Coordinated Transient Load Sharing in a Mixed GFM/GFL Source Microgrid

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***Abstract*—In microgrids with mixed synchronous and inverter-based generation, grid-forming (GFM) inverters can become overloaded due to poor load sharing during transients. This shortens the lifetime of the inverters, and strategies to prevent overload often lead to more severe voltage and frequency transients. Moreover, grid-following (GFL) inverters, which usually output a fixed power, are underutilized during these transients. This paper develops a coordinated load sharing strategy that involves offloading excess power demand from a GFM inverter to surrounding GFL inverters. The proposed method is tested in a simulated microgrid with one synchronous generator, one GFM inverter, and four GFL inverters, and it is found to improve power sharing while reducing voltage and frequency transients.**

***Index Terms*—power sharing, grid-forming, grid-following, synchronous generator**

I. Introduction

As more inverters are integrated into the grid, the power system is increasingly a mix of traditional synchronous generators (SG) and inverter-based resources (IBR) [1]. Challenges arise in the interactions between SGs and various types of IBRs. One such challenge is the poor transient load sharing between SGs and grid-forming (GFM) IBRs [2], which regulate voltage and frequency in a grid. Due to the high inertia of SGs compared to IBRs, GFM IBRs initially supply the majority of the demand during a load change. This can cause the IBRs to become overloaded, which can damage the IBRs, prevent effective voltage and frequency regulation, and even cause grid collapse [3]. This issue is particularly severe in scenarios with limited generation, such as in islanded microgrids.

One solution to improve transient load sharing involves virtual synchronous generator (VSG) control, in which an IBR emulates the behavior of an SG [2]. This improves transient load sharing, enabling the SG to take up more of the initial load change. However, as discussed in [2], this leads to larger voltage and frequency transients as the IBR cannot regulate them as closely. Other works have proposed coordinated secondary control strategies to improve transient load sharing. Reference [4] proposes a coordinated strategy to adaptively modify the control modes of an IBR and a diesel generator to prevent the BESS from becoming overloaded; however, the complexity of this strategy may limit its adoption. In [3], a control strategy involving coordination of IBRs and loads improves load sharing in a microgrid, but its reliance on smart loads limits its application scope.

Although many load sharing strategies focus on GFM IBRs, the majority of IBRs in the power system are grid-following (GFL), synchronizing to the voltage and frequency of the grid and following power commands [5]. Given the predominance of GFL IBRs, involving them in power sharing can improve the performance of IBR-dominated systems. Reference [6] proposes a coordinated control strategy in which GFL IBRs exchange error values to share load and regulate grid frequency. However, it does not address the role of SGs and GFM IBRs in load sharing. In [5], a coordinated control method improves power sharing among GFM and GFL inverters, but the power sharing decreases during load transients. References [7] and [8] coordinate GFM and GFL IBRs using a Kalman filter and mean field game theory, respectively. Reference [9] uses distributed optimization for GFM and GFL power sharing. These methods, however, have high computational cost. A distributed control strategy to improve harmonic power sharing in grids with GFM and GFL IBRs is proposed in [10]. This method focuses on a fully IBR-based grid and does not address the effect of SGs, which can worsen the transient load sharing.

This paper proposes a coordinated load sharing strategy for a microgrid with mixed SG, GFM IBR, and GFL IBR sources. The main contributions of this work are:

- A method involving coordination of a GFM IBR with GFL IBRs is developed to prevent transient overload in a mixed-source microgrid with IBR and SG sources.
- The proposed method enhances power sharing, voltage regulation, and frequency regulation in the microgrid.

II. Synchronous Generator and Inverter Controls

This section provides an overview of the study system and the SG, GFM IBR, and GFL IBR controls.

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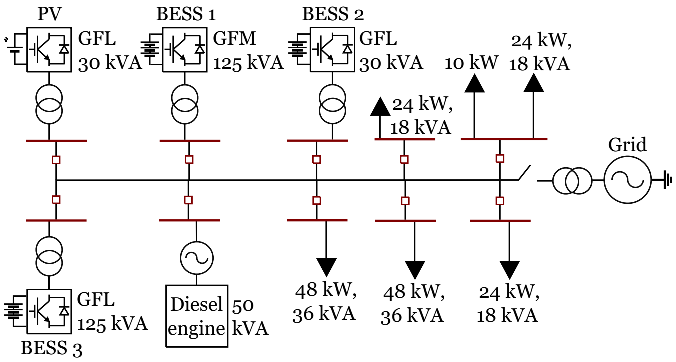

Fig. 1. Diagram of study system.

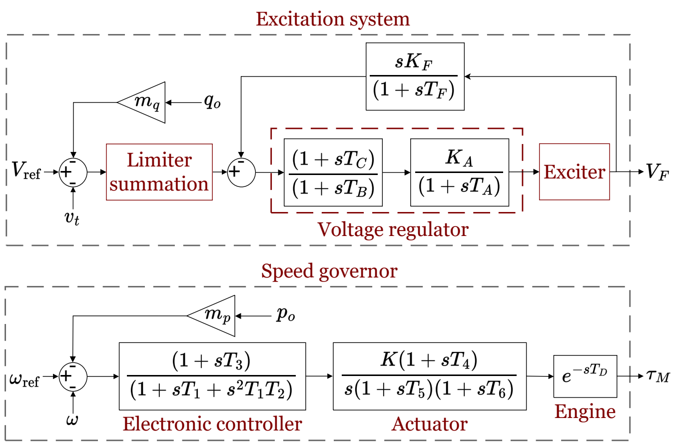

Fig. 2. Diagram of synchronous generator controller.

A. Study System

To study control interactions among resources, a study microgrid is simulated in PSCAD/EMTDC. Fig. 1 shows the study system, which consists of four IBRs and one SG. Of the IBRs, one is a GFM battery energy storage system (BESS), two are GFL BESSs, and one is a GFL photovoltaic (PV) array. The GFL IBRs follow set points, and the GFM IBR and SG supply the remaining demand. The microgrid is islanded to illustrate controller interactions under generation constraints.

B. Synchronous Generator Controller

The SG controller, shown in Fig. 2, consists of an excitation system to control terminal voltage and a speed governor to regulate output frequency. The excitation system is the standard type AC1C model [11] and adjusts the field voltage V_F to the generator's windings based on the voltage set point V_{ref}, terminal voltage v_t, output reactive power q_o, and Q-V droop constant m_q [2]. The speed governor is based on the standard DEGOV1 diesel generator governor model [12]. It follows a frequency reference ω_{ref}, which is adjusted using P-f droop. The governor outputs a mechanical torque τ_M to a diesel engine, which drives the SG.

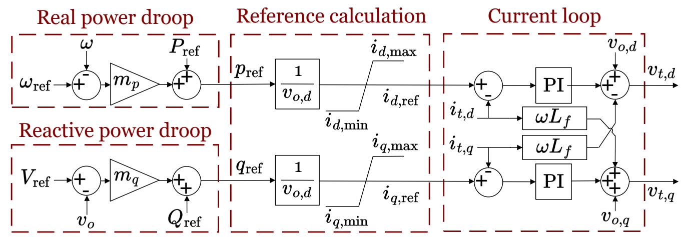

Fig. 3. Diagram of GFL inverter controller.

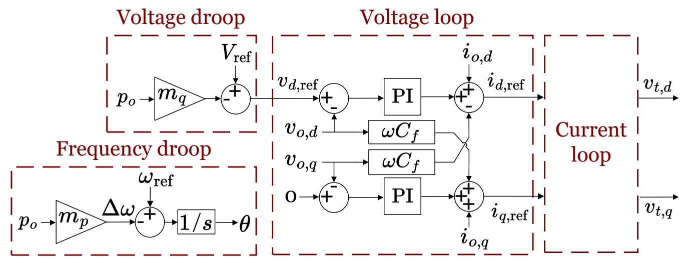

Fig. 4. Diagram of GFM inverter controller.

C. Inverter Controller

An IBR controller converts its measured terminal current i_t, capacitor voltage v_o, and output current i_o to the dq frame. In a GFL controller, shown in Fig. 3, the dq transformation angle θ comes from a phase-locked loop (PLL), which synchronizes the inverter to the grid voltage v_g. The GFL IBR follows real and reactive power references P_{ref} and Q_{ref}. These references are adjusted using a standard GFL droop scheme, enabling the IBR to provide auxiliary voltage and frequency support [1]. The current references are calculated as [5]

$$i_{d,\text{ref}} = \frac{p_{\text{ref}}}{v_{o,d}}, \tag{1}$$

$$i_{q,\text{ref}} = \frac{q_{\text{ref}}}{v_{o,d}}. \tag{2}$$

These references are passed to a fast inner current control loop, which generates gating signals for the inverter.

The GFM controller, shown in Fig. 4, generates its reference angle θ using a frequency reference ω_{ref}, adjusted using P-f droop. The voltage reference V_{ref} is adjusted using Q-V droop and passed to an outer voltage loop, which generates current references. These references are passed to an inner current loop, which uses the same control scheme as the GFL current loop. The GFM inverter regulates grid voltage and frequency while sharing power with the SG through droop control.

III. Proposed Load-Sharing Method

This section discusses transient load sharing in the microgrid and the proposed method for coordinated load sharing.

A. Transient Load Sharing

Compared to the GFM and GFL inverters, the SG has a slow transient response. This is partly because the response of the SG relies on mechanical power, which responds more slowly than electrical power [13]. Additionally, the transient

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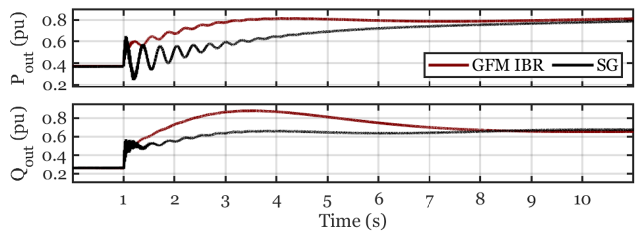

Fig. 5. Real and reactive power output of GFM inverter and synchronous generator during load increase.

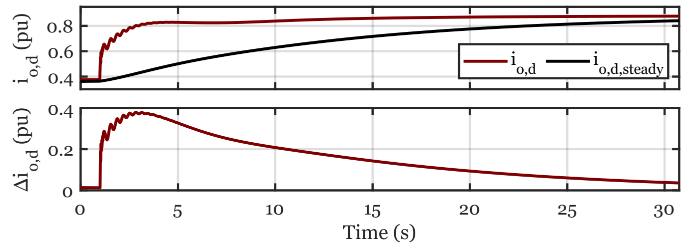

Fig. 6. Output current $i_{o,d}$ and calculated $\Delta i_{o,d}$ of GFM inverter.

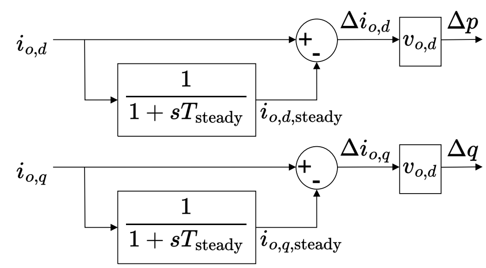

Fig. 7. Calculation of GFL IBR set point change based on GFM IBR output current i, o and output voltage v, o.

response of the GFM IBR depends on droop control, whereas the transient response of the SG depends on the slow action of the governor and voltage regulator [2].

Due to this response time discrepancy, a GFM IBR initially supplies most of the added demand from a load change when operating in parallel with an SG. This is shown in Fig. 5, which shows the per-unit real and reactive power output of a GFM IBR and an SG during a load change. Although the IBR operates within its rating after the transient, it must exceed its current rating for several seconds to supply the load as the SG ramps up its power. (The IBR could limit its current, but this would reduce voltage and frequency regulation [2].) GFL participation in transient load sharing is usually minimal. However, some GFL controllers incorporate voltage and frequency support functions [13]. These functions are less capable than those of GFM IBRs and do not guarantee power sharing [5]. Coordinated secondary control can more fully utilize the spare capacity of GFL IBRs.

B. Set Point Change Calculation

The proposed load-sharing method involves measuring the GFM IBR's change in current output and distributing it among GFL IBRs in the microgrid by modifying their set points. The steady-state current output of the GFM IBR is estimated as

$$i_{o,d,\text{steady}} = \frac{1}{1+sT_{\text{steady}}}, \tag{3}$$

$$i_{o,q,\text{steady}} = \frac{1}{1+sT_{\text{steady}}}, \tag{4}$$

where $T_{\text{steady}} = 10.0$ s to track long-term changes in current. During a load change with poor transient load sharing, the output current of the GFM IBR rises to a peak, then settles down. The estimated transient change is

$$\Delta i_{o,d} = i_{o,d} - i_{o,d,\text{steady}}, \tag{5}$$

$$\Delta i_{o,q} = i_{o,q} - i_{o,q,\text{steady}}. \tag{6}$$

Fig. 6 shows the GFM IBR's output d-axis current $i_{o,d}$, the steady-state current $i_{o,d,\text{steady}}$, and the resulting $\Delta i_{o,d}$ during a load transient. Using (1) and (2), $\Delta i_{o,d}$ and $\Delta i_{o,d}$ are converted to real and reactive power inputs for the GFL IBRs:

$$\Delta p = v_{o,d} \Delta i_{o,d}, \tag{7}$$

$$\Delta q = v_{o,d} \Delta i_{o,q}. \tag{8}$$

Fig. 7 shows the full calculation, which occurs in the GFM IBR controller.

C. Coordinated Load Sharing

To enable coordinated load sharing, the GFM IBR has communications links to each of the four surrounding GFL IBRs. As shown in Fig. 8, the calculated set point adjustments Δp and Δq are sent from the GFM inverter to N GFL inverters over the communication links. The power setpoints $i = 1, ..., N$ of the GFL inverters are adjusted as follows:

$$P'_{\text{ref},i} = P_{\text{ref},i} + m_i \Delta p, \tag{9}$$

$$Q'_{\text{ref},i} = Q_{\text{ref},i} + m_i \Delta q, \tag{10}$$

where m_i is a scaling factor. In this work, $m_i = 1$ for all GFL IBRs. By adjusting the set points in this way, the GFM IBR offloads demand to GFL inverters in the microgrid. This method takes advantage of the similarities of the GFL and GFM inner current control loops. The GFM IBR's change in current, which supports the grid voltage and frequency, is replicated by the GFL IBRs. This enables the GFL IBRs to momentarily participate in load sharing as well as voltage and frequency regulation. This method requires GFL IBRs to have spare capacity, at the cost of lower generation. However, recent grid standards recommend that GFL IBRs operate with headroom to provide support [5]. The method also requires high-bandwidth communication links; however, it can scale to multiple GFM IBRs, each communicating only with nearby GFL IBRs. This decentralized approach avoids a single point of failure and allows for short communication links. To simulate latency, the load sharing signals are delayed by $T_d = 5$ ms.

IV. Performance Evaluation

To evaluate the proposed method, various case studies are carried out in the microgrid using PSCAD/EMTDC.

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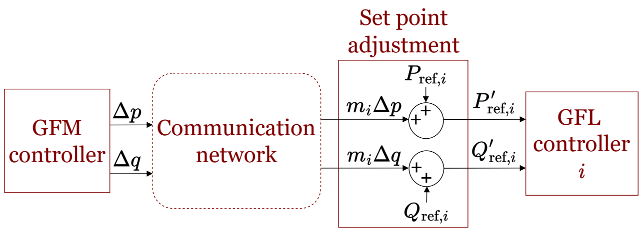

Fig. 8. Coordinated set point adjustment for transient load sharing.

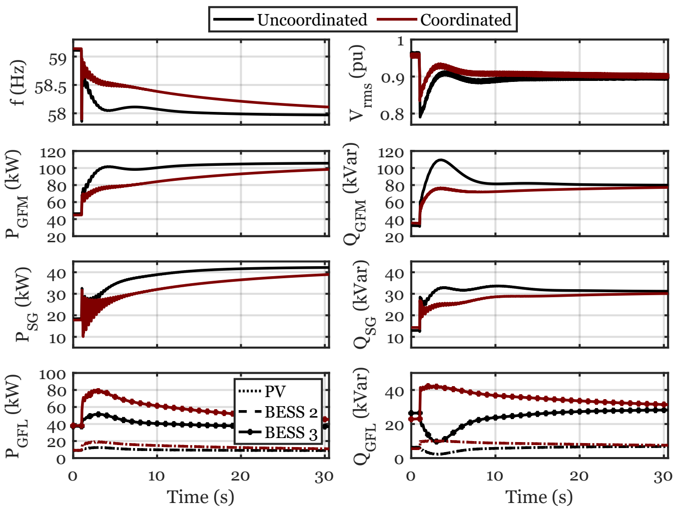

Fig. 9. Grid voltage and frequency and GFM, SG, and GFL power during a 120 kW, 90 kVar load increase, with and without coordinated load sharing.

TABLE I
PERFORMANCE OF METHOD IN CASE STUDIES

Scenario	P_{diff} (pu)	Q_{diff} (pu)	$V_{\min}/V_{\max}$ (pu)	$f_{\min}/f_{\max}$ (Hz)
Uncoordinated load increase	0.3596	0.2299	0.7903	57.86
Coordinated load increase	0.3511	0.1313	0.8341	57.90
Uncoordinated load decrease	0.4407	0.1452	1.1101	60.27
Coordinated load decrease	0.3142	0.0714	1.0445	60.25
$T_{\text{steady}} = 5.0$ s	0.3511	0.1393	0.8333	57.97
$T_{\text{steady}} = 10.0$ s	0.3511	0.1313	0.8341	57.90
$T_{\text{steady}} = 20.0$ s	0.3505	0.1287	0.8344	57.96
$m_i = 5.0$ s	0.3764	0.1884	0.7596	58.87
$m_i = 10.0$ s	0.2959	0.1103	0.7843	58.96
$m_i = 20.0$ s	0.2702	0.0627	0.8379	58.44

A. Load Increase

In this case, a 120 kW, 90 kVar load is connected to the microgrid at $t = 1.0$ s. Fig. 9 shows the real and reactive power output of the GFM IBR, SG, and GFL IBRs as well as the voltage and frequency of the microgrid during the load transient. Without the coordinated load sharing method, the SG increases its output slowly and the GFL IBRs contribute little power, causing the GFM IBR to become overloaded. With coordinated load sharing, the three GFL IBRs increase their outputs in proportion to their ratings and without exceeding their current limits. The aggregate output from the GFL IBRs rises to 120 kW and 60 kVar, then slowly decays. As a result, the GFM IBR increases its power output smoothly and without overload. Table I shows that the method reduces P_{diff} and Q_{diff}, the maximum real and reactive power difference between the GFM IBR and SG. The proposed method also raises the minimum voltage $V_{\min}$ and minimum frequency $f_{\min}$.

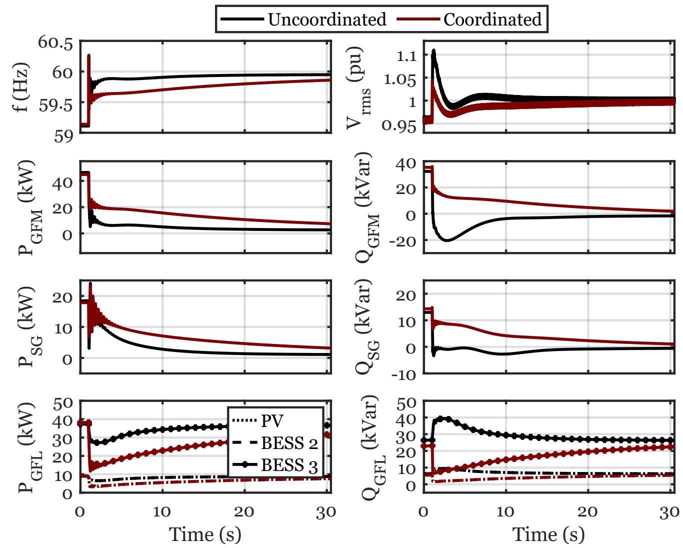

Fig. 10. Grid voltage and frequency and GFM, SG, and GFL power during a 72 kW, 54 kVar load decrease, with and without coordinated load sharing.

B. Load Decrease

Fig. 10 shows the disconnection of a 72 kW, 54 kVar load from the microgrid at $t = 1.0$ s. When operating in uncoordinated mode, the microgrid voltage spikes above 1.1 pu after the loss of load, and the GFM IBR must rapidly decrease its real power output to zero and absorb the excess reactive power. In the coordinated load sharing strategy, the GFL IBRs immediately step down their real and reactive power outputs, reducing excess power in the grid. As shown in Table I, this reduces the power sharing errors P_{diff} and Q_{diff}. It also reduces $V_{\max}$ and $f_{\max}$, preventing voltage overload.

C. Effect of Steady-State Time Constant

In this case, a 120 kW, 90 kVar load is connected to the microgrid, and the time constant T_{steady} is varied. With $T_{\text{steady}} = 1.0$ s, the system collapses; this is likely because the GFL output decays too quickly, leaving too little support for the grid. The other scenarios tested, $T_{\text{steady}} = 5.0$, 10.0, and 20.0 s, are plotted in Fig. 11. As T_{steady} increases, power sharing performance and voltage and frequency regulation improve. This is shown in Table I: P_{diff} and Q_{diff} decrease with T_{steady}, and $V_{\min}$ increases. ($f_{\min}$ is highest for $T_{\text{steady}} = 5.0$ s, possibly because the GFM IBR and SG provide more initial support.) Although a higher T_{steady} improves performance, it also increases settling time. Setting T_{steady} to the time taken for the SG to complete most of a step change (from Fig. 5, about 5-10 s) provides stable and relatively fast operation.

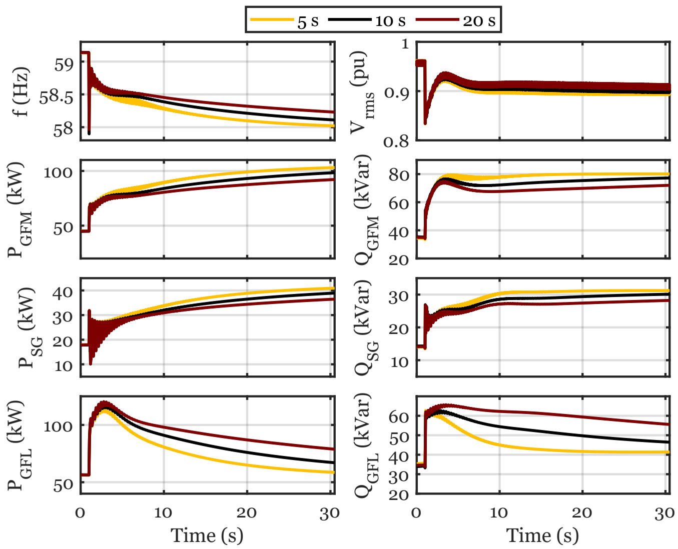

Fig. 11. Grid voltage and frequency and GFM, SG, and aggregate GFL power during a 120 kW, 90 kVar load increase for varying T_{steady}.

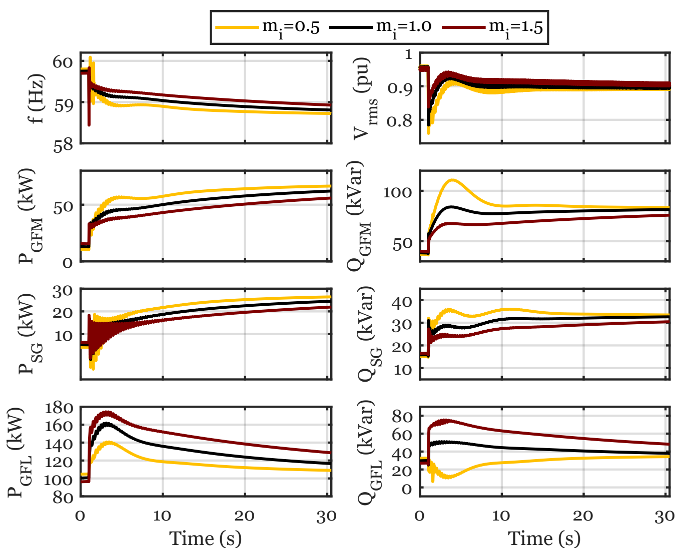

Fig. 12. Grid voltage and frequency and GFM, SG, and aggregate GFL power during a 120 kW, 90 kVar load increase for varying m_i.

D. Effect of Scaling Factor

To examine the effect of the m_i scaling factor, a 120 kW, 90 kVar load is connected to the microgrid and m_i is set to 0.5, 1.0, and 1.5 in three scenarios. The BESS 3 GFL operates close to its power limit. Fig. 12 shows the resulting voltage, frequency, and power curves. With $m_i = 0.5$, the GFM IBR is overloaded. With $m_i = 1.5$, BESS 3 reaches its current limit and its output momentarily saturates. As shown in Table I, increasing m_i improves power sharing and voltage regulation. However, the grid frequency reaches its lowest value with $m_i = 1.5$. This is likely due to excess power injection from GFL IBRs when they are out of synch with the grid frequency. Thus, m_i should be selected to provide sufficient support to the GFM IBR without injecting excess GFL power.

V. Conclusion

This work proposes a coordinated control strategy to improve transient load sharing in a microgrid with a combination of synchronous and inverter-based generation. The method distributes power demand from GFM to GFL IBRs so that the GFL IBRs contribute to transient load sharing. The proposed method is found to improve power sharing as well as voltage and frequency regulation. It takes advantage of existing spare headroom in GFL IBRs for voltage and frequency regulation, and it uses a decentralized communication network for robustness and short communication distances. The impact of the design parameters T_{steady} and m_i on the performance of the method is examined, and guidelines for setting these parameters are provided. Future work could expand on the load sharing strategy to account for multiple GFM IBRs and the limited spare capacity of GFL IBRs.

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