PSCAD assessment of the effectiveness of grid forming batteries

April 2021

Acknowledgement

This project received funding from ARENA as part of ARENA's Advancing Renewables Program.

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1. Executive summary

This report is the third and final report as part of the ARENA supported Powerlink study into the cost effective management of system strength, and builds on these prior reports:

- The first report, *Managing System Strength During the Transition to Renewables*, provides an overview of the role of system strength in the power system, the issues encountered as system strength is reduced, and the full range of responses which are available. This report also included analysis into the merits of a centralised approach to addressing low system strength across an area versus a model in which each renewable generating proponent implements their own solution.
- The second report, *Assessment of the Effectiveness of a Centralised Synchronous Condenser Approach*, demonstrated and quantified the effectiveness of a synchronous condenser option to facilitate the connection of inverter based renewables in an area of the power system with low system strength. This analysis was based on detailed PSCAD analysis, as would be undertaken for a connection assessment, and provided explanations of the various issues which were encountered.
- This report demonstrates and quantifies the effectiveness of grid forming inverters (GFMIs) with battery solution (henceforth referred to as a 'grid forming battery'). It is based on the same situation and uses the same analytical techniques as the second report, to allow for comparison. Suppliers of grid forming batteries were invited to submit a PSCAD model for potential use in the study. However, because of the very detailed and time consuming nature of PSCAD modelling, only one model was taken forward to the detailed analysis. As a courtesy to all vendors, the details of the model which was assessed, will not be published. The decision on which model to take forward for detailed analysis was based on which model was felt to be most likely to yield positive results. It should not be assumed that the results of this study can automatically be applied to all grid forming batteries in all situations. Rather, specific analysis is required.

GFMIs are different to grid following inverters (GFLI) which have historically been used to connect batteries, and solar and wind generators to the grid.

A GFMI works in a fashion which is more akin to how a synchronous generator operates. Instead of using the grid voltage to generate its reference for control, a GFMI creates its own internal reference and continually adjusts this based on the power which is flowing out of the inverter. Instead of directly controlling the power output itself, the inverter controls the voltage angle it presents to the power system, and relies on physics to determine the power that actually flows. During stable system operation this results in the controlled flow of power to the grid, similar to a GFLI. However there is a significant difference in what happens during system disturbances when the power system's voltage phase angle can vary sharply. With a GFLI, the power output will only change once the inverter's control system has had an opportunity to sense the disturbance and calculate the appropriate response. However, with a GFMI, the sudden change in the voltage phase angles will spontaneously result in a change in the power that flows from the inverter (driven by physics). This instantaneous response to system disturbances more closely matches the response of a synchronous generator, and hence a grid forming battery can provide many of the same system benefits.

Although the primary difference between a GFLI and GFMI is in how its controller functions, this change has significant implications for the physical design of the inverter:

- Firstly, the inverter needs to have sufficient current rating to accommodate the additional power that will inherently flow during a disturbance. The extent to which this is necessary may vary between situations but could often be around 130-200% for 60s of the nominal rating. This additional rating is a design feature of the inverter hardware.
- Secondly, the system needs to have access to stored energy to be able to supply the sudden surge in power output. This is why grid forming technology is only applicable to batteries at this stage. Using GFMIs for a solar or wind farm is theoretically possible, but would require a certain amount of energy storage to also be embedded behind the inverters.

The ability to supply fast frequency response (FFR) doesn't necessarily imply grid-forming, as grid following batteries are also capable of responding quickly to a sustained frequency disturbance (certainly much faster than the 6 second frequency control ancillary service). The term “virtual/synthetic inertia” is used inconsistently – sometimes implying a grid forming function, but sometimes as a synonym for FFR.

Grid forming batteries can increase the system strength and therefore help to support the operation of inverter-connected renewables, in a similar manner as synchronous condensers. Provision of this service has minimal impact on a battery’s commercial services. In the study we demonstrated that a grid forming battery of similar MVA capacity as the synchronous condenser (identified in the previous study) could be used to support the stable operation of an otherwise unstable IBR generator, and this supporting function was only dependent on the battery being online, with no need for it to be operated in a particular fashion.

In addition, the modelling showed that the grid forming battery could provide the same damping capability as the synchronous condenser with only half the MVA capacity after implementing site specific tuning.

Tuning of the battery controller is important to maximise its effectiveness. Unlike a synchronous condenser where control tuning has limited impact, the response of a grid forming battery can be heavily influenced by control parameters, and can have a significant impact on its effectiveness. Tuning will be required initially, but flexibility of retuning as the power system evolves will help in maximising the effectiveness of grid forming batteries. The study identified that with situation-specific tuning it was possible to reduce the required capacity (MW rating) of the battery by half and still achieve the same improvement in generator stability. However it was also identified that this tuning was particular to the situation and may need to be updated over time as the situation changed.

Grid forming batteries can provide a range of other services, including services that support the network and the ability of renewables to operate. However, many of these services have a dependency on the battery having an appropriate: location, capacity, technology, contractual arrangements, and integration with the grid – and thus needs to be thoughtfully considered. In the particular situation studied in this report, a grid forming battery solution was found to be effective at alleviating a transient stability constraint. If a synchronous condenser had instead been used to address the system strength issue, the transient stability constraint would have become the next-most-limiting condition, and would have limited the ability of nearby renewable generators to operate freely. To achieve this result would require the grid forming battery to be installed at a particular location and integrated with the network’s protection and control systems to trigger it to full charging following certain network contingency events – and to hold that state for a short period (perhaps up to 5 minutes) while the nearby renewable generation ramped back its output. Other than this modest incursion, providing this transient stability support service would not significantly impact the battery’s other commercial services.

Although grid forming batteries can help nearby GFLIs to operate stably, they are themselves prone to another type of instability (similar to synchronous generators). This form of instability is interchangeably known as “small signal instability”, “oscillatory stability”, or inter/intra-area modes of oscillation. This issue pre-dates the uptake of renewables, and significant expertise already exists within networks and operators of synchronous generators, although this issue may be unfamiliar to renewable proponents. It would be highly advantageous for any GFMIs to include supplementary control facilities similar to the power system stabilisers (PSS) which have historically been used to manage small signal stability with synchronous generators. From a system perspective, it would also be advantageous to have a smaller number of larger grid forming batteries as opposed to a large number of smaller batteries, given that each additional independent grid forming battery increases the risk of this instability occurring, and complicates its mitigation. This issue was not directly observed in the simulations for this study, but has the potential to become an issue as and when the population of grid forming devices increases. Conceptually this increases the appeal of battery installations which can be progressively enlarged over time, with additional battery modules operating under a single battery controller.

Grid forming batteries are not directly equivalent to synchronous condensers, which makes a cost-benefit analysis more complex. A comparatively sized grid forming battery presently costs substantially more than a synchronous condenser, but can provide other commercial services (including arbitrage, FCAS and various network support services) which may offset this cost. Such economic assessment was beyond the scope of this study, and would be highly dependent on the particular circumstances of each battery, but is noted here for completeness.

In summary, grid forming batteries are a welcome additional option in the toolkit and can play a very constructive role enabling renewables and supporting the operation of the power system. However, similar to any dynamic device (including synchronous condensers) they are a not a ‘silver bullet’. Rather, the thoughtful deployment of grid forming batteries alongside other technologies and techniques will be critical to managing the transition to renewables.

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Abbreviations

AC	Alternating Current
AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
BESS	Battery Energy Storage System
DC	Direct Current
EMT	Electromagnet Transient
FFR	Fast Frequency Response
GFLI	Grid Following Inverter
GFMI	Grid Forming Inverter
IBR	Inverter Based Renewable
NER	National Electricity Rules
PSCAD	Power System Computer Aided Design
PSS	Power System Stabilisers
PSSE	Power System State Estimation
RMS	Root Mean Square
STATCOM	Static synchronous compensator

2. Background

Powerlink Queensland with its project partners Pacific Hydro, Sun Metals and GHD applied for and obtained funding from the Australian Renewable Energy Agency (ARENA) to develop materials to help promote a better understanding of system strength throughout the power industry. The project consists of three main work packages outlined below:

- The first report[1] focused on explaining system strength, and outlining the range of remediation options available to manage low system strength and the circumstances in which they might be applicable. It also explored the economic merit and commercial and regulatory issues associated with a shared and scale-efficient model for implementing system strength remediation. It undertook a fault level study to explore how system strength flows throughout the network and identified a number of implications that should be considered when developing renewable connections. The report noted that fault level based analysis may significantly understate the effectiveness of synchronous condensers in dealing with situations in which multiple inverters are interacting with each other.
- This second report[2] aimed to expand on the first report by illustrating the general principles and validating the high level analysis with more comprehensive PSCAD analysis, reflective of what would be undertaken to assess the connection of a new renewable generator.
- This third and final report investigates Grid Forming Inverter (GFMI) technology through detailed PSCAD analysis to determine their effectiveness in remediating issues associated with low system strength. The report is based on the same situation and uses the same analytical techniques as the second report, to allow for comparison.

In preparation for this third report, suppliers of grid forming batteries were invited to submit a PSCAD model for potential use in the study. It was clarified up front that after an initial review of the models only one model (due to the very detailed and time consuming nature of PSCAD modelling) would be taken forward to the detailed analysis. As a courtesy to all vendors the details the model which was assessed would not be published.

The decision about which model to take forward for detailed analysis was based on which model would be most likely to yield positive results. It should not be assumed that the results of this study can automatically be applied to all grid forming batteries in all situations. Rather, specific analysis is required.

3. Study Overview

3.1 Approach to Modelling

The first report highlighted the limitation of conventional forms of power system analysis to identify the issues associated with low system strength and especially the potential for adverse interactions between multiple inverter based renewable generators. This is because traditional ‘load flow’ and transient stability analysis, which has historically been used to analyse network connections (using applications like PSSE and PSS Sincal) do not model the power system with sufficient detail. Rather electromagnetic transient (EMT) modelling using tools such as PSCAD must also be used.

EMT analysis is performed using extremely detailed models of each generator and the network (e.g. with a full representation of the control system for each inverter, synchronous plant, Static VAr Compensators and STATCOMs) to assess the potential for unstable interactions between multiple inverters. Due to the detailed nature of these models, they are typically provided by equipment manufacturer on a confidential basis.

As in the second report, the modelling in this report was undertaken using PSCAD analysis. It used the same electrical model of the power system, and is based on analysing the same situation.

3.2 AEMO System Strength Assessment Methodology

AEMO’s ‘System Strength Impact Assessment Guidelines’ sets out two different forms of assessment:

1. The preliminary assessment is a simple screening tool to identify where there is enough risk of instability to warrant detailed investigation. It is based on comparing the size of a new project with the available fault level.

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[1] https://arena.gov.au/knowledge-bank/managing-system-strength-during-the-transition-to-renewables/

[2] https://arena.gov.au/knowledge-bank/assessment-of-the-effectiveness-of-a-centralised-synchronous-condenser-approach/

2. The full assessment involves a detailed assessment based on PSCAD analysis, which models the complex interactions between multiple inverters.

The Preliminary Assessment methodology was developed based on the best available knowledge of system strength at that time. Over the last couple of years, Powerlink has gained a greater understanding of system strength related issues and now considers that this fault level based methodology does not provide sufficient confidence as a screening methodology as originally intended.

Powerlink now understands that an important limitation to the hosting capacity for inverter based renewables is the potential for multiple generators, and other transmission connected dynamic plant, to interact with each other in an unstable manner. These dynamic plant control interactions manifest as unstable or undamped oscillations in the power system voltage. The frequency of the oscillation is dependent on the participating plants, but is broadly characterised as between 8Hz and 15Hz. The only way to gain an understanding of these oscillations is through detailed EMT system-wide modelling.

The analysis undertaken for this report has been in line with AEMO's Full Impact Assessment Methodology. The level of modelling is equivalent to that undertaken as part of section 5.3.4(b) of the NER. The results are specific to the particular example and care should be taken not to apply the outcomes to other situations without project specific detailed EMT studies. Powerlink recommends that individual proponents should undertake their own analysis to assess whether GFMIs would provide assistance in their particular circumstances.

3.3 Guide to Interpreting the Results

The analysis provided in this report will examine the response of electrical network properties such as Active Power, Reactive Power and Voltage under fault conditions.

- Active Power is provided by generators and is the portion of electricity that supplies energy to the load.
- Reactive Power can be provided by generators, synchronous condensers and other equipment and directly influences electric system voltage. It is the portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment.
- Voltage in a power system is analogous to water pressure in a hydraulic system, and is the force that causes an electrical current to flow. In all of the plots in this report, the voltage is shown as either:
  - RMS voltage is a representation of the amplitude of the voltage waveform. In practice the voltage is a sinusoid shape and is constantly varying. If the magnitude of the voltage sinusoid is constant, a plot of the RMS voltage would appear as a flat horizontal line.
  - "Per-unit" (pu) is an engineering concept but simplistically can be thought of as percent, where 1.0pu equals 100% of the network's nominal voltage. Note: It is common for the transmission system to be operated between 1.0pu and 1.1pu (i.e. 100% to 110% of its nominal voltage). Whilst this voltage might seem to be too high, this is standard and best practice to maximise the network's capacity and minimise losses. It is also within the network's design envelope (i.e. whilst 100% is the 'nominal' voltage, it is not the design limit). The voltage can be adjusted down to 100% of nominal as power leaves the transmission network through transformers.
- In the graphical results presented below, the X-axis represents time in seconds.

When the power system is stable these quantities will be at a satisfactory equilibrium. When the system is secure, these quantities may initially be disturbed following a credible power system disturbance, but will return to a new satisfactory equilibrium level over time. Credible power system disturbances include the short circuit and subsequent trip of single elements, and changes in the load or generation.

There are various forms of instability in the power system, and one form of instability is where these parameters begin to oscillate. The National Electricity Rules (NER) require that the power system is effectively dampened, so that any oscillations that start quickly decay. This situation is illustrated in Figure 1 on the left where an initial disturbance (where the voltage suddenly drops and then recovers) initially creates an oscillation but this quickly decays. The opposite situation is illustrated on the right where the same initial disturbance creates an oscillation, but instead of decaying the oscillation is sustained and in fact grows over time.

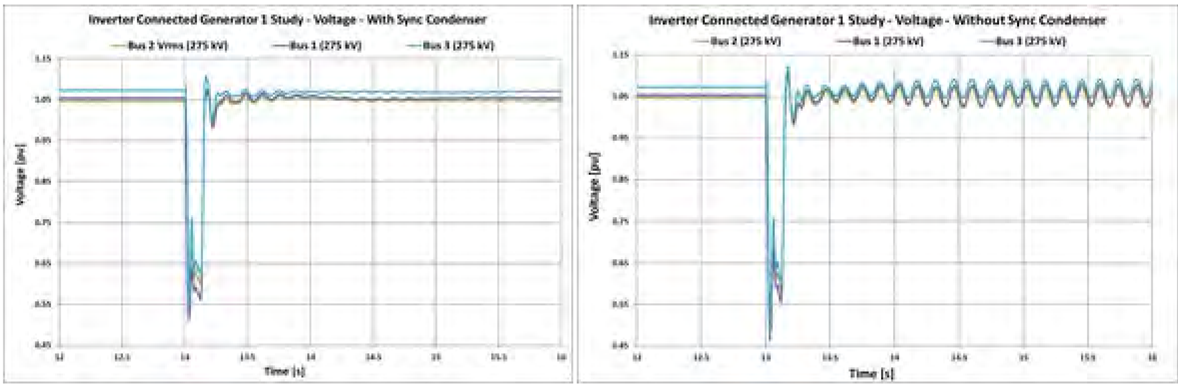

Figure 1 - Example of a stable (left) and unstable (right) response to a disturbance.

The practical consequence of a sustained or growing oscillation is that the control systems of generators and other network equipment are fighting to retain control of the system voltage. A sustained or growing oscillation can lead to the unplanned tripping of generation (to protect itself), which could further exacerbate the instability and lead to a snowballing failure of the power system.

Section S5.1.8 of the NER requires that power system oscillations be adequately damped. The rate at which the oscillation needs to decay depends on the oscillation's frequency. Damping is considered adequate if any oscillatory response at a frequency of:

a) 0.05 Hz or less, has a damping ratio of at least 0.4;
b) between 0.05 Hz and 0.6 Hz, has a halving time of 5 seconds or less (equivalent to a damping coefficient –0.14 nepers per second or less); and
c) 0.6 Hz or more, has a damping ratio of at least 0.05 in relation to a minimum access standard and a damping ratio of at least 0.1 otherwise.

Any control interactions that result in sustained or growing oscillation of active power, reactive power or voltage magnitude between any items of plant would fail to meet the NER's stability requirements.

The effectiveness of the grid forming battery can be assessed by modelling the response of these power system quantities to power system disturbances[3] with and without this grid forming battery. An effective response with a grid forming battery connected will dampen any oscillations at the rate required by the NER and return it to a new satisfactory equilibrium state.

4. Introduction of grid following and grid forming inverters

Inverters are power electronic devices used to convert the direct current (DC) or variable frequency electricity produced by solar and wind farms, and stored in batteries, into the nominally 50Hz alternating current (AC) form of electricity used by the power grid. However, a key challenge is that whilst the grid's frequency is nominally 50Hz, in actual fact it is constantly varying due to any instantaneous mismatch between demand and supply balance in the power system. Thus it is necessary for inverters to have some mechanism to stay in sync with the grid, which is particularly challenging during system disturbances when the local grid's voltage waveform can become significantly distorted.

Historically GFLIs have been used for grid connected applications but have been susceptible to instability with low system strength. GFMI technology originates from off-grid applications, but extensions of this technology used in grid connected applications are emerging as a potential solution to low system strength related instability. At this stage GFMIs are only applicable to batteries, which is why this analysis is focussed on grid forming batteries. As noted below, using GFMIs for a solar or wind farm is theoretically possible, but would require a certain amount of energy storage to also be embedded behind the inverters in a hybrid model, and presently there are no such products under operation in the market.

To briefly clarify terminology, the ability of a battery to supply fast frequency response (FFR) doesn't necessarily imply it is grid-forming, as grid following batteries are also capable of responding quickly to a sustained frequency disturbance (certainly much faster than the 6 second frequency control ancillary service). The term

[3] A network disturbance generally results from a network fault and results in outages, forced or unintended disconnection or failed re-connection of circuit breaker.

"virtual/synthetic inertia" is used inconsistently – sometimes implying a grid forming function, but sometimes as a synonym for FFR.

4.1 Grid following inverter

In a Grid Following Inverter (GFLI), the inverter attempts to track the grid's voltage waveform, adjusting its current (and hence power) output to remain in synchronism with the grid. With low system strength the local power system's voltage waveform becomes highly pliable, and can give rise to a number of complications for GFLIs:

- The voltage waveform seen by the inverter varies significantly in response to changes in the inverter's own output. This can create a feedback loop in which the inverter is essentially fighting against itself. Appropriate control settings can help to manage this issue but it becomes progressively more difficult the lower the system strength becomes (and hence the more pliable the voltage becomes). Initially this was the dominant concern for inverter based renewables, but has since been largely overtaken by the following complication.
- If there is more than one GFLI in an area, the output from each inverter can cause a disturbance in the grid voltage and this voltage disturbance will be seen by the other inverters in the area. This can potentially provoke a subsequent response from the other inverter(s) which leads to further disturbance in the grid voltage, and thus the cycle continues. This phenomenon is known as inverter control interaction and is presently the dominant source of concern.

Please refer to the first report in this series for an expanded explanation of these issues.

4.2 Grid forming inverter

A Grid Forming Inverter (GFMI) works in a fashion which is more akin to how a synchronous generator operates. Instead of using the grid voltage to generate its reference for control, a GFMI creates its own internal reference and continually adjusts this based on the power which is flowing out of the inverter. Instead of directly controlling the power output itself, the inverter controls the voltage angle it presents to the power system, and relies on physics to determine the power that actually flows. During stable system operation this results in the controlled flow of power to the grid, similar to a GFLI. However there is a significant difference in what happens during system disturbances when the power system's voltage phase angle can vary sharply. With a GFLI, the power output will only change once the inverter's control system has had an opportunity to sense the disturbance and calculate the appropriate response. However, with a GFMI, the sudden change in the voltage phase angles will spontaneously result in a change in the power that flows from the inverter (driven by physics). This instantaneous response to system disturbances more closely matches the response of a synchronous generator, and hence a grid forming battery can provide many of the same system benefits.

Although the primary difference between a GFLI and GFMI is in how its controller functions, the sudden surge of additional power which will inherently flow during a disturbance gives rise to two significant implications for the physical design of the system:

- Firstly the inverter needs to have additional power rating. The extent to which this is necessary may vary between situations but could often be around 130-200% of the nominal rating. This additional rating is a design feature of the inverter hardware.
- Secondly the system needs to have access to stored charge. This is why grid forming technology is only applicable to batteries at this stage. Using GFMIs for a solar or wind farm is theoretically possible, but would require a certain amount of energy storage to also be embedded behind the inverters.

In this report, the term "grid forming battery" is used as a short hand way of referring to a GFMI with a Battery Energy Storage System (BESS) used in a grid connected application. The term "grid forming inverter" is used when discussing issues which are specifically related to the inverter component of the overall grid forming battery (and which might also apply to the future application of grid forming inverters to connect solar and wind generation to the grid).

5. Power system analysis

This section of the report describes the results of the PSCAD analysis. The steps of the analysis were as follows:

1. Firstly demonstrating the need for some form of system strength remediation by demonstrating the instability that would otherwise result;
2. Demonstrating the impact of adding a grid forming battery as well as a synchronous condenser (for comparison);
3. Demonstrating the voltage and transient (angular) stability issues that subsequently arise once the initial system strength related issue has been dealt with;
4. Exploring the effectiveness of different options to manage the voltage and transient stability issues, including: pre-contingent throttling and post-contingent runback renewable generation, a grid forming battery, and a synchronous condenser; and
5. Demonstrating the importance of coordinating the grid forming battery response with the post-contingent runback of renewable generation.

This study is based on a realistic and detailed model of the power system, and focusses on an extremely weak subset of the grid which is prone to sub-synchronous voltage oscillations, voltage instability and transient instability (all of which will be discussed in the following sections).

A simplified representation of the network under consideration for this analysis is shown in Figure 2. It shows a double circuit 275kV line (purple) in parallel with a double circuit 132kV line (orange). The grid-following Inverter Based Renewable (IBR) generators (Plant 1 and Plant 2) are connected to the 275kV buses, 3 and 4 respectively.

A synchronous condenser and grid forming inverter are later added (separately to each other) at bus 5 for the comparison.

Plant 1 and 2 have a combined capacity of approximately 300 MW. Powerlink modelled scenarios with battery sizes of 100MW and 50MW, as well as a synchronous condenser of approximately 120MVA.

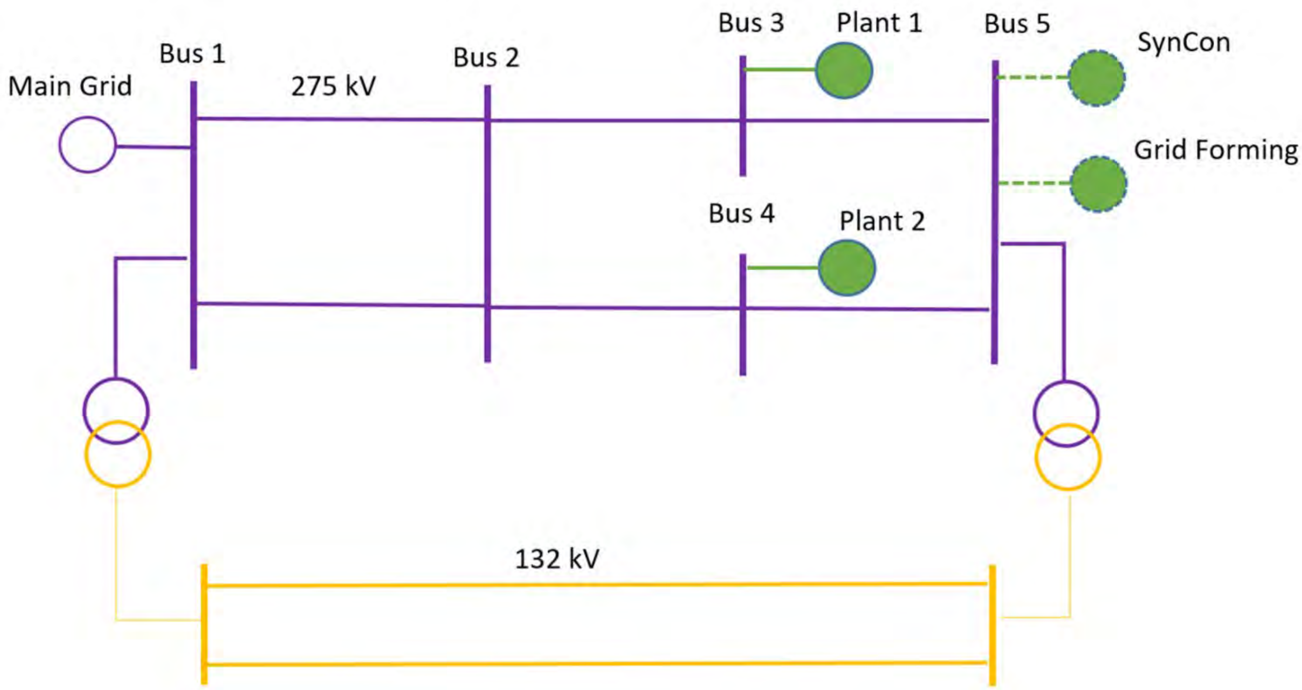

Figure 2 - Network topology

5.1 Establishing the need for system strength support

As renewable generation penetration level increases, grid following renewable generators can face control malfunction due to the lack of system strength in the area. In particular, un-damped voltage oscillations are observed at all the buses of the studied network, in the absence of any system strength mitigations.

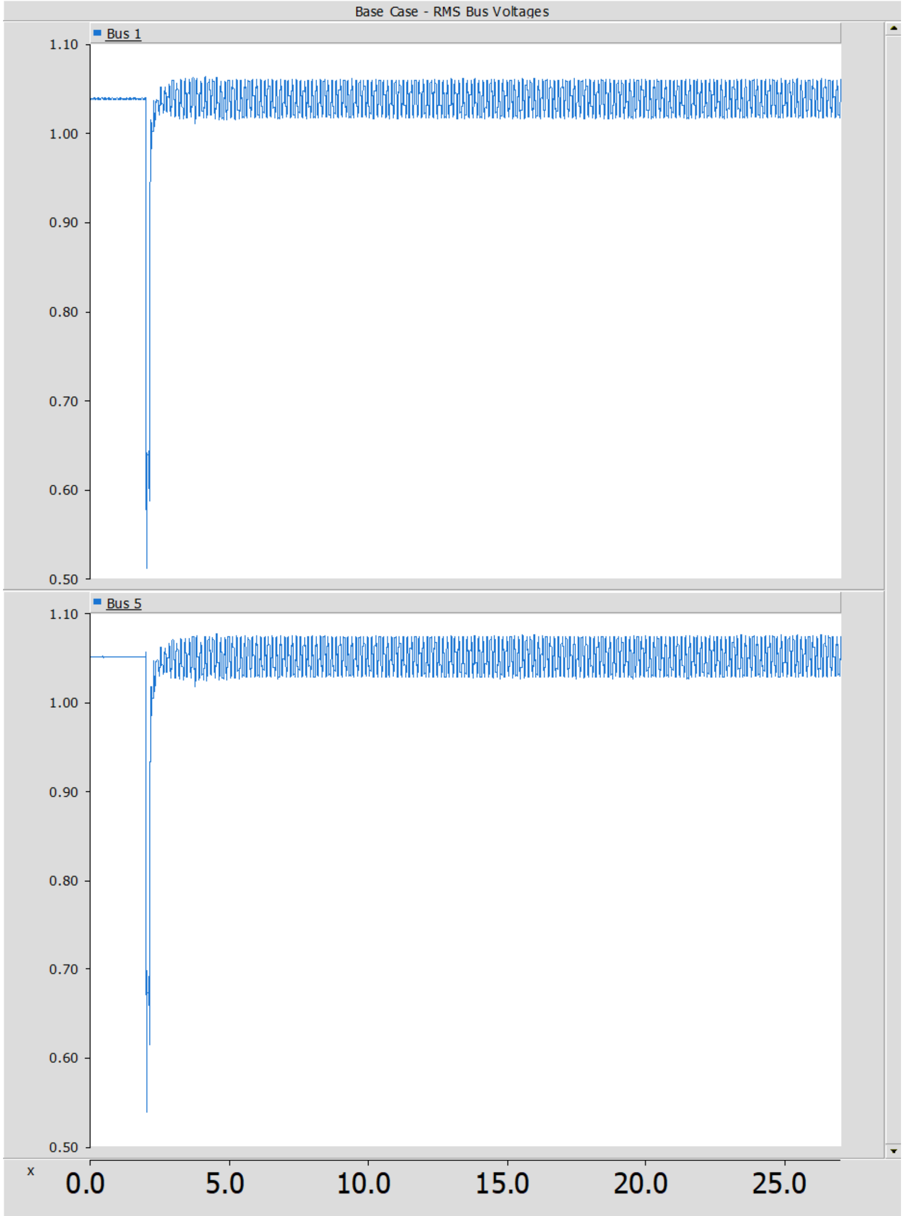

Figure 3 - Un-damped voltage oscillations with inadequate system strength

5.2 Effectiveness of system strength mitigations

Two options to address the IBR instability resulting from low system strength were analysed to assess their effectiveness:

- A synchronous condenser was considered at Bus 5. The specification and location of the synchronous condenser was informed by analysis undertaken for the previous report in this series.
- A grid forming battery, also connected to Bus 5.

5.2.1 Synchronous condenser

It can be seen in Figure 4 that the synchronous condenser provides effective damping to the voltage oscillations. The capacity of this synchronous condenser leverages analysis undertaken for the previous report in this series.

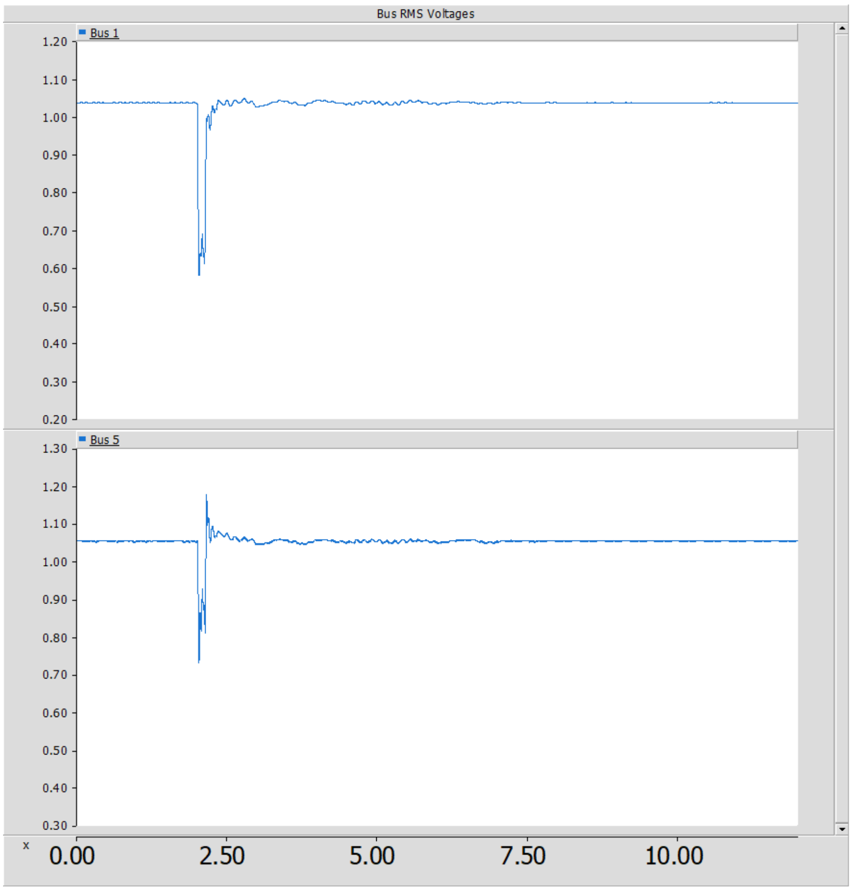

Figure 4 - Grid Bus voltages with a synchronous condenser at Bus 5

5.2.2 Grid forming battery

A grid forming battery was also tested for its effectiveness for system strength support.

- Initially a battery with the same continuous-MVA rating as the synchronous condenser was assessed and found to be effective.
- The response of grid forming batteries is quite flexible and can be adjusted using various control parameters. After tuning the controller parameters to suit the particular circumstances, it was found that the continuous MVA capacity of the grid forming battery could be halved and still effectively remediate the system strength related instability.
- In determining this result, the synchronous condenser size was not optimised. The outcome is also dependent on the network configuration including the location of the battery and surrounding generation mix.

These results are shown in Figure 5 below.

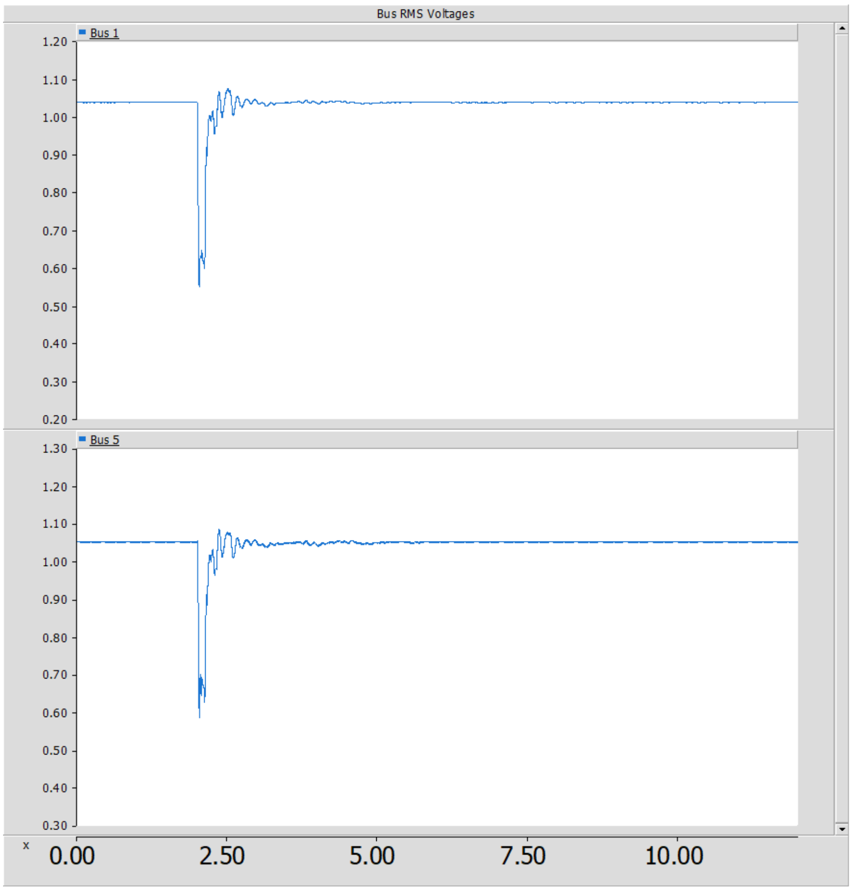

Figure 5 - Grid Bus voltages with a grid forming battery at Bus 5

5.3 Subsequent voltage stability and transient stability issues

The power system requires a broad range of issues to be managed simultaneously. It is often the case that only once the most-limiting problem is resolved is it possible to understand what that next-most-limiting conditions are. And so it is in this case: with the system security issue under control, an issue with both voltage and transient stability becomes apparent.

More specifically, when the transmission lines between Bus 1 and Bus 2 are disconnected due to a contingency, the significant change in power flow and the system conditions after the fault can create issues related to the voltage and transient stability of the power system. This is illustrated in Figure 6 which is a plot of the voltage at a couple of locations.

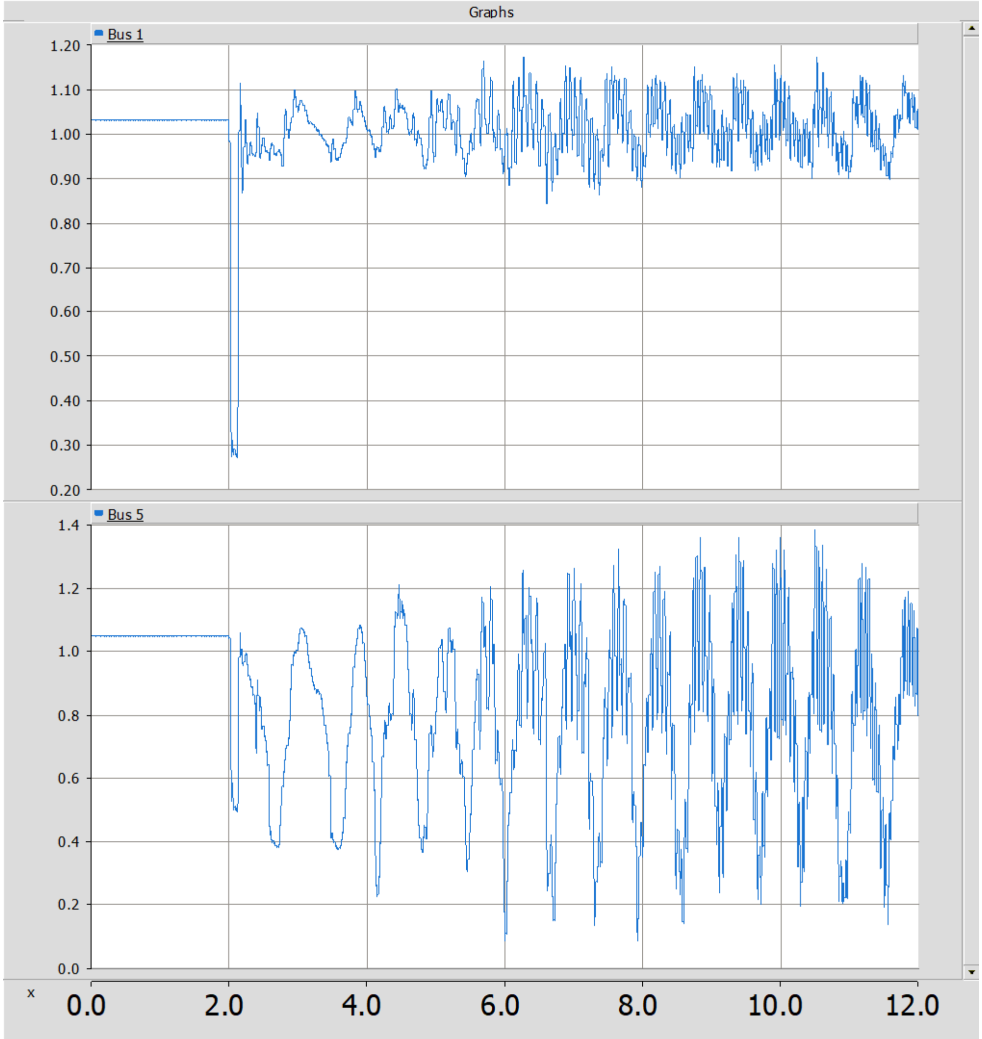

Figure 6 - Grid Bus voltages collapse after the fault

Synchronous devices such as synchronous generators and synchronous condensers are not immune from the effects of this voltage and transient instability. Figure 7 shows another nearby synchronous generator losing synchronism due to the transient stability disturbance.

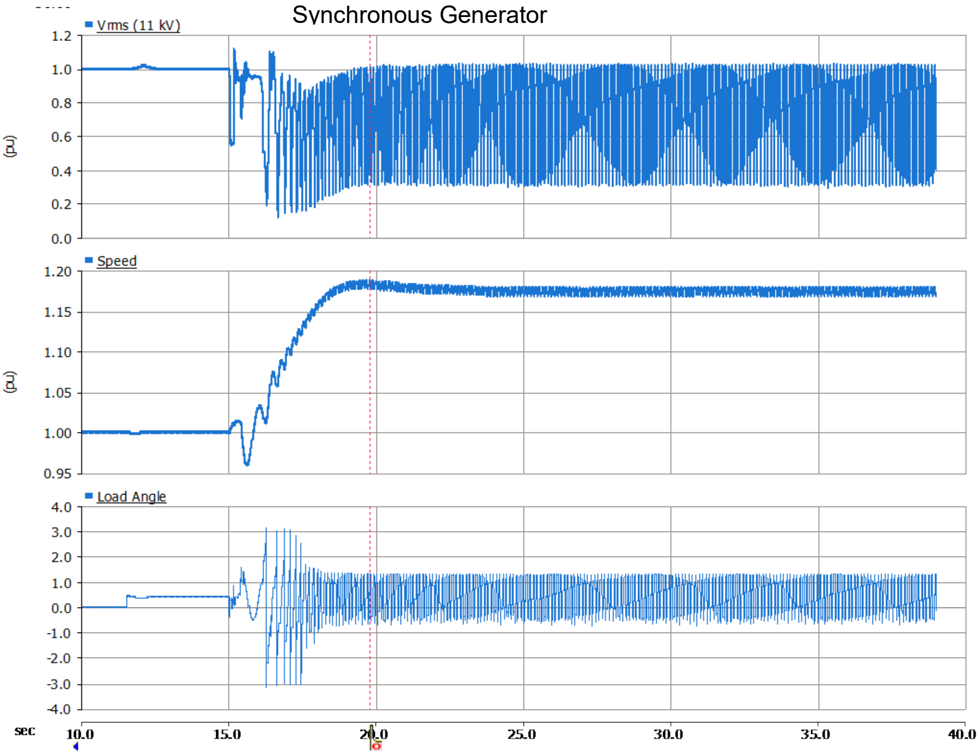

Figure 7 - Nearby Synchronous Generator loses its synchronization

5.4 Effectiveness of responses to transient and voltage stability issues

To manage these issues it is necessary to quickly reduce the power being exported from the area following a fault. This implies quickly reducing the active power output from the renewable plants. Due to the slow nature of the active power ramp down capability of the IBR generators, tripping those plants after the fault is becoming critical to maintain the voltage stability. However, the very rapid nature of this effect makes even this challenging. Additionally, the tripping of the plants causes temporary drop in the grid voltage, which can also have negative impact on the transient stability of those nearby plants. Hence, there is the need for post-contingent generation runback to be accompanied by other measures. Three options are explored in the following subsections.

5.4.1 Pre-contingent limitation in power output

Even with fast transmission protection (around 100ms) tripping the generators following the IBR renewable generators following the fault, it is not possible to avoid instability. Only when the renewable plants' active power productions are limited to 80% before fault and all of the remaining IBR generation is tripped very fast after the fault, is it possible to maintain a stable system under the critical contingency. However, pre-contingent limitation on the renewable generation output would be detrimental to their operation and financial viability.

Tripping of plant post fault needs to be dealt with very carefully as there is only a limited amount of generation that can be tripped from the system without causing issues elsewhere in the power system.

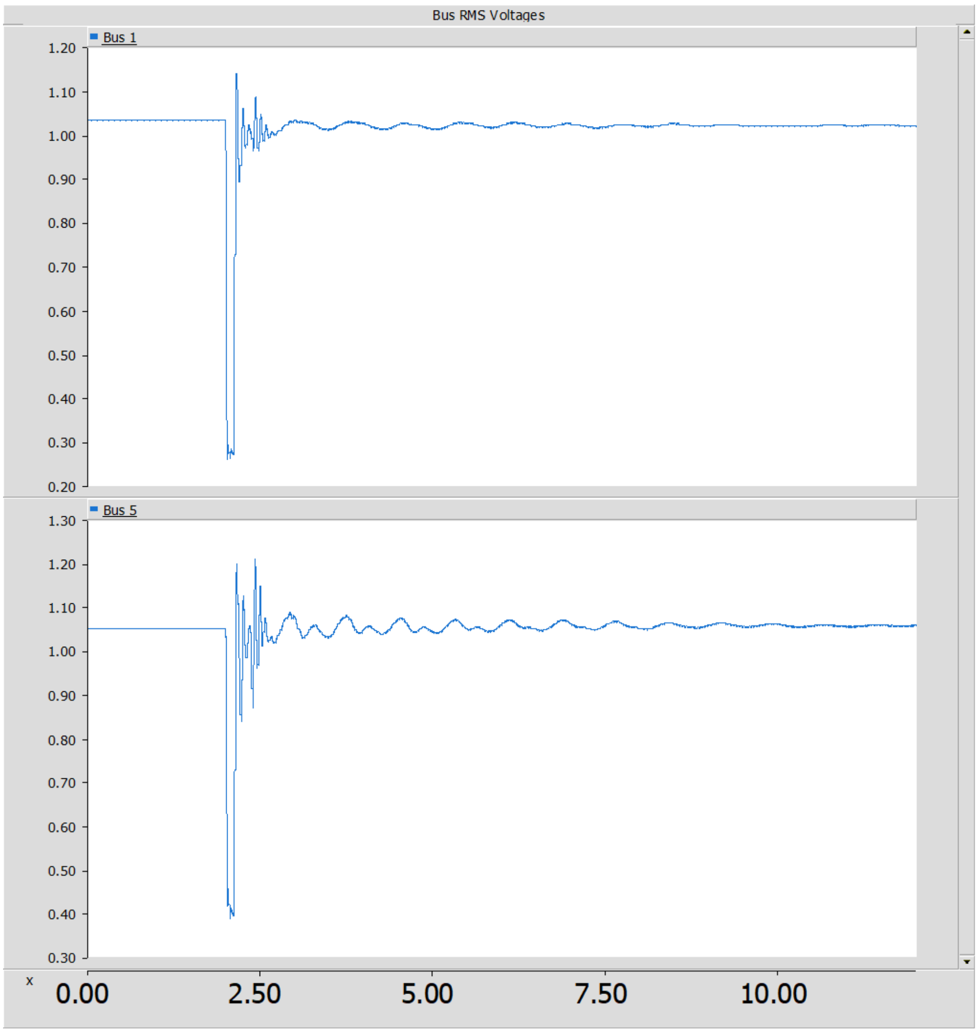

Figure 8 - Grid Bus voltages remain stable only if both renewable plants reduced to 80% (pre-contingent) and tripped fast after the fault

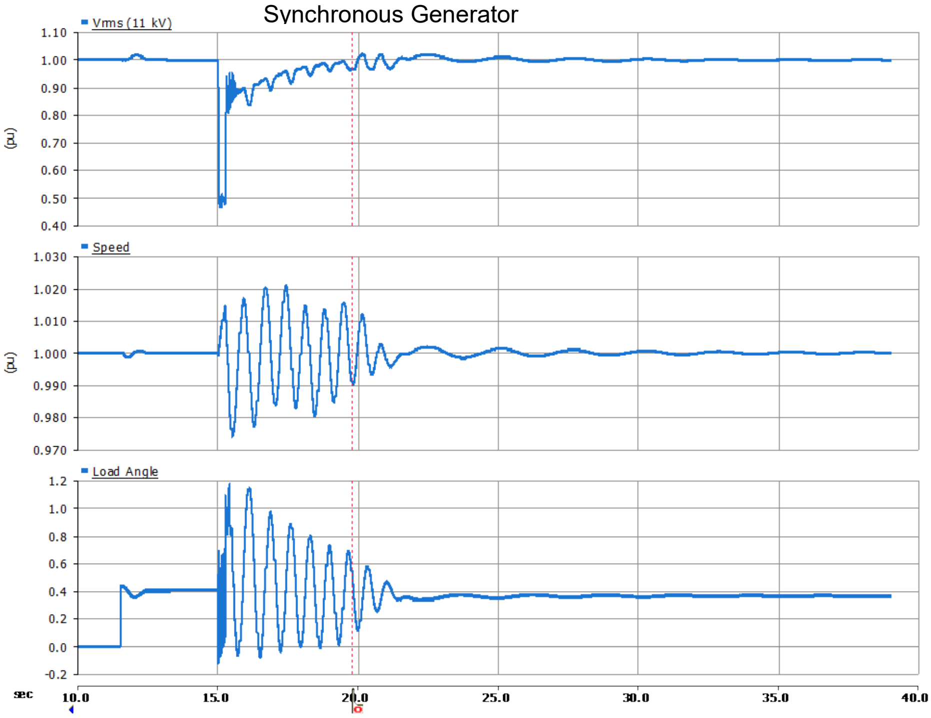

Figure 9 - Nearby synchronous generator remains stable only if both renewable plants reduced to 80% (pre-contingent) and tripped after the fault

5.4.2 Synchronous condenser

A synchronous condenser was studied at Bus 5 to understand how effective it would be at managing transient and voltage stability issues after a fault. The analysis showed at least one renewable generator would still have to be tripped after the fault even with a synchronous condenser. However the plants are not required to reduce their output power at normal operation.

The simulation results with these combined measures are shown in the following graph.

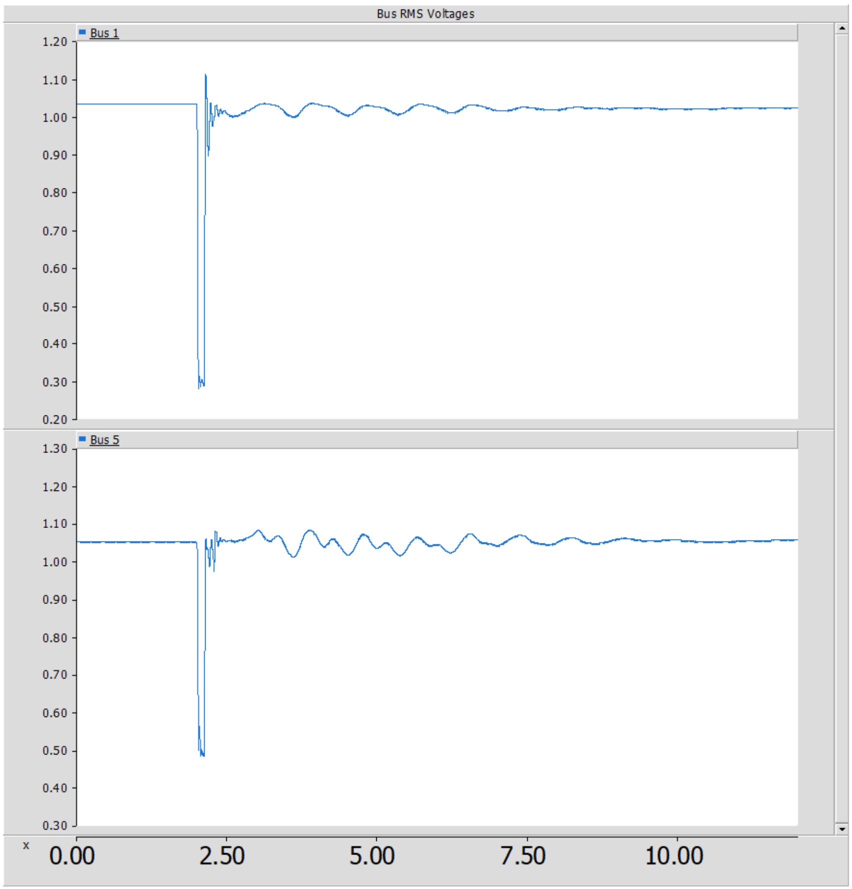

Figure 10 - Grid Bus voltages with proposed synchronous condenser at Bus5 (at least one renewable plant has to be tripped)

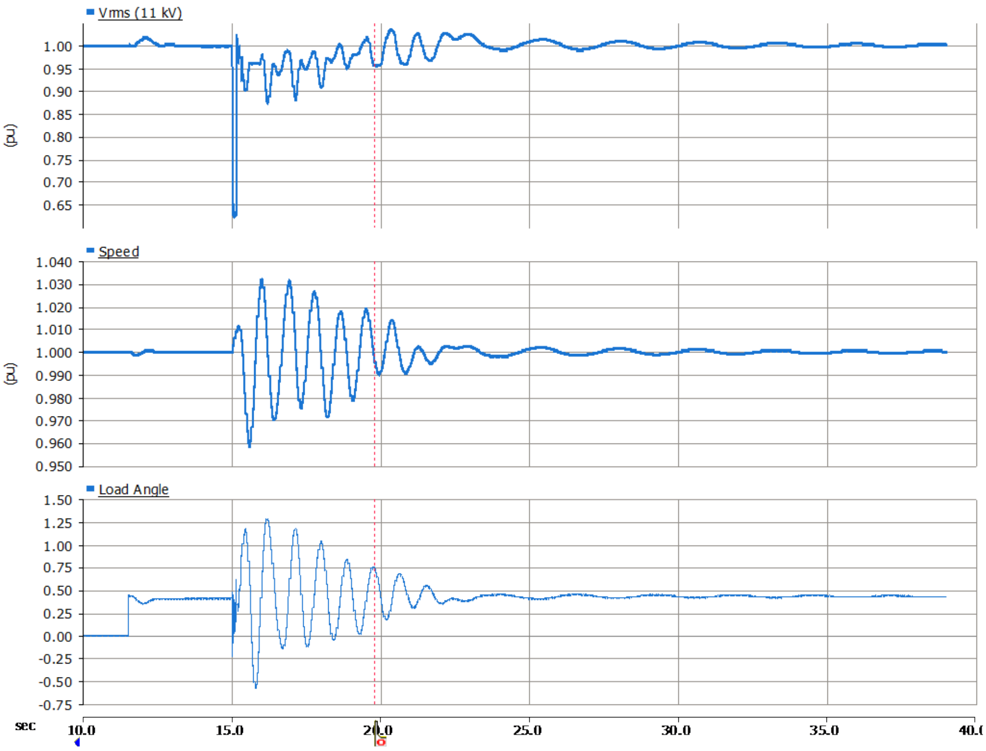

Figure 11 - Nearby Synchronous Generators with proposed synchronous condenser at Bus5 (at least one renewable plant has to be tripped)

5.4.3 Grid forming battery

A grid forming battery was also tested at Bus 5 and found to be very effective, providing two complementary benefits:

- the grid forming inverter can provide fast voltage control and reactive power support similar to a synchronous condenser; and
- the grid forming battery can quickly switch to charging mode, and this local absorption of power helps to offset the power being produced locally by the grid following renewable generation and helps to avoid transient instability. This battery response buys time for IBR generator to ramp down their active power output to below a stipulated threshold instead of being tripped.

To practically realise this result would require the battery to be integrated with the transmission network's protection and control systems. This is because there isn't enough time for that battery to start observing the disturbance itself before reacting. Rather, the response would need to be directly triggered by network protection systems as soon as the fault was detected.

The following plots demonstrate this response, with the battery switching to full charging for 15 seconds, by which time the collective output from the IBR generation has reduced to below the pre-configured threshold. The grid forming battery in this study is intentionally chosen to be in full discharging mode at pre-disturbance since that is the worst scenario for transient stability. For this study, if the grid forming battery at pre-disturbance is with full charging mode then there is no need for the grid forming battery to absorb more active power to maintain transient stability.

In this situation, with the network in a degraded outage condition, the new power output limit would be approximately 50% of each generator's full capacity to avoid instability.

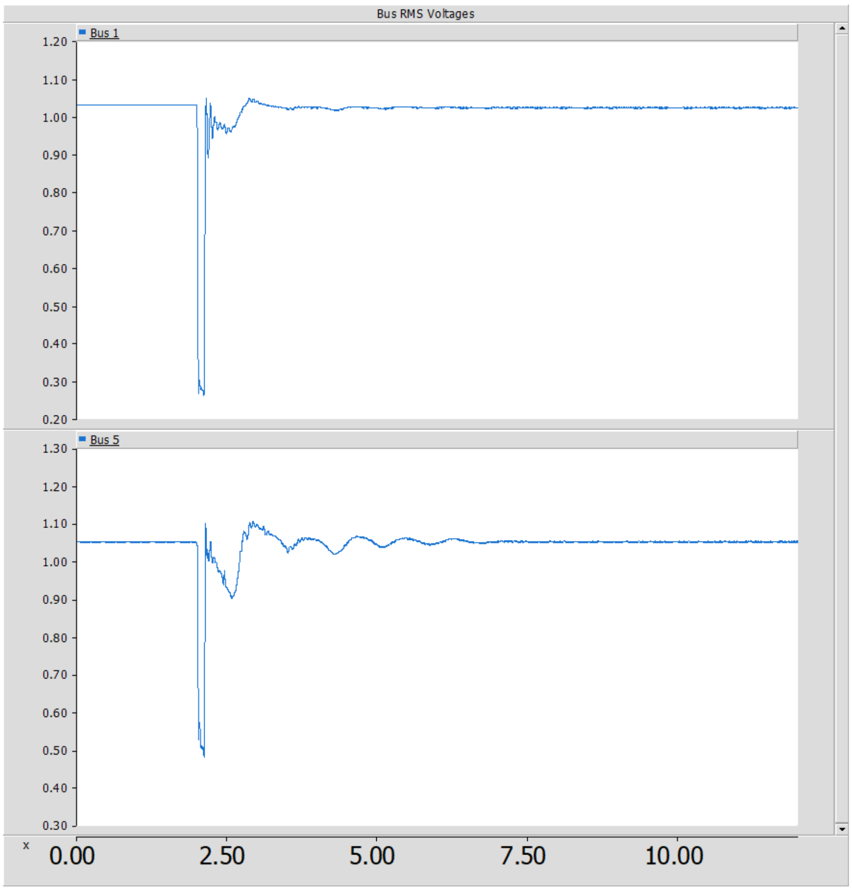

Figure 12 - Grid Bus Voltages with proposed grid forming battery at Bus 5, and with coordinated control between the battery and renewable plants

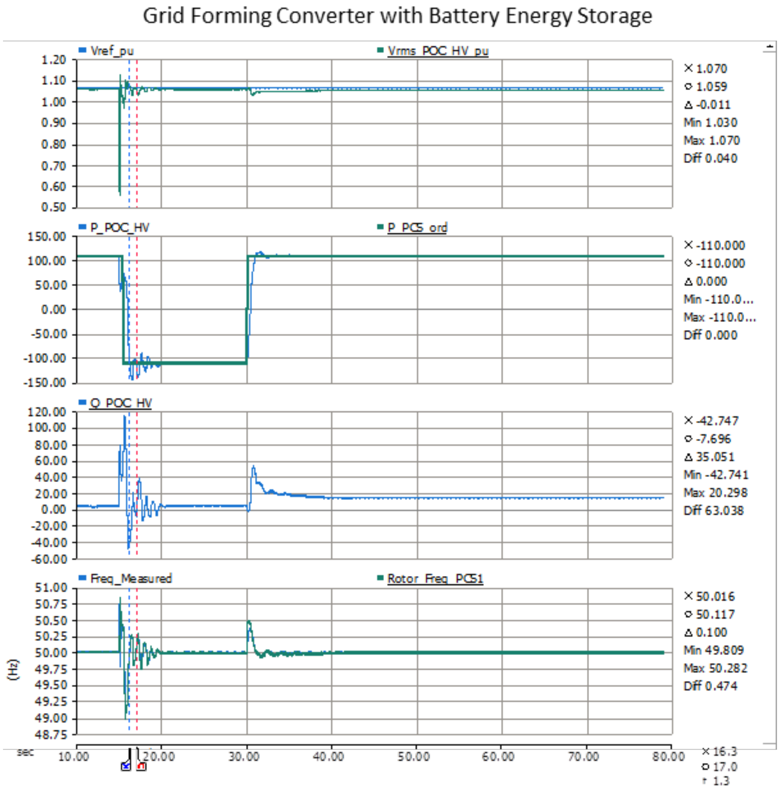

Figure 13 - Grid forming battery's voltage, active and reactive power under coordinated controller with renewable plants

This analysis also identified that it is critical that the battery's response is well coordinated with the ramp down of the local IBR generation. If the renewable plants and grid forming battery system are not coordinated, the system will become unstable.

The following plots show what happens if the battery were to switch away from full charging mode before the renewable plants had sufficiently ramped down their power outputs. It can be seen that the system becomes unstable at the time when the grid forming battery system's active power ramps back from full charging mode to discharging mode.

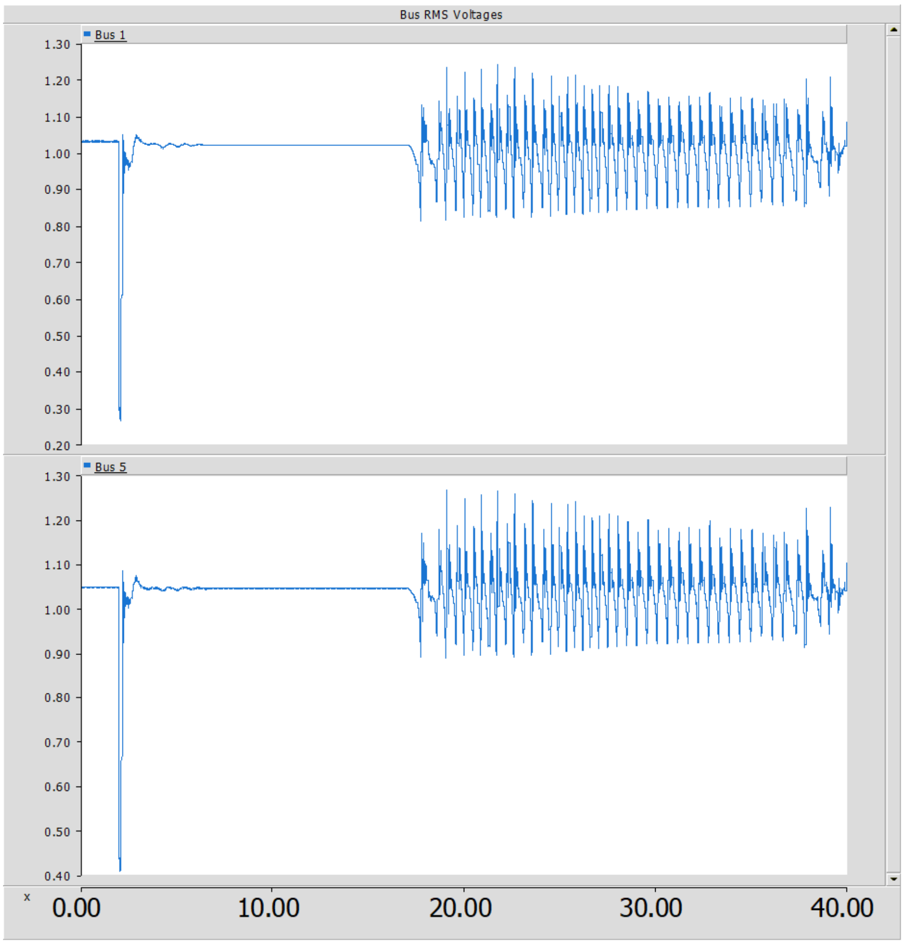

Figure 14 - Grid Bus Voltages, without coordination between the grid forming battery and renewable plants

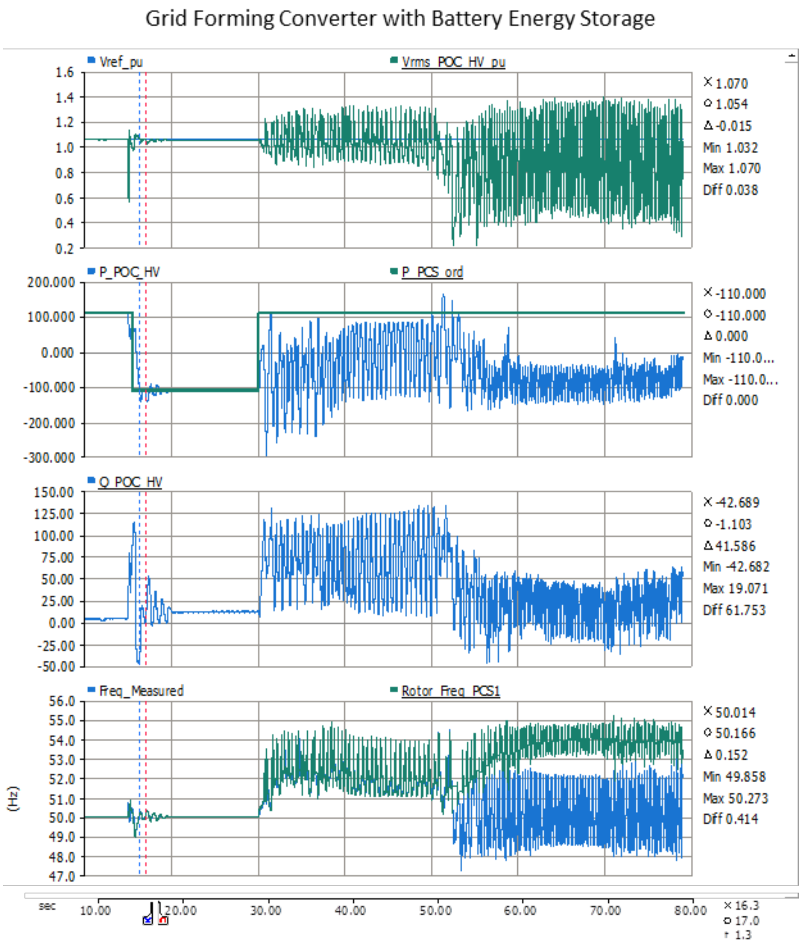

Figure 15 - Grid forming battery's voltage, active and reactive power without coordination with the renewable plants

5.5 Implications of the power system analysis

Based on the above simulations and discussions, it is concluded that a grid forming battery would have a number of advantages compared to a synchronous condenser:

- Both a synchronous condenser and grid forming battery can provide enough damping to the sub-synchronous voltage oscillations which were resulting from inadequate system strength. However because of its flexibility, the grid forming battery may be able to be tuned to provide the same damping with a smaller capacity – in the case of this study only half the capacity was required (on a continuous MVA basis – noting that the grid forming battery's inverter would be required to be capable of certain over current capability on a short term basis – refer to section 6.1).
- For the transient stability and voltage stability issues, leveraging the battery's real power capacity can allow the nearby renewable plant to ramp back their output rather than being tripped. However, this needs to be carefully implemented, with coordination to ensure that the battery only switches away from its full-charging response once the renewable plant had sufficiently ramped back their output.

6. Other considerations

The following points should also be considered when evaluating the suitability of a grid forming battery.

6.1 Need for purposeful design

This analysis has demonstrated that grid forming batteries can provide a range of other services, including services that support the network and the ability of renewables to operate. However, many of these services have a dependency on the battery having an appropriate: location, capacity, technology, contractual arrangements, and integration with the grid – and thus needs to be thoughtfully considered. The particular situation studied in this report required:

- A grid forming battery
- Installed at a particular location
- With a specific minimum continuous capacity, and short term capacity of 200% for 1s and 150% for 60s, and inertia constant of 10s
- Using control parameters tuned to the network conditions, and the ability to update this tuning over time
- Integrated with the transmission network's protection and control systems
- The ability to trigger the battery to full charging following certain network contingency events and to hold this state for a short period while the nearby renewable generation ramps back its output.

Obtaining the power system benefit from the battery is contingent upon all of these requirements being met. Dropping any one of these would compromise the batteries effectiveness. This holistic design is unlikely to be achieved without an intentional and coordinated design process.

6.2 Requirement for short term over-current capability

To function effectively, a grid forming battery's current rating has to be sufficiently oversized to maintain its performance as a stiff voltage source. In this study, the inverter short term current rating is oversized to 2.0 pu for 1s and 150% for 60s which gives a satisfactory performance in this situation. The oversizing of the current rating will have cost implications.

6.3 Requirement for energy storage

The inertia constant (H) or frequency ramp rate limit is an important control parameter in a grid forming battery that has implications on its physical design. In this study, a relatively high inertia constant H was needed for stability purposes. However, this relatively high inertia constant (H) necessitates a relatively large energy buffer on the DC-link to prevent excessive DC voltage variation.

6.4 Additional cost, but additional value streams

As of today, the cost of a grid forming battery by itself would be more expensive than some other forms of remediation. However, a grid forming battery could also pursue additional value streams that may offset this additional cost. This evaluation would be highly context specific and is beyond the scope of this study. However it was identified in this analysis that the services required from the battery to support system strength and stability in this area would have very modest impact on the battery's ability to pursue additional revenue streams:

- To support system strength, provided the battery has been appropriately designed and tuned, it merely needs to be online.
- To support voltage and transient stability, the battery would need to always be ready to switch to a full charging state and to hold that response for as long as it takes for the IBR generation to ramp back its output. This response would only be required following an actual network contingency event (which is infrequent), and the duration of the response would be short (15 seconds in this study). It is the knowledge that the battery could offer this response if called on (like an insurance policy) that enables the network to be operated closer to its technical limit, freeing up capacity for renewable generation.

6.5 Potential for confusion with the term "virtual inertia"

The ability to supply fast frequency response (FFR) doesn't necessarily imply grid-forming, as grid following batteries are also capable of responding quickly to a sustained frequency disturbance (certainly much faster than the 6 second frequency control ancillary service). The term "virtual/synthetic inertia" is used inconsistently – sometimes implying a grid forming function, but sometimes as a synonym for FFR.

6.6 Potential for confusion with grid forming for 'islanded operation vs grid connected'

Grid forming inverters have been used for islanded operation for long time however, there can be significant differences between grid forming inverters that can only be used for an islanded system and the one that is used while connected to the grid. This report only refers to the later and requires due consideration for over current capacity rating of the inverters.

6.7 Susceptibility to small signal instability

Although grid forming batteries can help nearby GFLIs to operate stably, industry experience with synchronous generators is that they are prone to another type of instability (similar to synchronous generators). There is an understanding that GFMIs will experience a similar form of instability. This is interchangeably known as "small signal instability", "oscillatory stability", or "inter/intra-area modes of oscillation". This issue pre-dates the uptake of renewables, and significant expertise already exists within networks and operators of synchronous generators, although may be unfamiliar to renewable proponents.

It would be highly advantageous for any GFMIs to include supplementary control facilities similar to the power system stabilisers (PSS) which have historically been used to manage small signal stability with synchronous generators. From a system perspective, it would also be advantageous to have a smaller number of larger grid forming batteries as opposed to a large number of smaller batteries, given that each additional independent grid forming battery increases the risk of this instability occurring, and complicates its mitigation.

This issue was not directly observed in the simulations for this study, but has the potential to become an issue as and when the population of grid forming devices increases. Conceptually this increases the appeal of battery installations which can be progressively enlarged over time, with additional battery modules operating under a single battery controller.

6.8 Requirement for situation-specific tuning and ability to retune over time

Tuning is critical to the effectiveness of any IBR generation and applies to a grid forming battery as well, both to maximise its benefits (as in this study, where it was found that the capacity of the battery could be halved provided it was well tuned), and to minimise the potential for negative consequences.

An inappropriately tuned GFMI has the potential to introduce oscillations and interactions. The tuning required to avoid these effects is particular to each situation, and thus has the potential to vary over time as grid conditions change.

This requirement calls for early engagement with the NSP, and a detailed full system impact analysis to test its control parameters considering different grid conditions and grid issues.

6.9 Fault current limitation

A grid forming inverter behaves as a voltage source behind an impedance. Thus, a grid forming battery under a grid voltage disturbance will have faster and larger current change compared with a GFLI. To protect the inverter from exceeding its over current capability, the grid forming inverter will either switch to a current control during the fault period, or implement hardware or software solutions to clamp the maximum inverter current.

Both of the above solutions have their challenges. Therefore, to a certain extent a grid forming inverter needs to be specified with sufficient overload capacity. In this analysis, a short term 2.0pu over current rating was used, but any inverter specification should be informed by specific analysis of each situation.

7. Conclusions

In this study, it has been shown that grid forming batteries can play a very constructive role enabling renewables and supporting the operation of the power system. Thus they are a welcome addition to the toolkit of possible responses.

In this example, this study has shown that a 100MW battery can support the connection of 300MW of inverter based generation. These results are specific to the particular case examined and care should be taken not to apply the outcomes to other situations. Powerlink recommends that individual proponents should undertake their own analysis to assess whether GFMIs would provide assistance in their particular circumstances.

However, similar to any dynamic device (including synchronous condensers) they are not a 'silver bullet' and to be effective, there are a range of factors which need to be carefully considered.

The thoughtful deployment of grid forming batteries alongside other technologies and techniques will be critical to managing the transition to renewables. Given the positive findings of the study, the logical next step is to install a GFMI with battery in a weak grid context in the NEM, and validate the results through field trials.