Robust Control Design and Testing of Grid Forming Converter with Main Grid Disturbances

Sushobhit Sharma
Department of Electrical Engineering
National Institute of Technology Warangal
Telangana, India
ss22eem3r22@student.nitw.ac.in

M. N. Alam
Department of Electrical Engineering
National Institute of Technology Warangal
Telangana, India
mnalam@nitw.ac.in

***Abstract*—This paper presents a comprehensive study on the role and performance of Inverter-Based Resources(IBRs) in grid stability, particularly focusing on the transition from Grid Following Mode (GFL) to Grid Forming Mode (GFM). The limitations of GFL, such as its inability to sustain disturbances and operate autonomously in weak grids, are discussed. The paper highlights the advantages of GFM, which allows IBRs to quickly respond to system changes, aiding in grid stabilization. While GFM is currently prevalent in islanded microgrids. In the context of the GC0137 standards, various GFM control strategies are tested on a test model and their performance is validated on MATLAB Simulink with different real time scenarios.**

***Index Terms*—AC Microgrids, Energy Storage Systems, Grid Integration, Grid Forming Inverters, Grid Stability, Inertial Response.**

I. Introduction

The transition towards Renewable Energy (RE) is accelerating in very fast pace that aim for net zero emissions is also transforming our power grid. Traditionally Coal Power plants utilized synchronous generators which are now being substituted with Inverter Based Resources(IBRs) such as solar power plants and Battery Energy Storage Systems (BESS). This shift towards a power grid made dominance of IBRs changes the way of grid functionalities. Consequently, IBRs are now tasked with providing key services to maintain a dependable, robust, and secure grid. This setup which can provide power within electrical boundaries can be termed as Microgrid.

Microgrids, self-reliant mini power grids, harness Renewable Energy Resources, including Photovoltaic Solar power. BESS are used to enhance the reliability of these installations, storing energy for use when solar power is not available. Particularly useful in rural areas without existing power infrastructure [1], microgrids offer a decentralized system. They have proven valuable during unexpected disasters or weather changes, providing reliability where traditional power grids may fail. However, relying solely on Battery Storage Systems has its limitations. Supercapacitors, expected to become more prevalent in future electrification and energy storage, can overcome these challenges by helping to manage transients during sudden shifts to DC sides.

Voltage transients in grids or sudden shifts in voltage levels can cause frequency drops in power systems. These transients can be caused by various events like lightning strikes, switching operations, grid faults, or natural disasters. While they were known to potentially damage equipment, their impact on frequency stability is often overlooked. Transients can disrupt the power balance, causing frequency shifts and system instability. Hence, strategies to mitigate voltage transients effects on frequency stability are urgently needed.

Presently Power system operators in India use a variety of measures to prevent and correct issues [2]:

1) Surge Protection: Devices like surge arresters and transient voltage suppressors are installed to control the size of voltage transients entering the system, which helps to lessen their impact on frequency.
2) Voltage Regulation: By applying effective voltage regulation strategies, voltage levels can be kept steady within acceptable limits, which helps to reduce the occurrence of voltage transients.
3) Reactive Power Compensation: The use of reactive power compensation devices such as capacitors and reactors enhance the system dynamic response to voltage transients, which assists in frequency regulation.
4) Grounding and Bonding: Establishing a low-impedance route for transient surges to dissipate through proper grounding and bonding can lower the risk of electric shock and electromagnetic interference.
5) Harmonic Filters: The use of filters to lessen the effects of harmonics on high-voltage systems can be effective in reducing the effects of transients.

By implementing these strategies, power systems can effectively lessen the impact of voltage transients, ensuring the stability and reliability of the electrical infrastructure. But with increased IBRs these integrated systems will be more complex to control as these strategies made with consideration of Traditional Synchronous generation system grid, so Modern controls are required to implement in IBRs which mimics as Synchronous generators. This paper contributes in design of GFM inverters controls along with simulation testing of these controls on different scenarios as per Grid Forming Standards given in GC0137 [3].

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II. GFL v/s GFM Mode Control Infrastructure

GFL inverters in power systems synchronize with the grid voltage and frequency, controlled by synchronous generators. They detect the grid voltage, synchronize, and modulate their voltage based on the grid configuration, controlling their current and power exchange. However, in low-strength grid conditions, GFL inverters may struggle to maintain synchronization, potentially causing instability and negatively impacting grid performance.

Fig1 shows a traditional switching converter with an inductive-capacitive (LC) filter, controlled to function as a GFL inverter. For synchronization with the grid, the detected voltage is supplied to a specific synchronization component that determines its phase angle and frequency. This phase angle is then input into other control units. For power management, the observed grid voltage and current are initially used to compute the exchanged real and reactive power. These are then supplied to a power control unit. This unit computes the necessary current that the inverter must inject to reach the desired power set points. The computed current set points are then supplied to a current control unit that sets the references for a pulse-width modulation (PWM) block. This block is responsible for generating the inverters switching commands. On the other hand,GFM inverters set their own frequency and voltage reference [4] based on the power they are supplying, rather than merely following the grid voltage and frequency. In few scenarios where the grid becomes weak, GFM inverter continues to perform seamlessly, maintaining the grid voltage and frequency stability.

When multiple GFM inverters operate in cascade, they coordinate their movements and adjust their power output to compensate for any inverter who is losing its strength for ensuring the grid stability. This requires expert fine-tuning and adjustment of control settings, considering the overall system characteristics and requirements. GFM control in inverters synchronizes with the grid while maintaining constant internal voltage for steady power injection, allows IBRs to quickly respond to system changes, aiding in grid stabilization.

GFM inverters have the capability to offer a wider range of services to power systems compared to GFL inverters. Despite this, their structural design is essentially the same as traditional GFL inverters, including key components such as switching converter, energy source, dc supply link, control board & output filter. The primary distinction between GFM and GFL inverters is found in their synchronization and control logic. Moreover, it is important to note that both GFL and GFM inverters are types of voltage source converters. Conversely, The GFM inverter controls its power exchange with the grid by adjusting the voltage size, frequency, and angle at its connection point. This is done through a cascade control structure where a primary loop sets the voltage angle and size for an inner control loop [5]. This inner loop then provides the references for the PWM block. This process is depicted in Fig 2 as a standard GFM inverter system. The primary control function is to set the frequency (and angle) and

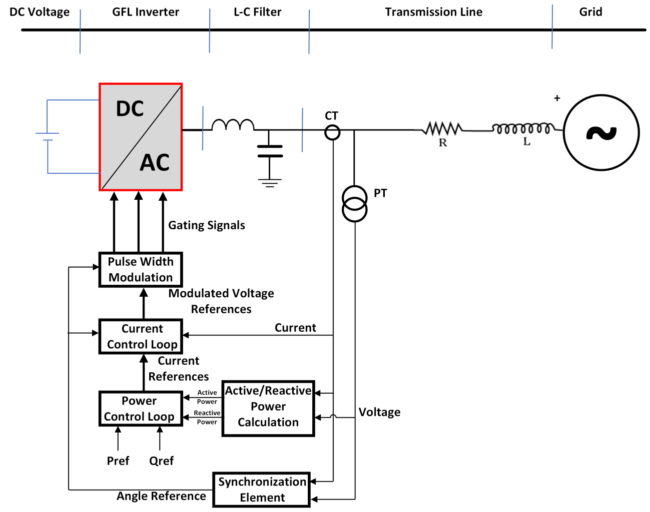

Fig. 1. Control Architecture of Grid Following Mode

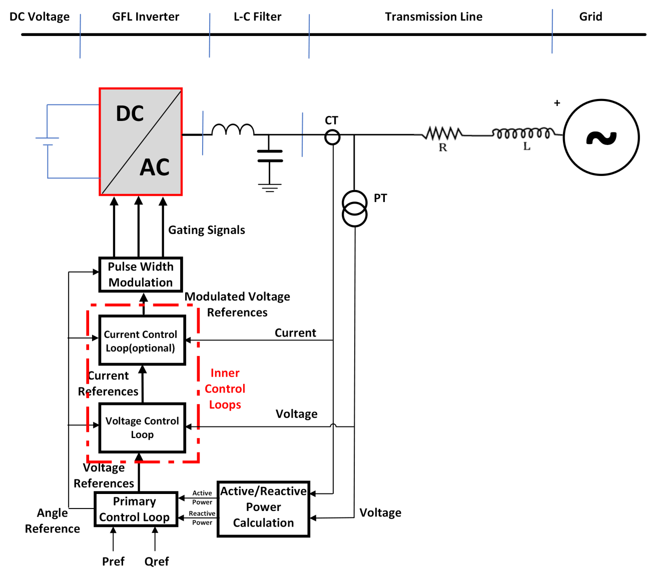

Fig. 2. Control Architecture of Grid Forming Mode

voltage references of the GFM inverters, based on the active and reactive power, assuming these elements are independent and guarantee grid synchronization. The primary loop sets the target for the voltage size and frequency, taking into account the error. The primary control loop in GFM inverters manages the synchronization functionality and adjusts the reference frequency based on changes in real output power. This is due to the strong correlation between real power and frequency, and reactive power and voltage magnitude in power systems. Two methods, droop and virtual synchronous generator(VSG) controls as shown in Fig 3 given in literature [5] are used in different types of GFM inverters. The droop method, which originates from power-sharing concepts between parallel synchronous generators, adjusts the reference frequency proportionally to power changes.

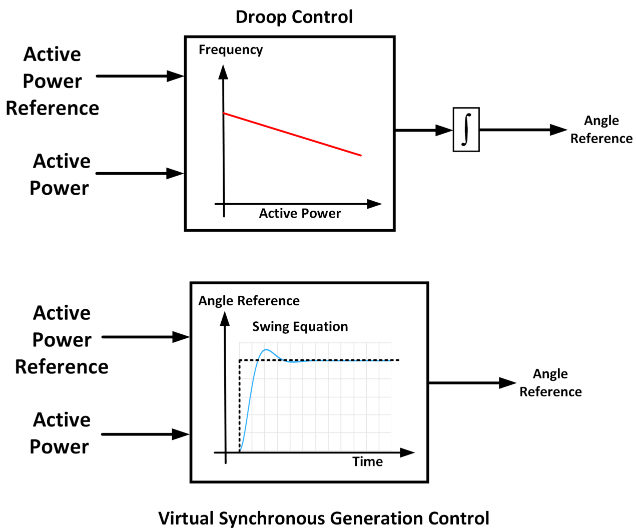

Fig. 3. Types of GFM control

On the other hand, the VSG method uses the swing equation, a second-order characteristics oscillation equation of synchronous generators [5], to balance a machine kinetic energy with the electrical power it produces. This method mimics the behavior of synchronous generators and provides an inertial response for inverters.

Despite the different contexts in which droop and VSG techniques have evolved, they are functionally similar when a low-pass filter accompanies the droop gain in the power path in the droop method.

The primary control loop sets the voltage magnitude reference based on the reactive power. The voltage reference is determined by the difference between the observed and reference reactive power, similar to the operation of the GFM inverter frequency control loop. This operation can be executed using a variety of techniques, including the droop characteristic, filtered droop characteristic, or the second-order characteristic (rotor-flux model characteristics) [6].

Recent adjustments to the Rate of Change of Frequency (RoCoF) limits are crucial for power grid stability. They provide flexibility in reducing inertia floor, accommodating variations from Inverter-Based Resources (IBR) and preventing relay tripping. They also maintain system strength, linked to voltage integrity and waveform stability. Synchronous generators reinforce this by providing reactive power support and maintaining short-circuit current levels [6]. However, increasing IBR penetration can compromise system strength. Adjusting RoCoF helps prevent generator trips that could disrupt grid stability [7]. In this Test setup study that factor is also considered.

III. GFM Inverter Capabilities and Control Block

GFM inverters play a crucial role in enhancing the stability of the power system. They should be able to deliver the same services as current GFL inverters but with superior performance. The control architecture of the GFM converter is shown as below in Fig 4

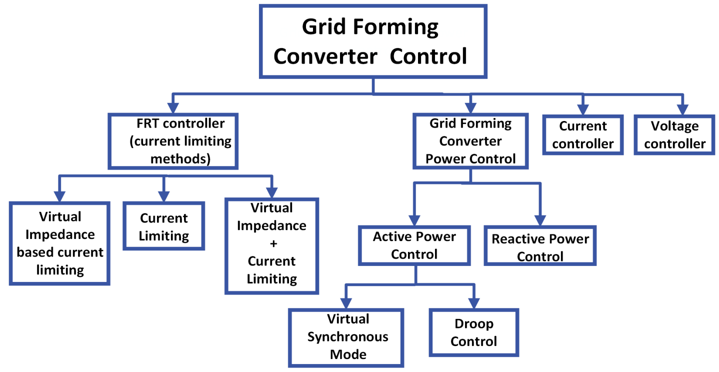

Fig. 4. Architecture for control strategy of GFM converter

Furthermore, GFM inverters might be required to offer new services, such as the capability to reboot a power system following a blackout, a process often known as a black start. The services offered by GFM inverters depend on their capabilities and can be categorized into "core" and "additional" . The core capabilities include:

1) Fast and inherent current injection: This allows for rapid adjustment of current levels.
2) Primary and fast frequency response: This ensures the system can quickly respond to changes in frequency.
3) Surviving the loss of the last synchronous connection: This means the system can continue operating even if the last synchronous connection is lost.
4) Oscillation damping: This helps to stabilize the system by reducing oscillations.
5) Weak grid operation and system strength support: This allows the system to operate effectively even in conditions where the grid is weak.

These are additional capabilities: -

6) Power quality improvement: This refers to the ability to enhance the quality of power delivered.
7) Current capacity above the continuous rating: This means the system can handle a current load greater than its continuous rating for short periods.
8) Black start capability: This is the ability to restart the system from a total or partial shutdown without relying on external power sources.

The core capabilities of GFM inverters can be achieved with minimal modifications to the plant hardware and operational procedures compared to GFL inverters. These changes primarily involve updates to the software and control algorithms. It is expected that these core capabilities will be standard across all GFM inverters. To fulfill these core capabilities, a GFM inverter should be able to provide a small energy buffer, either through its design or operation. Furthermore, for a device to be classified as a GFM inverter, the energy should be instantly available to the grid with minimal delay caused by DC side

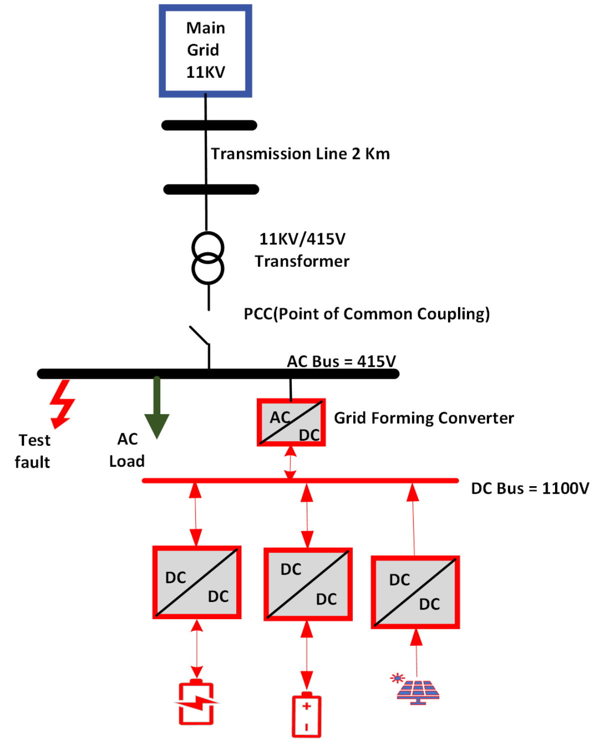

Fig. 5. Single Line Diagram for 500kVA Grid Forming Inverter Test Setup

control algorithms. Testing for these capabilities are also very crucial at the device level, so in this study, implemented a test model for checking few of the capabilities as described above.

IV. Modelling of Test System

This Test system includes the DERs along with grid Forming inverter whose Single Line Diagram is shown in Fig 5. The parameters of the test system is shown in Table I. To specify this inverter as Grid Forming converter, there are some control strategies to be used for this inverter which modify the switching schemes as per the control Logic as shown in Fig 6.

A. Modelling of the Assets Parameters

1) Modelling of the Grid: Grid can be modelled as swing Bus or slack Bus, which can compensate the active and reactive powers demand in the network. Voltage of Bus considered as 11kV It can be modelled as Thevenin's equivalent.

2) Modelling of Transformer: As per the 95% efficiency & 6% Voltage Regulation ,calculated all the parameters of Impedances including SCR factor.

3) Modelling of Transmission Line: Assumed a copper wire of current density of $3A/mm^2$ with length of 2 km.

4) Modelling of design parameters of converter: Grid Forming based inverter which used IGBTs or MOSFETs as switches for converting the DC voltage of 1100V into 415V AC RMS value.

Evaluation of other parameters regarding control loops are calculated from the observations of reference [9][10].

TABLE I
Parameters of Test System

S.no	*System Quantities*		*Values*
1	Inverter Data	Apparent Power	500kVA
2		Frequency	50Hz
3		DC side voltage	1100V
4		AC RMS output voltage	415V
5		Power Measurement(T)	100e-6
6	Grid data	Voltage level	11kV
7		Equivalent Resistance	3Ω
8		Equivalent Inductance	0.05 H
9		Default X/R ratio	5
10		Default SCR	2.5
11	Transformer data	Turns ratio	415/11000
12		Efficiency	95%
13		Voltage regulation	6%
14		Primary Resistance(pu)	0.03
15		Secondary Resistance(pu)	0.02
16		Primary reactance(pu)	0.0416
17		Secondary reactance (pu)	0.0624
18		Zero Sequence Reactance(pu)	0.0976
19	Transmission Line	Length	2 km
20		Inductance	5mH
21		Resistance	4.0468
22	Active Power	Mp(Frequency Slope)	0.01 pu
23	1. Droop Controller(data)	LPF Time constant	0.015
24		Lead-lag (T1 & T2)	0.005 & 0.006
25	2. VSM controller	Inertia	1
26		damping Coefficient	1.056%
27		Freq. Droop	10%
28		max. damping Power	0.7
29		min. damping Power	-0.6
30		sampling time	100e-6
31	Reactive power	Voltage droop	0.3
32	Controller data	Q measurement (T)	1e-3
33		Voltage ref.	1pu
34		LVRT gain	1.5
35	FRT data	Resistance coeff.	0.1875%pu
36	1. Virtual impedance	X/R coeff.	13.2%
37		Max. Current limit	1.2% of max
38		Filter Tc	1e-3
39		Isat.	1.4%
40		Sat. Delay	1e-3
41	Voltage controller	Kp	0.3
42		Ki	180
43		Id max.	+1.8 pu
44		Id min	-1.8 pu
45		Iq max	1.8 pu
46		Iq min	-1.8 pu
47		LPF Tc	5e-3
48	Current Controller	Ts	100e-6
49		Kp	1.5
50		Ki	10

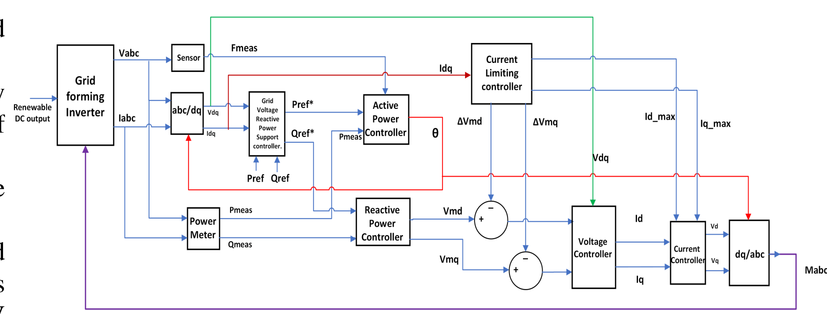

Fig. 6. Control Block Diagram of GFM converter

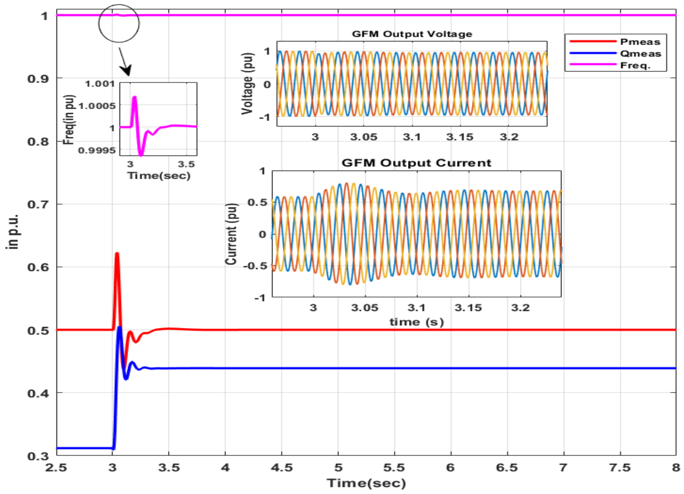

Fig. 7. Change in Grid Voltage from 1pu to 0.9pu at t=3sec.

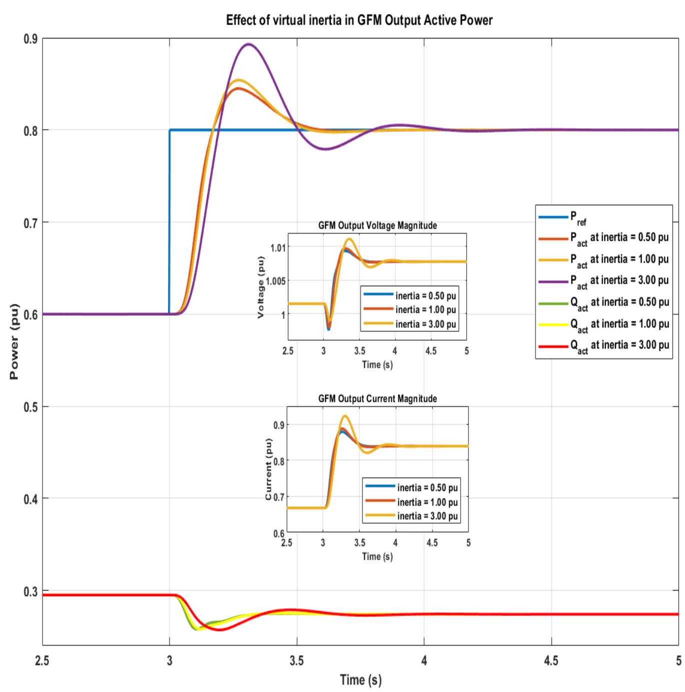

Fig. 8. Change in Virtual inertia at t=3sec.

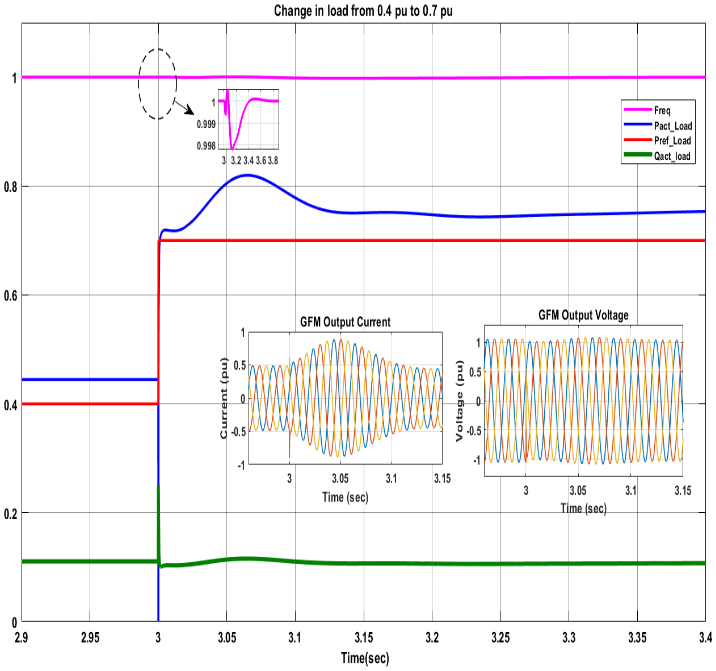

Fig. 9. Change in Load from 0.4 pu to 0.7 pu at t=3 sec.

V. Simulation Results

The test system as shown in Figure 5 is modeled on MATLAB Simulink for running this 500KVA Grid Forming Inverter test setup runs for different scenarios which is given in standards for grid forming inverters reference [3] [8] are described below:

1) Scenario 1: Grid Disturbances: In this scenario, There is a disturbance taken into grid side in voltage. Voltage of the grid side is changed from 1 pu to 0.9 pu. Even with a change in grid voltage from 1 pu to 0.9 pu, the GFM inverter output voltage and frequency is maintained across the output within 0.3 sec, and the Grid forming output current is maintained within 0.1 sec, thats shows the robust control for this grid forming converter as shown in Fig 7.
   Active power output of this grid forming converter is almost settled after few fluctuations, but for making voltage level constant GFM inverter starts delivery of reactive power to maintain the voltage of the output of converter at PCC as shown in Fig 7.
2) Scenario 2: Different Inertia Values in VSM Mode: In this scenario, Grid forming Mode inverter is utilising the Virtual Synchronous Mode.The system performance was evaluated with different virtual synthetic inertia values (0.5, 1, 3 pu) to observe the output active power.The Observation is as increasing virtual inertia resulted in a higher peak overshoot during power transfer, but the GFM inverter was still able to maintain power output within 0.37 sec as shown in Fig8.Instead of overshoot, steady-state value is settled as er the reference is set as 0.8 pu. The output voltage and output current magnitude is also observed for this scenario, steady state value is settled in all cases but peak overshoot is observed in higher inertia values.
   The Reactive power overshoot is also observed in this scenario, but as per the controller capability , steady state value is finally settled as per the reference value.
3) Scenario 3: Sudden Load Change: In this scenario, Load is changing from 0.4 pu to 0.7 pu,As to maintain the system followed the demand without disturbances in the inverter output.As reference in load is increased , Voltage and frequency were maintained within 0.1 sec, and reactive power remained constant while changing

active power values across loads as shown in Fig 9. At steady state, as per the set point values are coming, this shows the robustness of grid forming converter control architecture.

VI. Conclusion

This paper presenes as given, ted here offers a comprehensive understanding of the role of GFM IBRs in grid stability. The study key contribution is the demonstration of the robust control of the GFM inverter, which has been tested under various real time conditions and confirmed using MATLAB Simulink. This research is expected to be beneficial for future studies focusing on the progression of MGs for more number of IBRs in system. Thus, this study makes a significant contribution to the field by enhancing our understanding of how to develop stable and reliable power systems.

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