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Grid Forming Converters for Low Inertia Systems-Capabilities and Limitations: A Critical Review

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ABSTRACT The rapid integration of renewable energy sources into the power grid has resulted in the high utilization of power-electronics devices and operating power systems where inverter-based resources are dominated. Such a transition has led to a reduction of inertia and system strength. In recent research, grid-forming converters (GFM) are introduced and developed to alleviate the grid-following converter (GFL) functionalities and to address the limitations concerning grid support capability, stability, and synchronization issues. However, the efficacy of GFM technology is still under investigation, and the level at which GFM converters can replace traditional GFLs is still under question. This article aims to bridge the gap in literature by revisiting the up-to-date research on the capabilities and the limitations of the proposed GFM converters compared to the traditionally utilized GFL converters, allowing a better understanding of the current status and future requirements. This includes the GFM converter's topologies and their performance for small- and large-signal stability issues, the GFM converters' ability to enhance grid synchronization, and transient stability performances. Furthermore, the challenges and limitations of the dynamic behavior of GFM converters from the point of view of fault ride through (FRT) capability, including grid codes and FRT requirements, FRT methods of GFM converters, postfault behavior, and open research directions, are also comprehensively reviewed. Finally, this article has been concluded by highlighting the main findings, considerations, and future recommendations.

INDEX TERMS Control of grid-forming converters (GFM) converter, current limiting, droop control, large-signal stability, low inertia systems, postfault stability, power synchronization, small-signal stability, stability issues, system strength, transient stability, weak and strong grids, fault ride-through (FRT) capability.

NOMENCLATURE

RESs	Renewable energy sources.
GFM	Grid forming.
PLL	Phase-locked loop.
FRT	Fault ride through.
LF	Low frequency.
CVI	Composite virtual impedance.
VPS	Virtual power source.
LPF	Low-pass filter.
DERs	Distributed energy resources.
CLGCS	Current limiting gain control strategy.
APECS	Active power enhancement control strategy.
VLGCS	Voltage limiting gain control strategy.
TSEC	Transient stability enhanced control.
SM	Synchronous machine.
VSM	Virtual synchronous machine.
SG	Synchronous generator.
VSG	Virtual synchronous generator.
VOC	Virtual oscillator control.
MC	Matching control.

MSM Matching synchronous machine.
QEO Quasi-electromechanical oscillation.
SSO Subsynchronous oscillation.
EQS Enhanced quasi-stationary.
FRD Frequency restoration dynamics.
GFL Grid following.
ROCOF Rate of change of frequency.
PCC Point of common coupling.
HF High frequency.
SCR Short-circuit ratio.
ACL Amplitude control loop.
PCL Phase control loop.
NSC Negative sequence component.
KRR Kernel ridge regression.
SCE Symmetrical component extraction.
PSS Power system stabilizer.
SLVM Single-loop voltage magnitude.
VSCs Voltage source converters.
CCA Critical clearing angle.
SIRC Synchronous inertial reference coordinate.
LOS Lose of synchronization.
VTI Virtual transient impedance.
DCL Direct current limiting.
DVR Dynamic voltage restorer.
TSO Transmission system operator.
WF Wind farm.
FCI Fault current injection.
DVC Direct voltage control.
IBRs Inverters-based resources.

I. INTRODUCTION

A. OVERVIEW

In recent years, the world has been looking toward 100% penetration of RESs by installing many solar photovoltaic (PV), WFs, and hydroelectric dams due to fossil fuel depletion, global warming, and environmental pollution [1], [2]. According to the International Renewable Energy Agency, the percentage of the RESs to the total energy use in the world registered at around 25% in 2017, and it is expected to reach up to 88% in 2050 [3]. This increased penetration of RESs would contribute to reducing not only the carbon dioxide emissions but also the power generation cost [1], [4], [5]. The global pathway to net-zero CO_2 emissions by 2050 requires all governments to successfully implement their energy and climate policies by satisfying the following: more than 90% of heavy industrial production is low emissions, 85% of buildings are zero-carbon-ready, and around 70% of the electricity generation globally from solar PV or wind sources which enabling the capture of 7.6 gigatons of CO_2 [6]. Table 1 tabulates that by 2050, the share of renewable sources in a generation will increase by 88%.

For example, the share of U.S. power generation from renewable would be expected to increase from 21% in 2021 to 44% in 2024 based on the annual energy outlook 2022 (AEO2022), as shown in Fig. 1(a). Notably, the increase in RESs is mainly for solar and wind power, as shown in Fig. 1(b) [7].

TABLE 1. Renewables Sharing in Generation From the Electricity Sector [6]

	2020	2030	2050
Renewable share in generation (%)	29	61	88
Total solar PV (GW)	134	630	630
Total wind (GW)	114	390	350

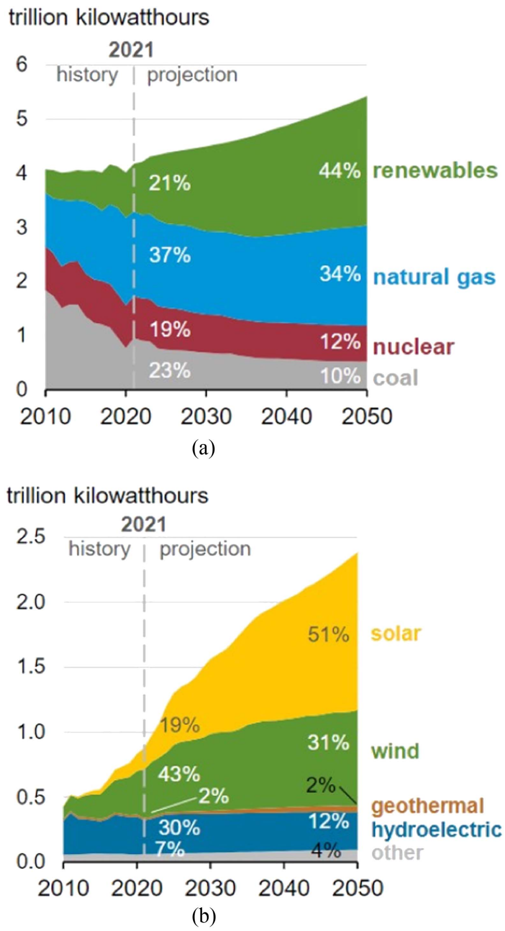


FIGURE 1. (a) U.S. electricity generation and (b) renewable electricity generation in trillion kilowatts hour based on AEO 2022 from 2010 to 2050 [7].

However, the increased penetration of RESs is associated with a decrease in both the system inertia and strength [8], [9]. Also, it makes the grid more sensitive to disturbances, and may result in an increasing ROCOF leading to load shedding or tripping of generating units. Consequently, the grid becomes sensitive to sudden generation loss, load variation, and short-circuit faults [5], [10]. In this regard, many of the challenges of low-inertia power systems have been highlighted in recent papers and can be summarized as follows: challenges to maintain acceptable frequency profiles, increasing the ROCOF, larger frequency deviation, and distributed PV, or generator trip [11], [12], [13], [14], [15], [16], [17], [18].

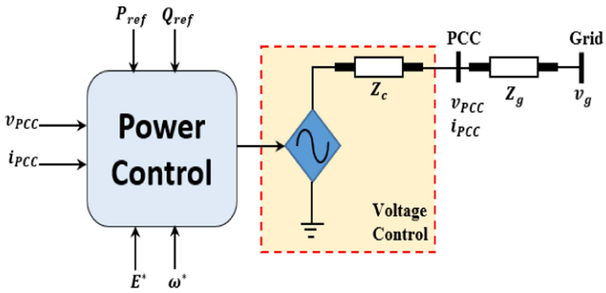


FIGURE 2. GFM converter simplified structure.

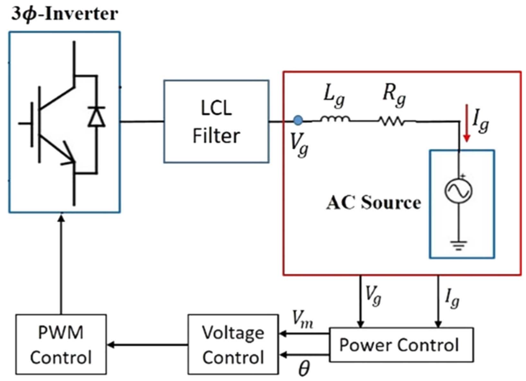


FIGURE 3. Simplified representation of the GFM converter working principle.

The work in [12] revised all frequency control challenges in future low-inertia power systems, which is summarized as follows: error estimation of the frequency and ROCOF [14], [19], [20], [21], inertia estimation challenges [11], [22], [23], [24], and the risk of generation disconnection [25], [26], [27]. The grid-connected converters of RESs in literature adopted many control topologies; the most common one is the GFL control, where the grid is synchronized, integrating the PLL [28], [29], [30]. In weak and low-inertia grid conditions when the GFL is integrated, a small disturbance might cause a large frequency fluctuation, resulting in LF demand disconnection and power grid collapse [31]. The issues and challenges of the GFL converters, especially in low-inertia grids are comprehensively reviewed in [24]. Some of the drawbacks of GFL converters that necessitates developing more enhanced and powerful converters are as follows [32].

1) They are unstable due to PLL oscillations.
2) They decrease the grid strength.
3) They do not possess black start capability.
4) They result in a decrease in system damping.

Considering the GFL converter's issues and limitations, especially in weak grid conditions, the GFM converters have been strongly promoted as a potential improved alternative to replace the GFL ones. Recently, GFM converters have been integrated with the grid, and they have attracted the attention of many researchers worldwide, encouraging the development of new control structures for improved and more robust performance. The simplified structure of a GFM converter is shown in Fig. 2, which shows that GFM converter acts as a voltage source connected in series with low-impedance Z_c value where the voltage and current at the point of common coupling (v_{PCC} and i_{PCC}) generates the reference voltage (E^*) and phase (ω^*) of the inner loop which is a part of the power control [33], [34].

Then, it is used to calculate the reference active and reactive powers (P_{ref}) and (Q_{ref}). A GFM converter represents a converter with a control approach that has the ability to directly control the grid voltage by considering the necessary reserve and storage capacity introduced for micro- and islanded grid applications [35]. Also, GFM converter acts as a source of inertia and damping [36].

The simplified working principle of a GFM converter is shown in Fig. 3, where the GFM converter can self-synchronize the parameters to the utility grid. The voltage phase angle and amplitude set points are adjusted according to the utilized control method used.

Regardless of the potential benefits and the advantageous properties and functionalities the GFM converters might bring to the systems, the efficacy of such GFM technology is still under investigation, and the level at which GFM converters can replace traditional GFLs is still under question. These issues and challenges associated with GFM converters and their implementation in power grids will be comprehensively reviewed in this article to allow a better understanding of the capabilities, limitations, and future prospects, more specifically when considering low inertia systems and future power generation mix where IBRs would be dominated.

B. RESEARCH METHODOLOGY

The modality of conducting this review paper is a critical review approach that takes into consideration distinct major research questions which are as follows.

1) What are the most related research/literature to GFM converter conceptual approaches?
2) How this specific conceptual approach is discussed/analyzed and enhanced as well?
3) What are the existing challenges or limitations according to different GFM converter perspectives?
4) How these different perspectives are evaluated with respect to our intended research survey?
5) What are the issues that still stuck and need further research?

Based on that, the research process considers collecting the most recent and appropriate literature, where articles that are published and indexed in peer-reviewed journals, conferences, book chapters, and meet at least one of the search terms relative to this review article's title, abstract, and keywords are included. According to this, the scientific objectives of this research are summarized as follows.

1) To survey the available literature for determining the most common conceptual approaches of GFM converters.

2) To identify and classify the most relevant studies handling GFM converter challenges according to various criteria: method used, disturbance source, objectives achieved, etc.
3) To evaluate the performance of the up-to-date research prioritizing GFM converter challenges.
4) To identify mostly all of the relevant research problems the GFM converter is suffering.
5) To knock the door to get the attention of researchers about the open issues of GFM converter technology.

The methodology of conducting this review article depends on refining the most relevant and recent literature related to the issues of GFM converters. The work is then extended to handle the challenges of GFM converters by extensively comparing the available research. Finally, open issues and future directions for GFM converter integration that still need more investigations are discussed. Hence, the first part of this article begins by introducing the limitations of the GFL converter and the motive behind the transition to GFM converters. In this context, the simplified structure and working principle of the GFM converter are analyzed. Furthermore, the most common control methods of the GFM converter, including the droop control and SM control methods, are discussed in detail. Extensive discussion supported by comparison tables of the recent literature is performed for the droop control and the SM control methods, including the structure, type of control method, enhancements, and limitations.

The second part of this article presents the main challenges and limitations of the GFM converters, starting with stability considerations. An in-depth discussion along with comparison tables is introduced to include the state-of-the-art literature on small-signal stability, transient stability, and postfault stability. Another aspect barely discussed in the literature is the GFM converter performance according to grid strength. This section discusses the most relevant research when the GFM converter is operating under a weak or strong grid where the SCR is the criterion that decides how the GFM converter would behave. The FRT capability in terms of grid codes' requirements and most recent FRT control methods are investigated. Then, a comparative evaluation of this review article is conducted with respect to up-to-date, most relevant, and recent literature to highlight how this article differs from or adds to the existing literature. In the end, some open directions for future work on the theme of this topic are introduced. These open issues cover the behavior and protection of GFM converters under unbalanced/unsymmetrical faults, antiwindup methods, and coordinated control of GFM and GFL converters under faulty conditions, which still have not been fully addressed in research and academia and, hence, need more investigation.

In this regard, the merits of this survey article, relative to similar review contributions, are concluded on providing a comprehensive overview, discussion, and analysis done in the area of GFM converter's conceptual approaches, challenges, and limitations, evaluating the strength and weaknesses of the most recent literature in this area.

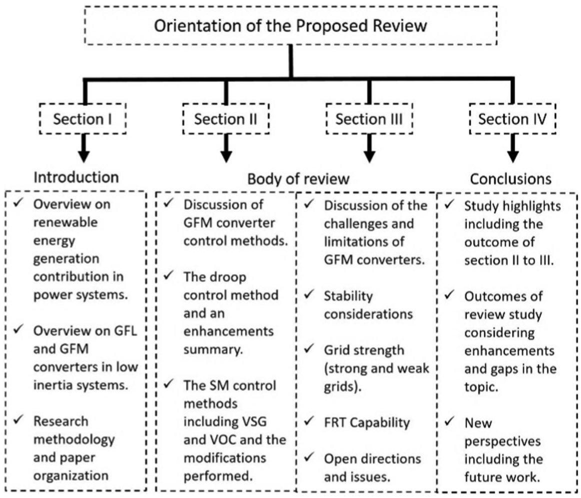


FIGURE 4. Organization of this review article.

C. ARTICLE'S ORGANIZATION

The organization of the review paper is depicted in Fig. 4 where, following the introduction, it is organized as follows. Section II introduces the type of GFM control methods in terms of their structure, the operating principle, and the enhancement. This section focuses on the droop-control and SM-based control methods due to the increased improvement in recent research. Section III summarizes the challenges and limitations considering the small-signal and transient stability and postfault stability considerations. The performance of GFM inverters according to the grid strength in weak and strong grids is also studied. Besides FRT capability for the GFM converter, focusing on available grid codes and FRT requirements, FRT control methods of GFM converters are also discussed. Moreover, open directions and issues concerning the GFM converters voltage source behavior under disturbances, protection, antiwindup methods, and coordinated control between converters are also investigated. Finally, this review article is concluded and highlighted in Section IV.

II. GFM CONTROL METHODS

In this section, the most common control concepts of the GFM converter are revised based on their structure, importance, issues, and enhancements in recent years. These control concepts are divided into two major groups: droop control and SM control. The GFM converter control should be able to operate accurately in low system strength conditions, stabilize grid voltage and frequency, and resynchronize with the grid after the occurrence of the disturbance. In addition, FRT capability, system restoration, and black-start capability are required to be improved when the fault occurs [37].

A. DROOP CONTROL

1) DROOP CONTROL STRUCTURE

Over the previous decade, different control methods have been separately developed, such as virtual impedance, angle

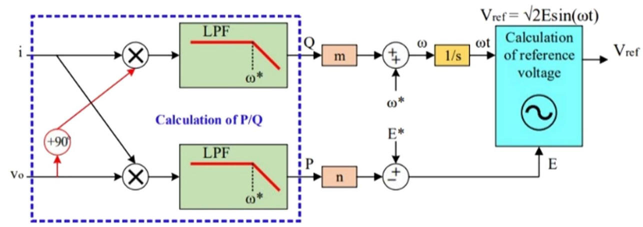


FIGURE 5. Block diagram of the conventional droop control method [41].

droop, and frequency droop. Each method has advantages and drawbacks if used independently, summarized in [38]. The virtual impedance and angle droop control have many advantages, such as achieving constant frequency regulation, improving power sharing, and working without communication. However, they suffer from slow dynamic response, poor robustness, marginally stable, and cannot guarantee accurate power sharing. Also, frequency droop with virtual impedance and PD controller type has many advantages, such as accurate active power sharing, satisfactory transient progress, and robustness to system parameters. However, they suffer from frequency deviation and require relatively high bandwidth for the controller.

The conventional droop control method is one of the most widely and simply control methods integrated with the GFM converter, which includes an active power-frequency ($P - f$) and reactive power-voltage ($Q - V$) droops [39], [40], [41], [42], [43], [44]. The block diagram of the conventional droop control method is shown in Fig. 5, which generates a reference output voltage (V_{ref}) based on the set points of the real and reactive output powers (P) and (Q) to improve the system synchronization and power-sharing capability. The droop gains should be designed carefully according to the grid conditions to ensure stable operation in LF range. The coupling of the conventional droop control is such that the real power is controlling the frequency and the reactive power is controlling the voltage magnitude [45].

The work in [39] studies the impacts of GFM drooped-controlled characteristics on the overall system stability. The study considers two major ranges: grid synchronization stability in the LF range (near the fundamental frequency) and the HF range. Besides, the positive and negative impacts of adding virtual impedance (Zv) on system stability are studied in [46], [47], and [48]. It was found that the HF harmonic instability issues can be eliminated for all grid conditions. In addition, Zv is used to shape the desired output impedances in uninterruptible power systems or to decouple P-Q and eliminate reactive-power differences in microgrids.

However, adding Zv negatively affects the LF stability by reducing the system's inertia and damping ratio. An active power angle droop control has been added to solve this issue.

The droop control method is well-established to ensure a stable operation of the GFM converters, and there are two basic GFM droop controls, one of which can be a single-loop or multiloop droop control. The work in [40] comprehensively reviewed the main differences between each droop control type and their impacts on the dynamic response and stability. Table 2 compares advantages and drawbacks of single- and multi-GFM droop controls in terms of their structure, equivalent circuit, control parameters, controller types and measurements.

The work in [41] analyzes the droop and oscillator-based GFM controls regarding steady-state terminal response, transient stability, and harmonics compensation, where it can be noted that the oscillator-based control does not require inner voltage and current control loops to reduce the number of required sensors compared with droop based control. In droop control, the real power and frequency response are independent of the voltage magnitude, while a significant coupling appears with the voltage magnitude of oscillator control. Also, the oscillator-based GFM converter requires more straightforward controller implementation for harmonics current suppression capability.

An improved droop control using CVI and VPS in a low-voltage microgrid is introduced in [49] to solve the conventional droop control drawbacks. The power coupling is generated when the traditional control is used mainly during transients, and any voltage change or frequency variation affects the active and reactive power values. So, the virtual impedance and VPS are introduced for accurate power decoupling and reactive power sharing. Also, a fractional-order PID (FOPID) controller controls the inverter voltage and reduces the control error. Table 3 summarizes the recent GFM droop control from their structure and the achieved finding.

2) DROOP CONTROL ENHANCEMENT

This section reviews and summarizes all recent research on solving challenges of the GFM droop control associated with Section II-A.1, such as the low-inertia, voltage, frequency, transient stability issues, inverter current limiting, and FRT capability under abnormal grid conditions. Pattabiraman [50] combined the single-loop voltage control with the virtual impedance-based fault current limiting, and it is integrated with a droop-controlled GFM converter to take advantage of conventional droop control, such as fast dynamic response and effective system damping in normal operation. In addition, it enhances the performance under phase jumps and fault occurrences. The physical impedance behavior is emulated using the virtual impedance, where a first-order LPF is used in the controller, and fault logic block is used to generate the set point of the droop control. This enables the inverter to successfully restrain fault current within the allowable limits with stable performance, especially during transient events.

One of the emerging concerns in GFM converters is the power coupling issues, which may result in frequency oscillations and trigger voltage deviation, causing potential damage during overvoltage or undervoltage grid conditions. As a conclusion, power coupling highly affects both voltage and frequency, which may increase the grid instability [51], [52], [53].

TABLE 2. **Comparison Summary Between Single-Loop and MultiLoop GFM Droop Controls [40]**

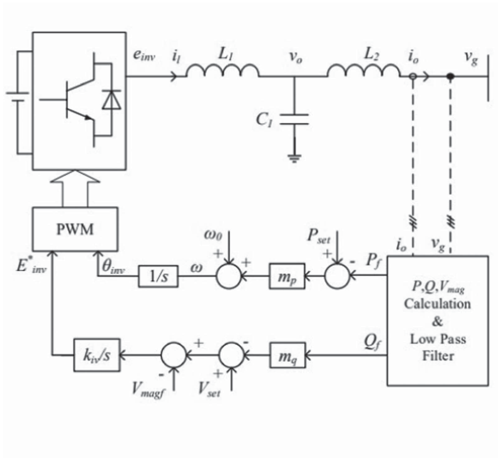
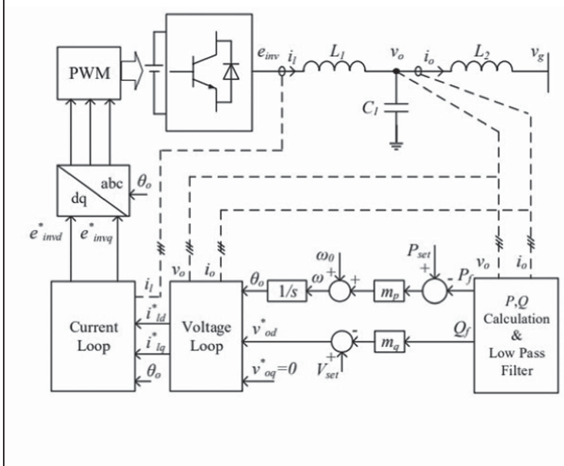
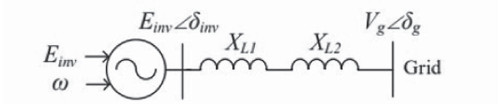
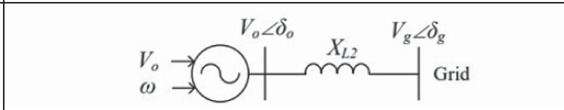
GFM droop control type	Single-loop GFM droop control	Multi-loop GFM droop control
Structure		
Equivalent circuit		
Control parameters	Angular frequency (ω) and the magnitude of the inverter's internal voltage (E_{inv})	Angular frequency (ω) and magnitude at the inverter's filter capacitor voltage (V_o)
Controller type	It includes $P-f$ & $Q-V$ droop control loops.	It includes $P-f$ & $Q-V$ droop control loops in cascade. In addition to inner voltage and current control loops.
Controller measurements	- It measures grid-side voltage (v_g) & output current (i_o). - It calculates active power (P), reactive power (Q), & voltage magnitude (V_{mag}) in $\alpha\beta$ −stationary reference frame.	- It measures the filter capacitor voltage (v_o) and output current (i_o). - It calculates the instantaneous P and Q in the dq rotational reference frame.
Advantages	- Simple structure - It provides better dynamic performance in microgrids. - It results in a more significant coupling reactance, which helps to improve dynamic response and stability.	- It regulates the angular frequency and magnitude of the filter capacitor voltage. - The over-current during faults can be limited due to the existence of the inner current loop.
Drawbacks	- Extra controls are required for over-current limiting such as virtual impedance.	- Complex structure. - It prone to be less damped and loses stability more easily under some circumstances.

TABLE 3. **The Summary of Available GFM Droop Control**

References	Year	Structure	Findings
[38]	2017	- Improved droop control by combining the virtual impedance and frequency droop.	- Transient response can be regulated without affecting the steady-state value. - It enhances the damping of power oscillation and dynamic stability.
[39], [43]	2021	- Conventional droop control ($P-f$) and ($Q-V$) droops. Outer power and inner voltage-current loop are used. - Virtual impedance and feedforward control functions are added. - Angle droop control block is added to eliminate the negative impact caused by the virtual impedance control block.	- HF-harmonic instability issues can be eliminated from all grid conditions.
[41]	2020	- Droop-type control based on distinct time-scale separation of control loops.	- It requires two-current and two voltage sensors. - It requires explicit passive or active damping measures for stabilizing current and voltage - It is only well-defined near synchronization.
[49]	2016	- An improved droop control using CVI and VPS in a low-voltage microgrid. - Virtual negative resistance and inductance are added. - The FOPID controller is utilized.	- It improves the grid reliability under a disturbance. - It improves the power decoupling and accurate reactive power-sharing, especially for low-voltage microgrids.

The phase difference and the interaction between the inner and power control loops will cause power coupling and stability issues. Also, the conventional virtual inductance approach is ineffective in suppressing the coupling of the frequency–droop and angle–droop $(P - \omega)$ and $(P - \delta)$ controls. To solve these issues, a comprehensive study is introduced in [54], which presents a q-axis-based virtual impedance method with the phase difference compensation. These improvements eliminate the quasi-steady-state power coupling with a broader range selection of droop gains and small virtual inductance. Also, the phase difference compensation has the advantage of enhancing the ability of the coupling weakening of the typical virtual impedance. Many nonlinear droop controls in the literature utilize many nonlinear and complex functions, such as quadratic, exponential, logarithmic, and arc-tan functions [55], [56], [57], [58], [59], to improve the frequency stability, accurate load sharing, enhance overall dynamic response, and enhance adaptation under varying load conditions. However, most nonlinear droop controls require additional communication links, increase the implementation cost, and reduce the system's reliability. Harasis et al. [60] introduced the novel logistic function-based droop control, which has many features, such as an S-shaped curve, flexible and gradual ramp-down operation, especially in GFM DERs, to enable the switching between the island and grid-connected microgrids. The active and reactive power droop coefficients selected depend on the DERs size, type, and maximum allowable deviation in frequency and voltage under normal operating conditions. These papers offer easy implementation and flexible operation. Compared with the conventional droop control, many advantages are achieved, such as improving stability, allowing smooth variation in output power, and preventing sudden frequency deviation under transient conditions and sudden load changes. Also, it is easy to shape with precise power sharing and minimum voltage and frequency variation under high loading conditions.

The CLGCS is utilized with GFM converters to limit the overcurrent and the negative-sequence current under asymmetrical grid faults, such as single-line-to-ground faults, line–line faults, and line-to-line-ground faults due to simplicity and good dynamic performance [61], [62]. Zhang [63] integrated the CLGCS with the following: APECS, VLGCS, and negative-sequence current-feedback-based voltage compensation (NSCFVC) for enhancing active power transition and FRT capability under asymmetrical grid fault condition. It can be concluded that using the VLGCS and CLGCS can limit the inverter's overcurrent and overvoltage without fault detection. Also, the negative-sequence fault currents are eliminated using NSCFVC. Moreover, one of the noticed advantages of the APECS is the independence of the network impedances, fault locations, and types. The TSEC is also integrated to avoid any transient instability problem under asymmetrical grid faults.

The power–frequency $(P - \omega)$ droop suffers from transient stability under voltage dips. Therefore, the power–angle frequency droop $(\delta_{\text{inv}} - \omega)$ control is introduced in [64], where the inverter power angle is estimated as input to obtain the inverter's frequency. This modification enhances the transient stability margins under current limitations and provides the grid frequency support without requiring any modification or mode change after the fault clearance. However, at the start time of recovery, the fluctuation of the instantaneous current control results in a slow dynamic of the $(\delta_{\text{inv}} - \omega)$ droop control and requires the addition of the modification structure to alleviate this issue. The summary of the improved droop GFM converter is introduced in Table 4 from the required components, the enhancements, and limitations.

B. SM CONTROL METHODS

In this section, various control methods related to the SMs available in the literature have been thoroughly revised to take advantage of the inertia support and GFM capability. The VSM control methods are introduced to solve the weaknesses of the droop control methods, enhance the inertial support, and effectively control the transient changes [65]. The inverter operating mechanism and its characteristics enable it to operate as an SG. Due to the high integration of the nonsynchronous inverter-based resources, a lack of inherent inertia and multiple system stability challenges have appeared [66], [67]. Also, various VSG challenges have been revised, and the possible enhancements have been summarized in this section. Synchronverter is another concept based on the VSM and is designed to mimic the SG by emulating the dynamics of the governor, rotor, and excitor, providing controllability to the following factors, such as inertia, friction, damping, and inductance [68]. Also, synchronization problems during normal and abnormal conditions are solved without utilizing the PLL [69]. Another method discussed in this section is the VOC method. The VOC is the time domain controller that enables interconnected inverters to rapidly stabilize arbitrary initial conditions to a synchronized sinusoidal limit cycle [70], [71]. These methods are revised regarding the structure, limitations, and possible enhancements, as summarized in the following sections.

1) VSG METHOD

a) VSG control structure: VSG is the supplementary controller used to take advantage of the behavior of the SM for voltage angle regulation, where the swing equation in (1) emulates the SM's control and dynamics and describes the electromechanical effect where P_m and P_e are the mechanical and electrical power, J is the virtual inertia value, ω_0 is the nominal angular frequency, ω is the angular frequency, and ϑ is the rotation angle

$$P_m - P_e = J\omega_0 \frac{d\omega}{dt}. \tag{1}$$

The work in [72] is comprehensively reviewed and provides a different classification of the VSG control method. Also, the small-signal stability response of the inertia emulation characteristic of the VSM-based control method is considered

TABLE 4. Summary for the Improved Droop Controls and Their Enhancements

Refs.	Improved Droop GFM Structure	Required components	Enhancements	Limitations
[50]	A combination of single-loop voltage control & virtual impedance based on fault current limiting.	- Two LPF. - Fault logic. - Single-loop voltage control.	- It achieves stable performance with fault current limiting during the transient events.	- High inverter penetration levels required additional recovery time, causing instabilities in the power system.
[54]	q-axis-based virtual impedance method with $P-\omega$ and $P-\delta$ controls.	- Phase compensator. - Inner voltage / current control. - LPF.	- It effectively eliminates the quasi-steady power coupling. - It offers more stability estimation.	- The controller gains selection is a tradeoff between active and reactive power coupling. - The optimal value of the cutoff frequency of the LPF should be selected.
[60]	A novel nonlinear (logistic functions) based $f-P$ and $V-Q$ droops controls.	- Logistic function. - LPF. - Inner voltage / current control.	- Smoothly respond to transient changes and unexpected load fluctuations. - Smooth and stable transitions during load changes.	- This work does not investigate the effect of voltage and reactive power control.
[63]	The APECS is integrated with VLGCS,CLGCS, and NSCFVC.	- TSEC. - NSCFV+VLGCS. - Inner voltage control + CLGCS.	- It enhances the FRT capability and active power transmission capability.	- The implementation complexity is increased.
[64]	The power-angle frequency droop $(\delta_{inv}-\omega)$ control.	- Voltage control with the current limiting capacity. - $(\delta_{inv}-\omega)$ droop control.	- It enhances the transient stability margins under current limitations and provides the grid frequency support without requiring any modification or mode change after the fault clearance.	- The fluctuation of the instantaneous current control at the start time of recovery slows the dynamic of the $(\delta_{inv}-\omega)$ droop control and requires adding the modification structure to alleviate this issue.

equivalent to the conventional droop-based control method for standalone and microgrid converters. The VSM's damping factor and inertia depend on the droop gain and filter constant of the power feedback in the droop controller.

In literature, since all available VSM concepts utilized the swing equation [73], [74], [75], [76], [77], the damping of the virtual mass inertia (D) is a crucial criterion where (1) is expanded as in (2) considering damping power (P_D) and mechanical power loss (P_m) due to friction and windage [78]

$$P_m - P_e - P_D = P_m - P_e - \frac{D}{2\pi}\omega = J\omega_0\frac{d\omega}{dt}. \qquad (2)$$

Based on (1) and (2), the block diagram of the VSM control is shown in Fig. 6, containing active power and reactive power regulation. The active power is directly proportional to the change of the frequency (f) with the factor called k_{pf} and the factor k_{df} is the damping constant that introduced to dampen the oscillations between the generators. However, in the reactive power, two factors are chosen k_v and T_v to specify the slope of the reactive power change as a function of f and the excitation time constant.

The work in [79] shows compatibility between the performance of the VSG and the droop control methods, showing that the VSG demonstrates larger inertia than the droop control and better frequency stability. However, the output active power of the VSG becomes more oscillatory. This issue can be removed by tuning both the damping factor and output reactance or one of them. The VSG can be implemented in the second-order system using the swing equation, and the inertia moment can be controlled depending on their

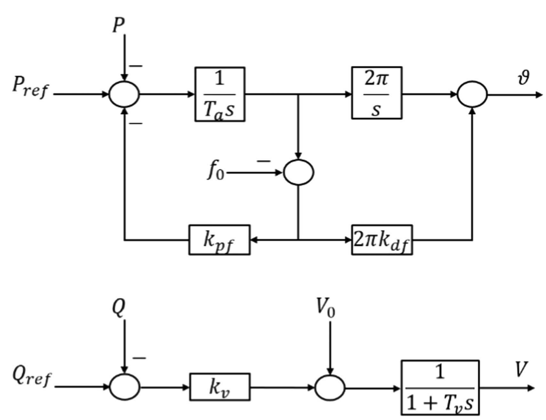


FIGURE 6. Block diagram of the VSG control.

operating point. However, it has limitations, such as a weak ability to compensate for the NSC, causing unbalanced current and power oscillation [77]. Different system services can be achieved by controlling the system using VSG methods such as emulation inertia, damping oscillation, and grid voltage support. The work in [77] revised the VSG for the high penetration of renewable energy generation in future power systems. Generally, the VSG control method can be divided into two categories based on the output type and the topology type. Regarding the output type, the VSG can be divided into controlled current and voltage sources [80], [81], [82], [83], [84], where it is impossible to integrate many RESs as a current source. Regarding the topology type, the VSG is divided into higher order, second-order, and first-order models, where the higher order models contain seventh, fifth, or fourth orders [80], [85], [86], [87], [88]. However, selecting the low order or high order of the VSM control method is a critical choice and still needs to be investigated. For example, the low-order VSM models become more stable and reliable than the high-order VSM models, especially under abnormal operating conditions. Also, the design complexity is reduced in the low-order models. The available literature mainly studies the implementation concept of the VSM. However, serious issues such as an unbalanced ac voltage and short-circuit occurrence were not considered, which has been considered in recent research.

b) VSG-based GFM converters enhancements: In this section, different enhancements to the VSM are introduced. The adaptive FRT controller is proposed for VSM-based GFM control [89], which improves the FRT capability by utilizing the cascaded or switchable current limiting. Also, postdisturbance and phase angle shifts have superior recovery, and instability issues have been removed with fast dynamic response, especially in the strong ac network. Furthermore, ac GFM-based VSM control offers self-synchronization and active support services, significantly increasing the dc voltage failure in solar radiation, resulting in the tripping of the PV systems and the absence of accurate and dispatchable droop response. The work in [90] combines the merits of the MC and the VSM control. The MC's power angle is adjusted to compensate for the power imbalance on the dc link. However, the MC's droop support is not dispatchable. So, the MSM is developed to provide stable and dispatchable support for GFM PV systems with enhanced dynamic of the dc voltage.

The work in [91] investigates the QEO in VSG grid-connected systems based on a small-signal approach resulting from dynamic interactions with the power systems. The method can lead to higher virtual inertia and reactive power–voltage droop coefficients, a smaller active power frequency droop coefficient, compromise LF stability, and may predispose the system to QEO. The VSG control method includes active power-frequency control, reactive power-voltage control, and double-loop voltage and current control. This enables the enhancement of the power system's damping, inertia, and stability. However, the following problems related to the QEO need to be further investigated: the power angle stability in isolated islands and offshore wind power transmissions, evaluation of the VSG's factors, such as system damping ratio and renewable energy permeability, and frequency oscillations problems.

The selection of the voltage control bandwidth, line impedance, and system inertia significantly affects the SSO, which resulted from the interaction between the GFM VSGs voltage controller and SGs. The work in [92] introduces two enhanced models: a full-order state-space model of the SG voltage-controlled GFM-VSG microgrid and the enhanced quasi-stationary (EQS) model, which are considered dominant oscillatory modes such as low-frequency oscillations (LFOs), SSO, and FRD. The voltage control bandwidth should be increased, and the virtual impedance should be inserted to suppress the SSO. Also, to improve the accuracy characteristics of the LOF, the SG's field winding and excitation system should be considered, and the GFM-VSG's inertia or damping coefficients should not be selected arbitrarily because these parameters affect the power-sharing and frequency characteristics. By comparing the two models, the full-order model is suitable for the detailed stability analysis. However, the design complexity is increased.

To ensure that all GFM converters be synchronized together after black-out or contingencies with optimal synchronization time, the work in [93] proposes the synchronization scheme based on selecting the optimal phase angle to ensure the reduction in the required synchronization time and the frequency transient by utilizing n numbers of the VSG controlled GFM converters in which each VSG is communicating the other in the grid cluster to share its phase angle. Also, the GFM converter enables synchronization with each other in considerably less time and sudden frequency changes compared with the one-by-one synchronization method. The work in [94] presents a detailed method for selecting the inertia and damping coefficients in the small-scale VSM-based GFM inverters. The eigenvalues of the VSM controller are used to verify Lyapunov's energy-like function theory. A tuned proportional–integral controller is applied to enhance the inverter performance.

The transient synchronization stability of the GFM converter-based VSG control is focused on considering the influence of the transient switch operation mode (TSOM), especially by the current saturation limitation [95]. It concludes that TSOM reshapes the $P - \delta$ characteristics of the VSG and some factors affect the system's stability such as the power reference, grid voltage sag, and grid impedance. It also concludes that the transient stability can be improved by reducing the power reference or increasing the grid impedance.

A synchronverter is another advanced method of the VSM emulating control method and connecting the synchronverter to the grid enables the dynamics seen from the grid side to be equivalent to the dynamics coming from the generator. One key advantage distinguishing the synchronverter from the SM is that the following parameters, including the inertia, damping, field, and mutual inductances, can be tuned to find

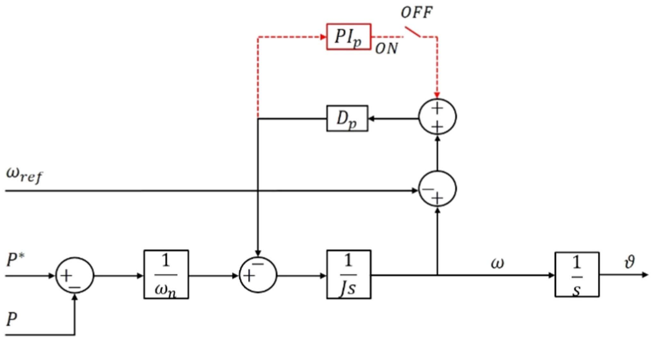


FIGURE 7. Block diagram of the Synchronverter control method [33].

the optimal values [96]. The synchronverter block diagram is given in Fig. 7. It has become most popular in recent years due to its ability to completely overcome the need for the synchronization unit for pre-synchronization and normal operation. The expression of the synchronverter angle (ϑ), including the dynamic of the PI controller, can be calculated as in (3), where the power difference between the power set point and the measured power is given as $P_{\text{diff}} = P^* - P$ and PI_p is the transfer function of the PI controller [33]

$$\frac{\partial \vartheta}{\partial P_{\text{diff}}} = \frac{1}{s}\left[\frac{\frac{1}{J\omega_n}}{s + \frac{D_p}{J}}\right]. \tag{3}$$

The work in [97] adopted a synchronverter-based GFM (SynC-GFM) to investigate a system with 98% sharing under a high level of integration of the IBRs. Under a three-phase short-circuit fault and sudden load step changes, the SynC-GFM performs better in stabilizing the frequency and voltage than the DVC method. Also, the inertia dual in the voltage control loop is adjustable in this work, which consists of the adjustable nature of inertia constant and integral gain, showing the high impact on the ROCOF and voltage, respectively. It can be concluded that the Nadir and RoCoF both improved. However, the voltage dip was less severe.

An FCI is developed for the GFM inverter to improve the postfault transient stability of the synchroneverter-based GFM [69]. The postfault transient stability is enhanced by reducing the voltage angle deviation and improving the active and reactive power recovery in the postfault period.

The work in [98] solves the subsynchronous oscillation (SSO) issues resulting from the interaction between the grid-side converter and the weak-grid impedance in WFs. Battery energy storage system (BESS) provides various grid services and damps the SSO, which can be internally or externally integrated. For the external integration of the BESS, the GFM converter is integrated with a coefficient decoupling control to decouple the damping and droop coefficient in SynC-GFM control, which leads to the reduction of the battery power rating requirement while keeping the same SSO damping behavior. Otherwise, for the case of internal integration of the BESS, a synchronverter control method is used to emulate the damping behavior of the SSO and the frequency response from the external GFM converter side.

A virtual oscillator (VO)-based first-order frequency-locked loop (FO-FLL) is proposed in [99] where the VO is used for grid ripple frequency estimation and then added to the VSM control to better dampen the LFO, where the local virtual friction is used in the synchronverter control for LFO reduction. Table 5 summarizes different VSM control method modifications, showing their structure and the findings that were achieved.

2) VIRTUAL OSCILLATOR CONTROL (VOC)

VOC is one of the methods that is based on SM emulation. In literature, VOC is used for inverter's regulation to emulate the dynamics of weakly nonlinear oscillators. Also, it is a time domain controller that enables the interconnected inverters to rapidly stabilize arbitrary initial conditions to a synchronized sinusoidal limit cycle [70], [100], [101]. The computational burden based on the machine emulation is removed, so the frequency estimation can be done without utilizing the PLL. This requires modifying the VOC concepts to achieve fast synchronization and accurate power sharing in different modes of operation.

The work in [70] reviews different VOC implementations with an explanation of the stability analysis, harmonics, and presynchronization. Also, the FRT challenges, noninertial response, and coupled power control are investigated, as well as the solutions. The VOC is considered as a primary control with a voltage control loop combination and has many implementation types. All reviewed approaches consist of linear and nonlinear oscillators implemented in a digital controller. A unified virtual oscillator controller (uVOC) is utilized with a GFM converter for islanded and grid-connected converters, seamlessly transitioning between both. Also, the unified analysis, design, and implementation simplify the synchronization with arbitrarily low-voltage and fast overcurrent limiting (OCL) via series compensator with accurate FRT and without switching to the backup controller during the fault [100]. In [102], the PI controller is adopted with the VOC method to control the output current and power. The adaptation of the VOC method has superior performance. However, it suffers from compatible regulation weakness due to the nature of the VOC method, where the secondary control design is complex and the third-order harmonics at the VOC output voltage are severed. To take advantage of the VOC and achieve a fast primary control response, the compatible hierarchical control structure is integrated into the VOC method in islanded and grid-connected modes [103]. In the case of island mode, this controller enables the achievement of voltage and frequency regulation and grid synchronization. In contrast, it cooperates with the notch filter for excellent current harmonics suppression, and accurate power reference tracking in the grid-connected mode. The dispatched VOC (dVOC) method is another VOC introduced in [100] and [101], where a distributed GFM control strategy is used in a

TABLE 5. Summary of Different Modifications of the VSM Control Method

Reference	Structure	Findings
[89]	An adaptive FRT controller with cascaded or switchable current limiting is utilized for VSM-based GFM control.	✓ It accurately recovers the post-disturbance from the ac fault and the phase angle shifts. ✓ The instability issues are removed with a fast dynamic response. ✓ The performance of ac strong and weak systems has improved.
[90]	The MSM control method is developed by integrating MC and VSM control loops to improve the active support of the GFM PV systems.	✓ It provides dispatchable active support and enhances the dc voltage dynamics.
[91]	The QEO in the VSG grid-connected systems using a small-signal approach.	✓ It analyzes the trajectories of LF characteristic roots to assess the model's stability. ✓ The droop coefficients for active power frequency, reactive power voltage, and virtual inertia are analyzed to clarify their impacts on QEO.
[92]	A full-order model of the SG voltage-controlled GFM-VSG microgrid and EQS model are developed.	✓ The dominant oscillations such as LOF, SSO, and FRD are considered. ✓ The full-order model is more suitable for the detailed stability analysis, while EQS can be expanded to a multi-generator form.
[93]	A synchronization scheme with n numbers of the VSG in which each VSG is communicating with the other VSGs in the grid cluster to share its phase angle.	✓ The synchronization time and the sudden frequency changes are considerably reduced compared with the one-by-one synchronization method.
[94]	Small-scale VSM-based GFM inverters are utilized where the VSM controller's eigenvalues are used to verify Lyapunov's energy-like function theory.	✓ The J and D values selection procedure is found by applying the Lyapunov energy-like function theory. ✓ The performance on large-scale VSM-based GFM is not introduced in this work.
[95]	A novel transient equivalent motion model is developed for the GFM converter with VSG control, considering that TSOM was introduced by the current saturation limitation.	✓ The impact of the TSOM on the transient stability of the GFM is discussed and guided the stability enhancement control design.
[97]	SynC-GFM is integrated with 98% of IBR with the adjustable inertia dual in the voltage control loop.	✓ The SynC-GFM control shows better performance than the DVC method under sudden load changes and three-phase faults. ✓ The impact of RoCoF and voltage change are investigated.
[98]	A synchronous-based GFM converter with coefficient decoupling control solves SSO issues in WFs.	✓ It reduces the battery power rating requirement while keeping the same SSO-damping behavior. ✓ It enables the emulation of the output behavior for two parallel converters operated in GFL and GFM modes.
[99]	VO-based FO-FLL is utilized with the synchronverter control.	✓ It better dampens the LFOs and accurately estimates the grid ripple frequency.

distributed intraregion control layer. It generates a reference value of angular frequency, maintaining frequency stability and power regulation between each new region, and enhances the transient stability and the system's communication reliability.

The nonlinear droop characteristic behavior of the dVOC-based GFM converter is studied in [104] to address the mode-switching issues between the OFF-grid and grid-connected modes and achieve smooth switching. When mode switches, the virtual power is introduced to achieve presynchronization and reduce voltage and current surges with a quick dynamic response when the DERs change from OFF-grid to grid-connected modes.

The dVOC-controlled GFM IBRs in an ultra-weak scenario operating with an SCR$<$1 is introduced in [105]. The decision-based algorithm determines the active power reference, output voltage reference, and reactive power droop coefficient for fault mitigation, where both ACL and PCL are utilized. This structure ensures a stable operation in the case of high impedance fault, which is appropriate for moderate inductive line impedance with low-voltage fault.

Since the GFM inverter acts as a controlled voltage source, they are expected to inject a fully controlled negative sequence under asymmetrical conditions. A sequence-based control strategy using a dual dVOC is integrated for GFM control purposes to control PSC and NSC. This modification allows the flexibility of injecting the programmable negative sequence currents and protects the GFM inverter-interfaced distributed generation system [106]. The power angle limiting approach is adapted for dVOC-controlled GFM inverters to avoid the reported issues related to the overcurrent conditions for both strong and weak grids [107]. It shows the potential to emerge as an effective solution for mitigating the large grid transients and limiting the current to a safe value with superior dynamic performance. The voltage and frequency control problems when the generators or loads interfaced through the GFM inverter are addressed in [108], where the primary control strategy determines the inverter's output voltage and

TABLE 6. Summary of Available Types of the VOC Method-Based GFM Converter

Reference	Structure	Findings
[100]	The uVOC method with GFM converter in islanded and gird-connected converters via series compensator.	✓ It simplifies the synchronization with arbitrarily low voltage and fast OCL. ✓ The FRT capability is enhanced without switching to a backup controller during the fault.
[102]	The PI controller is adopted with the VOC method.	✓ The conventional VOC method cannot regulate the output power. However, this modification enables the output power regulation.
[103]	The compatible hierarchical control is adopted with the VOC method in islanded and grid-tied modes.	✓ It is used for voltage and frequency regulation and grid synchronization purposes in the islanded microgrid. ✓ It is used for harmonics current suppression and accurate power reference tracking in the grid-tied microgrid.
[104]	The dVOC-based mode-switching strategy is introduced.	✓ Achieving a smooth switching from the off-grid to grid-connected mode.
		✓ It reduces voltage and current surges with stable and fast dynamic performances.
[105]	The dVOC-controlled GFM-based IBRs for fault mitigation.	✓ A FRT capability and transient stability are enhanced, which is appropriate for ultra-weak grids.
[106]	A sequence-based control strategy using dual-dVOC-loop for GFM inverter under asymmetrical grid conditions has been integrated.	✓ The PS and NS currents and voltages are controlled in a completely decoupled manner during an asymmetrical grid situation to ensure the protection of the GFM-IBRs.
[107]	The power angle limiting approach is adapted for dVOC-controlled GFM under large grid transients.	✓ It effectively rejects large grid transients and limits the current for the safe value in both strong and weak values.
[108]	Secondary voltage and frequency controls with dVOC-based GFM inverter.	✓ It stabilizes the voltage and frequency magnitudes and regulates them to their nominal values.

frequency by utilizing dVOC. Secondary frequency and voltage control are also introduced, whereas integral control is used. It is concluded that the primary control stabilizes frequency and voltage deviation while the secondary control is able to recover both frequency and voltage to their nominal values. The available types of VOC method-based GFM converters are summarized in the Table 6 showing their structure and finding that they achieved.

III. CHALLENGES AND LIMITATIONS OF GFM CONVERTERS

GFM converters are a potential solution for RESs integration to avoid the stability issues in weak inertial grids compared to the GFL converters. This is due to their superior capabilities, such as enhanced synchronization in weak systems, black start capability, and ROCOF capability. However, recent research has raised modern challenges such as high grid impedance, lower SCR, and lower inertia [109]. In these subsections, the small signal stability, transient stability, and postfault recovery have been considered. The saturation of the current limiter is another problem that has been raised [110], and it is solved by utilizing the virtual impedance-based voltage limiting strategy covered in these subsections. Grid strength affects the GFM performances, stability, and performance, either in weak or strong grid conditions.

A. STABILITY CONSIDERATIONS

The literature classifies the stability analysis and consideration into small-signal, transient, and postfault stability analyses. The power system stability can be analyzed through the GFM converter's performance under voltage control, frequency control, and fault protection [109]. GFM converter's voltage stability is studied by considering the large and small disturbances for long and short terms. In large grid disturbances, such as three-phase ac faults, overcurrent problems have appeared and current limiting strategies must be installed [111]. The low-grid inertias lead to a higher ROCOF and let the nadir frequency oscillate outside the acceptable limit. Power imbalance, inertia, and reserves are the factors affecting the frequency stability. The stability considerations in recent research on the GFM converters are summarized in the following subsections.

1) SMALL-SIGNAL STABILITY

The work in [112] presents novel insights to understand the small-signal stability of low- and no-inertia systems. It also proposes a method to improve the stability margin under different scenarios and configurations through their interaction with various power system components at various time scales. The method utilized a high-fidelity dynamic model of a generic low-inertia power system. The time scale separation between the VSC and SG controllers effectively leads to instability under large-scale integration of IBR. The low inertia systems have adversely triggered different protection schemes based on ROCOF measurements, and the controllers can interact with synchronous and inverter-based generators, leading to frequency and voltage instabilities. Also, the operating point of the installed inverter capacity may affect the optimal power flow dispatch, which may change the nature of unstable modes and underlying dynamics. In [113], a holistic small-signal model based on a region-based small-signal stability

TABLE 7. Summary of the Small-Signal Stability Consideration-Based GFM Converter

Reference	Stability analysis method	Source of small-signal stability
[112]	High-fidelity dynamic model of a generic low-inertia power system	- Different protection schemes are being triggered based on ROCOF measurements. - The interaction between controllers and synchronous inverter-based generators. - The operating point of the installed inverter capacity.
[113]	A region-based small-signal stability approach and AI-assisted KRR approach.	✓ The IBRs lack physical inertia, causing the operational dynamics of modern distribution systems more complicated than those of conventional rotational generators.
[114]	Small-signal with full-order state space model and eigenvalues analysis of the VSG-based-GFM inverters.	✓ The interaction between the RESs and the power grid when employing paralleled GFM inverters.
[115]	A geometrical approach with small-signal synchronization stability of GFM inverters.	✓ The divergent and overloaded GFM converters if not correctly damped.
[116]	A small-signal stability model for sequence decomposed GFM control utilizing a single-loop vector current control structure.	✓ Symmetrical fault or overload disturbance.
[117]	Placement of the GFM converter with large-scale PLL-based converters using the matrix perturbation theory.	✓ The operation of the PLL under weak grid conditions. ✓ Interaction between the GFL and GFM converters.

approach is introduced, considering mixed GFM and GFL inverters and their interaction. Also, the artificial intelligence (AI)-assisted KRR approach is utilized to find the stability region boundary. Most IBRs lack physical inertia, causing the operational dynamics of modern distribution systems to be more complicated than conventional rotational generators, leading to small-signal instabilities under abnormal grid conditions. However, when the number of installed GFM inverters is increased, implementing the region-based small-signal stability approach becomes more complex. Small-signal with full-order state space model and eigenvalues analysis of the GFM inverter are studied in [114] by considering their control loop, interaction, reference frame, transmission, and time delay. The eigenvalues of the state-transition matrix are used to analyze the impact of the inertia and damping on the small-signal stability of the GFM inverters to keep the operation stable when connected to an extremely weak grid.

The small-signal synchronization stability of the GFM inverter through the geometrical approach is introduced in [115], which maps the line impedance variation on a 2-D plane and identifies the stability boundary geometrically. This is required to derive the stability region to maintain the power grid synchronization under line impedance uncertainties and variations. Then, the virtual inductance control is used to achieve robust synchronization stability.

A small-signal stability model for sequence-decomposed GFM control utilizing a single-loop vector current control structure is introduced in [116], where a virtual admittance generates the positive and negative sequence current references. Sequence decomposed GFM control enables simplified analysis, eliminating the cross-coupled dynamics characteristic of SCE.

The impact of the GFM converter on the small-signal stability of power systems integrated with large-scale PLL-based converters is studied in [117]. The matrix perturbation theory demonstrates that the placement of GFM converters is equivalent to increasing the power grid strength and thus improving the small-signal stability of PLL-based converters. However, the optimal placement of the GFM converter, considering both frequency and small signal stability, will be investigated in future research. All recent considerations of the small-signal stability of the GFM converter are summarized in Table 7.

2) TRANSIENT STABILITY

Replacing SMs with GFM converters in a high level of penetrations significantly affects the grid frequency stability due to the interactions with PSS, and the dynamic changes of the grid dramatically impact the system frequency nadir and ROCOF where returning the PSS is required to maintain system stability. Comparative studies introduced in [118] and [119] highlight the positive impacts of integrating the GFM technology on improving the frequency stability, where the interaction between the SMs and the converters resulted in sudden load changes and loss of SMs. Also, the limiting dc or ac through the interaction with the fast dynamic response of the converter and slow dynamic response of the SMs can destabilize some of the GFM's control methods, such as droop control, VSM, and dVOC [118]. All GFM converters with a no-inertia system can exhibit more resilience than mixed SM-GFM with a low-inertia system for significant load variations [119].

The transient stability of the GFM inverters is studied in [120], introducing a SLVM control method and phase portrait analysis. The dynamic relationship between the converter-bridge voltage magnitude and the voltage magnitude at the point of connection is derived from analyzing the impact of the SLVC on the transient stability. Then, the GFM's transient stability is assessed by combining the dynamic of the voltage magnitude with that of the power control loops.

The sources of the first-order transient under the fault or voltage sage occurrence, which concerns noninertia controls, such as frequency- and angle-based droop controls, are summarized in [121] and [122]. The transient stability analysis in the VSCs under weak grid conditions is studied in [121] using the first-order power synchronization control (PSC), showing that PSC-VSCs maintain synchronization after transient disturbances if the equilibrium points exist due to overdamped response. The CCA is utilized with PSC-VSCs when no equilibrium points result after the postfault clearance, which is concluded that the PSC-VSC resynchronizes after around one cycle of oscillation and even if the fault clearing angle (time) is beyond the CCA. The transient stability behavior under large-signal disturbances is addressed in [122] by introducing a design-oriented transient stability analysis based on the typical four GFM control methods: PSC, droop control with LPF, and the VSM control methods. These controls are reviewed from the dynamic response based on a large-scale model under transient stability, which concluded that the conventional droop control and the PSC methods retain stable operation due to the first-order nature and the noninertia transient response. In contrast, the droop control-based LPF and VSG destabilized due to the second-order nature and the lack of damping of their inertial transient reactions. This work suggests combining the $P - f$ droop gain and the LPFs' cutoff frequencies to ensure the frequency and transient stabilities for high-inertia GFM-based VSC.

The $P - f$ droop-controlled GFM inverters are studied in losing synchronism under significant grid disturbances [123]. The virtual power angle characteristics analysis proves that the current limitation significantly decreases stability margins and leads to instability problems.

Lyapunov's direct method is used in [124] to investigate the transient angle stability of the VSG resulting from the imbalance between the reference active power and the output power. The reactive power control loop is also considered, showing that current limitations can lead to complicated instability mechanisms and significantly decrease the stability margin.

Impedance-based modeling of the GFM-based VSG in SIRC is introduced in [125] with the low-inertia power systems to mitigate the LOF and HF oscillation resulting from the low-grid strength.

In the case of current-constrained fault occurrence, both voltage and power dynamics are strongly coupled and play a critical role in transient stability analysis. So, the large-signal nonlinear analysis is introduced to the uVOC-based GFM to analyze the transient stability under both current constrained and unconstrained symmetrical faults [126]. The phase-plane analysis uses holistic insight into voltage and power angle dynamics through a single graphical representation. The noninertial controls have a smooth response and are free from overshooting, so the first-order power-angle dynamic of the noninertial controllers is integrated into the GFM inverter to recover a fault even when the critical clearing time is exceeded. It demonstrates that the uVOC achieves a fast response, and built-in FRT parameters exhibit strong stability characteristics. Angle stability after the fault occurrence is introduced in [121], [127], and [128] when the VSG or synchronverter control methods are integrated into the GFM inverters, which results in overshoot and power oscillations in power angle and active power. He et al. [129] studied the effect of the interaction of the GFM and GFL inverter on the transient stability using the second-order phase portrait analysis. The change in the power angle of the GFL inverter causes the variation in the GFM inverter terminal voltage. To enhance the transient stability of the mixed GFL-GFM power system, the authors suggest increasing the GFL-inverter output current.

The transient stability of the power system, which is codominated by different types of typical GFM methods, such as SGs, VSGs, and droop-controlled inverters, is studied in [130]. In comparison, the SGs and VSGs provide inertia to the system, while droop-controlled converters are inertialess. So, the hybrid system compromises an inertia-provided SGs and inertia-less droop-controlled inverter where a second-order equivalent motion equation implements its transient behavior. The droop control dramatically enhances the damping effect and significantly affects the transient stability region. However, the frequency state variable exhibits a jump during fault disturbances, impacting the postfault initial-state location and stability assessment.

The transition of the GFM converters from the islanded to the grid-connected mode, causing transient stability, is addressed in [131]. The reconnection of the GFM inverters to the main grid resulted in a step change in the output power reference. The active power references significantly impact the transient stability after the reconnection, which depends on the local load, active power reference, and the SCR, causing the grid to LOS.

The transient stability of power systems with both GFM converters and SGs is studied in [132] under significant fault events. It concludes that even if the SGs and GFM converters are operated under the same frequency during the fault, the same damping, and inertia, a GFM can output negative postfault active power, making unstable operation. In [133], the dq-reference frame asymmetrical virtual impedance control method is introduced to enhance GFM's transient stability under significant disturbances. The VTI scheme is introduced to improve the power transmission capability and restore the GFM's equilibrium points, which concludes that it effectively and timely prevents the GFM's instability with a well-regulated output power. Also, utilizing a dq-frame asymmetrical VTI Control enables the GFM inverter to work properly during severe grid fault conditions, providing power and grid support to the local power system then increasing the ability to prevent the system from collapsing and black-out.

The transient synchronization stability issues appear when the operation mode of the GFM converter is switched from the voltage source mode to the current source mode, causing the current limiters to go to saturation under grid faults, as studied in [134].

A DCL method is introduced for transient stability enhancement based on the optimal active and reactive current distribution method, which regulates the current limits according to the voltage drop depths. Also, this method ensures operation without overcurrent damage and sustains transient stability after the mode switching. The design complexity is reduced since only the current limiting signals are required, and no complex transient control components or hardware are needed. Transient stability considerations of the GFM converter are summarized in Table 8, showing the transient stability source, the method used to analyze the transient stability, and the findings achieved.

3) POSTFAULT STABILITY (VOLTAGE RECOVERY)

Fault protection is a crucial component in GFM converters, and installation is required to protect the GFM converters from high current levels during short-circuit events. The effectiveness depends on several factors, such as the clearance time under frequency and voltage disturbances, SCR conditions, and postfault stability. The ideal fault protection scheme should operate under different fault types and all SCR conditions and have an instantaneous response to a fault [68]. Also, when the GFM converter enters the current saturation mode, it includes nonlinear dynamic behavior and postdisturbance transient angle stability issues [135]. The influence of voltage stability under voltage critical grid disturbances and its effect on the system's stability is studied in [136].

This article also introduces a systematic short term and long term of the GFM's voltage stability with current limitation where the active power reference during the current limiting is controlled, and with its combination with anti-windup, it can stabilize the GFM effectively. However, the effectiveness depends on the GFM control and the stability scenario. The mode-switching mechanism is introduced in [137] to provide fault detection before mode transition is activated under symmetrical and asymmetrical line faults, where the controller adopts a current-oriented operation mode during fault situations for overload protection. In GFM inverters, the power synchronization law is destroyed when the current limit is triggered. Huang et al. [138] proposed a power angle limiting method with virtual-admittance-based GFM inverters for output power and current limiting so that the GFM's stability under the overcurrent conditions can be guaranteed, showing a good performance and stability under weak and strong grid conditions. However, GFM inverters with conventional current reference limiting method operates unstable under grid frequency drop. Zhang et al. [139] proposed a virtual power angle limiting method to solve this issue. In this method, the output power is limited by limiting the power angle instead of limiting the current reference. The output current can be limited automatically during grid voltage sag or frequency drop events without the requirement for fault detection or tuning control methods. A power matching-based current limitation method is adopted by the GFM converter in [140], which can efficiently limit the output current to the maximum allowable value and avoid instability and power fluctuation compared with the conventional current reference limiting method.

The adaptive virtual impedance method is inserted between the voltages and current loops, which can completely compensate power-sharing errors without the need for communication links by adjusting the impedance between the inductor and grid to limit current flow. However, the work in [141] introduces the adaptive virtual harmonics resistor to improve the grid-connected currents in single-phase grid-tied inverters operating in weak grids and for high-order harmonics compensation. However, the complexity and the calculation burden are increased due to the need to separate each harmonic current and construct the adaptive harmonics impedance. To alleviate this issue, only low harmonic currents are considered to reduce the low-order harmonic content.

In [142], the virtual impedance-based fault current limiter (VI-FCL) method is introduced to avoid the adverse impacts of the large fault current in islanded ac microgrids and to alleviate the influence of symmetrical three-phase faults. This method can suppress the large current flowing through the system and mitigate the oscillations during the faults and postfault restoration process. This method requires no hardware devices, making it a low-cost approach.

Based on the grid codes of the low-voltage ride-through (LVRT) requirements and during the fault, the power references should be reduced to limit the power supplied to the allowable limit of the converter, especially when inverters are required to generate positive and negative sequence active/reactive currents [143]. An improved LVRT method is introduced in [144] to maximize the converter capabilities during unbalanced voltage drops. This method can limit the amount of the injected current to the maximum allowable inverter's current. Also, active power control is in normal operation, and active power oscillations are avoided under voltage grid sags.

The conventional current limitation used in GFM converters has constraints on the duration of the saturated current and the initial loading. Xu et al. [145] proposed the voltage limitation method to avoid overcurrent damage and maximize the converter's active or reactive power output according to the grid condition. Only the positive-sequence control loop is considered, requiring a saturation block in the voltage reference. However, the voltage of the PCC is unchanged in the case of overload issues, which cannot be achieved using the current limitation method. The harmonic effects, phase, and gain margins are mitigated by utilizing a frequency feedforward term in the $P - f$ droop power synchronization controller to enhance the stability under weak grid [146]. The LVRT-based GFM converters must limit the current and remain synchronized with the grid under postsevere voltage sags. To achieve it, LVRT-based reactive power synchronization (Q-Syn) is introduced in [147] to ensure stable maximum power support within the allowable current limit and faster recovery to normal operation.

The transient instability of the VSC occurs when the virtual power angle exceeds the CCA. Also, it occurs in the droop-controlled VSC when its current is saturated under large disturbances. To avoid instability issues, a stability-enhanced

TABLE 8. Transient Stability Considerations Available for GFM Converters

Refs	Analysis Method Used	Transient instability sources	Findings
[120]	The SLVM control method and phase portrait analysis.	The voltage-magnitude controller cannot accurately be decoupled from the power–angle control.	A small integral gain in the SLVM controller is recommended to enhance the transient stability.
[121]	The first-order PSC-VSC utilizes the critical cleaning angle method.	Operating the VSCs in weak grid conditions, especially under the fault or voltage sage occurrence.	It reduces the risk of system collapse caused by delayed fault clearance due to self-restoration property.
[122]	A design-oriented transient stability analysis based on the typical four GFM control methods: PSC, droop control with LPF, and the VSM control methods.	The high penetration of the distributed power generation systems reduces the grid stiffness.	The PSC and the droop control can retain a stable operation due to their noninertial transient responses. In contrast, the droop control with LPFs and the VSG control can be destabilized due to the lack of damping on their inertial transient responses.
[123]	The virtual power angle characteristics analysis integrated into $P - f$ droop-controlled GFM.	The current limitation and synchronous instability occur when the VSG is connected to the islanded microgrid.	The synchronous instability mechanism of droop-controlled VSC from the aspect of converter's virtual power angle characteristic with and without current saturation is analyzed, showing that current limitation makes the converter more prone to lose synchronous stability.
[124]	Lyapunov's direct method and the reactive power control loop are utilized in the GFM converter.	The imbalance and current limitation between the reference active and output power is due to the large integration of DERs.	- The reactive power control loop will reduce inverter's internal voltage through Q-V droop curve during the transient period and easily drive the system into instability. - The Lyapunov's direct method is used to predict the transient stability of the system.
[125]	Impedance-based modeling of GFM-based-VSG in SIRC.	The interaction between the VSCs and the weak power grid.	The proposed SIRC can be used to identify the voltage stability. Also, the frequency oscillations are mitigated by inertia-damping-enhanced control.
[126]	The large-signal nonlinear analysis is introduced to the uVOC-based GFM.	The voltage and power angle dynamics are strongly coupled and both play critical roles in the transient stability, especially under current-constrained and unconstrained symmetrical faults.	The uVOC achieves a fast response, and built-in FRT parameters exhibit strong stability characteristics.
[129]	The phase portrait analysis of the mixed GFL-GFM power system.	The interaction between the GFM and GFL models in the grid is essential when the grid suffers from large grid disturbances such as grid voltage drops and transmission line failures.	The variation of the GFM-inverter terminal voltage changes the GFL-inverter power angle. So, the transient stability of GFM-inverter is enhanced by increasing the GFL-inverter output current.
[130]	The hybrid system compromises inertia-provided SGs and inertia-less droop-controlled inverter. A second-order equivalent motion equation implements its transient behavior.	The high integration of power electronics devices in weak grid conditions.	-The droop control dramatically enhances the damping effect and significantly affects the transient stability region. - The frequency state variable exhibits a jump during fault disturbances, which highly impacts the postfault initial-state location and stability assessment.
[131]	The parametric effects of power controllers on transient stability are characterized using phase portraits.	The GFM's transition from islanded to grid-connected mode loses the synchronization during reconnection.	From the P - δ curve, the SCR has a critical impact on the existence of equilibrium points, showing the decrease of SCR makes the GFM inverter more prone to the LOS when reconnecting to the grid.
[132]	Adopting modal analysis-based model order reduction technique with virtual impedance current limiting control to the GFM converters.	Operating the VSC under significant grid disturbances, such as transmission facility faults, leads to a current saturation.	The operation of SGs and GFM converters under the same frequency during the fault, with the same damping and inertia, where a GFM converter can output negative postfault active power, making unstable operation.
[133]	The dq-frame virtual impedance of GFM inverters and VTI scheme are introduced to improve the power transmission capability.	Operating the VSC under significant grid disturbances, such as grid faults.	It enables the GFM inverter to work normally during severe grid fault conditions, providing power and grid support to the local power system.
[134]	The DCL method is introduced for transient stability enhancement based on the optimal active and reactive current distribution method.	The GFM converter's operation mode is switched from voltage source mode to current source mode.	-It ensures operation without overcurrent damage and sustains transient stability after the mode-switching.

TABLE 9. Summary of the Postfault Recovery Methods Adopted With GFM Converter

Method	Basic operation	Disturbance types	Refs
Mode-switching	A current-oriented operation mode during fault is adopted to protect the device from overloads.	Symmetrical and asymmetrical line faults	[137]
Power angle limiting	A power angle limiting method with virtual admittance is adopted with GFM inverters for output power and current limiting.	Overcurrent conditions in weak and strong grids.	[138]
Power angle limiting	A power-angle-based adaptive overcurrent protection scheme is adopted with GFM inverters where output power is limited by limiting the power angle instead of current limiting.	Grid voltage sag or frequency drop events.	[139]
Power matching-based current limitation method	A power matching-based current limitation method is adopted by the GFM converter, which can efficiently limit the output current to the maximum allowable value and avoid the instability issue.	Unbalanced loads and large grid disturbances.	[140]
Virtual impedance	An adaptive virtual impedance control with small ac injection for unbalanced and harmonic power sharing in islanded microgrids.	Harmonics and power-sharing issues in islanded microgrids.	[150]
Virtual impedance	The adaptive virtual harmonics resistor is adopted to improve the grid-connected currents in single-phase grid-tied inverters operating in weak grids and for high-order harmonics compensation.	Weak grids with low-order harmonics (third, fifth, and seventh harmonics) dominate the grid voltage.	[141]
Virtual impedance	The VI-FCL method is proposed for islanded microgrids comprised of multiple inverter-interfaced distributed generators (DGs).	Large fault current and symmetrical three-phase faults in islanded AC microgrids.	[142]
Reference parameter limiting	A power reference limiting is utilized when inverters are required to generate positive and negative sequence active/reactive currents.	Asymmetrical LVRT conditions.	[143]
Reference parameter limiting	An improved LVRT method is introduced to maximize the converter capabilities during unbalanced voltage drops.	Unbalanced voltage drops	[144]
Voltage limitation	The voltage limitation method is introduced to avoid overcurrent damage and maximize the converter's active or reactive power output according to the grid condition.	Asymmetric voltage dip.	[145]
Voltage-based frequency feedforward	A frequency feedforward term in the $P-f$ droop power synchronization controller is utilized to enhance the stability under the weak grid.	A weak grid and an LF current harmonics.	[146]
Current saturation	LVRT-based reactive power synchronization (Q-Syn) is introduced.	Postsevere voltage sag.	[147]
Current saturation	Stability-enhanced $P-f$ droop control is proposed where fault detection and on-line control switching are unnecessary.	Large grid disturbances.	[148]
Current saturation	An EPSM and a current limitation method are utilized to meet FRT requirements and overcurrent protection.	- Balanced and unbalanced grid conditions. -Symmetrical and asymmetrical faults.	[149] [150]
CSA	The FCI-based synchronverter converter improves the postfault transient stability by enhancing the active and reactive power recovery in the postfault period.	Postfault transient stability under three-phase faults and LVRT.	[151]

$P-f$ droop control is proposed in [148], where fault detection and on-line control switching are unnecessary. An extended power synchronization method (EPSM) is proposed in [149], allowing the system to operate under balanced and unbalanced grid conditions. Also, a current limitation method is utilized to meet the FRT requirements and to provide overcurrent protection under symmetrical and asymmetrical faults. The resynchronization function enhances the stability margin values [150]. However, different current limitation methods, such as virtual impedance, voltage limiters, and current saturation algorithm (CSA), can be adopted. The CSA is widely used for ease of adaptation and better performance during faults. However, the CSA has a significant disadvantage in which poor postfault stability support where the internal angle during the fault cannot be controlled. The postfault transient stability of the synchronverter is enhanced in [151] by developing the FCI method showing that the active and reactive power recovery in the postfault period is improved and also enhancing the postfault transient stability by reducing the voltage angle deviation. The postfault recovery methods adopted in recent research are summarized in Table 9 showing the method used, the disturbance type clearance, and the principle of operation.

B. PERFORMANCE ACCORDING TO GRID STRENGTH

Grid strength can be defined as the ability of a power system to keep the voltage and frequency within allowable limits under the grid disturbance. The grid strength is described using the SCR, a short-circuit fault level ratio to the power rating of the component connected at this point. Power grids are typically considered strong or weak, depending on the SCR. So, the strong grid has SCR greater than 3 while the weak grid has SCR less than 3 [152], [153].

1) STRONG GRIDS (HIGH SCR)

When GFM inverters are integrated into low-impedance systems and high-SCR grids, inverter controller interaction, grid dynamics, and power controls can be observed. The work in [154] integrates active and reactive power control methods in GFM control to regulate voltage and frequency. The controllers' coupling in active and reactive power loops highly affects the dynamic performance. It restricts the phase, gain margins, and the upper boundary of the controller's bandwidth.

The work in [155] examines the effect of power coupling, such as active and reactive power controls during transients and postdisturbance, on steady-state stability and dynamic performance. The virtual impedance is also integrated to improve the steady-state stability, and the effect of grid impedance, SCR, and phase compensator is reduced. The coupling properties of the typical VSG and droop controls are analyzed in [155] by developing the unified dynamic power coupling model, which concludes that the droop control can weaken power coupling. At the same time, VSG is prone to amplify the coupling, resulting in steady-state error in reactive power and long-term oscillations.

The conventional virtual power-based control method can effectively decouple the active and reactive powers of the GFM inverter. However, the shared active power is not equal in the case of a parallel GFM inverter. An improved virtual power-based control method for droop-controlled parallel inverters is proposed in [156]. The advantage of this method is that the coupling between active and reactive power is mitigated by introducing an LPF between them, where effective power decoupling and good stability are achieved. Another effective method used for decoupling the active and reactive power is introduced in [156], which uses a virtual frequency and voltage frame where stability performances are improved by automatically updating the maximum reactive power limit.

The GFM instabilities in strong grids result from power surges and oscillations when the controllers interact with power control loops and the grid. A virtual admittance concept is introduced in [157], including synchronization based on active power regulation. This structure can emulate the SG behavior and offer voltage and frequency regulation, grid stability support, and power balance sharing. The physical coupling behavior is introduced in [158] to mitigate the dynamic power interaction in ultra-strong grids with SCR over 30. The decoupling controller uses an approximate transfer function, which can also increase the stability margin and boost the power synchronization bandwidth.

2) WEAK GRIDS (LOW SCR)

Weak grids become sensitive to unexpected changes in operating conditions, such as large voltages and fluctuations, which increase the system's instability in the weak grid. The SSO results from the interaction between the converter interfaced generator, such as wind turbines and solar panels, with other power electronics components and grid, especially in weak grid conditions. Two subsynchronous damping controllers (SSDCs) are introduced in [159], which are fast-acting current controllers that provide positive damping in the sub-synchronous frequency range. The SSDCs based on a second-order LPF with a combination of gain and phase shifter have superior performance and minimize the risk of interaction and oscillations. A novel hybrid reconfigurable GFL and GFM for permanent magnetic synchronous generator, which integrates a superconducting magnetic energy storage (SMES) system, is introduced in [160] to improve voltage and frequency stability under different SCR's. The SMES acts as a DVR to compensate the voltage and ensure that the grid side converter voltage is at pre-fault condition. It operates stably with very low SCR and enhances the FRT capability under both symmetric and asymmetric grid faults.

With the extensive integration of inverter-based resources, weak grids or low system strength becomes a significant stability issue. The work in [161] introduces different stability enhancements such as STATCOM, synchronous condenser (SynCon), and GFM converter, which can be concluded that SyncCon and GFM can provide system strength support and stabilize GFL converter under weak grid conditions.

GFM converters present effective voltage source behaviors to enhance the power grid strength concerning small-signal stability issues. Also, it increases the power grid strength in the frequency range of PLL instabilities, improving the overall small-signal stability of the system. The work in [162] shows that operating all the converters in a power grid in GFM mode is unnecessary, where the results showed that a capacity ratio of around 17.8% or 21.4% can increase the stability margin significantly.

The GFM-based VSI with direct current regulation for hybrid solar-wind generators is introduced in [163] to ensure stable operation under weak and faulted conditions. The orientation angle required for grid synchronization is achieved by directly regulating active power, eliminating the inherent regulation of the injected grid current and adversely impacting the LVFRT performance. A permanent inner current control is also integrated to enhance the LVFRT performance.

The work in [164] proposes a converter with GFM and GFL capabilities to achieve effective voltage tracking in the GFM mode and current monitoring in the GFL mode. It possesses a good dynamic disturbance rejection response, a wide stability range, and robustness in both modes. This controller can operate in stand-alone mode and be connected to a weak or stiff grid with SCR up to 30.

A weak grid with low inertia and system strength can cause frequency oscillations, voltage instability, and hampers voltage-ride-through capabilities. These issues can be solved using the SynCon. However, it is inappropriate due to the high capital and operating cost, longer lead time, and transportation complexities of the remote wind/solar farm location. GFM inverter technologies are becoming popular for overcoming the complexities of RESs integrations, especially into weaker grid. The adaptive hybrid control between GFL and GFM can be adjusted by using the analogy of a hysteresis loop in [165] in response to varying SCRs to ensure stability under ultra-weak grid (SCR = 1) and very strong grid (SCR = 50), which merges the benefit of using GFL and GFM based on the system strength. The effect of GFM capacity is analyzed in [166] from the perspective of grid strength on the small-signal stability margin, where the influence of the GFM capacity is studied considering variation patterns of power grid strength under different capacity portions. Also, the relation between the generalized SCR and the converter capacity was investigated.

C. FRT CAPABILITY

Several disturbances occur in the power grid, such as transmission faults and tripping of large generators, resulting in electromagnetic transient and triggering system-level problems. FRT capability or voltage-ride-through or disturbance ride-through is introduced and defined in [167] as the ability of the inverter-based generation to withstand abnormal transients and remain connected. This section focuses on the FRT capability, considering the available grid codes, requirements, and shortages.

1) GRID CODES AND FRT REQUIREMENTS

The output currents of GFM converters not only depend on the external system condition but also on the FRT behavior, the internal settings, and the overrating capability of the converter itself [168]. While synchronous generators can supply 5–7 per unit (p.u.) overcurrent during disturbances at the PCC, the inverters may supply up to 2 p.u. overcurrent [169]. This would allow the inverters to contribute to the dynamic voltage support to maintain the voltage profile and achieve a smooth voltage recovery. Proper FRT strategies, including current limiting methods, are necessary for GFM converters to provide such supporting functionality during disturbances. Thus, the following requirements have to be achieved [170]:

1) current magnitude limitation;
2) fault current contribution;
3) fault recovery capability.

The GFM converters can meet these requirements by employing a proper control mechanism equipped with distinct current limiting control methods. Virtual impedance, current limiters, and voltage limiters are the most common methods in the literature for current limiting by GFM converters.

The necessity of meeting such requirements may increase with the increased penetration of power electronic converters in the systems, which imposes technical challenges on the power network, especially if these converters do not emulate the behavior of the SM. In this regard, other settings and grid code requirements might be necessary. For example, a set of requirements for GFM specifications discussed in a draft for Great Britain was determined as the following [171].

1) The GFM converter has to operate like a voltage source connected with a reactance and the frequency band should be between 5 Hz–1 kHz during, before and after the fault condition.
2) The contribution of the short-circuit current of the GFM converter has to be 1.5 p.u. from its rating. This value is a compromise between the preferable overcurrent capability of a SM and the hardware constraints.
3) The voltage magnitude, frequency, and phase angle of the GFM converter shall remain fixed at pre-fault values during a voltage dip or fault below 0.85 p.u. However, if the fault current magnitude goes beyond 1.5 p.u., the supplied current should be limited to 1.5 p.u., and the phase angle should be equivalent to the higher fault current phase angle. This is to formulate the GFM converter behavior during the fault and to build a guideline for riding through the fault.
4) The GFM converter has to be able to inject reactive power during the fault event, and this must done within 5 ms of the disturbance.
5) The GFM converter has to absorb the unbalanced currents up to 2% with no need to adjust the waveform of the voltage source.

2) GFM CONVERTER FRT CONTROL METHODS

The literature has extensively addressed the FRT control strategies of power electronic-based converters. However, most of these strategies have been predominantly developed for GFL converters, leaving the ones concerning GFM converters relatively underdeveloped. Recently, there has been a significant increase in research addressing this gap, leading to introducing several new FRT techniques. This is motivated by the inadequate FRT specification and mature grid codes for GFM behavior during disturbances. The proposed techniques focus mainly on preventing instability issues and limiting the GFM converter current without adjusting the GFM behavior during the fault.

Initial studies on FRT strategies for VSMs have been discussed in [172] and [173]. The constraints of control states employing nonlinear control methods were highlighted in [174] for the synchronverter, although this approach did not directly address converter overcurrent issues. Instead, it ensured that frequency and voltage remained within bounds without the need for saturation units. A detailed analytical evaluation of the inrush currents in a synchronverter, influenced by control parameters and arising from both symmetrical and asymmetrical grid faults, was presented in [175] and [176]. The method in [175] involves activating an inner current control loop, which relies on a hysteresis current controller when a fault is detected. In this approach, reference currents for the converter are determined using a virtual impedance, while active and reactive power set-points are adjusted to comply with grid code requirements. However, this method necessitates detecting the grid voltage angle. In [177], research into FRT and current-limiting techniques for

GFM converters under asymmetrical grid faults was carried out. A supplementary control mechanism for the NSC was introduced to operate during asymmetrical faults, utilizing a specialized unit to estimate the positive and NSC of the grid voltage. Furthermore, the approaches in [178] and [179] handle GFM converter control, which involves transitioning to a vector control mode immediately upon detecting a grid fault. However, even with this method, an effective current limiting strategy must be incorporated, which is often implemented by imposing saturation on the PI controllers within the cascaded control loops [180], [181], [182]. Consequently, suitable measures should be taken to prevent issues like "wind-up" or "latch-up," which are commonly associated with such conditions. An alternative and effective method that involves employing virtual impedances, where the GFM converter's reference voltage is adjusted based on dynamically varying fictitious impedance, has been proposed. This technique helps prevent excessively high reference current signals from being generated within the inner current control loop [183]. The study in [127] examines the challenges arising from the saturation of the outer control loop in a GFM converter when limiting currents, proposing a current limitation strategy that ensures system stability through coordinated operation between the outer and inner control loops. Despite this, the method does not address asymmetrical faults, which are among the most frequently encountered issues in practical applications. Lastly, an adaptive virtual impedance-based current limitation technique is explored in [184], which effectively restricts the converter's current magnitude by regulating both positive and NSC. However, the control design incorporates multiple filters, negatively impacting the converter's dynamic response. In addition, the proposed approach is validated solely through simulations, lacking experimental verification. The study in [185] reveals that GFM converters face transient voltage stability problems caused by the violation of reactive power absorption limitations between converters and grids. To improve FRT, the authors' proposes and designs voltage inertia control, which smoothen the voltage amplitude change and extends the stable region. An enhanced FRT strategy is introduced in [186] where the impacts of virtual impedance based-current limiting on reactive power characteristics of GFM control are investigated. It reveals that the VI may cause phase offset and deterioration of the natural and instant reactive power support capability, and the subsequent reactive power response faces a coupling with the active power control due to the current magnitude limitation. The work in [187] also presents a two-stage current limiting control strategy with FRT capability for direct-droop-controlled GFM inverters. The proposed two-stage approach comprises two current limiting controls in Stages 1 and 2. By implementing the current limiting actions in two stages, this approach can effectively limit the over-current within a few PWM cycles after the fault occurrence and ensure synchronism to the grid after long-term fault events. Furthermore, Tozak et al. [188] proposed a power supporting control method for GFM-VSC by tuning the active power and voltage magnitude reference. Compared with existing FRT methods, the proposed method could achieve higher power-supporting capability while maintaining the voltage source characteristics, which makes full utilization of power angle and voltage boundaries.

D. COMPARATIVE EVALUATION

This section aims to introduce the most recent literature of the GFM converter aspects and presenting the drawback or limitations with respect to our review article. To simplify the comparative evaluation, Table 10 provides a comparison summary between the intended review and the relevant literature. The comparison is constructed in such a way that the most relevant and recent publications are listed. The categorization of the table is subdivided into: the approach or work focus, the advantages or benefits of the approach, the drawbacks or limitations with our research study, and the availability of real world applications. It can be seen from the table that each recent work conducts a comprehensive review on one or two aspects of the GFM converter. Furthermore, some of them considers discussing an open issue or challenge faced by the GFM converter without making an extensive review of the available methods. For example, the work in [189], [190], [191], and [192] shed the light only into the control schemes and pilot projects of the GFM converter without extending their work into the challenges and limitations of the converter. On the other hand, the work in [170], [193], and [194] contributes in discussing specific issues related to the GFM converter missing detailed comparisons and other aspects related to the subject. In this regard, the intended review paper governs most of these aspects that are missed or discussed on a small scale in the most recent literature.

E. OPEN DIRECTIONS AND ISSUES

1) BEHAVIOR OF GFM CONVERTERS UNDER FAULTY CONDITIONS

In the case of severe disturbances of GFM converters, the output current vector angle can be accurately regulated to let the GFM converter act as a PLL-synchronized current source. Thus, the limitation of the current magnitude and contribution of the fault current can be achieved by adjusting the real and reactive current references in line with grid codes under disturbances [196], [127]. However, extra operation mode switching strategies are required to return to normal operation when faults are cleared. It can be noticed that during disturbance events, the vector angle of the output current can be set diffusely through the internal voltage source regulation and the equivalent impedance such as the voltage limiter and the virtual impedance. Besides, the GFM converter can inject reactive current within 5 ms when the voltage of PCC falls below 0.9 p.u., where such a compromise in such a time scale is optimal to keep the behavior of the GFM converter voltage source with a natural current response instead of regulating the vector angle of the output current. However, how to deliver the magnitude and phase angle of the GFM converter voltage source during severe disturbances in which current magnitude

TABLE 10. Comparison Summary Between the Intended Review and the Relevant Literature

Reference	Year	Approach/Work focus	Advantages and/or Benefits	Drawbacks and/or Limitations w.r.t our research study	Experimental data/Real-world applications
[193]	2024	- Understanding the working principle of GFL and GFM converters and the role of GFM control in power system dynamics and stability.	- Conducting state of the art comparison between the GFM control strategies under different characteristics and system conditions.	- Post fault recovery of GFM converters, FRT capability, and current limiting methods are not discussed in-depth.	GFMs' real-world demonstrations and their applications in several IBRs, such as WFs,
		- Providing practical insights into these stabilities using case studies.	- Exploring the stability, applications of GFM converter in various IBRs.	- The performance of GFM converter according to grid strength either with strong or weak grid is not discussed.	PV power generation stations, etc., are available.
[189]	2024	- Providing a comprehensive literature review on the modeling and control of grid-connected converters, particularly GFM-type. - Discussing the objectives of controlling the GFM converter in power systems. - Summarizing some completed and on-going GFM installation projects around the world.	- It serves as a guide for researchers who want to have a holistic perspective on the control, modeling, and analysis of GFM converters. - Advanced control techniques associated with the future perspective are presented. - Providing an up-to date and comprehensive summary of GFM converters.	- The paper mentioned the control objectives of GFM converters. However, only part of them are discussed. - Post fault recovery methods associated with GFM converter are discussed briefly and distributed within multiple sections. - Weak and strong grid conditions are not investigated in a comprehensive manner.	Some completed and ongoing GFM installation projects around the world where BESS, GFM wind, hybrid, and high-voltage dc exists.
[194]	2024	- Offering a comprehensive review of state-of-the art current limiting techniques for GFM converters. - Conducting an in-depth characterization of GFM current limiting strategies. - Discussing the impacts of various current-limiting methods.	- Using graphical methods that allow for intuitive understanding and visually aided comparisons of current limiting methods. - Discussing the latest standards and trends as they require inverter dynamics under off-nominal conditions. - Presenting the advantages and limitations of each current limiting method.	- The paper only discusses the current limiting methods of GFM converters without clear explanation on how these methods are effective among the various control methods of GFM converters. - The performance of GFM converter according to grid strength is barely discussed throughout the paper.	N/A
[190]	2023	- Providing various definitions of GFM converters and discussing the main differences with the GFL converter. - Single and hybrid storage devices and renewable resources in single and combined architectures were applied.	- Performance comparison between GFM and GFL converters were conducted. - The role of the interfaced resource to the GFM converter is discussed to determine the operation mechanism and the converter capability.	- The paper didn't offer an in-depth discussion and comparisons of the stability issues with the existence of GFM converters and have limited access to the post-fault recovery methods experienced by the GFM converter. - No detailed explanation is conducted considering the grid strength.	A summary of the recent and most relevant demonstrations and pilot projects of the GFM converter around the world are provided.
[191]	2023	- The basic definition and the conceptual differences between GFM converters and grid-following converters are discussed. - The model of the GFM converter is introduced to represent the dynamics of control system.	Control loops of GFM converters, including the outer and inner loops, are studied. - Different control structures such as cascaded control and DVC with linear and fractional order sliding mode controllers are presented.	- Stability considerations and FRT capability and performance according to grid strength were not discussed. - Performance comparison for the methods among the various stability issues (voltage stability, transient stability, and post fault stability) are not discussed.	The design of controllers is demonstrated and verified with case studies.
[192]	2022	- Providing a comprehensive review of GFM pilot projects and demonstrators developed worldwide. - Providing an accurate analysis of the technical features of each demonstrator.	The paper proposes a critical discussion on the motivations that have driven each installation and on the results which have been obtained or are expected.	The paper focuses only on the project pilots and demonstrators focusing on the technical characteristics and on the services they can provide. However, different aspects of the GFM converter challenges were not discussed.	The paper introduced pilot projects of the GFM converter worldwide.
[70]	2021	- Providing detailed review on different VOC implementations. Mainly, the studies related to the fundamental theory of oscillators and design process. - Discussing the stability analysis of VOC-based systems,	The paper discusses the challenges on the compatibility with heterogeneous controllers, FRT and other limitations of VOC including non inertial response and coupled power control.	In comparison to our research study, the paper discusses only some aspects considering the VOC control of the GFM converter. Several issues, such as post fault recovery, FRT capability and grid strength, were discussed insufficiently.	N/A
		harmonics and pre synchronization.			
[170]	2022	- Discussing the requirements of GFM control systems including current magnitude limitation, fault current contribution, and fault recovery. - Discussing various current-limiting control methods including current limiters, virtual impedance, and voltage limiters.	- Providing clear performance comparisons of different current-limiting control methods under symmetrical disturbances. - Presenting the emerging challenges that need to be addressed, including temporary overcurrent, unspecified output current vector angle, undesired current saturation, and transient overvoltage.	- The paper conducts a comprehensive review of only one aspect of GFM converters which is the current limiting property under symmetrical disturbances. However, VSM- and VOC -based GFM converter were not discussed. - The summary of the available types of such control were not discussed and the GFM converter considering strong and weak grids is barely investigated.	N/A
[195]	2022	- Presenting an inclusive review for the GFM VSC control schemes. Specifically, control structures, smart grid-support functionalities, stability issues, and fault current mitigations. - Investigating the applications of GFM VSC along with their benefits and drawbacks for both isolated and bulk power systems.	- Providing detailed explanation for the classifications of the various GFM based control schemes. - Discussing various challenges and limitations for GFM converter technology in terms of performance evaluation metrics.	- The paper focuses more on the GFM converter control schemes. However, the challenges and limitations were not discussed in detail. - No comparisons are performed regarding the massive research in neither stability considerations nor grid strength.	N/A
[33]	2021	- Discussing the conceptual differences between GFM converters and state-of-the-art GFL converters. - Discussing the open issues and challenges of GFM converters.	- A generalized structure of the GFM converter is presented, where different solutions for each of the identified subsystems are presented and compared. -The challenges and open issues related to synchronization stability, FRT and transition from islanded to grid-connected mode of GFM converters are discussed.	- Transient stability considerations were not discussed in detail. A lot of methods available in literature for the GFM converters are missed. - Discussion of the performance of GFM converter according to grid strength under weak and strong grid conditions is limited.	Some of experimental results are available.

limitation and fault current contribution are satisfied needs more investigation in research.

2) PROTECTION OF GFM CONVERTER

It is well-known that fault characteristics of SGs form the ac protection methods of various power system components, unlike when the power system is rich with extensive GFM converter integration. Here, the fault characteristics will rely mainly on the control of these converters. In this way, traditional protection strategies may lose their reliability and may no longer be appropriate for power networks interfaced with a high number of GFM converters. For instance, overcurrent protection may malfunction during ac faults when current limiting control is used as stated in [197]. The distance protection reliability or measured impedance may jeopardize when employing FRT control of the GFM converter, as discussed in [198]. The NSC can be affected in case dual-sequence control of GFM converter as stated in [199]. Thus, novel ac protection strategies that can involve dual operation of GFM converter control and elements of relay protection still need further investigation.

3) ANTIWINDUP METHODS

GFM converters should be able to restore their normal operation once disturbances are cleared and the current limiting mode is disabled, which is commonly known as the fault recovery process. Windup of voltage controllers is considered one of the crucial challenges in such cases. This problem occurs when the GFM converter voltage should be reduced to minimize the converter current magnitude during disturbances. Windup of voltage controllers is considered as one of the crucial challenges in such cases. This problem occurs when the GFM converter voltage should reduce to minimize the converter current magnitude during disturbances. As a consequence, the windup issue is faced by the voltage controllers in the control loops. Several antiwindup methods are developed in literature, such as the clamping and back-calculation methods. For example, the outer loop controllers in [148] and [200] are redesigned to avoid voltage controller windup giving priority for current limiters. However, enforcement of such methods proves that it is only feasible with specific inner and outer control loops and some system parameters. Thus, more sophisticated and robust anti-windup methods for various current limiting controls must be created to achieve the problems of undesired current saturation and fast fault recovery.

4) COORDINATED CONTROL BETWEEN GFM AND GFL CONVERTERS UNDER FAULT CONDITIONS

A straightforward, smooth switching method to facilitate seamless transitions between the GFL and GFM control in the grid-connected mode has been conducted in recent literature [201]. The key to seamless switching is maintaining consistent operation points before and after the transition. The proposed seamless switching method leverages the advantages of both GFL and GFM converters, enhancing the control flexibility of grid-connected converters and broadening the stability boundaries of power grids. However, the coordinated control between both converters under abnormal conditions still needs further research. Therefore, future studies should explore advanced coordination strategies for GFM and GFL converters during fault conditions to improve system reliability and stability. While current research primarily focuses on steady-state performance and basic transient responses, further advancements are needed in adaptive control mechanisms that enable converters to respond dynamically to grid disturbances. Enhancing FRT capabilities in both GFM and GFL inverters while maintaining stable voltage and balanced power-sharing remains a critical challenge. Moreover, the interplay between inertia emulation in GFM inverters and the dynamic response of PLLs in GFL converters under fault scenarios requires deeper investigation to prevent instability. In addition, future research should assess the influence of grid impedance fluctuations and communication delays on coordinated control to ensure robust performance across varying network conditions.

IV. CONCLUSION

Since GFM converters are crucial in operating modern power grids in stable and reliable operation, this article comprehensively reviewed a GFM converter structure and working principles. Various GFM control methods have been comprehensively revised in terms of the structure, importance, issues, and enhancements in recent years. It was concluded that the GFM converter control be able to operate accurately in low system strength conditions, ensuring stable operation of both voltage and frequency. However, this fact becomes inaccurate for some specific conditions of the power network. Therefore, this article highlights the challenges and limitations of the GFM converter with an increase of RESs' penetration level. Also, the performance of the GFM converter, considering the grid strength, was reviewed. Small-signal stability, transient stability, and voltage recovery were considered, and the possible improvements in recent research were shown. The available grid code requirements were revised. Moreover, this article discussed the FRT capability of GFM converters, considering the importance of overcurrent protection of GFM converters. The GFM converter performance under symmetrical and asymmetrical grids was also comprehensively revised. The new perspectives of GFM converter technology still have open future paths to be investigated. For example, unintentional islanding with GFM converters has little attention in research. Besides, the optimal location and number of installed GFM converters need further investigation in power networks with high penetration of RESs. Real-life applications of GFM converters are still limited in research, which necessitates employing more procedures in practice.

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