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REVIEW

# Grid-forming control for inverter-based resources in power systems: A review on its operation, system stability, and prospective

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**Abstract**
The increasing integration of inverter based resources (IBR) in the power system has a significant multi-faceted impact on the power system operation and stability. Various control approaches are proposed for IBRs, broadly categorized into grid-following and grid-forming (GFM) control strategies. While the GFL has been in operation for some time, the relatively new GFMs are rarely deployed in the IBRs. This article aims to provide an understanding of the working principles and distinguish between these two control strategies. A survey of the recent GFM control approaches is also delivered here, expanding the existing classification. It also explores the role of GFM control and its types in power system dynamics and stability like voltage, frequency etc. Practical insight into these stabilities is provided using case studies, making this review article unique in its comprehensive approach. Lacking elsewhere, the GFMs' real-world demonstrations and their applications in several IBRs like wind farms, photovoltaic power generation stations etc., are also analyzed. Finally, the research gaps are identified, and the prospect of GFM is presented based on the system needs, informed by GFM real-world projects. This work is a potential road map for the GFM large-scale deployment in the decarbonized IBR-based bulk power system.

## 1 | INTRODUCTION

Renewable power generation (RPG) induction into the power systems is evidently booming. For example, the global annual increase in renewable capacity was a record-breaking 6% in 2021, reaching 295 GW, and is expected to increase by 8% in 2022, touching a 320 GW peak [1]. Besides, the business for RPG is more favourable than ever before, with the reduction of PV module prices by 80% and wind turbines by 30−40% [2]. This rapid growth directly results from policies that reduce anthropogenic greenhouse gas (GHG) emissions. Though the average annual emissions are higher in 2010–2019 than in 2000–2009, the growth rate of the former decade is lower (1.3%/year) than the latter one (2.1%/year) [3]. Furthermore, by 2030, the United States alone plans to reduce GHG emissions by 50% [4].

Contrariwise, as most of these RPG sources are intermittent, inverter-based resources (IBRs) and are non-synchronous, they pose multiple challenges to the grid, such as power quality [5, 6], i.e. voltage and frequency fluctuations [7]. Therefore, the RPGs in this manuscript are referred to those that are IBR-based. The predominant cause of frequency-related problems is linked to the lack of inertia [8–10] and damping [11–13] in these IBRs-systems. Whereas, the voltage stability issues are mainly linked to the absence of reactive power reserves from IBRs [14, 15]. These power quality issues were well resolved in conventional sources (CS) synchronous machine (SM) based power systems [10]. However, the high pace of replacement of these CS by the IBRs requires attention to understanding the system dynamics and proposing different control strategies. In this context, control approaches such as grid following (GFL) and grid forming (GFM) for IBR grid interfacing are reported and discussed here.

Two primary converter topologies used in current power systems are the voltage source converter (VSC) and current source converter (CSC), employing transistor and thyristor technologies. VSC is typically favoured over CSC due to the losses associated with series switches and the lower efficiency of CSC [16]. The essential function of VSC lies in converting DC power into AC active power for integration into the grid, and vice versa, depending on the direction of power flow. Furthermore, there are two sub-classes of VSC operational control strategies: One is the commonly known current controlled source (CCS) behaving as a current source, identified as GFL [17, 18], and the other is the controlled voltage source (CVS) behaving as a voltage source and is recently called GFM [19, 20].

### 1.1 | State-of-the-art and scope of this paper

Under different conditions, GFM and GFL controls suffer from stability issues. Refs. [21, 22] investigate the small-signal stability issues of VSC, which are based on linear theory modelling that fails to perform in large-signal stability studies even when a stable equilibrium point exists. Whereas, [23–25] are based on large-signal stability modelling, i.e. nonlinear theory modelling. Here, ref. [23] uses the equal area criterion (EAC) with nonlinear characteristics in mind. However, the system with negative damping is not favoured for the EAC method. This shortcoming is handled in [25] using phase portraits. Besides, ref. [17] studies the VSC control strategy based on energy function modelling that produces the distribution of system damping, including negative and positive damping.

Moreover, a qualitative analysis in [26] explores the positive influence of GFM on addressing the frequency stability challenge in low inertia scenarios, taking into account the existing constraints of both DC and AC converters. The study suggests that additional research is necessary to facilitate a smooth operational transition between different control approaches, such as transitioning from GFL to GFM. The impact of inertia on the power system stability in the presence of a high level of integration of IBR is discussed in [7, 9]. With few exceptions, most of the above articles focus on the dynamics of GFL in the power systems. Furthermore, no comprehensive study is available that demonstrates each GFM model's performance in the context of different power system stabilities. Therefore, this review paper thoroughly explains GFM and its diverse benefits for different system stabilities and emerging complexities.

Another investigation that ought to be of keen importance is the application and demonstration of these inverters. References like [27, 28] provide a theoretical-based approach to performance analysis of GFM in high-voltage direct-current (HVDC) systems and frequency stability issues in the Irish power system. On the other hand, the installed worldwide GFM-based control strategies with examples are reviewed in [29]. These articles give a hint of possible strengths and weaknesses of the GFM inverters in terms of the system need provisions like black start capability [30] and system restoration that are conventionally otherwise provided by CS [31, 32]. Therefore, the relevant application-based review will be presented, accompanied by a comparative discussion on GFM and GFL's ability to operate according to their capabilities and power system needs.

Recently, an effort has been put forward in the literature available including review articles [9, 29, 33–35], research articles [26, 36, 37] and standards [38, 39] and grid codes [39–41] to understand the concept of GFM and GFL. Yet, no agreement or clear definition is given to the GFM by any authority. Most of the concerned bodies are defining it as per their requirement or in the context they are using it [39, 42, 43]. In contrast, the academic and industrial communities are deliberating to put forward a formal definition [20, 34, 42]. For system planners, operators, and equipment manufacturers, it is still an open question of what requirements and capabilities constitute the new inverters [40]. This article presents an effort to establish the needs of systems and assess the abilities and shortcomings of GFM.

### 1.2 | Comparison with the available review articles

The available review articles cover most of the developments regarding the GFM till the time of their publishing. Under the high penetration of RPGs, the grid flexibility concerning inertia is studied in [9]. Here, the discussion only surrounds the synthetic inertia emulation, estimation of inertia, and its coexistence with CS's -based inertia. A survey of the pilot projects is carried out in [29], where different types of GFM control approaches demonstrated worldwide are analyzed. On the other hand, articles [34] and [44] provide the various available control approaches of GFM. The classification in [34] is based on the subsystem functions that are later joined to make one complete control, which performs multiple tasks like frequency and voltage control. Whereas reference [43] classifies the GFM's approaches based on their main role, i.e. droop control, SM's inertial emulation etc.

Some of these articles oversight many control structures of GFM that are proposed in the literature. While other papers do not consider their application in different IBRs, especially wind turbine generators (WTG), photovoltaic (PV), and battery energy storage systems (BESS). Others do not provide case studies demonstrating the GFM's ability to control and stabilize the system in uncertain situations. To address the above shortcomings, this article covers many aspects of GFM, like its applications, demonstrations in the real world, stability, and dynamic analysis, and various up-to-date control structures as listed in the comparison to other review articles in Table 1.

### 1.3 | Contribution and research question addressed here

Herein, the GFM and GFL control strategies are comprehensively reviewed to understand their working principle while knowing their distinctions. GFM and its till date proposed control strategies and their role in power system stability and dynamics is also investigated. This investigating is supplemented by the GFM application in various IBRs. To summarize, this paper explores the below research questions by investigating more than 200 papers, reports, and books, of which around 140 relevant ones are reported here.

1. The current understanding of GFM and GFL by academia and industry is presented through a discussion on their distinct working principle.

**TABLE 1** Comparison of this paper to other review papers (Y means Yes, and N means No).

| Topics | [9][a] | [19] | [29] | [33] | [34] | [43] | [108][h] | [35][f] | This paper |
|---|---|---|---|---|---|---|---|---|---|
| Comparison of GFM and GFL | N | Y | Y | Y | Y | Y | Y | Y | Y |
| GFM control strategies | N | Y | N | Y | Y | Y | Y | Y | Y[b] |
| GFM operational principal | N | Y | N | Y | Y | N | Y | Y | Y |
| GFM application in IBRs | Y | N | N | N | N | Y[g] | Y[h] | Y[i] | Y |
| GFM and system stabilities[e] | Y | Y | N | Y | Y | Y[c] | Y | Y | Y |
| GFM demonstrations | N | N | Y | N | N | Y | N | N | Y |
| GFM capabilities and system needs | N | Y | Y | Y | Y | Y[d] | N | N | Y |
| Case study of GFM | Y | Y | Y | Y | Y | N | Y | N | Y |
| GFM deployment and future work | Y | Y | Y | Y | Y | Y | Y | N | Y |

[a]Only reference is given to GFM whereas the whole paper discusses the inertia role in renewable energy perspective.
[b]Extended whereby more control strategies are added in this article as compared to others.
[c]Only voltage and transient stabilities are discussed.
[d]System needs are not explicitly discussed.
[e]Most of the articles have not pointed out each GFM type role in the major stabilities.
[f]This article lacks discussion on GFM Operations, applications in PV, exclusive discussion on future work and deployment, and converter driven stability and frequency stability.
[g]BESS and HVDC are missing.
[h]Only WTG is discussed.
[i]PV is not discussed.

2. State-of-the-art proposed control approaches of the GFM inverters are also surveyed. Highlights of their comparison under different system conditions and characteristics are tabulated.
3. The role of GFM control in power system dynamics and stability is explored in detail and is supported by case studies. These include phase angle, voltage, frequency, and converter driven-based stabilities.
4. Applications of GFMs in various IBRs such as WTG, PV, BESS, and HVDC systems are reviewed in detail, supplemented by a survey of demonstrations of the GFM testing at the medium voltage (MV) level.
5. Insight into the system needs and GFM-IBRs capabilities is provided. Besides, the deployment plan of GFM-IBRs into a bulk power system is presented. Finally, identified future research questions and directions are put forward.

The rest of the paper is organized as follows. Section 2 discusses the GFL and GFM's working principles and various GFM control models. Section 3 investigates the GFM performances in power system stability and dynamics, whereas Section 4 analyses the real-world demonstrations of GFM and its applications in various IBRs. Section 5 sheds light on the system's needs with high penetration of IBRs. Section 6 presents the research gaps, future work, and deployment schedule for GFM. The paper concludes with Section 7, which summarizes the whole article.

## 2 | GFM AND GFL: THEIR DIFFERENCES, DUALITIES AND OPERATIONAL PRINCIPLES

Non-synchronous inverter-based resources (IBRs) are displacing conventional synchronous-based power sources in the power system at a noticeable pace [45]. This connection to the grid through the converters is the main reason IBRs are not the sole energy source of power systems [44]. Hence, there is an ongoing search for novel control methods. This crucial statement is elaborated on in the remainder of the paper. On the other hand, the CS technologies and related theories are quite mature and readily available [10], whereas the system in the presence of these sources is reasonably stable [45]. Subject to physical constraints, SMs are controllable in dynamic and steady states. Here, the performance is mainly predictable regardless of controls like excitation and governor behaviour due to the dominance of mechanical and electrical characteristics over the fast transients [10, 44].

On the contrary, the IBR-based power system is a new phenomenon, and the related power system dynamics and stability are hot research issues. The reason can be that the control strategies of the GFL-IBRs and CS differ regarding their response time and response principle to the disturbance. The potential remedy in such a context is a GFM that controls the voltage and frequency through grid ancillary services similar to CSs, which are discussed ahead. The basic diagram of GFM and GFL is shown in Figure 1, their differences in Table 2 [16, 45], whereas their capabilities in terms of their duality are listed in Table 3 [33].

In short, their primary objective is dispatching active (P) and reactive (Q) power to the grid by the GFL and GFM IBRs' control. The distinction comes during the transients, i.e. during and immediate post-disturbance time frames. This distinction is further elaborated below.

### 2.1 | Grid following inverter

The present IBRs are based on GFL, which injects the current into the grid by reading its voltage and frequency to provide the

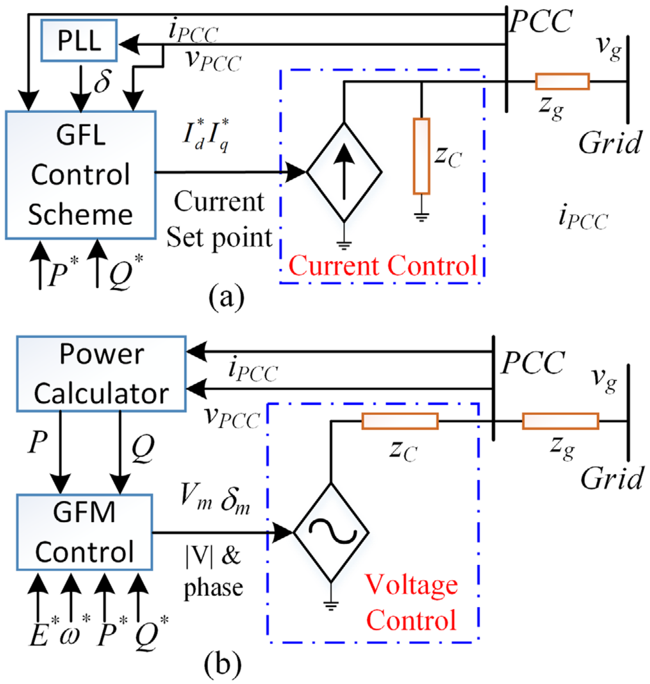


**FIGURE 1** Type of inverters for grid connectivity (a) GFL (b) GFM.

scheduled active and reactive power with an assumption that instantaneous AC voltage is formed in the grid by the sources in dominance, i.e. SM [16]. With no clear requirements and incentives from the market, the trend will stay the same, resulting in a further increase in GFL- IBRs [46]; however, this has to change due to the aforementioned reasons.

During the transient period, the GFL-IBR keeps the active and reactive current components constant. Thus, they appear to be constant current sources. Phase-locked loop (PLL)-type fast-acting synchronizing components are used to determine the grid voltage angle at the point of common coupling (PCC). This angle is used to "follow" the grid voltage by tightly controlling the current's active and reactive components. If this "following," i.e. the tracking of grid voltage fails, and the stable output of the GFL IBR is compromised [46].

Besides, the stability in the weak grid caused by high impedance in the grid will be negatively impacted by PLL [47]. For this reason, the current commercially available inverters do not participate in grid ancillary services, with some exceptions [48].

While ensuring the inverters' safe operation, the main objective of the PLL-based inverter control is the provision of active and reactive power as per pre-defined values. The reference current command must be generated as follows to achieve this objective.

$$|I_{\text{ref}}| \angle \psi_{\text{ref}} = \frac{P_{\text{ref}} - jQ_{\text{ref}}}{|V_{\text{PCC}}| \angle -\phi} \tag{1}$$

Here $|V_{\text{PCC}}|$ and $\phi$ is the magnitude and angle of the terminal voltage and the $P_{\text{ref}}$ and $Q_{\text{ref}}$ are the pre-defined active and reactive powers.

Furthermore, the reference current must be matched by the inverter's actual current fed to the network. For this, the output voltage $|E_{\text{IBR}}|\angle\delta$ is changed through an inner current control loop such that

$$|I|\angle\psi = \frac{|E_{\text{IBR}}|\angle\delta - |V_{\text{PCC}}|\angle\phi}{R_f + jX_f} = |I_{\text{ref}}|\ \angle\psi_{\text{ref}} \tag{2}$$

Here, the impedance of the output filter also includes the inverter transformer, and filter inductance is represented by

**TABLE 2** Differences between GFM and GFL.

| Tasks | GFL | GFM |
|---|---|---|
| Control | Feed scheduled power to an energized grid | Grid voltage and frequency set up |
| Objective | Magnitude and phase angle of AC current | Magnitude and frequency of AC Voltage |
| Variable needed for controlling | Active power current $I_p$ (known $\|V_{\text{PCC}}\|\angle\phi_t$) | Modulated angle |
| Stiff and stable voltage at the terminal | Required | Not required |
| Requirement of PLL in control | Yes | Not always compulsory |

**TABLE 3** GFM and GFL duality [33].

| Tasks | GFM | GFL |
|---|---|---|
| Characteristic of grid-interfacing | Forming voltage, following grid current | Forming current, following grid voltage |
| Control for synchronization | Droop control *(P-ω)* with gain $G_{FD}$ | $v_q$-PLL with Phase-locking controller $G_{PLL}$ |
| Characteristics of swing | $I$- $\delta$ or $P$- $\delta$ swings | $V$- $\delta$ or $Q$-$\delta$ swings |
| Stable operation | Ideal current source connection, or operating with open circuit having $Z_g$[a] $\to 0$ | Ideal voltage source connection, or operating with short circuit having $Y_g \to \infty$ |
| Unstable operation | Ideal voltage source connection, or operating with short circuit having $Z_g = 0$ | Ideal current source connection, or operating with open circuit having $Y_g = 0$ |

[a]$Z_g$ and $Z_c$ here are the grid and inverter impedances respectively. $Y_g$ and $Y_c$ here is the admittance of grid, and ac filter and inner current loop.

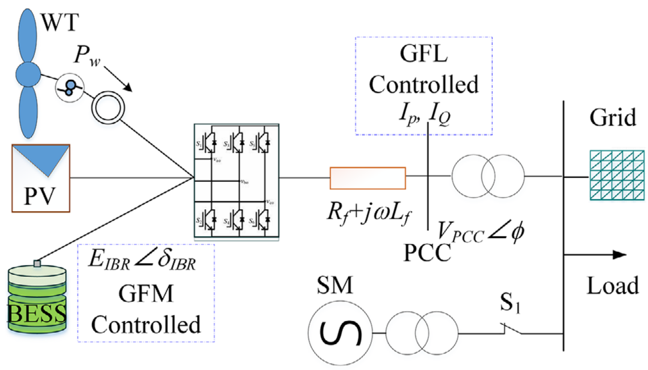


**FIGURE 2** GFM and GFL control parameters in IBRs when connected to Grid.

$R_f + jX_f$ as shown in Figure 2 [46]. After being exposed to a change, the evaluation of $|I|\angle\psi \approx |I_{\text{ref}}|\angle\psi_{\text{ref}}$ needs to be carried out quickly, as the inverters are current sensitive devices.

This "follow" concept is based on the assumption of a stiff system due to enough SM in the system that forms the grid voltage and frequency to remain stable. However, this assumption may not be true in the near future as the IBRs' penetration level may surpass that of SMs in the grid. For this reason, more advanced control strategies like GFM could establish the grid frequency and voltage and thus open the gateway for the 100 % IBR-based power system [46].

## 2.2 | Grid forming inverter

The GFM concept initially used for islanded and microgrid (MG) operation [20, 42] has the potential to sustain stability and operate with resilience in large interconnected power systems. The GFM-IBR keeps the voltage constant at the output, i.e. the internal phasor of the voltage is maintained during the transient time frame. In contrast, the magnitude and frequency are set locally at each inverter level. This feature makes GFM-IBR "forming" the voltage and frequency of the grid and thus enables them to synchronize to an external grid or operate in islanding mode. Furthermore, these features allow the GFM-IBRs to dispatch extra active and reactive power by instantly responding to external phase angle deviation during transient time when necessary. In short, the GFM-IBRs can support the grid in challenging circumstances and ensure grid stability. However, the loss of synchronization may still happen in certain adverse situations.

Contrary to the GFL, the GFM-IBRs appear as a voltage source to the grid in a transient time frame, conceding that the limits of resulted currents are not breached, and the energy capacity is available. This idea of supporting the grid during frequency deviation and power imbalance through the introduction of the virtual synchronous machine (VSM) concept dates back to 2008 [49], whereas the first appearance of the "grid-forming" term was in 2001 [50]. However, till now, there is no clear definition from the relevant bodies [29]. As this is a highly discussed issue now, there are some mentions of "grid-forming" like in the recent IEEE standards [39].

The control concept of GFM can be categorized into two types. The first involves the gradual adjustment of the inverter-based resource's (IBR) voltage in response to grid voltage and frequency, with concurrent control of current within specified limits. The second type entails modifying the IBR's active and reactive power based on grid voltage and phase angle derived from the PLL, while simultaneously regulating the current. The GFM can potentially contribute to the system strength by operating in low short circuit MVA, high voltage to current deviation ratio, and high rate of change of frequency (RoCoF). This is possible by increasing the hardware ratings, improving control methods, and participating in frequency regulations.

Active power regulation depends on the energy availability behind the inverters. Thus, frequency control can be provided with a great deal of consideration of the energy source. On the other hand, reactive power/voltage supports are solely handled by the inverter. The GFM can be defined based on the objectives, controls, and tasks mentioned in Tables 2 and 3 [47].

## 2.3 | Control strategies of GFM

The GFM inverters are in different forms in terms of their control methodologies, which are majorly classified into three major groups in the literature as presented in Table 4 [9, 34, 43]. These control strategies are majorly classified into three groups, i.e. droop control [22, 51–55], synchronous machine-based control [36, 56–62] and other controls (like virtual oscillator-based) [63–67]. This classification is mainly based on the linkage of active power to the frequency and reactive power to the magnitude of voltage. The droop-based controls are subdivided into droop control based on angle [52] and frequency [51], synchronous power control (SPC) [54], power synchronization control (PSC) [22], enhanced direct power control (EDPC) [55] and extend direct voltage control (DVC) [68]. A 98% GFM-IBRs-based system case study is provided in Supporting Information, demonstrating that the DVC can withstand a three-phase fault and sudden load changes similar to the SGs [69]. Most of these controllers can damp the oscillation and improve steady-state system operation as explained by the frequency ($w$) relation to the droop ($R$), i.e. $\Delta w = R\Delta P_L/DR + K_m$ [70], where $R$, $\Delta P_L$, $D$, $K_m$ is the droop constant, load change, damping term, and inertial term, respectively. However, it lacks inertia ($H$) capability. This shortcoming leads to a higher rate of change of frequency (RoCoF), i.e. $\partial\Delta w/\partial t = \Delta P_L f_b/2H_{\text{eq}}S_{b2}$, that can trigger a blackout. Here, $f_b$, $H_{\text{eq}}$ and $S_{b2}$ are system base frequency, equivalent inertia constant, and base apparent power.

The other controls are then further divided into virtual oscillator (VOC) [63], Robust $H_2/H_\infty$ [64], DC-link capacitor-based virtual synchronous control (ViSync) [66], and frequency shaping [67]. These control strategies have their own merits. However, most of them are nonlinear and composed of complex structures, making it hard for real implementation. To overcome these limitations, i.e. remove complexity and provide both droop and inertia emulation, the VSM control is better for providing voltage and frequency supports. Besides, they

**TABLE 4** Comparison among different control methodologies for GFM and their role in power system stabilities.

| Category | Control structure | | Virtual inertial tuning | Frequency stability | Voltage stability | Angle stability | Inverter based stability | PLL for snchronization[f] | Overcurrent protection | No communication | Dispatchable |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Frequency Droop | | N | Y | Y[a] | ?[b] | Y[d] | Y | Y | Y | Y |
| | Angle Droop | | N | Y | Y | Y | | Y | Y | N | Y |
| Droop | PSC | | N | Y | Y | Y | Y | Y | Y | Y | Y |
| Control | EDPC | | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| | SPC | | Y | Y | Y | | ?[b] | Y | Y | | Y |
| | DVC | | N | Y | Y | Y | Y | N | Y | Y | Y |
| | VISMA | | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Synchronous | VSG | | Y | Y | Y | Y | Y[c] | Y | Y | Y | Y |
| Machine | Augmented | CND | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Based | VSG[e] | GDC | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| Control | Synchronverter | | Y | Y | Y | Y | Y | N | N | Y | Y |
| | eSM | | Y | Y | Y | Y | ?[b] | N | Y | Y | Y |
| | VOC | | Y | Y | Y | Y | Y | N | N | Y | N |
| Other | $H_2/H_\infty$ | | Y | Y | Y | Y | Y | Y | Y | N | Y |
| Control | ViSynC | | Y | Y | Y | ?[b] | ?[b] | N | Y | Y | Y |
| Methods | Frequency shaping | | Y | Y | N | ?[b] | ?[b] | Y | N | N | Y |

[a]Voltage related issues are resolved through integral and derivative terms.
[b]The sign (?) here means that the author could not find a clear answer to this question and hence is an open research problem.
[c]The output impedance of VSG is influenced by the parameters of proportional coefficients in high frequency whereas due to the cascaded control loop structure makes the controller tuning challenging in low frequency for WTG.
[d]In power modes of low frequency oscillation can be observed.
[e]Here the transient response and overall damping is improved whereas in GDC the frequency response is improved.
[f]PLL use need critical attention during transient stability performance due to high chance of erroneous measurements.

have features like tunable virtual inertia, overcurrent protection, self-synchronization, dispatchability etc. In synchronization, the dispatchable VOC may outperform in multiple VSM-based IBR scenarios [71]. VSMs are further subdivided into virtual synchronous machine (VISMA) [57], synchronverter [62], swing equation emulation (VSG) [36, 58], augmented VSG [56] (that has further subtypes called configurable natural droop (CND) [59] and generalized droop controller (GDC) [61]), and matching control whereby its electronic realization of SM (eSM) and control design are realized in [60].

Furthermore, the overall control structure of GFM is divided into an outer control loop and an inner control loop [34]. The internal control loop is mainly used for calculating the modulation signal for PWM or responsible for synchronization [43] of the controller terminal voltage with the grid at PCC. The outer control loop that provides input to the inner control loops mainly generates the angle, frequency, and voltage amplitude signal. The outer control loop of the control approaches in Table 4 can be subdivided into a power synchronization loop and voltage profile regulation. The first one has an angle loop that calculates the angle and a frequency loop that determines the frequency of the inner voltage virtual source loop. The second profile management loop of voltage is responsible for its regulation that has a specific subsystem in the control strategies of Table 4 [34].

## 2.4 | Discussion on CS, GFM, and GFL's operational principals

CS is regarded as a voltage source with a strong appearance of voltage to the grid. These machines have a voltage of steady magnitude and relatively small series impedance as they have internal electro-motive force or voltage due to electromagnetic induction [10, 46]. On the other hand, a DC side voltage is defined by a large capacitor configured in most of the IBRs, from which the AC side voltage is formed through chopping or modulations by semiconductors. With the creation of this AC voltage entirely through inverter modulators and control loops this voltage is constrained by the DC voltage and power availability and the semiconductor's current ratings. The CS can provide seven times more than its rated current for a short period, i.e. 1–100 ms [44] whereas the GFM VSC can only offer around 20% of the overcurrent their rated current [72]. The IBR has a multiple loop-based control structure with power control at the highest level that dispatches the power as per the instructions or the maximum power point tracking (MPPT). Contrary to the GFM-IBR, the power control uses the measured real and reactive power to droop-control the frequency and voltage. For a basic understanding, the power control either establishes a voltage source (in the case of GFM) or a current source (in the case of GFL), as shown in Figure 2 [73].

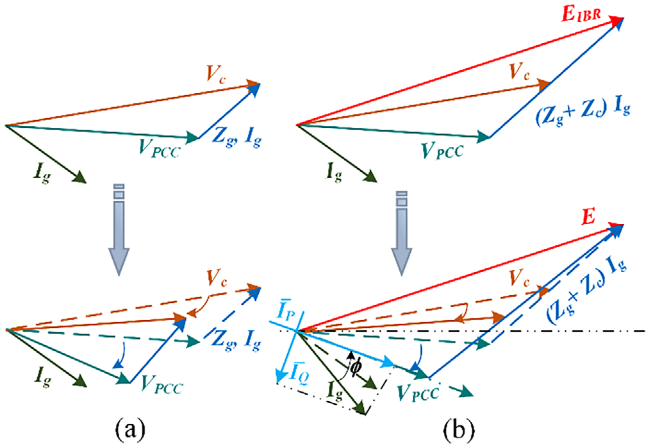


**FIGURE 3** Response of grid voltage to perturbation with (a) GFL controller (b) GFM controller [34].

From Figure 2, it is evident that the internal AC voltage $|E_{\text{IBR}}|\angle\delta_{\text{IBR}}$, and $|V_{\text{PCC}}|\angle\phi_t$ are separated by mostly inductive impedance $R_f + j\omega L_f$. The flowing current then will be as in (3):

$$I\angle\phi = \frac{|E_{\text{IBR}}|\angle\delta_{\text{IBR}} - |V_{\text{PCC}}|\angle\phi_t}{R_f + j\omega X_f} \tag{3}$$

This current ($I$) is ultimately viewed as flowing because of the established $E_{\text{IBR}}$ in the case of GFM or in the case of GFL, it is constant and follows a reference current through $E_{\text{IBR}}$ manipulations. For further details, read [50]. In terms of power, if the formulation is with respect to current, the converter acts as GFL, i.e. $P = \Re\,(\bar{V}_{\text{PCC}}\bar{I}^{*}_{\text{PCC}}) = V_{\text{PCC}}\ I_P\cos(\phi)$. Whereas in the case where the formulation is based on voltage, i.e. $P = \Re(\bar{V}_{\text{PCC}}(\bar{V}_{\text{IBR}} - \bar{V}_{\text{PCC}})/jX_c) = (V_{\text{PCC}}E_{\text{IBR}}/X_c)\sin(\delta)$, the converter acts as a GFM [16]. Here $X_c$ *and* $\delta$ are the impedance and angle difference between the voltages of IBR and PCC.

A duality of GFM and GFL is proposed for understanding purposes in [34]. These dualities include synchronization control, grid interfacing and swing characteristics, extreme operation, and interaction. Table 3 summarizes the duality between the GFM and GFL among the aspects above. Besides, the main difference between the GFL and GFM can be pointed out in their response to the grid events, as can be seen in phasor diagram Figure 3. In Figure 3(a) $I_g$ (current phasor) remained constant, both magnitude and phase wise resulting in the voltages ($V_{\text{PCC}}$ and the inverter terminal voltage ($V_c$)) variation in the GFL case. Meanwhile, in the GFM case, the internal voltage of inverters ($E_{\text{IBR}}$) remained constant while the rest of the parameters moved, including the phasor current. This trait makes the GFM attractive to the system operators [74].

Additionally, the small signal behaviour can also distinguish their reaction in weak and stiff grid conditions. Moreover, as per the grid code requirements [20, 75] the voltage and frequency regulation can be achieved by both controllers at the PCC through supplementary outer loops for set points modification of active and reactive power. However, these control strategies are in the realm of the real operating situation wherein the limitations of physical voltage and current should be considered [20, 42]. Furthermore, the synchronization method of both converters to the grid is also a main difference between them [34], which is further elaborated later.

## 3 | POWER SYSTEM DYNAMICS AND STABILITIES WITH GFM AND GFL-BASED IBRS

As stated before, the power system's global evolution towards renewable power sources mainly uses electronic-based inverters for interfacing with the grid. Traditionally, CS services provided the necessary stability to a power system with their synchronous capability. The displacement of CS by IBRs put the stability and other responsibilities burden (that are mentioned in Table 5 [45]) on the IBRs' shoulders. In the case of a 100% IBR-based system, the primary sources of stability become the IBRs. CS inherently possesses certain services, which are provided using synchronous torque and inertia. Thus, it is essential to enable the IBRs to offer such services [76] that lead to extra costs [77].

The dynamic characteristics of inverter-based resources (IBRs) differ significantly from those of synchronous generators (CS). In traditional power systems, the dynamics of CS are primarily influenced by its rotor, leading to a consistent increase in the rotor angle in the event of significant disturbance instability. Conversely, in a new power system relying on IBRs, the dynamics are predominantly governed by power electronics-based control processes. According to specified guidelines, there are specific objectives for Voltage Source Converter (VSC) control that must be met to maintain stability; otherwise, the system is deemed to be losing stability.

The outer control loop regulates the real and reactive power (P/Q) in accordance with the reference, while the inner control loop manages the current ($i$) to align with the reference

**TABLE 5** Problems with increased IBRs.

| Concerns | Reasons | Impact | Mitigation |
|---|---|---|---|
| Reduction in rotational inertia | Absence of rotational mass | High RoCoF | Virtual inertia |
| Reduced response to frequency event | Dispersed and huge number of units | Processing and communication delays | Robust control and faster communication |
| High probability of UFLS activation | IBRs sudden disconnection caused by disturbance | Frequency instability | IBR's frequency support |
| Cascading outages | Loss of mains protection activation | Load shedding and black out | Forecasting and unit commitment |

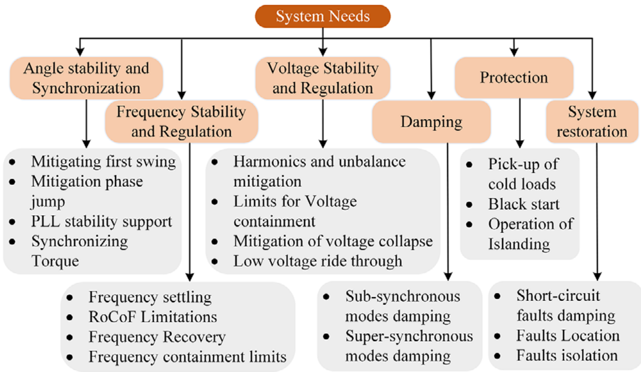


**FIGURE 4** Possible system needs and specific sub needs [31].

value. In this context, nonlinearities play a crucial role in causing instability during large disturbances [78].

The inverters today that are in service are generally GFL and have innate features that are essentially different from synchronous sources. Whereas the GFM that is being developed recently can be designed to fulfil, the system needs listed in Figure 4, including the angle, frequency, and voltage stabilities, similar to synchronous sources. These GFM's different control strategies performance abilities are compared in Table 4. With significant limitations, voltage, frequency, and other stability-related services can be carried out by the GFL. However, the black start is hard for GFL to execute as it requires a reference voltage signal to follow. In contrast, GFM, similar (not identical) to CS, can provide black start support to the grid [30, 77, 79]. It is worth noticing that both GFM and GFL control approaches face multiple physical equipment bounds in the form of energy limits, voltage, and currents.

The power system stability challenge is as old as the system itself [80]. It emerges in new forms with the evolutions in the power system over time. Similarly, the high IBR penetration also indicates new stability phenomena. The impact of IBR on frequency, voltage, angular, and inverter-driven stability will be discussed next [6, 77].

## 3.1 | Frequency stability

The conventional synchronous generators' inertia determines the initial RoCoF during a frequency event[1]. Next, the governor of generators kicks in to arrest the frequency drops, followed by the automatic generation control (AGC) to restore the frequency to nominal values (50 or 60 Hz) [76]. In this sequence, the activation of a protective scheme is avoided, which may lead to generation/load shedding or blackout in extreme cases. Whereas frequency dynamic lies in the range of seconds to several minutes. This frequency stability is deeply linked with inertia. Therefore, the stability can be compromised with its drop in the IBRs-based system [77]. The criteria of entering into service of IBRs with regards to frequency and voltage is summarized in Table 7.

[1] By frequency events it means the sudden disconnection/connection of generation or load

The frequency dynamics after disturbance are characterized by (1) the RoCoF, (2) its nadir, (3) and steady-state [81]. To resolve these issues in higher-level IBR-based power systems, state-of-the-art technology is needed for control and is discussed in detail in the coming sub-section. An oscillation problem may arise due to sharp or aggressive control responses. Therefore, system operators should continuously seek revised needs of frequency response in the context of regulation reserves and performance. GFM-IBR performance is demonstrated in Supporting Information, showing that they are similar to the CS in handling frequency stability [69].

Another issue that requires attention is the size of the contingency that can affect frequency stability, as the synchronous generator's size is much larger than that of the individual IBR. Failure of new common modes may occur, affecting many IBRs simultaneously because of their high share. In a wide-area interconnected power system, a low voltage propagation over a wider area may induce voltage-based frequency dips during a fault. Synchronous area splitting may also occur and can be a concern in the future grid that causes frequency stability issues [77].

### 3.1.1 | Inertial response

To address the imbalance in a low-inertia power network, quick current injection methods can be employed, with careful consideration of suitable ramp rate limits. Various sources exhibit distinct ramp rates; for instance, BESS may have a faster ramp rate compared to WTG. When dealing with lower ramp rates, a greater number of sources need to engage in frequency regulations to collectively meet the demand [45].

More solutions like must-run synchronous generator reserves can be used [81]. However, these solutions can be costly and sometimes technically challenging, as in the case of gas turbines. Another option is to assist the inertia of the power system through synchronous condensers (SynCons), flywheels, and GFM-based IBRs, and can also cope with the system split issue. In the case of GFM-based IBRs, they require the inverter's overcurrent capability and energy buffer to effectively provide inertia to the system [77]. Besides, it was concluded in [26] that in terms of the metrics of frequency stability, namely nadir and RoCoF, GFMs perform better than all-SM systems used as a baseline due to their fast response capability compared to the slower dynamics of SM turbines. Here, a matching control approach [60] was applied as it considers DC quantities in the angle dynamics and hence shows efficacy in mitigating the saturation of the DC-source.

The frequency response time might not meet for the frequency reserve due to high RoCoF values resulting in under-frequency load shedding. SMs can withstand larger values of RoCoF as compared to the IBRs because their design makes them tolerant to bolted faults [6, 10, 45].

Ref. [16] claims that inertia has an impact on both RoCoF and damping, which then results in a natural frequency increase. Besides, it has been observed that the inertia mainly affects the RoCoF, while damping of the system helps to reduce the steady-state oscillation [70]. According to our research, inertia

**TABLE 6** Requirement from IEEE P2800 standard for PFC.

| Description | Default value | Min–max |
|---|---|---|
| Reaction time (s) | 0.50 | 0.20 (0.5 for WTG)–1 |
| Rise time (s) | 4.0 | 2 (4 for WTG)–20 |
| Settling time (s) | 10.0 | 10–30 |
| Damping ratio (% of Change) | 0.3 | 0.2–1.0 |
| Settling band (% of Change) | Max (2.5 % of change or 0.5 % of ICR) | 1–5 |
| Existing services related to inertia | | |
| Power System | Services | Response time/duration |
| SONI/EirGrid (Northern Ireland/ Ireland) | Inertial response (synchronous) | Rapid/N/A |
| | FFR | 8 s |
| National grid (GB) | Frequency response (enhanced) | 1 s/15 min |
| ERCOT (Texas, US) | Inertial response (synchronous) | Rapid/N/A |
| | FFR 1 | 0.5 s/10 min |
| | FFR 2 | 0.5 s/as much required |
| AEMO (Australian Grid) | Regulation of fast response | 1 s/N/A |
| | Inertia (simulated) | Rapid/N/A |

has a small impact on oscillation damping; rather, it primarily influences the RoCoF [76] and, consequently, nadir. For better understanding, the RoCoF and nadir can be determined as.

$$\text{RoCoF} = \frac{\Delta P_L f_b}{2H_{\text{eq}} S_{b2}} \tag{4}$$

$$\text{Nadir} = f_b + \Delta\omega_e \left(T_{\text{peak}}\right) \tag{5}$$

Here $\omega_e$ is the electrical frequency, and the peak time related to frequency nadir is represented by $T_{\text{peak}}$. The RoCoF relays in distributed generators require an active power imbalance of 8.7% to 15% for islanding detection (with a time range of 60 to 200 ms with 0.1 Hz/s to 1.2 Hz/s relay setting) [82]. The requirement for primary frequency response set by IEEE P2800 Standard [39] along with existing services related to inertia [8] are given in Table 6. It is a question in the UK as to how much inertia the GFM converter (in the context of the HVDC network) should provide [83], and it could be in the range of 2–25 MW/MVA [40].

### 3.1.2 | Damping and synchronization of GFM-based system

The basis for the power system stability is the synchronization among the generation sources, which plays a vital role in preventing blackouts and undesired outages [13]. However, achieving synchronization is becoming increasingly challenging with the widespread adoption of non-synchronous generation sources (NSG). With this, the traditional stability preservation methods and synchronous sources' characteristics-based approaches that rely on certain assumptions may no longer be applicable. This shift arises from the kind of inertia and damping provided by the IBRs. The synchronization mainly affects stability and dynamics related to the frequency. This frequency has to remain consistent during steady-state conditions as this is a key variable for coupling across the power system network.

Not only the electrical engineering community but also physicists and applied mathematicians are attracted by this issue. In some of the literature, the power network is assumed to be a non-linear oscillator [84, 85], whereby to reach the alikeness level between the swing equation and the desired oscillator, many factors of critical importance are either neglected or simplified. Furthermore, refs. [86, 87] claims closed-loop solutions, out of which ref. [86] presents provisional conditions, and ref. [87] assumes the coupling damping factors homogeneity. Again, these assumptions deviate from the fact that the power system is heterogeneous, leading to a loss of potential inclusive investigation of the IBR-dominated power system. This concern of frequency synchronization adheres through three contributions in ref. [13]. These contributions are in the form of the consideration of (1) factor for heterogeneous coupling, (2) parametric synchronization of power network characterization, and (3) testing 100% IBR base system with enough damping element.

Regarding the differences between GFL and GFM, their synchronization to the grid is a key process, among others. As shown in Figure 1, GFMs do not necessarily require a dedicated unit for synchronism, whereas GFL requires units like PLL. To inject the proper amount of active and reactive power, this dedicated unit in GFL reads the angle of grid voltage and determines the converter current's phase shift. There is a chance of failure with PLL to lock onto the grid frequency after a disturbance in a low short circuit ratio (SCR) system [45]. For understanding, a stiff grid is considered to be with SCR > 3 as per the IEEE Standard [88]. An SCR is defined as the ratio between the AC system short circuit power ($S_{\text{ac}}$) and VSC station (source) rated power ($P_{dc}^{N}$) and determined as,

$$\mathrm{SCR} = \frac{S_{ac}}{P_{dc}^{N}} \tag{6}$$

Conversely, the GFM working as a voltage source behind the impedance makes them a potential candidate for weak grids. A detailed review on this issue is provided in Supporting Information on GFM performance [69]. Besides, the GFMs use the synchronism principle of SMs and, therefore, can self-synchronize [22, 62].

## 3.2 | Voltage stability

The maximum limit for transferring power over long distances is often constrained by the transient stability of the initial swing, crucial for maintaining synchrony in traditional systems. This poses a complex challenge for grid operators and planners. Introducing IBRs as replacements SGs can help address this challenge by ensuring acceptable angular and voltage stability within the grid. However, incorporating a significant proportion of IBRs also introduces new concerns related to voltage issues. This can be attributed to factors such as fluctuations in the number of controllers with high gain online, variations in the responses of IBRs, and potential interactions with other dynamic devices in the system [77].

Improper responses of IBRs during fault ride through (FRTH) situations after a fault can lead to low or high-voltage collapse in bulk power systems (BPS), especially when IBRs are concentrated in remote areas distant from load centres. Additionally, the high bandwidth and dynamic characteristics of IBR voltage control may introduce uncertainties and novel interactions with other reactive devices. Consequently, similar to SGs, there is a need to impose limitations on the control bandwidth of IBRs, as exemplified by the 5 Hz restrictions in Great Britain.

Besides, supporting voltage stability can be achieved through converters' reactive power capability, for example, injecting reactive power during extreme voltage dips. Under extreme conditions, staying connected to the grid, i.e. FRT capability, is now becoming a grid code requirement for electronic power converters. Furthermore, forecasting the output of wind and solar power can be challenging due to their intermittency, and this issue can be commenced with energy storage batteries [81].

According to requirements, the steady-state voltage of any phase throughout the feeder should be within a specific range, like ANSI C84.1 range A. This range is designed by the characteristics of load in the (MG). According to ANSI C84.1, up to 3% maximum voltage imbalance is recommended [38].

$$V_{\text{imbalance}} = \frac{\Delta\left(V_{\text{av, max}}\right)}{V_{\text{av}}} \times 100\% \tag{7}$$

here $V_{av}$ is the average voltage of any phase in the steady state. Whereas the voltage imbalance factor (VIF) is recommended to

**TABLE 7** Criteria for IBRs to enter into service.

| **Criteria** | | **Default** | **Available settings range** |
|---|---|---|---|
| Service permit | After enable | Disabled | Enable and disable |
| Range of allowed | Min | TS operator prerogative | 0.90 to 0.95 p.u. |
| Voltage | Max | TS operator prerogative | 1.05 to 1.10 p.u. |
| Range of allowed | Min | TS operator prerogative | 0.98 to 0.99 p.u<br>@60 Hz: 58.8 to 59.4 Hz<br>@50 Hz: 49 to 49.5 Hz |
| Frequency | Max | TS operator prerogative | 1.002 to 1.02 p.u.<br>@60 Hz: 60.12 to 61.2 Hz<br>@50 Hz: 50.1 to 51 Hz |

TS;Transmission system.

be less than 2% according to IEC 6100-3-x:

$$\mathrm{VIF} = \frac{|V_2|}{|V_1|} \times 100\% \tag{8}$$

where $|V_1|$ and $|V_2|$ are the positive and negative sequence voltages respectively. Besides the entering service criteria for and voltage is given in Table 7 [39].

Voltage imbalance can happen during normal steady-state operations due to load imbalance; therefore, it should be prevented to protect three-phase loads like induction motors from damage. According to some studies [45], if the GFM does not provide negative sequence voltage regulation, a severe imbalance of voltage can occur, and therefore, a clear requirement of this capability has to be stated; otherwise, the GFM may not provide this regulation by default. This voltage regulation from GFM requires enough capacity of negative sequence current for effective operation. On the contrary, it may aggravate the amount of DC capacitor power ripple and thus call for deploying a larger capacitor. A common requirement among various technical reports and grid codes is converters should behave as a voltage source behind impedance to provide frequency and voltage support during grid disturbances [83] such as voltage dips or swell and phase jumps. A three-phase fault case study is given in Supporting Information where the voltage has been swiftly recovered in a GFM-dominated system after the fault clearing [69].

## 3.3 | Phase angle stability

A reassessment may be necessary for higher penetration of IBRs into the system, as it may have a different impact on angular stability. The dynamic of this stability is linked to electromechanical oscillations and happens in the range of milliseconds to seconds.

Two aspects, large signal angle stability or transient stability and small signal oscillations, can be ascribed to the high presence of IBRs in the grid, which is further explored below.

### 3.3.1 | Large signal angle or transient stability

During grid faults, synchronism has been a long-standing proxy for maintaining large-signal rotor angle stability for the synchronous generator. This stability concept is based on the accelerating or decelerating magnetic fields of the stator and rotor angular displacement. The dynamics of clearing faults are dominated by the accelerating energy of the synchronous generator, which is accrued by the reduced mismatch between electrical and mechanical power.

Some research articles have studied transient stability using an active power control approach while overlooking the effects of reactive power control. For example, transient instability was investigated in [89] and [90] that arose due to voltage sag causing current saturation. In addition, the Lyapunov function was used to evaluate the transient stability of the low-pass filter-embedded droop control in [91]. Furthermore, different grid faults were applied to investigate the transient stability of the PSC-based VSC. There is a cross-coupling between the active and reactive control loops [92] therefore, it is important to consider this for realistic studies. An attempt was made in [93] to investigate the deteriorating impact on the VSG's transient stability using a qualitative analysis approach for reactive power control using a power-angle ($p$–$\delta$) curve. However, the fundamental challenge is the identification of control parameters like droop gains and virtual inertia and reactive power control's impact on transient stability posed by the inherent complexities due to its nonlinear dynamics. Therefore, a large-signal model is used for the systematic review of transient stability dynamics of the four GFM control strategies, i.e. VSG, droop control with and without low-pass filter, and power-synchronization control (PSC) in [22]. Subject to the equilibrium points, the basic droop control and PSC retain stable operation. However, due to the lack of damping in the responses to inertial transient, the VSG and droop control with LPF could not keep stability [94].

Another important aspect is the current limitation issue with transient stability. A strategy for limiting current references in the inner control loop based on a current saturation algorithm (CSA) is reported in [95]. A popular technique for limiting current while maintaining the voltage source nature of the GFM VSC, based on a virtual impedance (VI) approach, is presented in [96]. According to ref. [97], the VSC based on CSA is effective in managing current limitations but faces difficulty in synchronization after fault clearance. In contrast, VI-based VSC excels in synchronization post-fault clearance but encounters overcurrent issues in the initial 25 ms after a fault. A hybrid model combining CSA-based and VI-based VSCs is proposed to address these challenges and enhance overall system performance. Additionally, the current limiting strategies discussed earlier do not tackle the issue of transitioning out of current saturation mode upon fault clearance. To address this concern, a VSG-based VSC is explored in [98] to investigate transient stability. The proposed approach incorporates an enhanced current limiting strategy and a hybrid synchronization control that integrates both PLL and power–frequency ($p$–$f$) synchronization control characteristics. This strategy effectively restores the system from the current saturation mode by selectively activating or deactivating the current limiting reference loop.

### 3.3.2 | Small-signal oscillations

The ability to maintain synchronism by the power system after facing small disturbances like small changes in generation or load is known as small-signal or small disturbance rotor angle stability [6]. The angular stability and other notable aspects are the small signal oscillations damping that also needs attention in IBR-dominated systems. Practical experience to date has shown that IBR-based networks exhibit oscillations of up to 15 Hz, which is higher than the 4 Hz oscillations observed in CS-based networks that rely on electromechanical processes. There could be four reasons for these small signal oscillations. (1) The displacement of CS can lead to power system degradation and oscillations. These oscillations can be damped by modifying the control system of GFL-IBR and GFM-IBR and equipping the dynamic reactive power with power oscillation dampers. (2) Electromechanical oscillations and new modes may appear with the addition of SynCons. The system damping can be improved by adding flywheels to SynCon's. (3) GFL-IBRs can engender sustained low-frequency oscillations in weak systems, such as those found in Australian systems. (4) Oscillations can occur between devices due to GFM controls with machine-like behaviour resembling electromechanical instabilities [77]. Points (3) and (4) types of oscillations will be discussed further in the next section as they fall in the converter-driven based stability category.

## 3.4 | Converter driven-based stability

This newly added stability type to the classification of power system stabilities set is converter-driven stability [6]. The stability issues of this kind are primarily linked to IBRs and differ from the dynamic behaviour of conventional synchronous generators due to the leading VSC in the system [99]. The IBR may induce oscillations due to cross-coupling between electromechanical and electromagnetic transients, which can be exacerbated by the fast response capabilities of the control loops and algorithms that operate on a wide timescale [100]. The instability in such cases is further divided into two classes as: slow (<10 Hz) and fast (100 Hz to kHz) interaction-associated interactions converter-driven stability.

The dynamics-related fast-interactions occur between the power system's fast response components, such as SM's stator dynamics or transmission networks, and power electronic-based systems, such as GFM, GFL, FACTs, and HVDC etc. For example, the GFM or GFM inner-current loops interact with the system's passive components, resulting in oscillation of high frequency ranging from hertz to many kilohertz. On the other

**TABLE 8** Demonstrations of GFM through various pilot projects.

| Location | Name | Capacity (MW/MWh) | Technology | Source |
|---|---|---|---|---|
| FL 2021 | Micanopy microgrid | 8.25 MW | AS, RI | BESS |
| NY 2022 | National grid microgrid | 20 MW \| 40 MWh, 75 MVA | AS, EM, IO | BESS |
| Canada | Waterton microgrid | 1.6 MW \| 5.2 MWh BESS, 200 kW PV | Energy support | BESS & PV |
| St. Eustatius Island 2016 | | 2.3 MW peak load | AS, BS, RI | Storage and solar |
| Scotland 2019 | Dersalloch Wind Farm | 69 MW | AS, BS, IO | Wind turbines for 6 weeks |
| South Australia 2018 | Dalrymple BESS | 30 MVA \| 8 MWh | AS, EM | BESS |
| South Australia 2017–2020 | Hornsdale BESS | 150 MW \| 194 MWh | AS, EM | BESS and wind Farm |
| Switzerland 2012 | Zurich BESS | 1 MW/0.58 MWh | AS, EM, IO | BESS (GFM), EV, PV |
| Australia 2012 | Ausnet GESS | 1MW/1 MWh | AS, IO | BESS |
| USA 2012 | Mackinac HVDC | 200 MW HV | | HVDC |
| Europe-USA 2017–2019 | SMA Projects | 0.8-15 MW/0.4-15 MWh LV-MV | RI, IO | BESS (GFM), PV |
| Australia 2018–2019 | ESCRI-SA Project | 30 MW/8 MWh | AS, EM | BESS |
| Europe 2018 | La Plana Hybrid Project | 850 kW WTG/245 kW PV/222 kW CS/555 kW \| 545 kWh BESS | AS, BS, EM, IO | WTG, PV, CS, BESS |
| Europe 2018 | DEMOCRAT Demonstrator | 0.25 MW/0.22 MWh | BS, EM, IO | BESS |
| USA 2019 | NREL Campus | 1.25 MW/1.25 MWh | AS, RI | BESS |
| USA 2017–2019 | GE Projects | | AS, BS | BESS, PV |
| Europe 2018 | OSMOSE Projects | 0.1–0.72 MW/0.025–560 MWh | RI | BESS |
| ABB PEGS 2020 | | 20 MW | Other | |
| Europe 2021 | Fluence-Siemens Project | | EM, RI, BS, AS | BESS |

hand, the dynamics linked to slow interaction arise between the power system's slow response devices, such as some controllers of generators and SM electromechanical dynamics, and the power converters. Although their primary causes differ, slow interaction stability can be similar to voltage stability, particularly regarding the maximum power transfer between the system and the converter. For instance, the instability may be rooted in a weak system. 'Since 2014, sustained oscillation has been observed in real events in China's Xinjiang region caused by interaction between the AC weak grid and direct-drive permanent magnet generator (PMG) WTG. It is worth noting that as of the authors' understanding, the testing of GFM and GFL for this type of stability has not been conducted and remains an open question for the research community.

## 4 | GFM'S REAL WORLD DEMONSTRATIONS AND APPLICATIONS IN IBRS

At present, the GFM is mainly applied to MG and transmission systems that have low rotational inertia and fault current. According to [44] the penetration level of instantaneous NSG has reached 60% to 80% in many small power systems. Here, the instantaneous NSG penetration is defined as the power converters-based generation divided by the demand plus export. As an example, an 89% instantaneous penetration level of PV and battery have been observed in St. Eustatius see Table 8. Furthermore, UK, Hawaii, Germany, and Australia are some examples of power systems with a high share of IBRs. These power systems are moving towards incentivizing and reforming grid services to enable the IBRs to participate in them. With this increase of IBRs in BPS the GFM appearance is inevitable there. Pilot projects of GFM-IBR are already providing in-depth knowledge and experience in Australia and Great Britain. These projects can serve as a learning platform for other power systems to follow this trend [46].

A simulation-based study was carried out on an all-island Irish transmission system to investigate the minimum requirement for frequency stability when using 100% IBRs based on VSGs in the system [27]. An islanded AC microgrid is used to test a proposed bidirectional GFM converter that has fault tolerance and is applied through a centralized control architecture in [101]. Multiple projects are initiated on the ground, some of which are reported in Table 8 with details related to their capacity and the type of source used with GFM technology [29, 46].

Most of the pilot projects listed in Table 8 are operated at the medium voltage (MV) level of grid connection, with a few exceptions of projects connected at the high voltage (HV) level. A plausible reason for connections to the grid at this voltage level could be that the energy sources, such as WTG, PVs, and BESS interfaced through the GFM technology, are typically designed for application at the LV and MV levels. Besides, the immaturity of the GFM technology and uncertainties regarding its performance make demonstrations at the MV level a good compromise between testing the effectiveness of the service and the cost of the project installation and operation for the demonstrators. Furthermore, the services and targets offered by the demonstrators, such as black start, fuel consumption minimization, and MG islanded operations, are well-matched to the needs of distribution networks compared to the transmission systems. In the case of MGs, these GFM will be handier in extreme weather conditions to provide an uninterrupted power supply to users by utilizing the GFM features [102].

The primary stakeholders in this context are entities engaged in grid generation and power management sectors. Notably, the project demonstrators listed in Table 8 predominantly consist of major power converter manufacturers such as ABB, SMA, Siemens, GE, and a minor portion represented by transmission system operators (TSOs). This highlights a competitive landscape during the initial experimental phase, potentially yielding positive outcomes if the technology becomes integrated into the economic framework of the grid. Despite this, the significance of legislation remains constant and can play a pivotal role in incorporating this technology into national development plans.

These demonstrations show that GFM has great potential to replace the CS and can even make 100% power supply from IBRs possible. However, it can be concluded that further research is needed before going into the implementation phase, which is further elaborated in the coming section. Next, research on GFM applications in PV and WTG systems is discussed, whereas a detailed review of GFM for HVDC can be found in Supporting Information [69].

## 4.1 | GFM for photovoltaic (PV) system

The IBRs can operate either with other GFL-IBRs or in parallel with GFM-IBRs. Disparate energy sources like BESS or PVs can be connected to the grid through these inverters. When operating through GFL inverters, PVs can provide services to the grid, such as injecting reactive power, supporting steady-state voltage, dynamic voltage support, FRT, and primary frequency control (PFC) [41, 103, 104]. However, these services are not very effective through GFL for different reasons. Conversely, GFMs-based IBR has promising potential for allowing increased level integration into the grid as they can establish the frequency and voltage of the grid [99, 105] its services, when deployed in PV systems, are summarized in Table 9 [40, 69, 106–108]. It is claimed that the GFM can outperform the GFL and SMs in short-term stability [109] and frequency stability dynamics [26].

In the literature, many articles assume energy storage like a battery or ideal source [26, 109, 110] this assumption does not represent reality as the nature of the primary source of RPG, like PV and WTG, is intermittent and should not be ignored. In the case of PV, they can provide ancillary services in two ways: (1) by operating below the MPPT (i.e. curtailed operation), or (2) through PV and energy storage hybridization [103, 111–114]. Both approaches have their own merits and demerits. For example, a curtailed operation may result in unavailability during night time, but is relatively simple. In contrast, PV and energy storage hybridization may be expensive, and there is a risk of under-usage. There is a growing consensus regarding the adoption of GFM for PV use in BPS [111–114].

**TABLE 9** Summary of GFM based IBR's services provided to the grid [40, 69, 106–108].

| Services/characteristics | PV | WTG | BESS | HVDC[f] |
|---|---|---|---|---|
| Angle stability | Y | Y | Y | Y |
| Inertia | N | Y | N | N |
| PFC | Y | Y | Y | Y |
| SFC[c] | N | N | Y | N |
| Voltage | Y | Y | Y | Y |
| FRT | Y | Y[b] | Y | Y |
| DC-link dynamics | N | Y | Y | N |
| Black start | Y | Y | Y | N[e] |
| Current limitation[a] | Y | Y | Y | Y |
| Need of energy storage[d] | Y | Y | Y | Y |

[a]schemes of current limitation are generally applied to protect the inverters.
[b]Current limiting scheme should be in conjunction with FRT.
[c]SFC requires power reserves from seconds to minutes which is not available in case of IBRs.
[d]Energy storage will boost the GFM abilities of most of the IBRs.
[e]Wind farms connected through HVDC can be energized hence enabling black-start.
[f]Generally energy storage is required for HVDC to support the grid.

During curtailed operation, monitoring the MPP is a challenge as it varies with time. Some approaches [112, 113] have been attempted to monitor this MPP based on estimation under deloaded conditions for GFM-based PVs. These studies, however, lack testing of these controllers under multiple common disturbances, such as irradiance changes, load changes, and network faults. Besides, accuracy in the estimation, uncertainty of parameters, and performance degradation during sudden irradiance changes are also unresolved issues in the literature [114]. For example, the irradiance change is recorded up to 150–200 $W/m^2s$ due to the prompt movement of clouds. The estimation and current limiting issues are addressed in [106] through a model-free method and a new scheme for current limitations using a modified current reference.

Another factor to consider is the presumption of a consistent DC-link voltage, a practical condition achievable through the use of sizable capacitors or battery energy storage systems (BESS). However, this approach adds significant costs, particularly in BPS. This assumption overlooks the intricacies of the DC-link capacitor, DC-source, and DC-to-DC converter control, all of which play a crucial role in determining how the DC-source responds to abrupt changes in load [115]. Neglecting the limitations of the DC source can impede the inverter's effectiveness, resulting in discrepancies between input and output power and a subsequent decline in DC voltage [116]. To sustain the voltage at $v_{\mathrm{ref}}$ (reference value), the drop of DC voltage should not be more than $v_{\mathrm{ref}}/1.1$ where the modulation index is 1.1. GFM-based PV systems without the support of energy storage have been investigated in [117] and [106]. However, ripples of lower voltage are produced while tracking the frequency when VSG-based GFM was used for PVs [117]. Besides, the DC-link dynamics are considered in [118] and [106], wherein the DC-link stability is assured. To summarize, the PV equipped with GFMs can potentially replace SGs; however, further research is required to know their integration level and their combination with GFL and SGs.

## 4.2 | GFM for wind turbines generator (WTG)

Among the different RPG types, WTG has a major contribution, with their per unit size and rated power also growing recently [107]. However, wind power's variability and uncertain nature challenge balancing the power system [15]. To overcome these issues, there is an urgent need for control strategies to guarantee the stability of power systems under the higher influence of wind power [68, 119]. The traditional WTG is mainly based on GFL, which requires strong grids to provide fixed frequency and voltage, as mentioned in the PV section. GFL-based WTGs provide no support for active power during contingencies since they operate as constant current sources with the turbine's kinetic energy practically decoupled [20]. Despite this limitation, there are a few approaches using GFL-based current sources that enable WTGs to participate in the frequency regulation of power systems. This provision is carried out through (1) maintaining power reserve, (2) providing controllable power generation units, and (3) simulating virtual inertia [120].

There are a few shortcomings related to these above GFL approaches. In the first method, there is no direct involvement in frequency response; rather, it adjusts the active power in response to the system frequency. The second approach involves using diesel generators, which have a slower response compared to the IBR. BESS, on the other hand, is expensive to install in bulk. While virtual inertia is useful for resisting very fast frequency changes, it is only available for very short intervals and cannot support the frequency in the long term.

To overcome the above issues, a GFM-based inverter is required for WTGs, whose characteristics are enlisted in Table 9. A study of an ideal doubly-fed induction generator (DFIG) WTG and BESS-based hybrid standalone system is conducted in [121] that utilizes GFMs. The performance improvement in terms of inertial response and active power tracking through a Synchronverter-based GFM for PMSG's grid-side converter under variable wind speed situations is claimed in [122]. GFM-based Type 3 [123] and Type 4 [124] WTGs have been investigated for their potential use with HVDC systems. The GFM, which is proposed for the grid-side converters, can restrain fault current in weak grid situations; also, the GFM suggested for Type 4, i.e. VSG, has better impedance characteristics as compared to conventional methods of DFIGURE These studies ignore the characteristics of primary wind energy and the dynamics related to electromechanical transient as these studies are designed for large-scale wind farms. A decentralized GFM control strategy for an MG with high penetration of DFIG-based wind power is investigated in [120]. This strategy doesn't rely on PLL and use DFIGs and BESS as GFM-based voltage source. As compared to other articles, Ref. [120] considers the use of GFM control for wind power with high penetration in an autonomous grid, providing continuous voltage and frequency support. In addition to analyzing the rotor speed dynamics and electromechanical transient dynamics, a stability analysis of the full-order small signal system is also provided.

Currently, the use of GFM is a relatively new topic, and there are few literature reviews available solely on WTGs using GFM converters. A comprehensive assessment limited to GFM-based Type 4 WTG-PMSG is conducted in [107]. It categorizes GFM for WTGs based on DC-link voltage regulation strategies, which differs from the categorization used in [43] where GFM control methodologies are mainly based on constant DC-link voltage assumptions. Most of the strategies in Table 4 are classified as grid-side GFM (G-GFM), machine-side GFM (M-GFM), and external energy storage GFM (E-GFM). The comparative study shows that during faulty conditions, the multi-loop and single-loop M-GFM perform better because the machine-side converter controls the DC-link voltage, which is decoupled from grid disturbances [107]. Another review article investigates GFM control strategies for Type 3 and Type 4 WTGs, examining various DC-link control and energy reserve schemes. It is found that the control scheme of DC-link voltage on the machine side performs better for Type-4 WTGs, whereas the control for DC voltage based on PLL is favoured for Type-3 WTGs due to zero steady-state error and speedy dynamics [125]. To conclude, the WTG based on GFM is favourable regarding ancillary supports like frequency control, whereas it is recommended to provide additional constant power sources such as BESS and synchronous machine reserve etc., for reliable operation. The GFM-based BESS is reviewed next.

## 4.3 | GFM for BESS

BESS is a low-hanging fruit for deploying GFM capability [46]. For example, an energy storage of 100 GW is planned to be added to the system by the US Energy Storage Association [126]. However, as mentioned in the previous sections, technical and economic concerns exist in electrochemical batteries, which form a major part of the project [126, 127]. Despite these concerns, BESS is not only a dispatchable source. Still, it is one of the best candidates for grid ancillary services such as active voltage and frequency support, black start capability to standalone systems, and other supports like coping with voltage sags, harmonics, and surges. A more economically viable option is the usage of electric vehicles batteries for grid services [76]. In [128] the vehicle to grid concept is used to provide good harmonic rejection and voltage support using a coordinated virtual based control scheme for three phase four leg inverters. These sources can respond fast to events like frequency and have high energy density. While the provision of inertia emulation has not yet been reported in the industry, BESS has the potential to participate in this service to a degree in the future [129]. Nonetheless, they play a role in transitioning from grid-connected modes to islanded modes and vice versa using some algorithm-based controllers. One of these controllers is the GFM methodology, which can potentially provide most of the services lacking in GFL-based control methodologies.

Several articles have been published on the integration of BESSs and their role in the operation of power systems

**TABLE 10** IBR potential of meeting the system needs.

| | Stability and power quality | | | | Security and service quality | | | |
|---|---|---|---|---|---|---|---|---|
| **IBRs Characteristics** | **Synchronization & angle stability** | **Frequency regulation** | **Voltage regulation** | **Damping** | **Energy** | **Capacity** | **Protection** | **Restoration** |
| Energy | N | Y | N | N | Y | Y | N | N |
| P | Y | Y | N | N | N | N | N | Y |
| Q | Y | N | N | N | N | N | N | Y |
| Non-active current | N | N | Y | N | N | N | N | N |
| Over-load current | N | N | Y | Y | N | N | Y | Y |
| Control bandwidth | N | N | Y | Y | N | N | N | N |

[108, 130–132]. The pros and cons of AC–DC inverters, topologies, and performance of battery technologies related to the BESS integration into the distribution system at the MV level are discussed in [132]. However, it doesn't cover the participation of BESSs in ancillary services, their operations, integration standards, and interoperability. The provision of behind the meter (BTM) and ancillary services are discussed in detail in [108, 130]. Where the opportunities, obstacles, requirements, policies, and techniques are highlighted. However, the discussion in [130] is limited to a very narrow scope of BTM, where the control mechanism is absent. On the other hand, ref. [133] provides a comprehensive review of BESSs, including grid-interfacing control strategies, common variations in BESS architecture, standards, and requirements for grid connections. Besides, practical applications of BESSs and their coordination with PVs are also discussed. Furthermore, refs. [51, 134] explores an islanded converter-based AC microgrid using small-signal precise mathematical modelling. Modelling and stability analysis based on an independent MG droop control is presented in [51] whereby low-frequency oscillations are generated by the droop controller without PLL. However, these articles consider ideal BESSs in the system without RPG.

According to [111] inverters used for BESS are divided into four categories: GFL, GFM, grid-supporting, and grid-feeding, based on the interconnection to the grid and the services it can provide. Meanwhile, inverter topologies are classified into 2-level and multilevel topologies [133]. As this article focuses on GFM, readers can refer to [111] for further details. With the ability to maintain AC voltage and frequency at the main terminal AC bus and allow a bidirectional power flow, the industry and system operators for BESSs favour GFM. In short, the duo of GFM and BESS acts as a synchronous generator operating in a conventional power system. While both 2-level and multilevel inverter topologies can be used for GFMs, the multilevel topology is preferred over the 2-level inverter topology. In short, energy storage like BESS will be essential for the IBRs' large-scale deployment as it would assist other sources in performing different grid operations.

With the summary in Table 9 highlighting various services provided to the grids by these different IBRs, the application section ends here. However, its use in HVDC is also reviewed in Supporting Information [69].

## 5 | SYSTEM NEEDS WITH HIGH-LEVEL IBR INTEGRATION

There are eight identified system needs that fulfil the primary objectives of the system in all credible conditions. These eight needs, as reported in Table 10, are divided into two groups: (1) stability and power quality and (2) security and service quality [46, 135]. While energy and capacity are the primary factors in investment decisions, there is a recognized shift towards other needs, particularly with high IBR and RPGs in the future [31, 32].

The six additional system requirements are subdivided into various categories, as illustrated in Figure 4. Presently, there is a lack of precise definitions for these subcategories of services and their corresponding needs. This ambiguity arises from the intricate interconnection and overlap between the two main groups. Although the specific types and subtypes of requirements may differ based on the system, they should collectively span the entire spectrum, being applicable in all plausible scenarios with minimal interdependence whenever feasible.

It is important to note that a system need differs from a service that an IBR can provide. For example, a GFM-based IBR can emulate inertia and thus offer this service to the grid during frequency events. While inertia energy is not a fundamental system energy need, it is a feature of SMs that plays a vital role in regulating the grid frequency. By using special controls, IBRs can emulate inertia, thus competing with and even replacing the inertial energy generated by the rotating mass of SMs [31, 46].

Another need for a power system is the black start capability; it is required after a power system shutdown, which leads to a loss of electric power. Blackouts can directly impact daily life, causing food spoilage, loss of life-support systems in hospitals etc. Restoring the system requires identifying a cranking path to find the voltage and frequency by using the first source, mainly energy storage systems, in the case of IBR-dominated systems. This ability requires the source to provide in-rush current for the transformer, line charging currents, and starting currents for induction motors. A GFM IBR can be used for this black start capability, and not all sources need to possess this capability. For reader's reference, a case study of the black start and grid restoration capability of GFMs is presented in [30] to show the efficacy of these inverters and their potential to perform like CS.

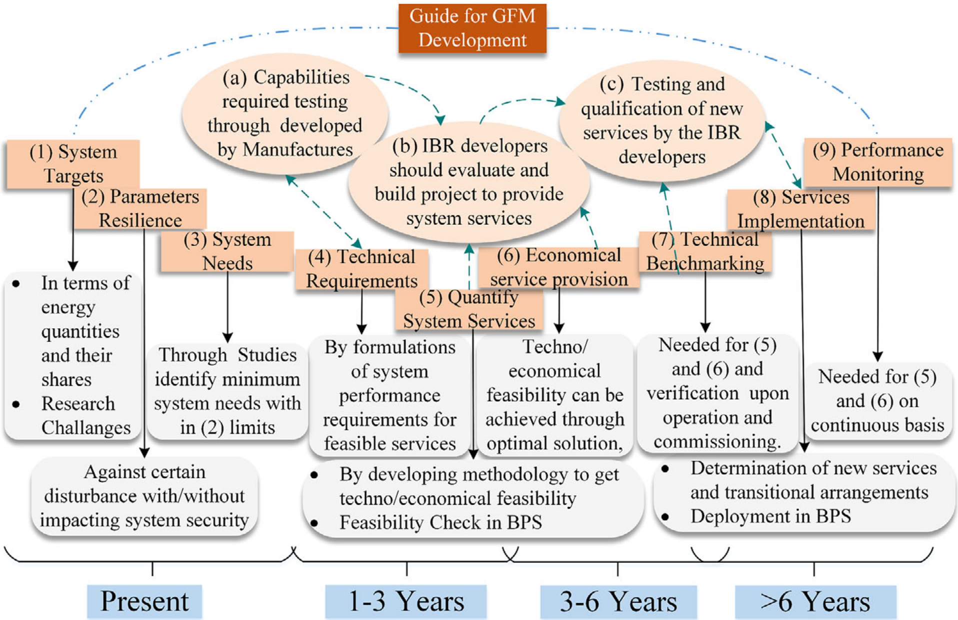


**FIGURE 5** Possible roadmap for the deployment of GFM.

## 6 | DEPLOYMENT AND FUTURE PROSPECTIVE OF GFM

GFM technology has to pass through multiple research, modelling, testing, and implementation stages to reach maturity and be widely accepted, as shown in Figure 5 [46]. To increase the interfacing of generations and storage with the grid through inverters, speedy developments, research, and field trials are required, especially for GFM [111, 136]. In the medium term, priorities for GFM will change so that they can materially contribute to improving the performance of certain grids; where cheaper technologies cannot improve performance, the preferences will/are changed. Early devolvement will help in building consensus and standardizing GFM performance for grid operation improvement. Experience is required to scale GFM to a BPS. The multi-year activities are conceptualized in Figure 5, demonstrating the trends and key elements related to stability and integration into the grids associated with GFM.

To move toward the GFM, the guides are stipulated in the chart in Figure 5. A 9-step guideline is provided for the potential GFM deployment, which may lead to the evolution of the technology and concepts. The three oval-shaped guidelines, labelled (A) to (C), represent the links between the manufacturers of IBR equipment and owners and project developers [46]. Scaling and other aspects of GFM technology are discussed in the following subsections.

### 6.1 | From MGs to BPS

A longer timeline (~10–30 years) is required for the GFM to replace synchronous machines. This is a mammoth task that can only be accomplished when a robust standards environment defines the GFM functionality and an extensive research base is established for their control, protection, and interoperability. The maturation process of GFM will continue to expand for many years as operational experience and expertise are gained. GFM has shown promising demonstrations at various MG-level settings over the past 20 years, for example, the Certs MG Testbed [137].

Besides, islanded MGs with high IBR penetration, such as that in Kauai, Hawaii, have seen GFM inverters as an emerging solution. By demonstrating its reliability in various contexts, GFM provides the confidence and foundational knowledge necessary to introduce it into larger electric grids.

### 6.2 | Ancillary services from GFM marketization

The non-uniformity of market structure is particularly evident in the regulatory reserves, which are faster than frequency containment reserves, which IBR mainly offers. This can be attributed partly to the fact that no power system without CSs currently operates with significant loads. With the development of these new services, the existing structure of ancillary services requires revision in preparation for marketization. For example, the AEMO is taking significant steps towards introducing new services like other grid operators.

### 6.3 | Environment for technical standards for GFM

The distinct behaviour of GFM, such as voltage source characteristics, calls for tailored standard and grid codes [138]. GFMs are primarily used for voltage regulation instead of current regulation, while the current standards [75] focus on limiting reactive power, current harmonics, and anti-islanding functions at the distribution level. Such an effort of harmonic rejection is achieved in [128]. The harmonic rejection capability of GFMs also needs a detail critical review and is a potential future work. During islanding conditions, GFMs are expected to provide an uninterrupted power supply. Grid authorities should focus on revising and modernizing grid codes such as the standards the function of unintentional islanding etc.

### 6.4 | Accurate models and simulation tools for GFM and high-level IBRs testing

Existing state-of-the-art power system analysis tools are predominantly tailored for CS-dominated power systems. However, the growing integration of IBRs and their associated impacts challenge the validity of the assumption that synchronous speed remains near nominal values during and after transients in these tools. Consequently, there is a pressing need to prioritize research focused on refining models and advancing simulation tools to accurately capture these dynamics. Additionally, predicting adverse performance requires simulating inverters, such as GFM, as implemented in real-world scenarios.

In summary, an IBRs-dominated grid necessitates substantial curtailment, suitable configurations to accommodate their high integration, and improved supply-demand alignment across various timescales. It is essential to advance compatible technologies as IBR comes in numerous types, replacing conventional sources that are well-understood [99] and coordinated [139].

## 7 | CONCLUSION

This paper critically reviews the GFM and GFL control approach for IBRs and its integration in a power system, focusing on the latter. These two inverter technologies are compared, considering their control structures, operations, and applications. Due to the unavailability of a universally agreed-upon definition for these two control methodologies, an understanding is derived from the existing literature while considering the context of their applications. Besides, the role of GFM in various aspects of power system stability is investigated, particularly in frequency, voltage, angle, and converter driven-based stability. The key process of synchronization process of IBRs with the grid through both types of these control approaches is also discussed.

Furthermore, the current pilot projects utilizing GFM are listed, emphasizing their productivity in providing grid ancillary support. System needs and GFM-IBRs capabilities are also identified with details on the applications of GFM in WTG, PV, BESS, and HVDC are also critically investigated. Finally, the paper highlights the GFM prospective and challenges faced by its deployment in BPS and identifies the research gaps.

Future research should prioritize the modelling of IBRs and their interface with the grid through GFM. Additionally, comprehensive testing of GFM against various system stabilities is necessary prior to its widespread deployment. Overall, this research work aims to contribute to the reliable operation of independent, standalone systems and BPSs, enabling high penetration of NSG with the assistance of GFM.

## NOMENCLATURE

| | |
|---|---|
| AC | Alternating Current |
| AS | Ancillary Services |
| BESS | Battery Energy Storage System |
| BS | Black Start |
| CS / SM | Conventional Sources / Synchronous Machine |
| CSC | Current Source Converters |
| DFIG | Doubly Fed Induction Generator |
| EM | Energy Market |
| FFR | Fast Frequency Response |
| FRTH | Fault Ride Through |
| GFL | Grid-Following |
| GFM | Grid-Forming |
| IBR | Inverter-Based Resources |
| IO | Islanded Operation |
| LV ∖ MV | Low Voltage ∖ Medium Voltage |
| MPPT | Maximum Power Point Tracking |
| PV | Photovoltaic |
| RI | Renewable Integration |
| RoCoF | Rate of Change of Frequency |
| VSC | Voltage Source Converters |
| VSG | Virtual Synchronous Generator |
| VSM | Virtual Synchronous Machine |
| WTG | Wind Turbine Generator |

## AUTHOR CONTRIBUTIONS

**Musa Khan**: Conceptualization; methodology; software; writing—original draft. **Wenchuan Wu**: Conceptualization; funding acquisition; supervision; writing—review and editing. **Li Li**: Formal analysis; investigation; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data supporting this study are included within the article and/or supporting materials or can be found in the online repository: M. Khan, W. Wu, and L. Li, Supporting Information of Grid-Forming Control for Inverter-Based Resources in Power Systems: A Review on its Operation, System

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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