PERFORMANCE OPTIMISATION OF A GRID FORMING BATTERY ENERGY STORAGE SYSTEM

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Abstract

The Australian National Electricity Market (NEM) has witnessed the large-scale integration of solar and wind inverter-based resources (IBR) into the bulk power supply system. Predominantly these IBRs have been based on grid following control strategies which have known performance limitations under weak grid conditions and may require system strength remediation. IBRs using grid forming (GFM) controls have the capability to provide this service but introduce additional dynamic characteristics as a result, requiring a careful selection of control parameters.

This paper presents the application and control setting selection of a Virtual Synchronous Generator based GFM Battery Energy Storage System (BESS) project connecting to the NEM. A discussion and demonstration of the capabilities of the plant is provided. An approach to optimising the GFM plant's performance within the context of the local network and the constraints imposed by existing grid codes is also presented. The paper discusses the major trade-offs involved in the performance optimisation, followed by the presentation of an open loop method to efficiently tune plant performance with wide area simulation data.

1. Introduction

Australia's National Electricity Market (NEM) has been having a significant uptake and integration of solar and wind Inverter Based Resources (IBR). These IBRs have utilised Grid Following (GFL) control strategies which have known performance limitations under weak grid conditions. Examples of this have already been observed in various networks [1]. On the other hand, IBRs using grid forming (GFM) controls have the capability to support system strength and avoid such performance issues but may introduce additional dynamic characteristics as a result [2] [3].

This paper presents the experiences gained from studies carried out to support the connection of a proposed GFM Battery Energy Storage System (BESS) in an electrically weak region in the NEM. This structure of this paper is as follows:

- Section 2 provides a description of the proposed plant and a demonstration of its grid forming capabilities.
- Section 3 presents the approach taken for performance optimisation of the proposed plant.
- Section 4 presents an open loop simulation method to efficiently tune performance with wide area simulation results.

2. Proposed GFM plant description and behaviour

Many control strategies for grid forming inverters have already been presented in the literature [4] [5]. However the flexible nature of the control strategy implementation suggests additional unique designs from OEMs are possible. In this section an overview of the proposed plant's connecting network and the structure of its controls are provided. The GFM capability of the proposed plant is demonstrated using two different approaches before the qualitative salient aspects of its dynamics are described.

2.1. *Plant control overview and project context*

The GFM plant is proposed to connect to a location within the NEM which is classified as having low system strength [6]. This area has limited capacity to host further GFL IBRs and system strength support is required to avoid control interactions.

The proposed plant consists of battery supplied inverters connected to the grid via step up transformers and a collector network. The main characteristics of the plant controls are summarised below and shown graphically in Fig. 1:

- Fast inverter level controls that regulate inverter terminal voltage and current to emulate a voltage source behind an impedance. These controls operate on a sub-millisecond timeframe.

- Slower inverter level controls that emulate synchronous machine mechanical (inertia and damping) and flux dynamics. The time-constants of these controls can range from tens of milliseconds to seconds.
- A Power Plant Controller (PPC) which regulates plant level active and reactive power output in alignment with steady state voltage and frequency droop characteristics at the plant's point of connection (POC). These controls generally have time constants greater than a second.

Key differences between the plant's GFM controls and a GFL equivalent plant are those applied at the inverter level; the proposed GFM plant implements fast voltage control and synchronous machine emulation rather than fast current and power control in conjunction with a phase locked loop.

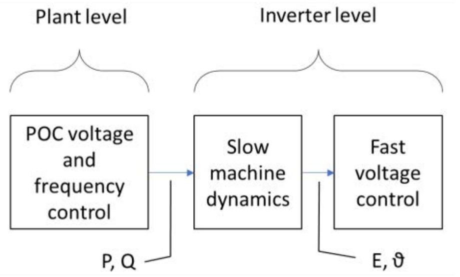

Fig. 1. Overview of proposed plant control with reference signals communicated between major blocks (P: active power, Q: reactive power, E: voltage magnitude and ϑ: voltage phase)

2.2. *System strength, fast voltage control and GFM capability*

Prior to describing the system strength contribution of the proposed plant, a brief discussion of what is conventionally meant by this term is required. System strength within a network is influenced by both the capacity of online synchronous machines and GFL IBRs [7]. GFL IBRs generally reduce system strength because they can inject additional currents in response to a disturbance which acts to exacerbate perturbations in system voltage. As a GFL inverter's fast control loops (e.g. current control and phase locked loop) are responsible for this behaviour, the perturbations can occur on very short time frames (e.g. less than a cycle). Synchronous machines on the other had improve system strength because their voltage source like behaviour acts to reduce the sensitivity of the system voltage to current injections within a grid [8] specifically on a sub-cycle time frame. With insufficient system strength in a network, the GFL IBR dynamics can produce various forms of converter control related instability [9].

In this context, the GFM capability of an IBR is related to its ability to improve system strength by decreasing the voltage sensitivity (by resisting voltage variations) of the system to which it connects, within the sub-cycle timeframe. Therefore, an IBR's system strength contribution could be measured by the scale of its response to oppose a disturbance within a short timeframe, which necessarily involves voltage source behaviour like a synchronous machine.

With the above definitions, two classes of test can be undertaken to demonstrate GFM capability. The first involves examining the instantaneous (space phasor) power output of a device when subjected to a step like voltage disturbances from the grid in a Single Machine Infinite Bus (SMIB) setup [10]. A GFM capable device should:

- Inject additional instantaneous reactive power to oppose a grid voltage magnitude step change
- Inject additional instantaneous active power to oppose a grid voltage phase angle step change

The responses from a GFM capable device must be fast enough (e.g. sub-cycle) and the magnitude of the response is indicative of the system strength contribution. The proposed plant demonstrates this capability with its fast responses to step changes in the grid voltage magnitude and voltage phase angle which are shown in Fig. 2. For comparison, the proposed plant's response is overlayed with the response from an equivalent sized synchronous machine and GFL IBR which are tested separately; it is evident that both the GFM IBR and synchronous machine responses rapidly oppose the disturbance whereas the GFL IBR does not. Note that oscillations in the synchronous machine response are due to the DC offset in its current waveform.

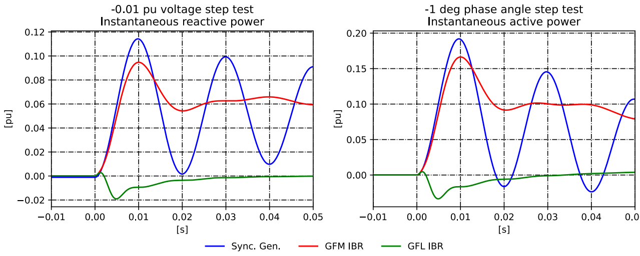

Fig. 2. Instantaneous responses to a -0.01 pu magnitude step (left) and a -1 degree phase angle step (right) of the grid voltage at t = 0 s.

A separate approach to defining GFM capability instead focuses on its final effect on the grid to avoid (or improve) existing converter driven instability. This test involves the integration of the GFM IBR into a test case consisting of a weak grid (high source impedance) and a large GFL IBR. The capability of the GFM IBR to improve stability of fast GFL IBR dynamics following a contingency is tested. The results shown in Fig. 3 demonstrate that the proposed plant is able to stabilise a system which otherwise exhibits converter driven instability.

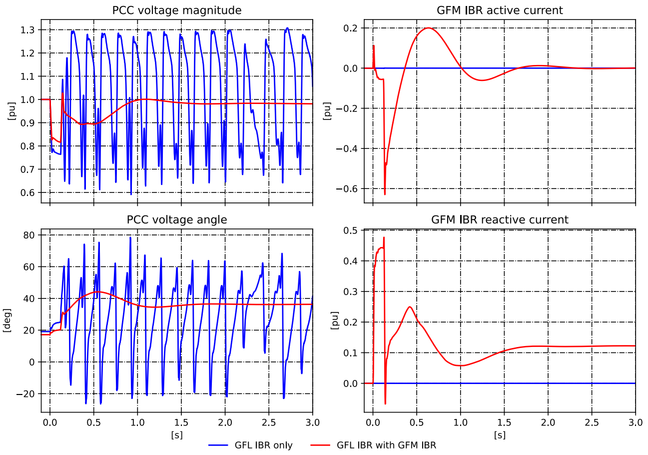

Fig. 3. Demonstration of the stabilising impact of the GFM IBR on a weak network with a large GFL IBR.

2.3. *Machine dynamics and plant control*

The proposed plant's GFM inverter controls emulate the behaviour of a synchronous machine in a simplified manner, which occur on a slower timeframe compared to the fast voltage control. Though slower and not directly related to voltage control and hence system strength, these dynamics are critical to the stable operation of the GFM inverters and their ability to stabilise slower modes of oscillation emanating from the external grid.

In the case of the machine voltage dynamics, for a step in voltage magnitude the controls exhibit the immediate injection of reactive current which decays over a long (user configurable) timeframe. This is akin to the decrement in AC current output observed when a synchronous machine subjected to a fault. The response of the proposed plant and a synchronous machine are compared in Fig. 4.

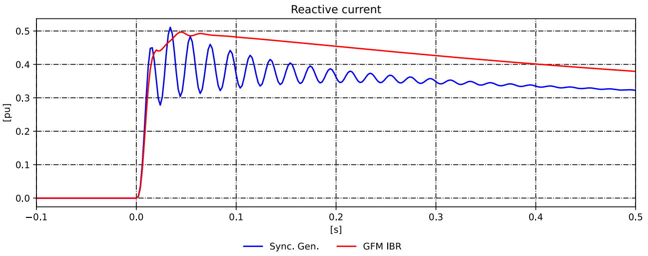

Fig. 4. Comparison of reactive current resopnse to a voltage magnitude disturbance for the GFM IBR and synchronous machine.

The machine mechanical dynamics are also critical in this regard as they ensure the GFM voltage source remains synchronised to the grid. The primary aspects of these dynamics are the virtual inertia and damping with a simplified block diagram representation shown in Fig. 5. The structure is similar to that found in literature [4] [5]. Unlike a synchronous machine which has fixed inertia and damping, these parameters are configurable for the GFM IBR.

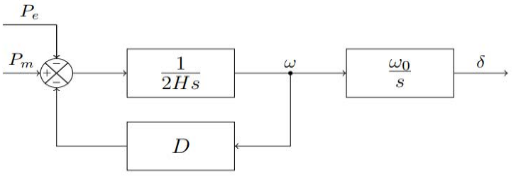

Fig. 5. Block diagram of simplified mechanical dynamics. (P_e: electrical power output, P_m: input power, ω: machine speed, δ: machine rotor angle, ω_0: nominal speed, H: inertia constant, D: damping constant).

The proposed plant also has plant level voltage and frequency control implemented in a PPC. The PPC regulates the total plant output by sending targets to all the inverters to meet voltage and frequency droop characteristics which are agreed with the network operator. This control loop operates in the slowest timeframe of all those presented.

3. GFM plant performance optimisation

The proposed plant has several layers of control each having numerous parameters which have the potential to define the nature of the plant's dynamic response. Hence the first step to selecting the plant's parameters is to determine the performance objectives and priorities. In the case of the proposed plant, the main objective is to provide grid support and improve stability for the low system strength network to which it connects. In this context, the performance objectives adopted for the proposed plant were in order of priority:

- Achieve stable responses from the plant when operating in isolation from other plant
- Maximise the plant's system strength contribution and the capability to stabilise external oscillations emanating from other plant within the grid
- Meet the minimum access standard (slowest) requirements of the National Electricity Rules (NER) for the speed of response and, where possible meet the automatic access standard requirements (fastest)

Due to the potential interaction of the various control layers, it is necessary to approach the control parameter selection in a coordinated and systematic manner. In general, for control systems containing cascaded control loops the tuning process starts from the faster loops and progressively moves to the slower loops. In the case of the proposed plant, the primary performance objectives (system strength contribution and capability to stabilise external oscillations) are also mostly influenced by the faster inverter level control loops. Therefore, the plant parameter selection was carried out as follows:

- The GFM inverter level and installation impedances were selected to balance the system strength contribution, equipment fault ratings and equipment capability.
- The GFM inverter level slow machine dynamics were selected to achieve stable responses and maximise stabilisation of external oscillations.

- The PPC level voltage and frequency settings were selected to provide stable yet fast performance.
- Checks using simulation results from a wide area model (containing external plant) were carried out to validate the tuning, which are described further in Section 4.

Since detailed OEM based implementations have bespoke elements within their design and performance, specific aspects of the tuning process presented may not apply for other GFM implementations. Hence a critical part of the tuning process is to undertake testing of the GFM implementation to determine its specific strengths, weaknesses, and potential trade-offs in performance. The following sections delve into the tuning process for the proposed plant in greater detail.

3.1. System strength contribution

The system strength contribution of a synchronous generating plant has been conventionally estimated from its current infeed to a bolted three phase fault stated in MVA [7] [8]. For a synchronous generator the current infeed to a bolted three phase fault is inversely proportional to the impedance between the faulted bus and the generator's internal voltage source. The collective effect of these voltage source impedances across a network then determines the sensitivity of voltage to current injection at a bus. Hence for a synchronous generator, fault current contribution is an adequate proxy for system strength contribution as defined by voltage sensitivity.

However, this is generally not the case with GFM inverters as unlike a synchronous generator, a deep nearby fault is likely to cause the inverter's current output to saturate due to its relatively lower current rating. The response of a GFM inverter to voltage disturbances is fundamentally different depending on whether the output current saturated because when saturated, a small voltage disturbance would lead to negligible change in current response. Hence while in unsaturated operation, a GFM IBR can be as effective as a synchronous generator in responding to voltage variations (see Fig. 6 for example).

For system strength, the primary concern is the post-contingency (i.e. post-fault) response of the GFM IBR, when system voltages are closer to their nominal values. If the GFM IBR's output current is not expected to be saturated in a sustained manner post-contingency, then the GFM IBR's maximum fault current infeed is a poor metric of its system strength contribution. This is shown in Fig. 6 by the relative slope of the GFM IBR curve during expected operation, which is the same as an equivalent synchronous machine. However GFM IBR apparent curve which is what would be estimated from the GFM IBR's maximum current output during a fault; this latter estimate is be lower than the plant's actual capability in improving system strength.

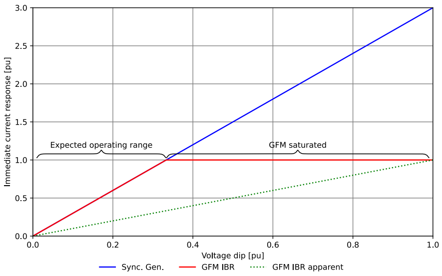

Fig. 6. The immediate change in reactive current reponse as a function of voltage magnitude dip at the device terminals comparing a GFM inverter to a synchronous machine. The apparent slope as calculated from the current injection to a bolted fault is also shown for the GFM IBR in green.

Given that a GFM inverter has fast control loops which regulate voltage, a better measure of its system strength contribution is obtained by determining the total impedance between the point of interest and the node which is regulated. This total impedance is influenced by factors such as the physical impedances of the installed plant, any virtual impedance implemented within the inverter controls and the total number of parallel inverters. This total impedance can then be used to calculate a synchronous generator equivalent system strength contribution value in MVA; lower impedances will produce higher system strength contributions. This is equivalent to determining the slope of the unsaturated part of the GFM IBR curve in Fig. 6.

The influence of this total impedance on the system strength contribution of the proposed plant is analysed using several simulation cases. In the first case, a step disturbance to the grid voltage magnitude or phase angle is applied in a SMIB model containing the proposed plant. The magnitude of the plant response is observed to be inversely proportional to the total impedance (see Fig 6). A larger response from the inverters would maintain a stiffer system voltage and therefore correspond to a greater system strength contribution. In the second case, the proposed plant is connected to a weak system with a large GFL IBR. The ability of the GFM plant to stabilise the system response following a contingency event (i.e. its system strength contribution) is also observed to be inversely related to the total impedance value (see Fig. 8).

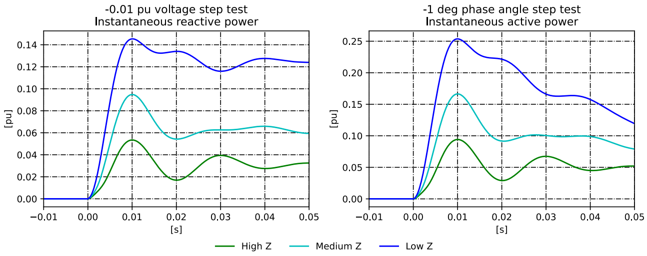

Fig. 7. Response of GFM IBR to step like disturnbaces with varying total impedance (Z).

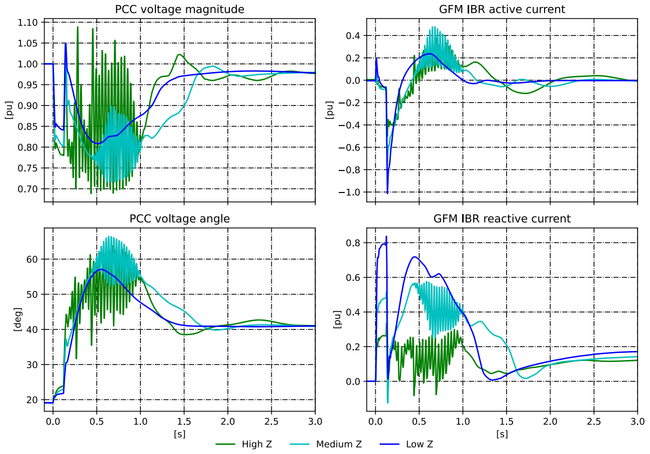

Fig. 8. Response of a system consisting of both GFM and GFL IBRs to a contingency for varying total impedance (Z).

However, there are other factors that limit how low the plant impedances and hence how high the system strength contribution can be made. The first factor has to do with avoiding sustained saturated output operation post-contingency. This condition would occur if there were insufficient inverter capacity and plant impedances were designed to obtain a very aggressive response from the GFM IBR. Aside from leading to sustained periods where the inverters are not capable of regulating voltage (and hence lose their GFM capability), this can also introduce ride through problems for the GFM plant [5].

The second factor concerns the economics of a design which incorporates plant with very low physical impedances. Such low impedances could imply the need for costly higher fault current rated equipment to form part of the installation. This is because in the NEM equipment must be procured to withstand grid design fault levels, which are intended to avoid equipment (particularly circuit breaker) ratings being exceeded for the life of the plant. In weak areas the design fault rating may be an order of magnitude larger than the expected grid fault levels. Increasing the overload capability of the inverters would also increase the required fault ratings of low voltage equipment. Compared to a synchronous generating unit, the effect of the fault current contribution from a GFM IBR plant on equipment ratings may be worse because the distributed nature of the inverters means that some equipment may need to be rated for the combined fault contribution of both the grid and the GFM inverters.

3.2. Machine mechanical dynamics and PPC frequency control

Selecting appropriate mechanical dynamic parameters for the GFM inverters is a key aspect of ensuring both a stable response and enhancing the ability of the proposed plant to stabilise external oscillations. The critical parameters for the mechanical dynamics are the inertia and damping of the virtual machine. For the proposed plant, the selection of these parameters was observed to involve a trade-off between the following items:

- Oscillation damping – damping of GFM inverter active power response after a phase angle disturbance and damping of phase angle oscillations emanating from the grid.
- Inertial power – magnitude of the active power injection during severe frequency disturbances.
- Frequency following – ability for the virtual machine to not lose synchronism with the grid during severe frequency disturbances.

The performance achieved with different parameter values for the above performance objectives are summarised in Table 1 with key results shown in Fig. 9, Fig. 10 and Fig. 11.

Table 1 Performance trade-offs for various mechanical dynamics parameter values

Inertia	**Damping**	**Inertial power**	**Frequency following**	**Oscillation damping**
Low	Low	Very poor	Very good	Poor
Low	High	Poor	Good	Good
High	Low	Good	Poor	Poor
High	High	Very good	Very poor	Good

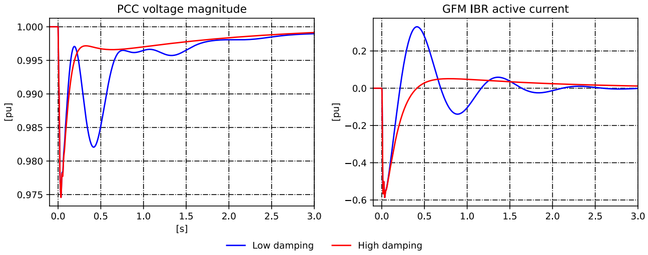

Fig. 9. Response to a voltage phase angle jump with different damping parameters.

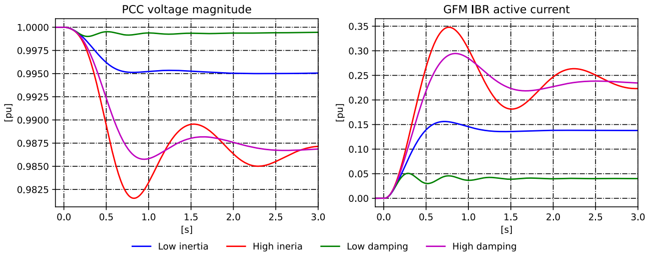

Fig. 10. Response to a moderate frequency disturbance (0.5 Hz/s) with different inertia and damping parameters.

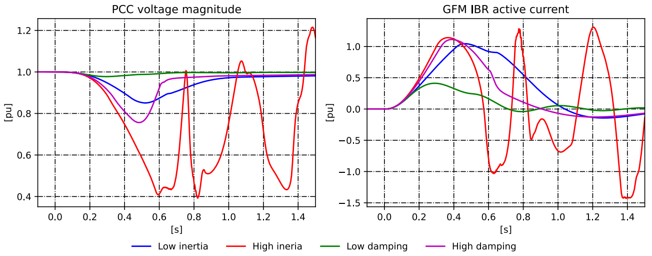

Fig. 11. Response to a severe frequency disturbance (4 Hz/s) with different inertia and damping parameters.

In the case of the proposed plant, low inertia and high damping were selected to maximise the damping of oscillations whilst minimising the risk of losing synchronism during a severe grid frequency disturbance event. Additionally, because the plant connects to the significantly larger NEM system and there is minimal risk of islanding, high inertial power is a low priority objective. Again, because of the large NEM system, the proposed plant's active power output has very little impact on the system frequency. Hence, there is no coupling between the inverter level mechanical dynamics and the PPC level frequency control. Therefore, the latter was set independently of the machine mechanical parameters to achieve the requirements negotiated with the network operator.

3.3. Machine voltage dynamics and PPC voltage control

As previously described, the GFM machine voltage control dynamics of the proposed plant are like those of a synchronous machine; following a voltage magnitude step, the GFM inverters immediately inject reactive current which decays over time as governed by control loop gains and time constants. A representative simplification of the response of the inverter level controls (from terminal voltage disturbance input to terminal reactive current output) is to consider these dynamics to be equivalent to a first order high pass filter.

The bandwidth of this equivalent filter influences both the rate of decay of inverter level current injection following a disturbance and defines the lower limit for the frequency of external voltage oscillations where the inverter current response will be effective in opposing the oscillation. A lower bandwidth will result in the system providing a stabilising response for a wider range of external oscillation frequencies. An example is shown in Fig. 12 where an increase in the bandwidth (faster current decay) results in a reduced reactive current response opposing an external voltage oscillation.

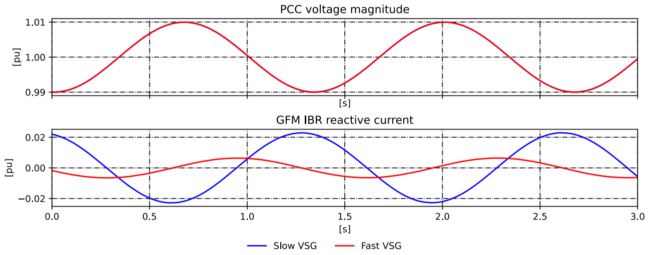

Fig. 12. Oscillatory response of the GFM IBRs with different bandwidth to an external oscillation. The optimal result is obtained with a low bandwidth (slow response).

As previously discussed, over long timeframes the inverters inject steady state reactive power in accordance with the target provided by PPC to regulate plant level voltage. In the NEM, this voltage control performance must comply with the requirements of the NER for the rise and settling time of the response which limits how slow this PPC control can be made. Additionally, the dynamics of the virtual machine and PPC voltage regulation are closely coupled as shown in Fig. 13. Excessively slow machine voltage dynamics (low bandwidth) will require an aggressive tuning of the PPC to achieve fast overall voltage response behaviour which can be detrimental to stability of the PPC voltage control loop. This reality imposes a constraint on how slow the machine voltage dynamics can be made.

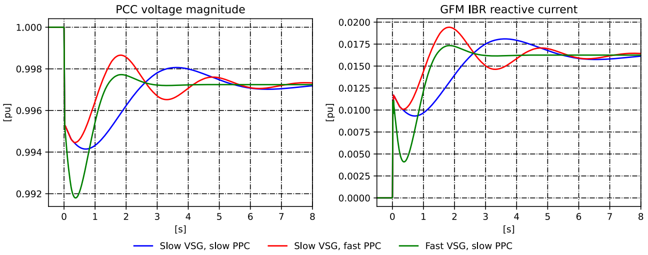

Fig. 13. Response of the plant to a small voltage magnitude disturbance with PPC and machine (VSG) paramters varied. The optimal response with respect to speed of response is a fast response (high bandwidth) from the machine and slow response from the PPC.

The above is further complicated by the fact that the control tuning is required to work under a wide range of system operating conditions, i.e. from a theoretical minimum to maximum grid strength. However, it is under weak grid conditions where an aggressive controller entails the risk of PPC control instability and oscillatory responses. When the grid is strong, the issue is with plant responses which are too slow to meet the NER criteria. However, it should be borne in mind that for a real disturbance, the inverter level fast voltage control acts immediately to provide an opposing reactive current response. This will lessen the impact of the disturbance on the power system even though the time taken for response to rise or settle might be long. Furthermore, the risks to the power system associated with a slow response under strong grid conditions are low – it is these conditions where large voltage excursions and voltage instability are least likely.

In the case of the proposed plant, control settings were selected to first maximise the bandwidth of the machine voltage dynamics response (to counter external oscillations) and achieve well damped responses under weak grid conditions. The overall voltage control response was configured to meet the minimum access standard requirements of the NER. High speed responses from the PPC loop were deemed to not be beneficial for the power system in this case.

4. Tuning approach for wide area system studies

The process described for setting up the plant's control parameters provided a good approach to arrive at an initial system with adequate performance. However, to further optimise the performance, studies using detailed (EMT) models of other grid connected plant (wide area models) and with realistic operating conditions and events are required.

However, there are challenges in tuning a plant based upon these studies. The first is that due to reasons of confidentiality, such wide area models are currently not available to project proponents. Hence the simulation data available may be limited to just the connection point quantities for the proposed plant for a small set of scenarios. However, even if such models are available, the excessively long simulation time makes an iterative tuning approach prohibitive. To address these challenges, an approach to carrying out analysis using an open loop simulation method and parameter sensitivities was utilised. This involved:

- Obtaining voltage results at the POC from a limited set of wide area model simulations.
- Using a strong voltage source connected to the plant's POC to replicate the simulated voltage waveforms from the wide area model into a SMIB model. The voltage magnitude and phase angle are critical quantities to playback.
- Monitoring the plant active and reactive power / current response compared to the voltage magnitude and phase angle to determine whether parameter changes will improve or degrade the performance.

Where specific oscillations are apparent, the plant response can be tuned to achieve similar behaviour to an ideal voltage source behind a reactance to improve the overall system performance. Such an ideal voltage source exhibits the following behaviour:

- Its reactive power / current response is 180 degrees out of phase to an external voltage magnitude oscillation.
- Its active power / current response is 180 degrees out of phase to an external voltage angle oscillation.

However, where mechanical rotor angle dynamics (either from GFM devices or synchronous machines) are suspected to participate in the oscillation, an active power response which is 180 out of phase with the bus frequency (or 90 degrees out of phase with a voltage phase angle oscillation) may be more effective. In the context of lightly damped mechanical systems, this provides component of torque which directly dampens mechanical oscillations. Larger responses from the plant generally correspond to a stronger voltage source more effect on the closed loop system response.

As a demonstration of this process, simulations are setup where the proposed plant is connected to two different fictitious grids containing GFL IBR plant with different dynamics. The response of the system to a contingency is a sustained 1.5 Hz oscillation in the first case and a lightly damped 0.5 Hz oscillation in the second case. The open loop test method was applied with key plant parameters varied. The magnitude and relative phase of oscillations in the plant's active and reactive current output (reactive current phase compared to voltage magnitude, active current phase compared to voltage angle) for each case and with parameters varied was analysed and is presented in Table 2.

Table 2 Open loop oscillation response (A = magnitude, φ = relative phase, H = inertia, D = damping, Z = virtual impedance, VSG flux = voltage control dynamics)

	Case 1 (1.5 Hz)				**Case 2 (0.5 Hz)**			
	Active current		**Reactive current**		**Active current**		**Reactive current**	
	A [pu]	φ [deg]	A [pu]	φ [deg]	A [pu]	φ [deg]	A [pu]	φ [deg]
Basecase	0.14	116	0.19	164	0.08	18	0.03	149
Increased H	0.24	126	0.21	164	0.10	18	0.03	144
Increased D	0.11	132	0.18	169	0.16	62	0.04	154
Reduced Z	0.14	105	0.28	164	0.08	18	0.04	140
Faster VSG flux	0.14	116	0.20	142	0.08	18	0.01	140

For case 1, the oscillation involves very large variations in voltage with a frequency which is slightly too high for the participation of the virtual mechanical dynamics. It is expected that a larger reactive current response that is counter phase to the voltage will be best in improving the system response. The open loop test results show that a reduced virtual impedance best meets this objective. This is then confirmed by a simulation of wide area (close loop) system response, where only a reduction in the virtual impedance is effective in achieving a well damped response (see Fig. 14).

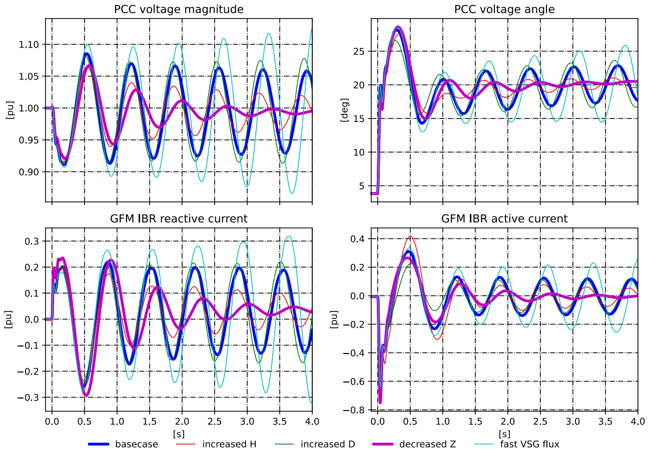

Fig. 14. Case 1 closed loop responses with the basecase and optimal solution (reduced impedance) highlighted.

For scenario 2 on the other hand, the oscillation involves significant variations in voltage phase angle and the frequency of the interactions is well within the range for the plant's mechanical dynamics to participate in it. Therefore it is expected that additional damping power (larger active current which is closer to 90 degrees out of phase with the voltage angle) will be most effective in improving the damping of the overall response. In the open loop tests, an increase in the mechanical damping parameter of the plant provides a response which most closely meets this objective. This is again confirmed by examining the response of the closed loop system to the same parameter variations, where only an increase in mechanical damping is effective in significantly improving the system response (see Fig. 15).

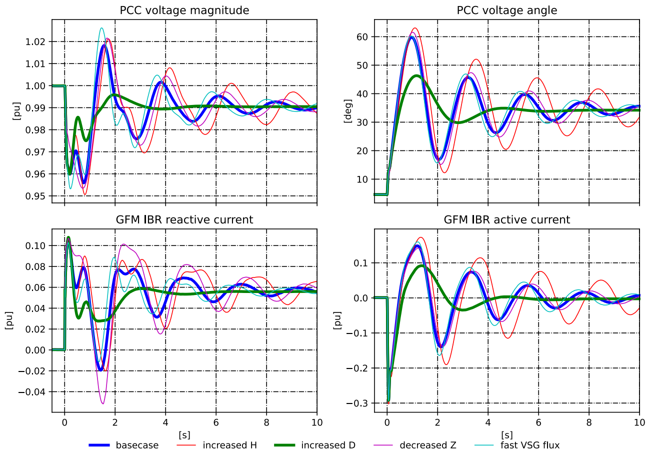

Fig. 15. Case 2 closed loop responses with the basecase and optimal solution (increased damping) highlighted.

The method provides a good method to determine which parameters are likely the most effective in improving the system response during the initial phase of the tuning process. However, further iterations with closed loop responses are required to refine final parameter values.

This approach to parameter tuning can also be carried out using measurements from site, though additional investigation using models would be warranted.

5. Conclusion

This paper has discussed the capabilities of a GFM plant proposed to connect to the NEM. An approach to optimising the performance of the plant considering performance trade-offs and power system requirements was outlined. Lastly an open loop method to efficiently tune plant performance with wide area simulation data was presented. It is important to stress that judgement around system dynamics involved in oscillations which are observed will dictate which GFM control loops are most effective in achieving an improved response.

A key aspect of the performance optimisation that requires emphasis is for the designer to thoroughly understand the strengths and weaknesses of the particular GFM solution and to have a clear understanding of the specific performance objectives and priorities. The paper has shown that a well-designed system can successfully contribute to system strength and have good control performance.

6. Acknowledgements

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7. References

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