting factor for how far (geographically) from the GFM BESS network elements could be energised.

3.4.3.2 Sensitivity on GFM MVA to restart capability

A sensitivity was performed to understand the comparative GFM (primary/source) sizing required to support energisation and operation of a GFL (target) generating system. The target GFL BESS sizing was kept constant, while the primary/source GFM BESS size was reduced to determine at what point stability issues or other failure criteria were observed. Scenario 2 (study A4b) was used as the base scenario for the sensitivity, with the following GFM:GFL inverter sizing investigated. Inverter sizing was based on inverter MVA rating, as opposed to active or reactive power rating.

- 2.13 (GFM) : 1 (GFL)
- 1.07 (GFM) :1 (GFL)
- 0.70 (GFM) :1 (GFL)
- 0.53 (GFM) : 1 (GFL)

It was observed that although a smaller GFM:GFL ratio did not cause the target GFL to trip or fail to energise, a lack of reactive power capability prevented the source GFM from maintaining network voltage in all/most of these sensitivity cases. Over-voltage caused HVRT mode to activate on the target GFL BESS which would act with constant current output, and hence no longer respond to control voltage or frequency. In all other cases apart from the default 2.13:1 ratio, the GFM BESS was observed to intermittently inject active power during the over-voltage condition. An example of this behaviour is provided in Figure 3-5 from 90s onwards.

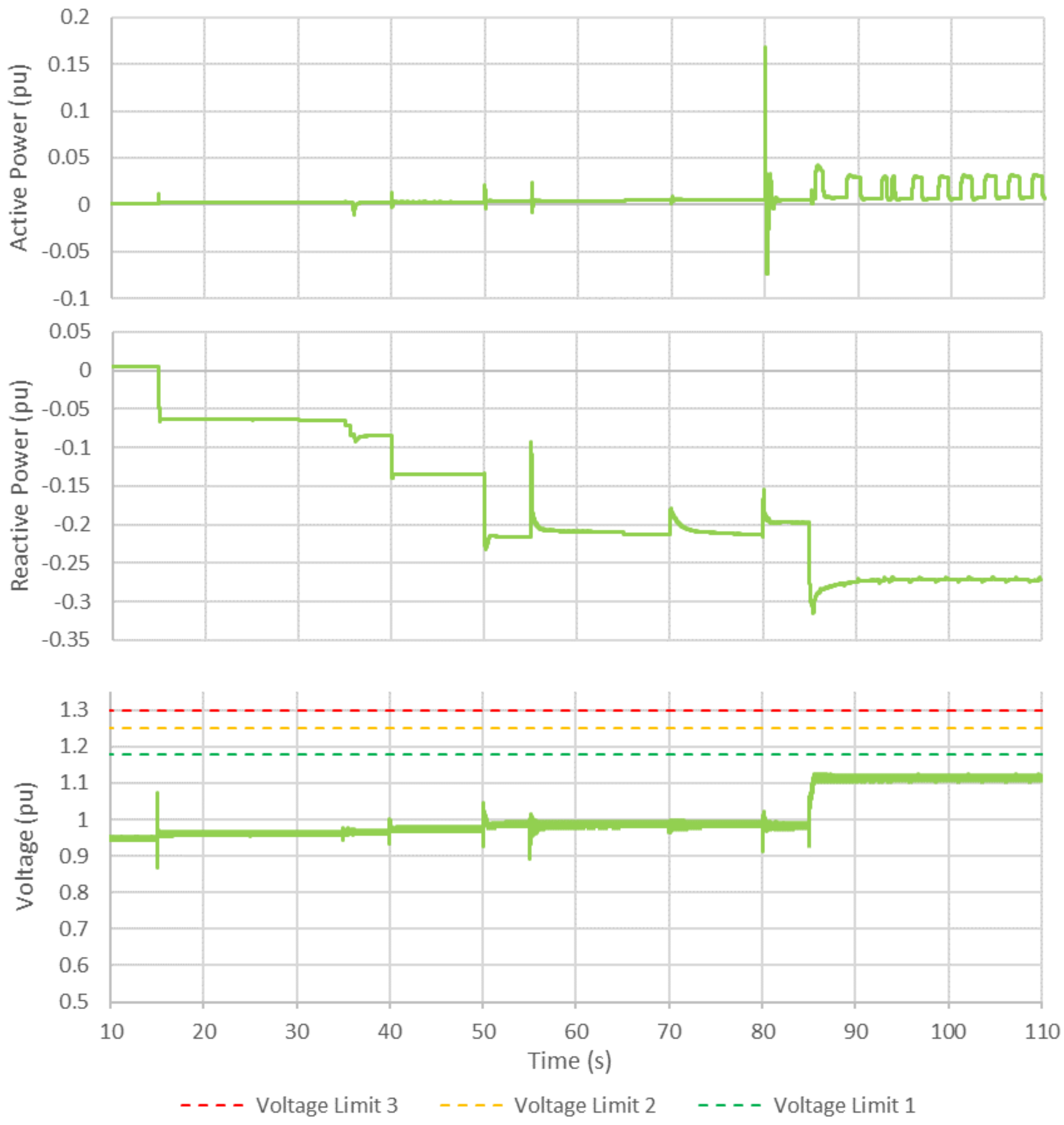

Figure 3-5: Example of active power steps during over-voltage

3.4.3.3 Synchronous generator

The use of existing synchronous generators to externally energise a REZ was investigated, and it was observed that initial phase system restoration could be performed successfully. The Coal generator 3 as the primary black start device was able to energise, depending on the station and line reactors utilised, up to at least 5 substations from its connection point and facilitate start-up of a GFL BESS. Across all scenarios considered, sustained low frequency oscillations in active power were observed following the energisation of at least one transmission line. In scenario A7c the oscillations were damped once the GFL BESS was energised and operational. The damping of these oscillations potentially indicated they were driven by operating conditions including the low loading level of the Coal generator 3, prompting further sensitivity studies investigating different loading levels and outlined in the following section.

3.4.3.4 Loading level sensitivity

To understand whether increased loading levels on a (black start source) synchronous generator would improve its operational stability, a sensitivity investigating different active power dispatches for the (target) GFL BESS was investigated. The base scenario utilised was Scenario 1 (study A7a), with the following dispatch conditions.

- GFL BESS target dispatched to 0 pu active power output
- GFL BESS target dispatched to -0.2 pu active power output
- GFL BESS target dispatched to -0.5 pu active power output

Figure 3-6, Figure 3-7 and Figure 3-8 present the synchronous generator performance under each of the three GFL BESS dispatch conditions listed above, with the GFL BESS being energised at 75 s. The ratio between GFL BESS MVA and synchronous generator MVA was 1:2.625, with the following figures being presented in per-unit on the synchronous generator MVA base.

Note that the models provided did not offer the soft-energisation capability. As such all cases were required to be initialised at the desired steady-state voltage.

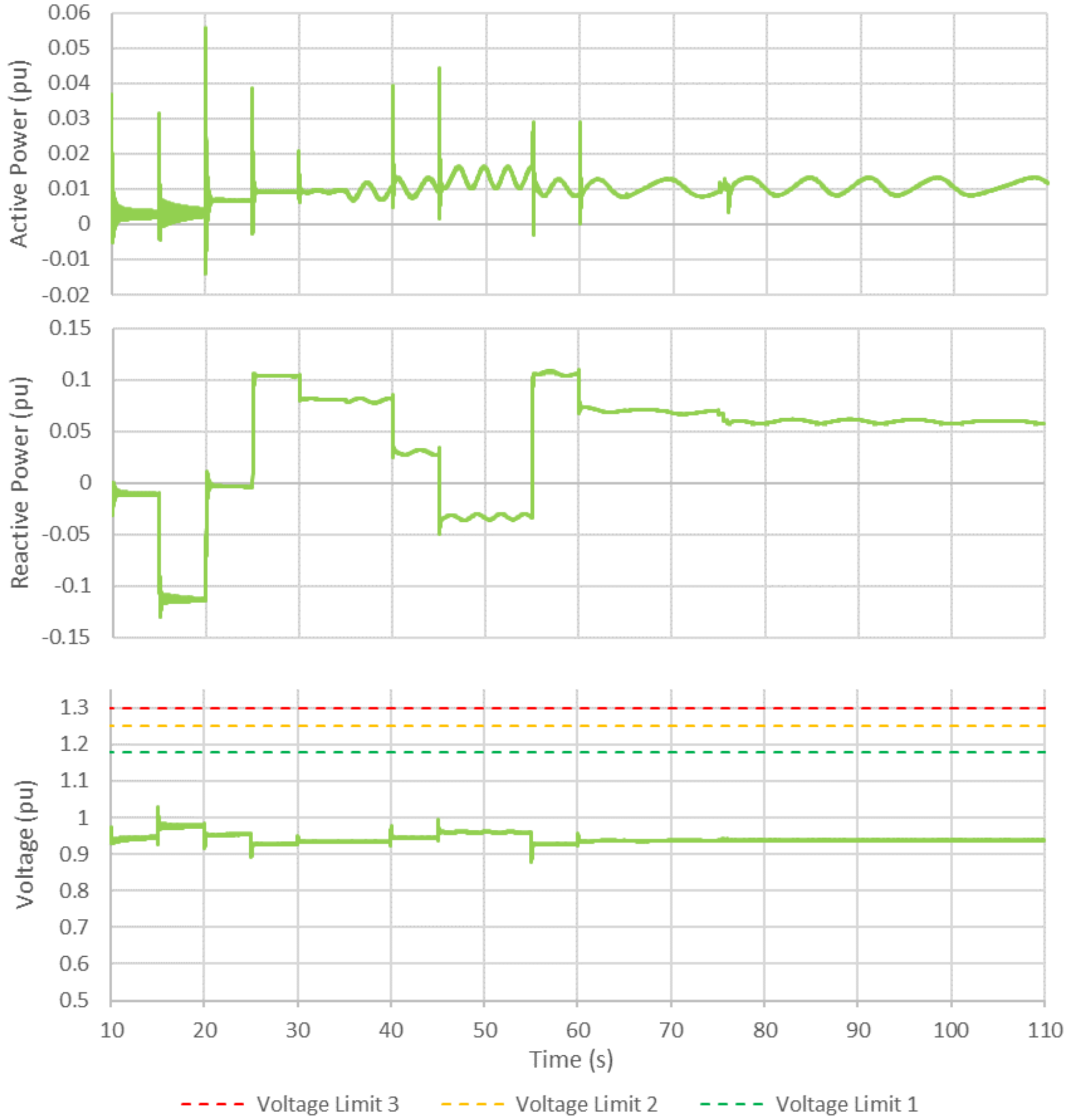

Figure 3-6: Synchronous generator response – GFL BESS at 0 pu output

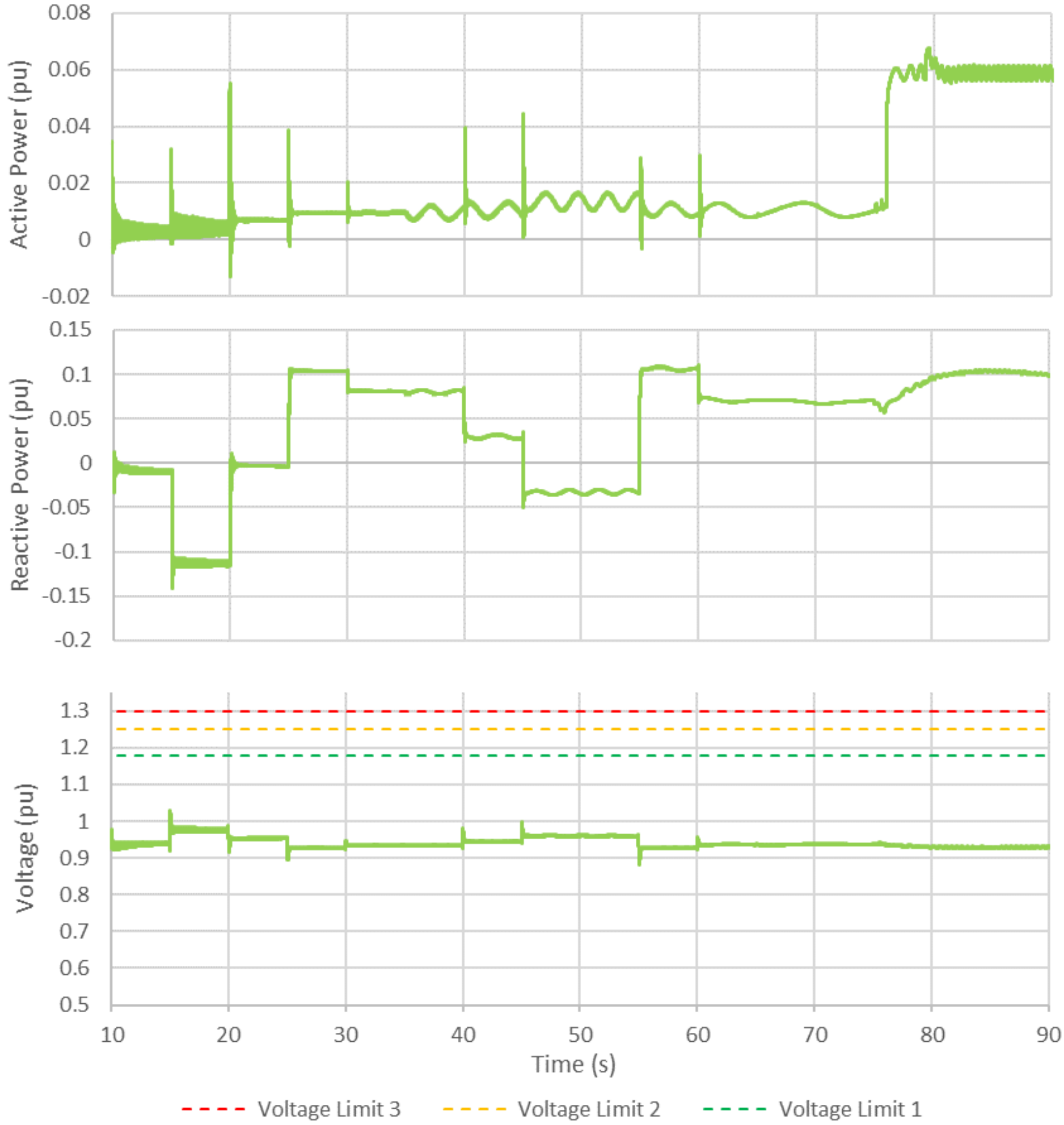

Figure 3-7: Synchronous generator response – GFL BESS at -0.2 pu output

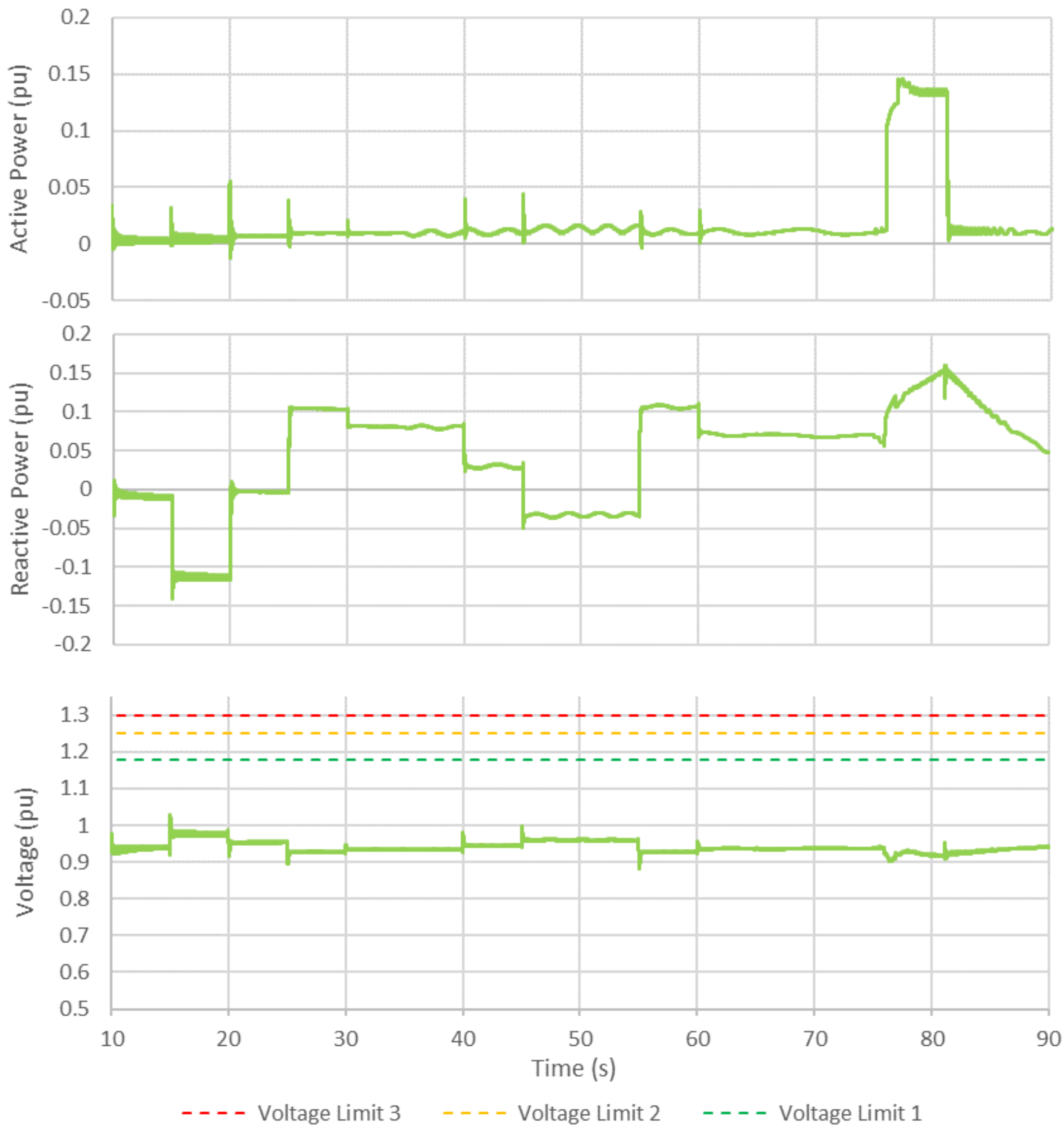

Figure 3-8: Synchronous generator response – GFL BESS at -0.5 pu output

Under large charging (load) conditions (-0.5 pu), the GFL BESS is observed to draw the network voltage down sufficiently low to result in under-voltage tripping occurring on the GFL BESS. The under-voltage tripping could potentially be mitigated by managing the network capacitors and inductors switched in during restart. At moderate charging levels (-0.2 pu) on the GFL BESS, low frequency oscillations on the Coal generator 3 were observed to be removed, but were instead replaced by a higher frequency, approximately 1.3 Hz) oscillation in active power. The results of this sensitivity analysis indicate that higher levels of charging can negatively impact voltages in the network. However, it is also recognised that for some synchronous generators operation at higher loading levels sufficiently above their minimum stabilising load requirements would be desirable to ensure internal stability from a thermodynamical perspective.

3.4.3.5 SynCon and GFL BESS

The combined use of a SynCon and a GFL BESS as a potential black starter was then investigated. The results of this investigation show that a successful system restart scenario could be achieved with the use of a co-located SynCon and GFL BESS, and furthermore that control system tuning could potentially lead to viable scenarios also with a remotely located SynCon. From the studies conducted the following key learnings are noted:

- The SynCon inertia must be sufficiently large to prevent a frequency collapse until the GFL BESS (co-source) can be energised. This will most likely require the use of SynCon with flywheels. The required inertia is dependent on the electrical distance from the SynCon to the GFL BESS and time required to energise the GFL BESS.
- The GFL BESS should be operated at fixed reactive power control mode with a setpoint of 0 Mvar. This disables any voltage control capability of the GFL BESS and allows the SynCon to take full control of the voltage, thereby ensuring (reactive power) control system interactions do not occur. Alternatively, appropriate tuning of both the SynCon AVR and GFL BESS control system would also likely mitigate this issue, as proposed in our 2023-24 research plan.
- The GFL BESS frequency droop settings should be set to the least aggressive permissible system normal settings, in order to prevent overshoots, thereby minimising the risk of sustained frequency and active power oscillations. The (other) frequency control settings of the GFL BESS should also be coordinated with the SynCon dynamical characteristics to prevent sustained oscillations, which were observed in all scenarios studied.
- The electrical distance between the SynCon and GFL BESS plays a part in the success or otherwise of this black start combination. To investigate this further, the distance between the two components was artificially reduced in simulation. It was observed that a sufficient reduction in the distance between the two primary devices will stabilise the outcome of several otherwise unstable scenarios.
- The process whereby the SynCon is restarted with the aim of energising the GFL BESS, and the associated switching actions, should be expedited as quickly as possible. This is because until both components are restarted and synchronised, neither is in a fully stable operating condition so that there is a risk of tripping due to sustained under-frequency operation. This suggests that the lower the number of switching actions required, the higher is the likelihood of success for this black start option.

3.4.4 Fault ride through sensitivity

Sensitivity tests were performed with regard to the fault ride through capability of the GFM BESS and the black start synchronous generator. The specific scenarios used for the sensitivity analysis were:

- Scenario A1.2: GFM BESS energising to Coal generator 1
- Scenario 1 (study A7a): Coal generator 3 energising to GFL BESS

Deep three-phase and two-phase-to-ground faults with zero residual voltage were applied for a range of fault durations. The ride through capability of the black start source was then analysed. Note that conformance with technical performance standards of the active and reactive power injections were not studied (either during the fault or after fault clearance) as the objective was to determine the success or otherwise of the re-energisation. The full list of sensitivity studies performed is summarised in Table 3-4.

Table 3-4: Fault ride through sensitivity summary

Black Start Device	Fault Type	Residual Voltage at Black Start Device POC [%]	Fault Duration [ms]	Performance
GFM BESS	3PhG[5]	30	100	No tripping or instabilities observed
GFM BESS	3PhG	30	200	No tripping or instabilities observed
GFM BESS	3PhG	30	300	No tripping or instabilities observed
GFM BESS	3PhG	30	400	No tripping or instabilities observed
GFM BESS	3PhG	30	500	No tripping or instabilities observed
GFM BESS	2PhG[6]	60	500	No tripping or instabilities observed
Coal generator 3	2PhG	50	300	No protection activated during fault
Coal generator 3	2PhG	50	400	No protection activated during fault
Coal generator 3	2PhG	50	430	Negative sequence and V/Hz protection activated
Coal generator 3	3PhG	30	300	No protection activated during fault
Coal generator 3	3PhG	30	400	Simulation crashed on fault clearance, typically indicating a model trip or crash occurred.

An example of the two-phase to ground 430ms fault Coal generator 3 response is presented in Figure 3-9.

[5] Three phase to ground
[6] Two phase to ground

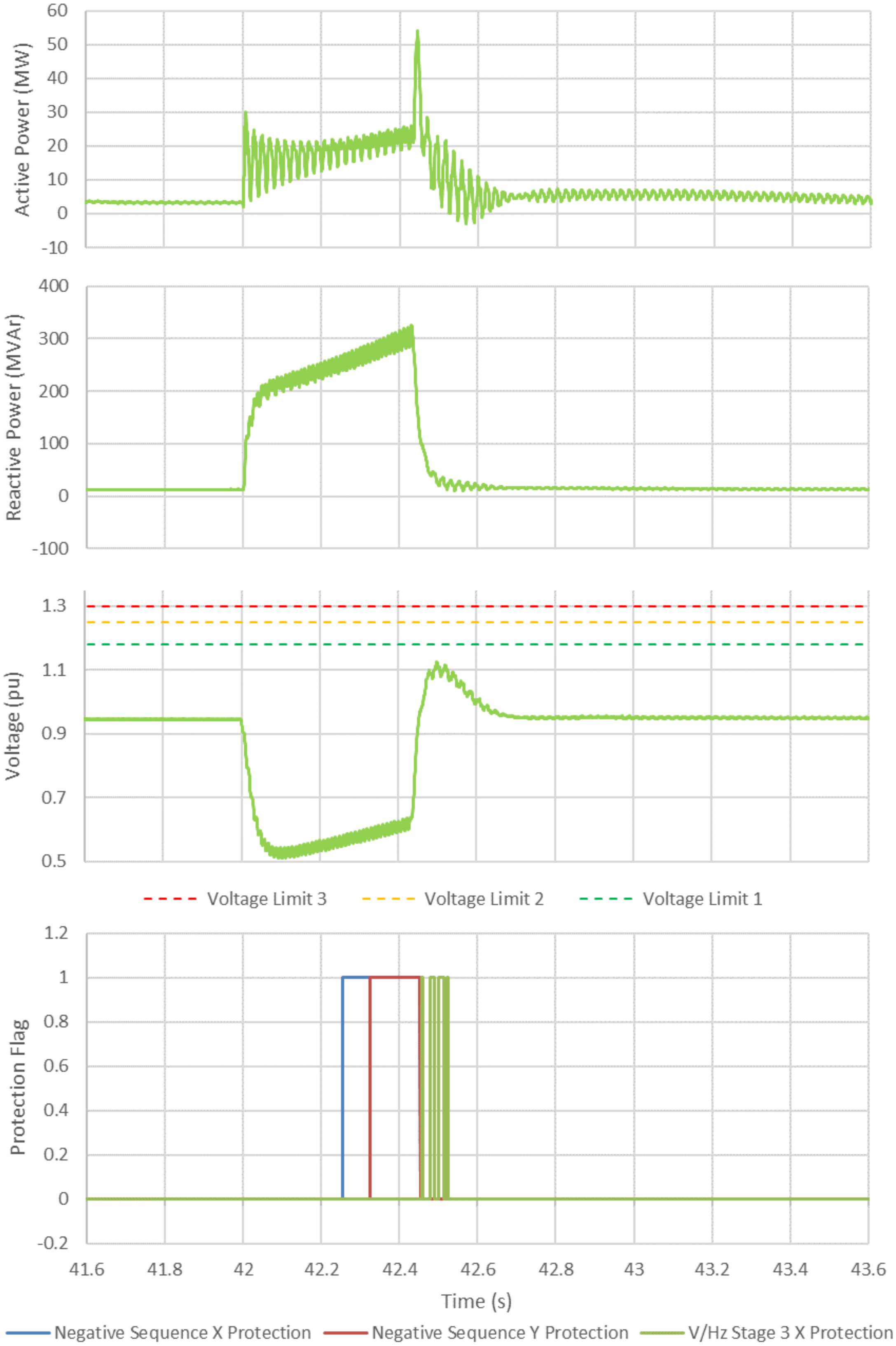

Figure 3-9: 2PHG 430 ms Coal generator 3 fault response

As presented in Table 3-4, the GFM BESS was able to ride through slightly longer duration faults, up to 500 ms, of comparable severity than a synchronous generator without disconnecting or exhibiting unstable operation on fault clearance. Greater fault ride through resilience provides more confidence in the reliability of a system restart path and can prevent the risk of further faults during the restart process causing a recurrence of a black system. Note that 3PhG faults are generally the most onerous type of faults for synchronous machines. The same is not necessarily true for IBRs as the level of negative-sequence voltage and current due to an unbalanced fault could impact the response sometimes more importantly than the size of the voltage dip.

3.5 Further learnings and recommendations

This section provides a summary of discussions with AEMO and CSIRO during the progress meetings held focusing on aspects other than those directly concluded from the simulation studies conducted.

- The use of SVCs during the restart process
  - The use of the existing SVCs in North and Far North Queensland power system would provide additional reactive power capability for the black start source. This could potentially address some of the unsuccessful scenarios discussed in this report due to the limited reactive power range, e.g., A1a. As noted previously models of SVCs were not used and, as such, this could not be confirmed with certainty. The same applies on whether the GFM BESS can provide sufficient fault level for stable operation of the SVCs. An additional consideration with SVCs is that, as an inverter-based reactive power support plant, they have similar susceptibility mechanisms to those of the GFL plant discussed in this report, for various system restoration scenarios studied. Sometimes SVCs are equipped with an automatic, or operator enabled, gain reduction which reduces the SVC responsiveness when a significant drop in the network fault level is measured. This will reduce SVC's susceptibility under these low system strength conditions. However, it is not clear whether all associated models have this function enabled and verified. Excluding SVC components allowed opportunities to stress test the black start options considered, in turn providing alternative insights into the failure mechanisms.
- Application of grid formation in Flexible AC Transmission (FACTS) controllers to support restoration
  - The work documented in this report focuses on grid-forming capability provided only by a BESS black start source. It is understood that commercial GFM products based on some of the FACTS devices, and in particular grid-forming STATCOMs, have recently become available in the market. Various designs can be found including those with and without storage. Whilst such a device cannot be used as an independent black start source, it can be considered as an enhanced SVC, without those low system strength susceptibilities, under system restoration conditions.
- The amount of balancing load that needs to be picked up by a GFM BESS
  - The work discussed in this report demonstrates excellent dynamic performance of the GFM BESS where ample energy can be provided within millisecond and second timeframes. A key limitation of the GFM BESS, and BESS in general, is their limited long-duration storage capability. Currently most BESS installed or being considered in the NEM come with two hours storage capability (MWh) relative to the MW rating. This means that operation at full or high discharge levels cannot be sustained for more than a few minutes. BESS with four hours storage capability are being deployed recently. This will reduce but will not fully address the extent of this limitation. To put it into perspective a traditional black start source is generally capable of maintaining its full power for at least 30 minutes. To overcome this limitation, it is recommended to use the GFM BESS to supply other power stations including wind/solar farms first (if the plant can be energised and sufficient resource, e.g., wind, is available). This will allow those power stations to service sizeable loads rather than using the GFM BESS directly to service the load. This means that a good level of storage will be maintained in the BESS for the conditions where the provision of this energy may be critical, e.g., providing frequency response or virtual inertia during a disturbance.
- Instability of GFM when heavily loaded
  - A further concern with operating GFM BESS during system restoration, at high MW, under very low system strength conditions, and if the GFM closely emulates the rotor angle response of a synchronous generator, is the potential for angular instability. This recognises that, for a synchronous generator, the the steady-state rotor angle increases with output, hence high output generation increases the likelihood of an instability following a fault. Furthermore, the coupling between voltage and frequency under these conditions could lead to a frequency response causing an undesirable voltage disturbance. Further investigation is required to determine if this could be mitigated by control system retuning of the GFM BESS. However, note that the black-box nature of the models available will restrict a comprehensive investigation.
- Benefit and opportunity of placing synchronous condensers in the location of currently existing (but to be retired) synchronous generators

  - Subject to the SynCon being in close proximity to (or ideally co-located with) a GFM or GFL BESS, this will provide improved reactive power capability, hence increasing the energisation reach of the black start source by supplying reactive power to a larger number of unloaded or lightly loaded transmission lines and network transformers. The possible contribution is similar to that discussed for the GFM STATCOM, as neither device has known susceptibilities under low system strength conditions and differentiates them from the SVC with known susceptibilities. However, it should be noted that almost 80-90% of the inertia provided by a thermal synchronous generator resides in its turbine. As such converting a retiring synchronous generator to a SynCon would result in a very low inertia. As observed in both the stage 1 and stage 2, a low inertia SynCon was prone to instabilities with a recommendation made to equip the SynCon with flywheels. Overall, this option might be valuable from the standpoint of steady-state reactive power capability, but its dynamic performance will be inferior compared to other options unless sufficient inertia can be retained.

- Improvement of restart capabilities through redevelopment of the current restart paths
  - Network parts studied in this work are primarily remote and distant both from load centres and from areas of concentration of synchronous generators. As such currently no known black start source exists in those parts of the network. However, the studies conducted here demonstrate that, with judicious combination of the black start source and other devices providing system restoration support, it is possible to energise large thermal power stations in Central Queensland. It was noted that not all restoration paths investigated here are viable, and re-sequencing or the use of alternate transmission lines would sometimes be necessary to avoid various failure mechanisms discussed in this report.

Appendix A
Step by step description of cranking paths studied

4.1 Energising Coal generator 1 via GFM BESS

A1a Scenario 1

1) Black start GFM BESS and energise connected substation
2) Energise 275 kV transmission network from GFM BESS to Coal generator 1
3) Energise Coal generator 1 main grid transformer
4) Energise Coal generator 1 generator auxiliary load

A1b Scenario 2

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 1
   a) 1 x 84 Mvar substation inductor utilised
3) Energise Coal generator 1 main grid transformer
4) Energise Coal generator 1 generator auxiliary load

A1c Scenario 3

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 1
   a) 2 x 84 Mvar substation inductors utilised
3) Energise Coal generator 1 main grid transformer
4) Energise Coal generator 1 generator auxiliary load

A1d Scenario 4

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 1
   a) 2 x substation 84 Mvar inductors utilised
   b) 1 x 29 Mvar line inductor utilised
3) Energise Coal generator 1 main grid transformer
4) Energise Coal generator 1 generator auxiliary load

A1e Scenario 5

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to GFL BESS
3) Energise and dispatch GFL BESS to 0 MW output
4) Energise transmission network from GFM BESS to Coal generator 1

a) 2 x 84 Mvar substation inductors utilised
b) 1 x 29 Mvar line inductor utilised
5) Energise Coal generator 1 main grid transformer
6) Energise Coal generator 1 generator auxiliary load

A1f Scenario 6

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
3) Energise network to and start-up Hydro generator 1
4) Perform step change on active power output of Hydro generator 1
5) Energise another transmission level 275/132 kV transformer
6) Energise network to and start-up Hydro generator 2
7) Perform step change on active power output of Hydro generator 2
8) Energise transmission network from GFM BESS to Coal generator 1
   a) 1 x 84 Mvar substation inductor utilised
   b) 1 x 29 Mvar line inductor utilised
9) Energise Coal generator 1 main grid transformer
10) Energise Coal generator 1 generator auxiliary load

A1g Scenario 7

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
3) Energise transmission network to another transformer
4) Energise a second transmission level 275/132 kV transformer
5) Energise network to and start-up Hydro generator 2
6) Perform step change on active power output of Hydro generator 2
7) Energise transmission network from GFM BESS to Coal generator 1
   a) 1 x substation 84 Mvar inductor utilised
   b) 1 x 29 Mvar line inductor utilised
8) Energise Coal generator 1 main grid transformer
9) Energise Coal generator 1 generator auxiliary load

4.2 Energising Coal generator 2 via GFM BESS

A2a Scenario 1

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 2
   a) Energise a transmission level 275/132 kV transformer along the restart pathway
3) Energise Coal generator 2 main grid transformer
4) Energise Coal generator 2 generator auxiliary load

A2b Scenario 2

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 2
   a) Energise a transmission level 275/132 kV transformer along the restart pathway
   b) 2 x 84 Mvar substation inductors utilised
   c) 1 x 29 Mvar line inductor utilised
3) Energise Coal generator 2 main grid transformer
4) Energise Coal generator 2 generator auxiliary load

4.3 Energising Coal generator 3 via GFM BESS

A3a Scenario 1

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 3
3) Energise Coal generator 3 main grid transformer
4) Energise Coal generator 3 auxiliary load

A3b Scenario 2

1) Black start GFM BESS and energise connected substation
2) Energise transmission network from GFM BESS to Coal generator 3
   a) 2 x 84 Mvar substation inductors utilised
   b) 1 x 29 Mvar line inductor utilised
3) Energise Coal generator 3 main grid transformer
4) Energise Coal generator 3 auxiliary load

A3c Scenario 3

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
3) Energise transmission network to another transformer
4) Energise a second transmission level 275/132 kV transformer
5) Energise network to and start-up Hydro generator 1
6) Perform step change on active power output of Hydro generator 1
7) Energise transmission network from GFM BESS to Coal generator 3
   a) 1 x 84 Mvar substation inductors utilised
   b) 1 x 29 Mvar line inductor utilised
8) Energise Coal generator 3 main grid transformer
9) Energise Coal generator 3 auxiliary load

A3d Scenario 4

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
3) Energise transmission network to another transformer
4) Energise a second transmission level 275/132 kV transformer
5) Energise network to and start-up Hydro generator 2
6) Perform step change on active power output of Hydro generator 2
7) Energise transmission network from GFM BESS to Coal generator 3
   a) 1 x 84 Mvar substation inductors utilised
   b) 1 x 29 Mvar line inductor utilised

8) Energise Coal generator 3 main grid transformer

9) Energise Coal generator 3 auxiliary load

4.4 Energising Hydro generator 2 via GFM BESS

A4a Scenario 1

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
3) Energise transmission network to another transformer
4) Energise a second transmission level 275/132 kV transformer
5) Energise network to and start-up Hydro generator 2
6) Perform step change on active power output of Hydro generator 2

A4b Scenario 2

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
    a) 1 x 88 Mvar line reactor utilised
3) Energise GFL BESS main grid transformer
4) Energise GFL BESS reticulation network
5) Energise GFL BESS inverters and activate GFL BESS PPC
6) Energise transmission network to another transformer
7) Energise a second transmission level 275/132 kV transformer
8) Energise network to and start-up Hydro generator 2

4.5 Energising Hydro generator 1 via GFM BESS

A5a Scenario 1

1) Black start GFM BESS and energise connected substation
2) Energise a transmission level 275/132 kV transformer
3) Energise transmission network to another transformer
4) Energise a second transmission level 275/132 kV transformer
5) Energise network to and start-up Hydro generator 1
6) Perform step change on active power output of Hydro generator 1

4.6 Energising Coal generator 1 via SynCon and GFL BESS

Note: By default, the SynCon is located remotely to the GFL BESS at the same location at the GFM BESS for a like-for-like comparison of performance.

A6a Scenario 1

1) Black start SynCon and energise connected substation
    a) No external power source, beyond auxiliaries, provided to SynCon at this stage and only inertial response relied upon
2) Energise transmission network from SynCon to GFL BESS
3) Energise and start-up GFL BESS
4) Energise transmission network from SynCon to Coal generator 1
    a) 1 x 84 Mvar substation inductor utilised
    b) 1 x 29 Mvar line inductor utilised
5) Energise Coal generator 1 main grid transformer
6) Energise Coal generator 1 generator auxiliary load

A6b Scenario 2

Note: The SynCon is located adjacent to the GFL BESS, connected to the same substation as the GFL BESS.

1) Black start SynCon and energise connected substation
    a) No external power source, beyond auxiliaries, provided to SynCon at this stage and only inertial response relied upon
2) Energise and start-up GFL BESS
3) Energise transmission network from SynCon and GFL BESS to Coal generator 1
    a) 2 x 84 Mvar substation inductor utilised
    b) 1 x 29 Mvar substation inductor utilised
    c) 1 x 29 Mvar line inductor utilised
4) Energise Coal generator 1 main grid transformer
5) Energise Coal generator 1 generator auxiliary load

A6c Scenario 3

1) Black start SynCon and energise connected substation
    a) No external power source, beyond auxiliaries, provided to SynCon at this stage and only inertial response relied upon
2) Energise transmission network from SynCon to GFL BESS
3) Energise and start-up GFL BESS
4) Energise a transmission level 275/132 kV transformer
    a) 1 x 20 Mvar line inductor utilised during energisation to the transformer
5) Energise network to and start-up Hydro generator 2
6) Energise transmission network from SynCon to Coal generator 1
    a) 1 x 84 Mvar substation inductor utilised

    b) 1 x 29 Mvar line inductor utilised

7) Energise Coal generator 1 main grid transformer

8) Energise Coal generator 1 generator auxiliary load

A6d Scenario 4

Note: Breaker operations were applied 5s apart as opposed to the default 10s to facilitate GFL BESS energisation before frequency collapsed.

1) Black start SynCon and energise connected substation
    a) No external power source, beyond auxiliaries, provided to SynCon at this stage and only inertial response relied upon
2) Energise transmission network from SynCon to GFL BESS
    a) 1 x 29 Mvar line inductor utilised
3) Energise and start-up GFL BESS
4) Energise transmission network from SynCon to Coal generator 1
    a) 1 x 84 Mvar substation inductor utilised
    b) 1 x 29 Mvar line inductor utilised
5) Energise Coal generator 1 main grid transformer
6) Energise Coal generator 1 generator auxiliary load

A6e Scenario 5

Note: GFL BESS frequency droop settings were increased from the default setting of 0.17% to 0.5% provided a less aggressive active power response in this Scenario, but otherwise the applied restart pathway is identical to Scenario 1. Breaker operations were applied 5s apart as opposed to the default 10s to facilitate GFL BESS energisation before frequency collapsed.

1) Black start SynCon and energise connected substation
    a) No external power source, beyond auxiliaries, provided to SynCon at this stage and only inertial response relied upon
2) Energise transmission network from SynCon to GFL BESS
3) Energise and start-up GFL BESS
4) Energise transmission network from SynCon to Coal generator 1
    a) 1 x 84 Mvar substation inductor utilised
    b) 1 x 29 Mvar line inductor utilised
5) Energise Coal generator 1 main grid transformer
6) Energise Coal generator 1 generator auxiliary load

4.7 Energising GFL BESS via Coal generator 3

A7a Scenario 1

1) Black start Coal generator 3 and energise auxiliary load and connected substation
2) Energise transmission network to GFL BESS
    a) 3 x 84 Mvar substation inductor utilised
    b) 1 x 88 Mvar line inductor utilised
3) Energise GFL BESS main grid transformer
4) Energise GFL BESS reticulation network
5) Energise GFL BESS inverters and activate GFL BESS PPC

A7b Scenario 2

1) Black start Coal generator 3 and energise auxiliary load and connected substation
2) Energise transmission network to GFL BESS
    a) 2 x 84 Mvar substation inductor utilised
    b) 1 x 88 Mvar substation inductor utilised
3) Energise GFL BESS main grid transformer
4) Energise GFL BESS reticulation network
5) Energise GFL BESS inverters and activate GFL BESS PPC

A7c Scenario 3

1) Black start Coal generator 3 and energise auxiliary load and connected substation
2) Energise transmission network to GFL BESS
    a) 1 x 84 Mvar substation inductor utilised
    b) 1 x 88 Mvar substation inductor utilised
3) Energise GFL BESS main grid transformer
4) Energise GFL BESS reticulation network
5) Energise GFL BESS inverters and activate GFL BESS PPC

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