Grid frequency support from inverter connected generation.

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Abstract - **This paper presents a case study to demonstrate impact of current fleet of inverter connected generation (roof top photovoltaics and utility scale grid following inverters) that have been allowed to connect to power networks with no obligations to respond to system under frequency events. In this study, a grid forming inverter with droop control and grid following inverter connected to a modified IEEE nine-bus test system have been used to show system impact when inverters do not provide system support, and benefits when such inverters provide system support for under frequency events. The case studies performed show that there is potential for inverter connected generation to support transmission grid frequency subject to renewable resource availability or when backed up by energy storage facilities. There is need for grid codes to be reviewed further to put more obligation on intermittent inverter connected generation to provide more grid frequency support functionality, particularly for under frequency events which are the most common in power systems in comparison to over frequency events.**

Keywords – Frequency control, ancillary services, grid forming inverters, grid following inverters.

I. INTRODUCTION

The modern power system networks are experiencing high growth of inverter connected generation. The vast majority of inverter connected generation being connected to power grids is of grid following type. These typically operate in current control mode and cannot effectively control power system frequency and voltage [1]. The grid forming inverters are emerging technology that promises to address some power system control challenges introduced by increased penetration of grid following inverter connected generation. Various control approaches for controlling grid forming inverters have been investigated by a number of researchers, these include droop control, virtual synchronous machine, virtual oscillator control, matching control and direct power control [2]. In this paper, the grid forming inverter with droop control is investigated to assess its effectiveness as a contributor to the management of power system frequency at transmission voltage level, particularly for under frequency excursions events.

II. A CASE FOR FREQUENCY SUPPORT FROM INVERTER CONNECTED GENERATION

The penetration of inverter connected renewable generation naturally displaces the more expensive to operate synchronous generation. This has a follow-on effect of reducing power system inertia in a power system. Reduced power system inertia results in difficulties to control the system frequency within operating bands mandated by grid operating codes.

The National Electricity Rules (grid code used in the Eastern states of Australia) section s5.2.5.11(c2) requires that generation operate in frequency control and be able to increase active power output in response to a drop in system frequency subject to energy source availability [3]. Renewable power stations tracking available energy resource and constantly generating at their maximum rated output would not provide any support for a underfrequency event. In Western Australian grid code, Technical Rules section 3.3.4.4 (e2), the obligation on non-dispatchable generation is that they must have capability to reduce active power for a rise in system frequency [4]. The Technical Rules do not mandate for intermittent generators to support grid frequency when the power system frequency drops. Western Australia is currently transitioning to Wholesale Electricity Market (WEM) Rules [5] that requires all generation to respond to both over frequency and underfrequency events subject to resource availability, however, the existing generation are grandfathered under WEM Rules clause 1.40.5 and can use a reference standard that applied at the time of their connection. For most renewable generation in service, the reference standard that was applicable when they connected would be the Technical Rules which did not require renewable generation to respond to underfrequency events.

The market data on significant power system frequency excursions published by AEMO via its public market advisory platform [6] shows that in the previous twelve months leading up to June 2021, all the reportable frequency events were under frequency in nature in the Western Australia's South West Interconnected System (SWIS). Figure 1 shows the magnitude of frequency deviation from 50 Hz (nominal power system frequency) for the recorded twenty-two significant frequency events in SWIS from June 2020 to June 2021 published by

AEMO [6]. None of the intermittent generation would have been obligated to provide any under-frequency support under the current requirements of the Technical Rules for any of these events.

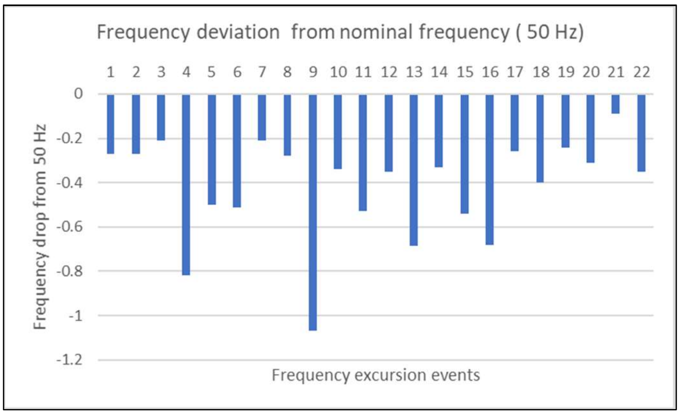

Figure 1: Power system frequency deviation in SWIS, June 2020 to June 2021.

At present there is an increase in trading intervals in Australia's electricity market where prices go negative with a lot intermittent generators frequently re-bidding to higher price bands to avoid generating during the high congestion periods [7]. What this shows is that the system has excess renewable energy capacity in some parts of the day that could be harnessed and used smartly for grid support. There is potential to review generation dispatch practices to use the 'spare capacity' in the renewable generation space in a way similar to 'spinning reserve' in synchronous generation subject to enabling technologies. Grid forming inverters could be that technology in the missing link to make it happen.

The United Kingdom and some countries in Europe are leading the way in aiming for net zero carbon emissions by 2050 [8, 9]. This may see more pressure on Australia to follow suite, and Australian power networks to move towards 100% inverter connected renewable generation in some parts of the day. This will require network operators to have strategies to manage both over frequency and under frequency events for networks dominated by inverter connected generation. One approach to manage would be placing more obligations on renewable generation to employ different dispatch strategies that may include getting inverter connected generation to track available renewable energy resources in real time and re-dispatching continuously to maintain a reserve margin that will give them headroom to respond to both over frequency and underfrequency events. Collocation of energy storage facilities with renewable generation could be made a requirement to support such generation to respond effectively to power system frequency events. This will be a shift from current approach of requiring these generators to respond subject to resource availability to requiring them to manage available resources to ensure that they actively manage their capacity to respond to frequency events.

Literature shows that both grid following and grid forming inverters can be configured to have grid support capability. Grid support enabled inverter can control and produce both active and reactive power to support grid frequency and voltage [10]. The differentiation being that the grid following inverters are typically configured with current source controllers and cannot support grid islands whereas grid forming inverters can. Regulation and technical codes need to harness this technology to support the system frequency management.

A case study has been carried out to demonstrate potential of inverter connected generation to support frequency control in a transmission network. A grid forming inverter employing droop control strategy and a grid following inverter operating as a current source with no grid support functionality have been used in the case study to illustrate benefit of inverter generation providing some support to mitigate under frequency events.

III. ROLE OF STORAGE IN FREQUENCY SUPPORT

There is a notable increase of media coverage in Australia of utility scale batteries installation. Utility scale battery proponents are installing these batteries to store energy during periods of excess renewable resource availability, and to discharge them during peak demand periods to provide short term base load capacity and ancillary services such as frequency regulation [11]. The utility scale batteries can be controlled to inject or absorb active power based on network operating conditions, however, in extended periods of resource unavailability (low wind speeds or cloud cover), the batteries may be drained [12]. In a possible 100% inverter powered grid scenario, diverse technology for storage will be required to ensure power system security and flexibility. Such storage devices may include pumped hydro storage schemes, hydrogen storage and super capacitor banks. Conversely, an inverter connected generation cannot provide an effective response if the energy resource is inadequate to meet system demand at that time, hence storage support would be required to support inverter connected generation to provide dependable frequency support ancillary services. An approach that involves coordination of storage and renewable generation dispatch levels has merit as a solution for power system security and power system flexibility management.

IV. GRID FORMING INVERTER DROOP CONTROL

In droop control method, each grid forming inverter varies its active power according to measured grid frequency at its connection point, and varies reactive power output according voltage amplitude at the connection point [13]. An important attribute of droop control schemes is that they use feedback of power system variables that are measured locally at the inverter terminals for control, and do not require physical communication of control signals between the inverters to make them work together [14]. Figure 2 shows a typical droop control implementation structure for a grid forming inverter adapted from [15].

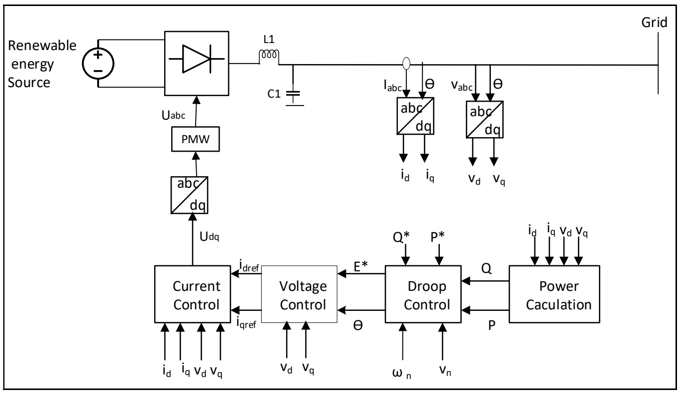

Figure 2: Typical inverter droop control implementation [15]

V. OVERVIEW OF THE 9 BUS TEST SYSTEM STUDY CASES

A nine bus test system as presented by Anderson and Fouad [16] is used as a base case to set up the study cases used in this work. The nine bus test system has three synchronous generators, three loads and six transmission lines as shown in Figure 3. The transmission line and transformer impedances are as shown in Figure 3.

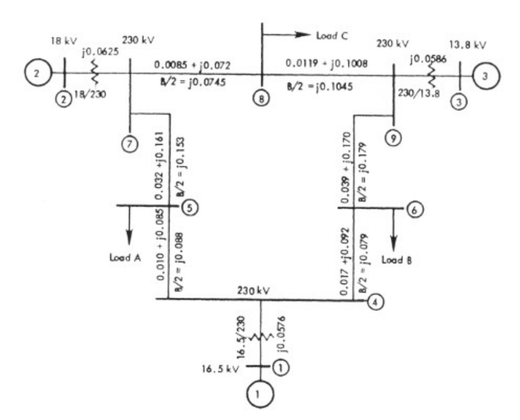

Figure 3: Nine bus test system [16]

Table 1 and Table 2 shows the loads and the three generators dispatch in the nine bus system. The generation rating were assumed as they are not stated explicity in [16], these have been selected to ensure that the generators have headroom to mitigate an under frequency event in the case studies.

Table 1: Nine bus system load details

Load ID	**Bus Number**	**Active Power Demand (MW)**	**Reactive Power Demand in MW**
A	5	125	50
B	5	90	30
C	8	100	35

Table 2: Generation capacity and dispatch

Generator	**Rating (MW)**	**Dispatch (MW)**
G1	168	71.6
G2	400	163
G3	168	85

VI. STUDY METHODOLGY

The 9 bus test system was modified to set up the three study cases as follows:

(a) Nine bus system with three synchronous generators (base case)
(b) Nine bus system with one synchronous generator (G2) displaced by a grid forming inverter with droop control.
(c) Nine bus system with one synchronous generator (G2) displaced by a grid following inverter.

The three synchronous machines are modelled with IEEE exciter models and IEEE governor models in PowerFactory software version 2021. The grid forming inverter is modelled with droop control for both voltage and active power control. The grid following inverter has a phase locked loop (PLL) to track and keep it synchronised to the transmission network system frequency and is modelled as a grid scale photovoltaic system current source. A droop of 5% is assumed for the synchronous generators and the grid forming inverter. Droop settings of 3 - 5% are generally used around the world [11]. The grid following inverter is assumed to be an aggregation of current source roof top solar photovoltaic panels that do not provide any active power response to grid frequency excursions.

A frequency disturbance in each of the three cases is initiated by simulating a generator trip event on generator 3. The system real time responses for each case were recorded and compared and presented in section VII. The post-contingent frequency for each case was observed and compared for each case.

VII. STUDY RESULTS AND ANALYSIS

Figure 4 to Figure 6 show power system responses for a generator (G3) trip for the network with three synchronous generators, network with two synchronous generators and grid forming inverter (droop control), and the network with two synchronous generators and grid following inverter respectively. Figure 7 shows the post contingent system frequency for the three study cases in a single plot. The frequency response for the case with the Grid forming inverter and two synchronous generators is comparable to the case with three synchronous generators. The case with the grid following inverter and two synchronous generators fared the worst as no grid support was provided by the grid following inverter.

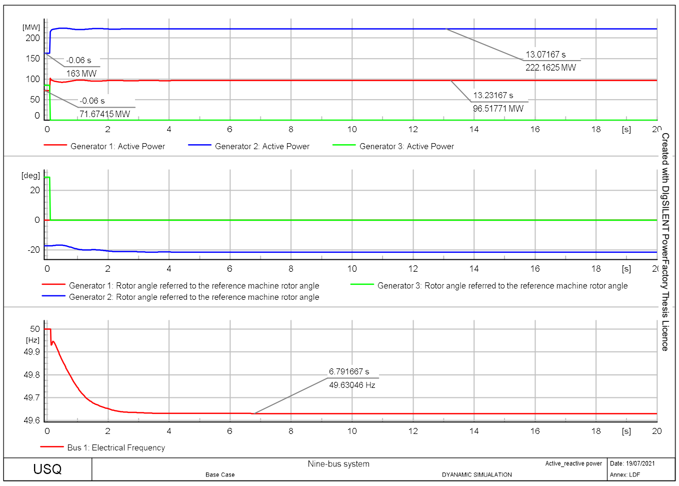

Figure 4: System response when 3 synchronous generators in service

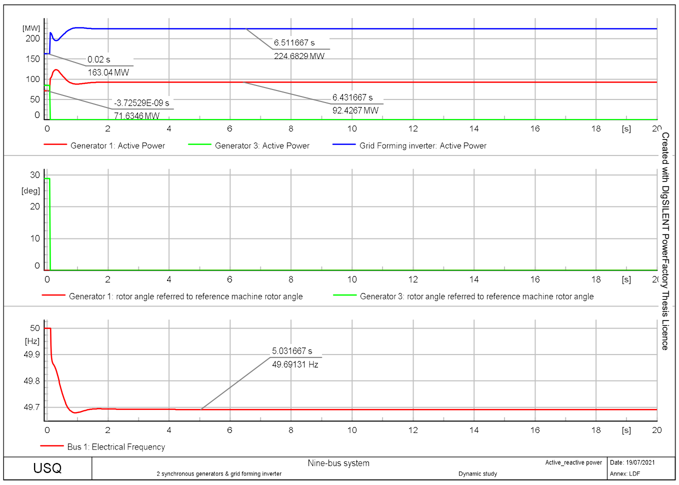

Figure 5: System response when 2 synchronous generators and 1 grid forming inverter in service

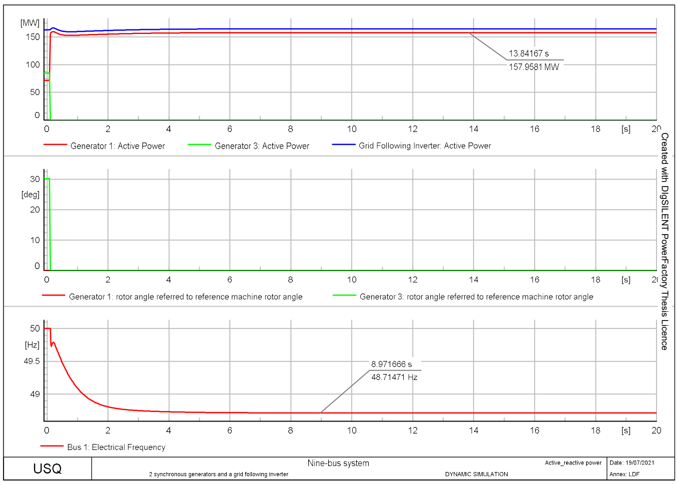

Figure 6: System response when 2 synchronous and 1 grid following inverter generators in service

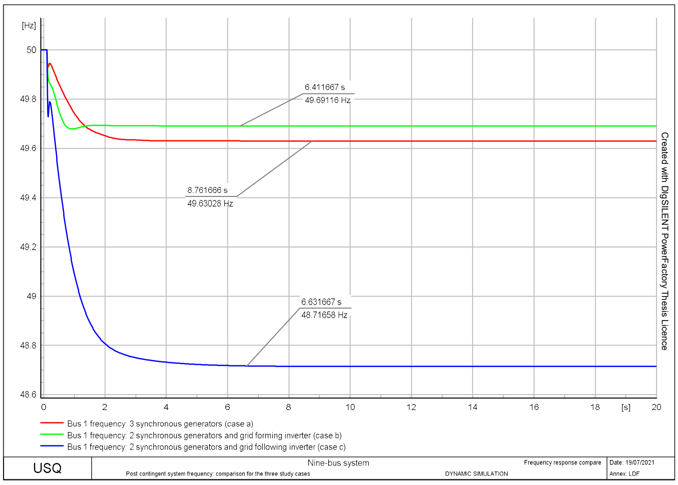

Figure 7: System frequency: performance comparison for the three study cases

In droop control, the relationship between active power and frequency deviation is described by the equation below[17]:

$$\frac{f - f_0}{f_0} = \left(\frac{P_0 - P}{P_0}\right) * m \qquad (1)$$

where f is system frequency, f_0 is nominal frequency, P_0 is rated power of the generator, P is generator active power output corresponding to frequency f and m is droop coefficient.

When generator 3 trips, the two remaining generators pick up and share the additional load, and settle at a new frequency equilibrium as governed by the frequency-active power droop relationship in equation 1. The change in generation output for each of the remaining generation units in parallel will be proportional to their rating output in the load sharing arrangement.

The lost generation G3 is dispatched to 85 MW as per Table 2. When G3 is lost, the output production is shared by the two remaining generators proportional to their rating as both have the same droop setting. Generator G1 is expected to pick up extra 25.15 MW and generator G2 to pick up 59.85 MW in proportion to their active power rating for both study case (a) and (b). For case (c) the remaining reference generator (G1) picks up all the output lost from generation 3 as the grid following is set not to provide any frequency response. The system frequency post contingent is determined by the formula below, rearrangement of equation 1.

$$\Delta f = f_{0*} \left(\frac{\Delta p}{p_0}\right) * m \qquad (2)$$

where Δf is the frequency deviation post generator 3 trip and Δp is the additional power picked up by remaining generators according to droop settings and active power rating. Table 3 shows the calculated system frequency post contingent. The calculated active power responses and resultant system frequency deviation in Table 3 align with observations from PowerFactory study case simulations. The simulations and calculations of case (b) demonstrate that inverter connected generation can provide frequency support subject to renewable resource or storage availability. Case (c) demonstrates the impact of the current practice that places no obligation on roof top solar photovoltaic installations and grid following inverter generators to provide frequency support for under frequency events.

Table 3: Active Power response for loss of G3

Case	**Gen**	**Output Pre-contingent MW**	**ΔP MW**	**Output post-contingent MW**	**Δf Hz**	**Post contingent frequency Hz**
(a)	G1	71.6	25.14	96.74	0.37	49.62
	G2	163.0	59.86	222.86		
(b)	G1	71.6	25.14	96.74	0.37	49.62
	G2	163.0	59.86	222.86		
(c)	G1	71.6	85.00	156.6	1.26	48.73
	G2	163.0	0	163		

VIII. CONCLUSION

In this study, a grid forming inverter with droop control has been used to demonstrate the potential of inverter connected generation to provide transmission grid support for system under frequency events. As inverter connected generation becomes more significant, power system response to significant loss of generation will be poorer if inverter connected generation continue to operate as per current practice, not providing response to under frequency events. There is need for grid codes to be revised to put more obligation on inverter connected generation to provide more grid support functionality, particularly for under frequency events which are the most common in power systems in comparison to over frequency events.

REFERENCES

1. Elkhatib, M.E., W. Du, and R.H. Lasseter, *Evaluation of Inverter-based Grid Frequency Support using Frequency-Watt and Grid-Forming PV Inverters*. 2018, IEEE. p. 1-5.
2. Unruh, P., et al., *Overview on Grid-Forming Inverter Control Methods*. Energies (Basel), 2020. **13**(10): p. 2589.
3. Australian Energy Market Operator. *National Electricity Rules*. 2021 [cited 2021 22 June]; Available from: https://www.aemc.gov.au/regulation/energy-rules/national-electricity-rules/current.
4. Economic Regulation Authority. *Technical Rules*. 2016 [cited 2021 22 June]; Available from: https://www.erawa.com.au/electricity/electricity-access/western-power-network/technical-rules.

5. Economic Regulation Authority. *Wholesale Electricity Market Rules*. 2021 [cited 2021 22 June]; Available from: https://www.erawa.com.au/cproot/21723/2/Wholesale-Electricity-Market-Rules-1-February-2021.pdf.

6. Australian Energy Market Operator. *Market Data Western Australia*. 2021 [cited 2021 9 June]; Available from: http://data.wa.aemo.com.au/#market-advisory.

7. australian Energy Market Operator. *Quarterly Energy Dynamics Q1 2021*. 2021 [cited 2021 23 June 2021]; Available from: https://aemo.com.au/library/major-publications.

8. Pancost, R., et al., *The pathway toward a net-zero-emissions future.* 2019.

9. Akrami, A., M. Doostizadeh, and F. Aminifar, *Power system flexibility: an overview of emergence to evolution.* Journal of modern power systems and clean energy, 2019. **7**(5): p. 987-1007.

10. Rocabert, J., et al., *Control of Power Converters in AC Microgrids.* IEEE transactions on power electronics, 2012. **27**(11): p. 4734-4749.

11. Meng, L., et al., *Fast Frequency Response From Energy Storage Systems-A Review of Grid Standards, Projects and Technical Issues.* IEEE transactions on smart grid, 2020. **11**(2): p. 1566-1581.

12. Garozzo, D. and G.M. Tina, *Evaluation of the Effective Active Power Reserve for Fast Frequency Response of PV with BESS Inverters Considering Reactive Power Control.* Energies (Basel), 2020. **13**(13): p. 3437.

13. Torres, L.A.B., J.P. Hespanha, and J. Moehlis, *Power supply synchronization without communication*. 2012, IEEE. p. 1-6.

14. Chandorkar, M.C., D.M. Divan, and R. Adapa, *Control of parallel connected inverters in standalone AC supply systems.* IEEE Transactions on Industry Applications, 1993. **29**(1): p. 136-143.

15. Rasheduzzaman, M., J.A. Mueller, and J.W. Kimball, *An Accurate Small-Signal Model of Inverter- Dominated Islanded Microgrids Using dq Reference Frame.* IEEE journal of emerging and selected topics in power electronics, 2014. **2**(4): p. 1070-1080.

16. Anderson, P.M. and A.A. Fouad, *Power System Control and Stability (Second Edition)*. 2003: Wiley-IEEE Press.

17. Tayab, U.B., et al., *A review of droop control techniques for microgrid.* Renewable & sustainable energy reviews, 2017. **76**: p. 717-727.