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Benefits of Grid-Forming Distributed Energy Resources in Grid-Connected Scenarios

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SUMMARY

Transmission-connected grid-forming (GFM) inverter-based resources (IBR) have been shown as beneficial in addressing challenges in the bulk power system such as weak grid and reduced physical inertia. Some transmission system operators such as Hawaiian Electric have started requiring GFM capability from transmission-connected battery energy storage systems (BESS). While GFM distributed energy resources (DER) have been used in inverter-based islanded microgrids (at the distribution level), it is still an open question as to whether there are benefits to operate the DERs in GFM mode when they are grid-connected under blue-sky scenarios.

Leveraging a real distribution feeder model and generic white-box models of GFM and grid-following (GFL) DERs, this paper explores the potential use cases for GFM DERs in grid-connected operation. The preliminary results from the simulation studies show that GFM DERs may be used to improve the grid strength and stability of the distribution systems to enable higher DER penetration. Meanwhile, it may also help mitigate or prevent fault induced delayed voltage recovery (FIDVR), which improves power quality of the distribution systems.

KEYWORDS

Distributed Energy Resources (DER), fault induced delayed voltage recovery (FIDVR), grid-forming inverter, power system stability, weak grid

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1 Introduction

Driven by the net-zero emission goals, an increasing amount of renewable energy resources are being integrated into power systems worldwide. Such renewable resources often connect to the power system through power electronics interface and are typically referred to as inverter-based resources (IBR). Due to the increase in IBR capacity and the retirement of large central synchronous generators (SG), the grid strength of certain areas of the bulk power system can be reduced. This can challenge the stable operation of today's IBRs, which are mainly designed to operate in the presence of (or parallel with) a stiff power system [1],[2].

To deal with the challenges, improvement of the present-day control design and various new forms of inverter controls have been proposed [3]. These controls are termed as "grid forming (GFM) inverter control" due to their capability in forming a voltage and operating without relying on SGs [1]. The benefits of utilizing GFM inverter control in weak transmission system locations to improve grid strength and system stability have been relatively well understood. Some transmission system operators such as Hawaiian Electric have started requiring GFM capability from transmission-connected battery storage systems (BESS).

However, on the distribution side, there is presently a lack of understanding regarding the need or value in utilizing GFM inverter control in distributed energy resources (DER) under blue-sky scenarios. Even though GFM inverters have been applied in inverter-based microgrid design, they are typically switched to grid-following (GFL) mode when connected to grid. This may not continue to be a reliable mode of operation as distribution-connected solar generation (both utility-scale and residential) and BESS proliferate the grid, and gradually constitute higher percentage of the overall system generation capacity.

This paper first investigates the possibility of DER instability under high DER penetration and weak grid conditions, and evaluates possible solutions including leveraging transmission- and distribution-connected GFM BESS to stabilize the DER operation. Whether transmission-connected GFM IBRs are sufficient or GFM DERs are needed to stabilize the DER operation is investigated through electromagnetic transient (EMT) simulation studies. In addition to improving stability of the distribution system, the fast reactive power support and voltage regulation capability of GFM DERs may also be leveraged to improve power quality of the distribution system, such as mitigating or preventing fault induced delayed voltage recovery (FIDVR). This aspect is also investigated, and preliminary results are presented in the paper.

The rest of the paper is organized as follows. In section 2, the transmission and distribution test system utilized in this work is discussed in detail. In section 3, a weak grid condition is simulated in the test system, and the challenges in operating a large DER in this weak grid condition is discussed. Subsequently, the potential use case of GFM DER to stabilize the distribution grid is discussed and compared with the transmission-based GFM solutions. In the next section, FIDVR is simulated by integrating single-phase motor loads representing HVAC units, and subsequent improvements to the voltage recovery due to addition of GFMs are studied. The last section concludes the paper.

2 Description of the Test System

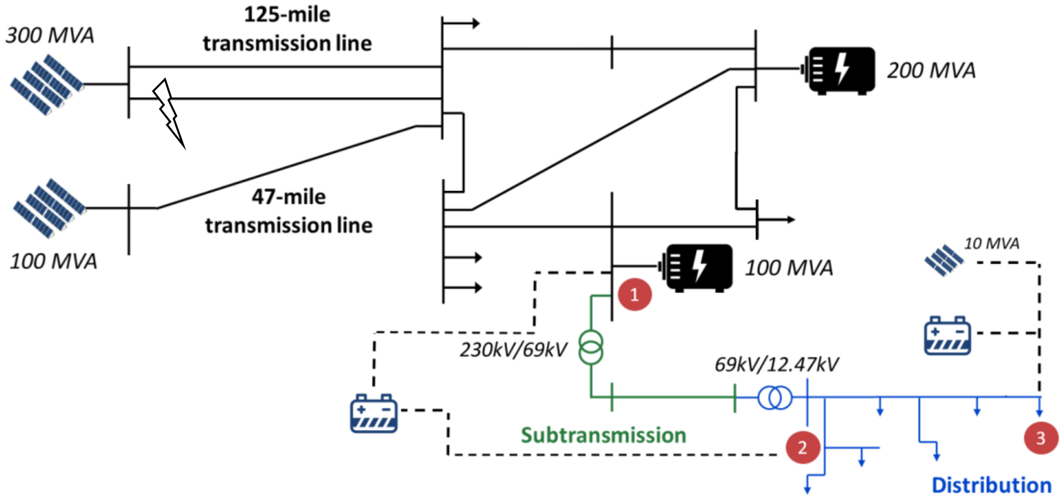


Figure 1 Transmission and Distribution Test System

In this study, an electromagnetic transient (EMT) model of a test system consisting of a simplified 230kV transmission network, a 69kV sub-transmission line, and a real-world 12.47kV distribution feeder is simulated using PSCAD/EMTDC. The test system is shown in Figure 1.

The transmission system includes two SG based central power plants with a total rating of 300MVA. In addition, two PV plants are transferring power to the load center through long transmission lines. The PV plants are IBRs with voltage and frequency droop control implemented in the plant controller, which represents most of today's transmission connected IBRs. Even though they have the capability to support grid voltage and frequency, due to the slow response of the plant controller, they cannot operate without SGs and hence are termed as GFL IBRs. Finally, the real-world radial distribution feeder is connected to the transmission system through a sub-transmission line. All the loads in the distribution feeder are represented as single-phase loads, which consist of both constant impedance and HVAC motor loads. The percentage of motor load varies in different studies. The loading (around 4MW) in this distribution feeder is unbalanced across the phases. Note that only one distribution feeder is modeled in detail. All other distribution systems and loads are aggregated and modeled as constant impedance loads directly connected at different locations of the transmission system.

To study various aspects of the potential benefits offered by GFM DER, the test system is modified in Sections 3 and 4 by changing the profile of generation as well as the connected loads. In Section 3, to investigate the potential challenges operating GFL DER under weak grid conditions, a 10MVA GFL PV plant is connected at the end of the distribution feeder (location 3 in Figure 1). In addition, GFM battery energy storage system (BESS) is modeled and placed at various locations to evaluate the potential benefit in supporting system stability. In Section 4, GFM BESS is placed at different locations on the distribution feeder to evaluate the impact on FIDVR. In all the scenarios shown in this paper, the BESS is operating with a power reference P_{ref}=0MW (idle when grid frequency and voltage are nominal but provides frequency and voltage response during or following disturbance).

3 Potential Use Case of GFM DERs to Improve Distribution Grid Strength and Stability

In this section, the test system in Figure 1 is utilized to show that a GFL DER connected at a weak distribution feeder location may become unstable following a fault in the transmission network. Further, the use of GFM DER as a potential solution is discussed along with their locational impacts.

3.1 Challenges to IBR Operation in Weak Grid Scenarios

As IBR penetration increases, weak grid scenarios may occur in both transmission and distribution systems. On the transmission side, weak grid challenges can be demonstrated in the test system by retiring the 100MVA SG. After the retirement, 75% of the transmission-connected generation capacity is inverter-based, which leads to small-signal instability of the system (growing oscillations in system voltage and frequency). Note that the percentage of IBR that can lead to instability depends heavily on many factors such as system topology, IBR functionality, and load characteristics. Therefore, the percentage obtained from this study should not be generalized to other systems. Moreover, the voltage and frequency waveforms are not shown for this scenario since the focus of the paper is on distribution system.

The transmission system can be stabilized by adding a 45MVA GFM BESS to the test system at location 1, the transmission side of the long 69kV sub-transmission line. Note location 1 is selected in this study as it is closest to the distribution feeder and is expected to have good stabilizing impact on both transmission and distribution systems. Other locations can be similarly studied. The BESS is assumed to be fully charged, online, but operates in an "idle" mode with a power reference P_{ref}=0MW. The GFM BESS is modeled using a generic white-box model [4],[5]. The GFM BESS has droop control and responds to voltage and frequency disturbances with fast reactive and active power response. Once the system reaches steady state, a 3-phase fault is simulated at a time t=10s on the transmission line close to the 300MVA PV-based generation, as shown in Figure 1. The fault is cleared without tripping the line after 0.1s. The performance of this system for this transient is shown in Figure 3, which shows the real and reactive power at each generator bus and voltage at various locations in the system. This result clearly shows that the test system is both small-signal stable and transient stable following the fault. Additionally, 45MVA is found to be the minimum GFM capacity required at location 1 to attain stable system characteristics.

It is worth mentioning that the distribution feeder model is included in this study where the loads are modeled as constant impedance loads. Moreover, no DER is considered in this study and the weak grid challenges with large DER is analyzed next.

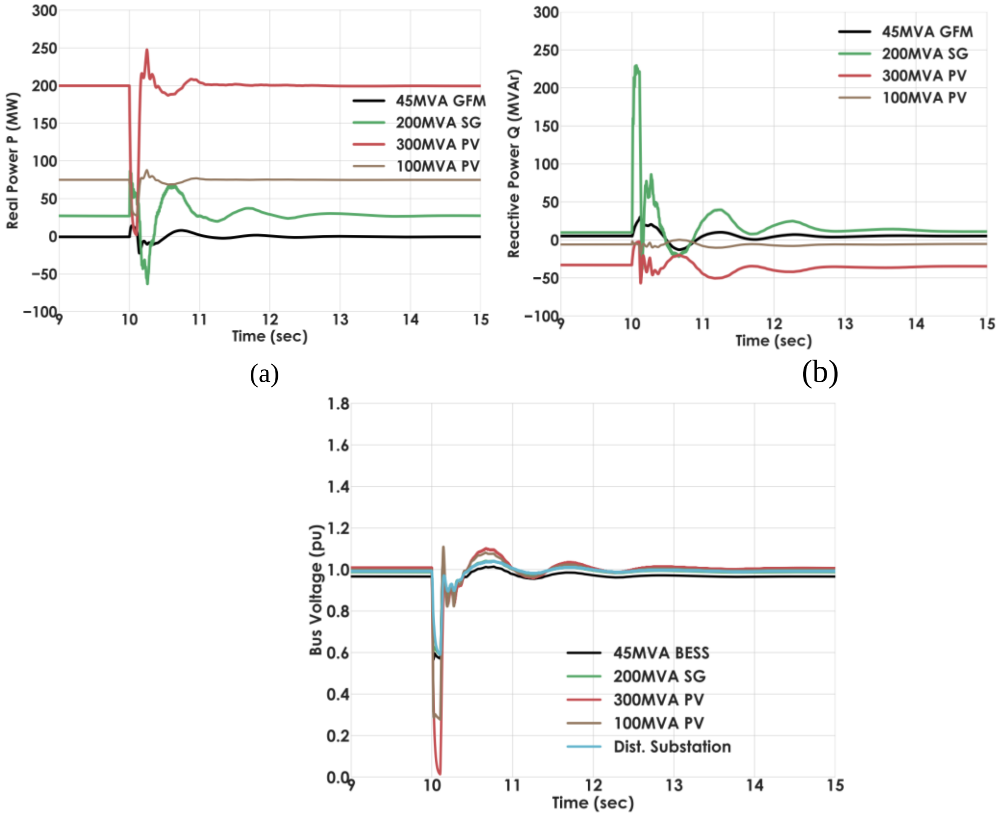


Figure 2 Performance of the overall system with 45MVA GFM BESS in location 1 (a) Real Power (in MW), (b) Reactive Power (in MVAr), and (c) Voltage (in pu)

In the same test system, a 10MVA PV plant, operating as a GFL DER, is added to the end of the feeder at location 3 in Figure 1. EPRI's white-box EMT PV inverter model [6] which follows IEEE 1547-2018 is utilized in the study to represent the GFL DER. The GFL DER has volt-var function activated with default Category B settings specified in IEEE 1547-2018. It does not provide dynamic voltage support under abnormal voltage conditions and the frequency-watt function is turned off. The DER is operated at a 1pu real power setpoint, which effectively results in back- feeding from the distribution to the transmission network. The same transmission fault is applied at the time *t*=10s. Figure 3 below shows the voltage at various buses in the system. The result clearly indicates instability of the DER after fault clearance. This instability is seen to affect voltage significantly on the distribution feeder, and at the transmission system buses as well; the impact at the transmission system is less due to the relatively small size of the DER compared to the transmission-connection generation. It should be noted that DER trip settings are disabled in the study to better observe the instability. In practice, the large voltage and frequency deviation will trip the DER shortly after the fault.

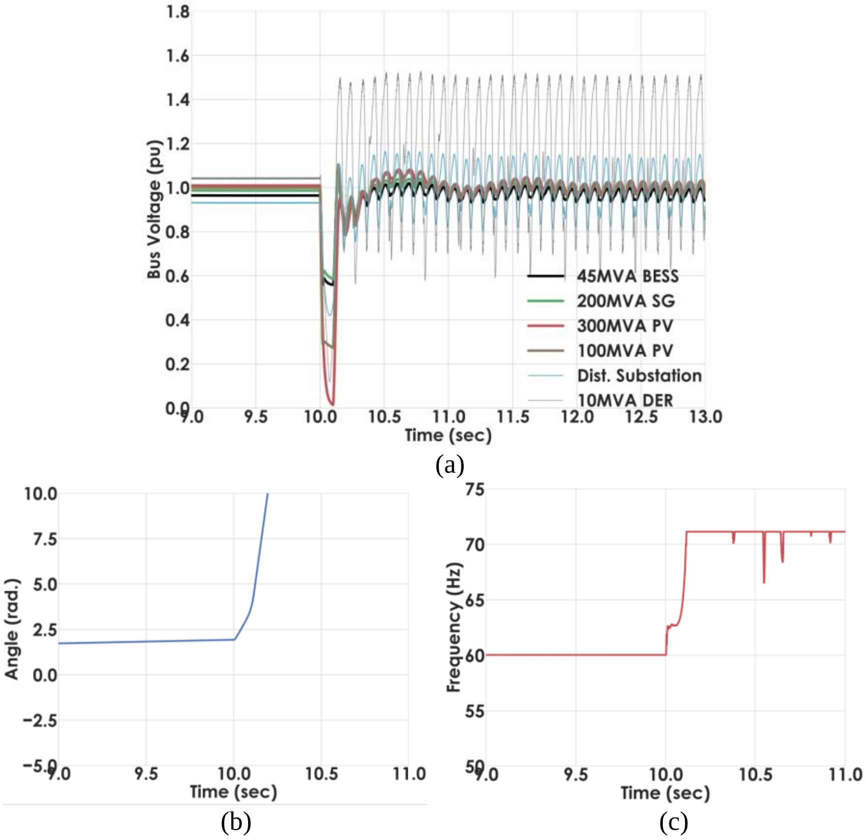


Figure 3 Impact of DER instability on overall system voltages (a) Voltage (in pu) at various buses in the system (b) Angle of DER (in rad), and (c) Frequency of DER (in Hz).

Effectively, with the presence of a long sub-transmission line, along with the connection of the DER to a remote location in the radial distribution network, the voltage sensitivity to DER current injection is high, which subsequently leads to the phase locked loop (PLL) losing angle synchronism with the rest of the system after fault clearance (as can be seen in the DER angle and frequency plots in Figure 3). Note the PLL frequency saturates at 72Hz because a limit of 20% deviation was implemented. More details of the instability mechanism can be found in [2]. This demonstrates that DER instability can occur even if the transmission system is stable before interconnection of the DER, as shown by the results in Figure 3.

3.2 Possible Solutions

While there are several options to improve system strength and facilitate high penetration of DERs, this work specifically explores the use of GFM BESS as a resource, especially, in distribution system to provide stability-related services. To evaluate this, a 4MVA GFM is added at location 2 of the test system in Figure 1. Again, the generic white-box model is used to model the GFM BESS in PSCAD. Similar to the transmission-connected BESS, the GFM BESS in location 2 is also set to operate with a P_{ref} = 0MW. The results from this study are shown in Figure 4, which suggests that the addition of the 4MVA GFM enables stable operation of the DERs for the transmission system fault considered. In other words, the 45MVA transmission-connected BESS together with the 4MVA GFM BESS in distribution system can stabilize the overall system including both transmission and distribution.

Another potential solution is to further increase the capacity of transmission-connected GFM BESS from the value reported in Section 3.1 to stabilize the DER. To evaluate this solution, the size of GFM BESS at location 2 is further increased to determine the minimum capacity of the installation that stabilizes the overall system. Through successive trials, a 90MVA GFM BESS at location 2 is shown to stabilize the DER and provide the same system performance as Figure 4. However, due to the long electrical distance between the transmission-connected GFM and the GFL DER, additional 45MVA GFM BESS capacity is needed at the transmission location 2, which is much greater than 4MVA if the GFM BESS is distribution connected. This suggests that instability of GFL DER can be more effectively addressed by placing GFM BESS electrically closer to the DER, if possible.

Essentially, the results from this preliminary case study suggest the importance of location and size of GFM IBRs in providing grid strength. It shows that with increasing inverter-based DER penetration, if GFM IBRs are only utilized in the transmission network, it can be infeasible or the GFM IBR capacity required can be very large to stabilize the DERs. In comparison, utilizing both transmission and distribution connected GFM IBRs may be an effective way to stabilize the overall system while reducing the total amount of GFM IBR capacity needed.

Regarding the reason for the stability improvement by the GFM DER, some preliminary results have shown that its fast reactive power response is the main contributor [7]. This aspect is being further explored. Moreover, how grid strength can be quantified in an inverter-dominated power system and whether and how grid strength can be leveraged as a metric to indicate the risk of GFL DER instability and the stability improvement by GFM DER is under investigation.

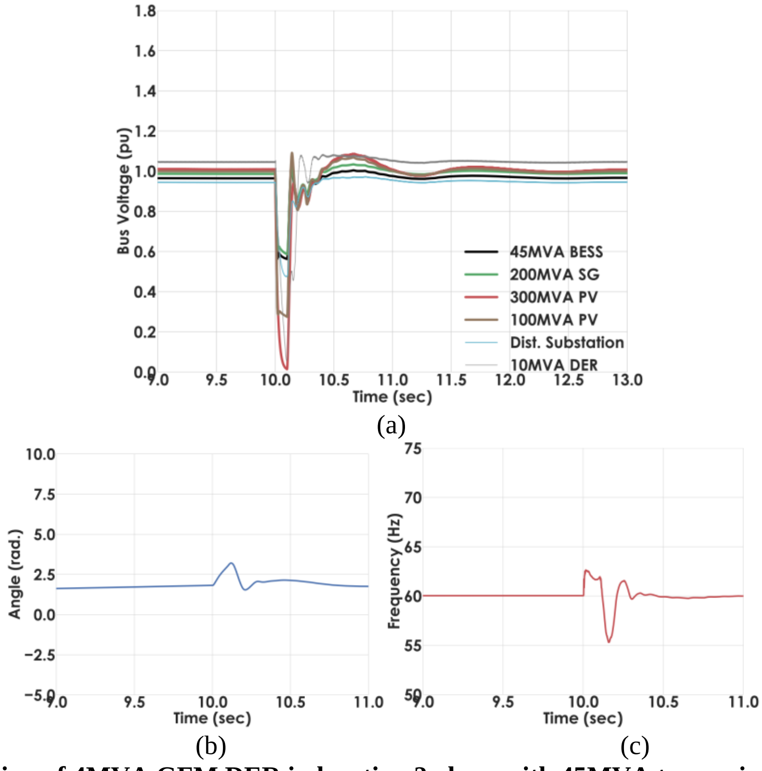


Figure 4 Addition of 4MVA GFM DER in location 2 along with 45MVA transmission-connected BESS at location 1 (a) Voltage (in pu) at various system buses (b) Angle of DER (in rad), and (c) Frequency of DER (in Hz)

4 Potential Use case of GFM DERs in Mitigating FIDVR

While the previous section discussed the value of GFM DER in stabilizing the distribution system and enabling higher penetration of the DERs, in this section, the utility of GFM DERs in improving power quality, specifically, in mitigating or preventing FIDVR is investigated through simulation studies.

4.1 FIDVR on a Distribution Feeder without DERs

FIDVR is an issue that occurs predominantly due to the stalling of single-phase induction motors in residential HVAC units during fault. Previous research [8], [9] suggests that single-phase induction motors are more susceptible to stall due to their smaller inertia compared to three-phase motors. In addition, previous research has also suggested that the severity of the voltage dips determines whether a motor recovers to pre-fault speed or remains stalled after the fault clearing.

Depending on the feeder characteristics, load compositions, and the severity of disturbance, a certain percentage of motors on the distribution feeder can stall after a fault. The stalled motors draw a large amount of current from the feeder resulting in high consumption of real and reactive power. Subsequently, this results in the post-fault voltage recovering to a value (e.g., 0.8pu) that is below the pre-fault value. The thermal protection in the stalled motors disconnect them from the grid between 5-30s after the onset of stall. This study focuses on the period from the onset of fault to the time the motors are tripped by thermal protection and examines the impact of GFM DERs in preventing the motors from stalling. Following the tripping of the stalled motors, there can be further voltage variations caused by the action of voltage regulation devices, restarting of the tripped motors, etc., which are not considered in the study.

The residential HVAC units in this study are represented by an induction motor model that drives a reciprocating compressor. The development of this model in EMT domain is discussed in [10]. As mentioned above, while a typical HVAC unit stalls for 5-30s before the thermal protection trips the unit, in this model, this is represented by a relay that trips the unit 5s into the stall phase. The shortest tripping time within the reasonable range is selected so that the issue can be studied with a reasonable simulation time. Note this is not expected to affect the conclusion of the study.

To simulate this issue in the test system in Figure 1, the distribution feeder loads are updated to a combination of 50% constant impedance loads and 50% aggregated motor loads representing single-phase HVAC units. In addition, for this study, the distribution system does not have any DERs connected. In the transmission system, the available generation is changed to represent a stable system with 50% renewable-based generation. In the test system in Figure 1, both the SGs are online, along with the 300MVA PV-based generation.

In this base case without GFM DER, a 3-phase fault is applied at transmission location 1 at a time t=12s after the system reaches steady state; the fault is cleared after 0.15s. The black curve in Figure 5 shows the voltage at the distribution substation, middle of the distribution feeder, and end of the feeder. This specific transmission fault results in stalling of about 83% of the motor loads on the feeder. The effect of this can be clearly seen in the figure where after fault clearance the system voltage recover to only about

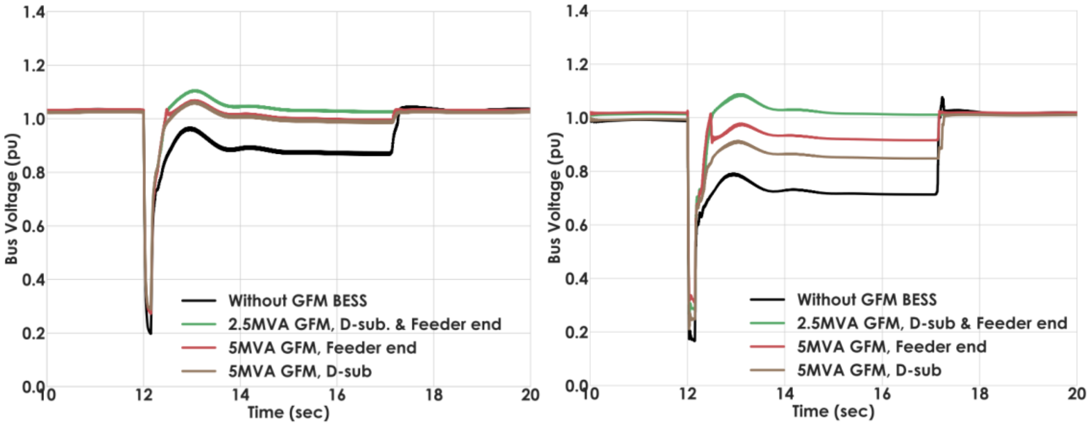
80% of the pre-fault levels due to the large power consumption by the stalled motor. Once the stalled motors are tripped by thermal protection about 5s after the beginning of stall, the system voltage recovers to nominal values. Note that since the focus of this study is on the power quality of distribution feeder, only one feeder is considered. The aggregated load on this feeder is quite low compared to the total generation capacity in the transmission system. Therefore, FIDVR is only observed on the distribution feeder but not in the transmission system.

4.2 Impact of GFM DERs

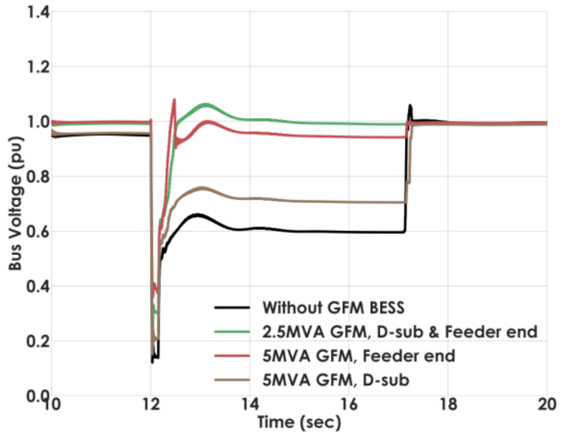
Considering the ability of GFM IBRs to provide quick reactive power support for changes in voltage at their terminals via their reactive power – voltage droop, they could be potentially utilized in reducing the voltage dip following transient events in the system, effectively mitigating or preventing motor stall and FIDVR. To evaluate this, GFM BESS operating at a P_{ref}=0MW, similar to Section 5, is utilized in the distribution system.

To evaluate the impact of location of the GFM BESS in the distribution system, three different scenarios are studied. In the first scenario, a 5MVA GFM BESS is installed at location 2, while in the second one, the 5MVA GFM BESS is placed at location 3 at the end of the distribution feeder. In the last scenario, 2.5MVA BESS is placed at locations 2 and 3. In each scenario, same as in the base case, a 3-phase fault is simulated at location 1 at a time t=12s, and cleared after 0.15s.

The results in Figure 5 show the voltage at different locations in the distribution system around the time of the fault. While the results clearly show that each case with a GFM DER improves the feeder voltage during FIDVR compared to the case without any GFM DER, the case with 2.5MVA GFM BESS at the locations 2 and 3 is most effective as it completely prevents the occurrence of FIDVR. In the scenario with 2.5MVA GFM BESS at the locations 2 and 3, the feeder voltage returns to pre-fault levels immediately after fault clearance.



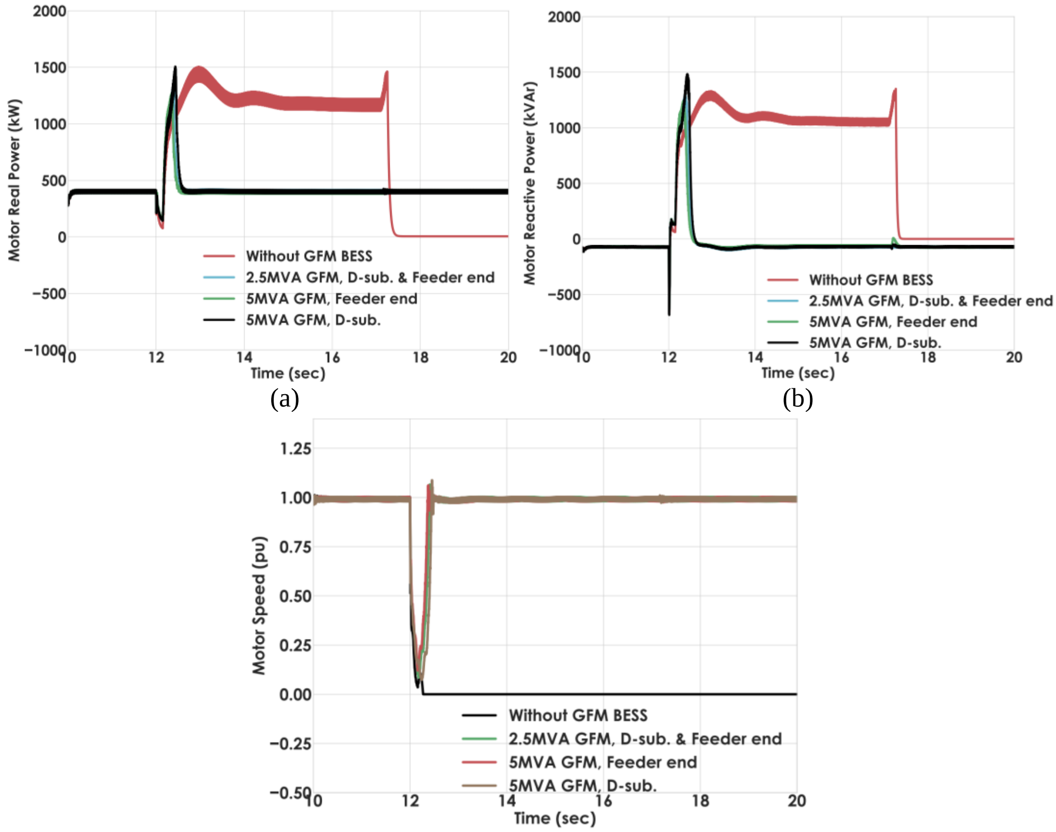
(a) (b)



(c)

Figure 5 Voltage (in pu) at the (a) Distribution substation, (b) Middle of the feeder, and (c) End of the feeder for a transmission system fault at t=12s and tripping of stalled motors at 17s

Additionally, Figure 6 shows the response from an aggregated 850kW single-phase motor load in the system. This load represents about 200 residential HVAC motor modeled as a single aggregated motor load. The figure shows that in the case without any GFM DER, the 850kW aggregated motor stalls after the transmission fault; during the stall phase, the motor draws much higher real and reactive power from the system causing depressed feeder voltages. The other scenarios with GFM prevent stalling of this motor, resulting in return to pre-fault operating levels right after fault clearance.



(c)

Figure 6 Performance of a 850kW aggregated motor load (a) Motor Real Power (in kW) (b) Motor Reactive Power (in KVAr), and (c) Motor Speed (in pu)

Further, the below table also summarizes and compares the percentage of motors that stall in each scenario, which further shows the dependence of location and rating of the GFM BESS in influencing the occurrence and severity of FIDVR. The percentage is calculated by comparing the total power consumption from all the motor loads before the fault and after the voltage recovery.

Table 1 Motor Stall with various configurations involving GFM BESS

Scenario	% Motor Stall
Without GFM BESS	83.3
5MVA GFM BESS, location 2	26.6
5MVA GFM BESS, location 3	18.5
2.5MVA GFM BESS, locations 2 and 3	0.0

5 Conclusion

This paper presents preliminary results on the potential use cases of GFM DERs in grid-connected blue-sky scenarios. The simulation case studies show that GFM DER may strengthen the distribution grid and stabilize grid-following DER connected at weak distribution locations. Moreover, preliminary results indicate that a small GFM BESS in the distribution system can provide similar stabilizing effect to the grid-following DER as a much larger sized transmission-connected GFM BESS. In addition, the potential use case of GFM DER in mitigating FIDVR is investigated and the GFM DERs are shown to effectively reduce the percentage of motors that stall during a fault improving the voltage recovery.

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