Arabian Journal for Science and Engineering (2024) 49:6187–6216
https://doi.org/10.1007/s13369-023-08399-z

REVIEW ARTICLE–ELECTRICAL ENGINEERING

Grid-Forming Converter and Stability Aspects of Renewable-Based Low-Inertia Power Networks: Modern Trends and Challenges

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Received: 12 June 2023 / Accepted: 5 October 2023 / Published online: 9 November 2023

Abstract

The broad demonstration of grid-forming converters (GFMs) in microgrid applications has been well documented. Following this, the idea of GFM was assessed for its potential use in large-scale linked networks that include transmission and distribution systems combined with renewable energy sources. As a result, a thorough examination of GFM performance became imperative. This study provides a comprehensive examination of GFMs, encompassing fundamental principles, control mechanisms, implementation strategies, operational aspects, and potential avenues for further research. The capacity of GFMs to withstand system disturbances is of utmost importance for ensuring the overall stability of the system, particularly in situations where inertial response is diminished. Classical control methods are inadequate in addressing transient stability circumstances, necessitating the development of current control approaches to overcome these limitations. The utilization of GFM control is becoming increasingly important in the global initiative to establish a sustainable energy system through the integration of renewable energy. GFM control is particularly significant as it determines the level of controllability over non-dispatchable and variable generation, especially on a larger scale, thus contributing to the practical realization of this initiative. Therefore, an extensive and evaluative examination of many control systems, control theories, and algorithms has been conducted in the last twenty years. This study provides a comprehensive classification of control objectives and applications, emphasizing their importance and effectiveness. The findings of this study are equally applicable to various interdisciplinary fields such as power system operation, power electronics, renewable energy integration, advanced control, and smart grids.

Keywords Converter control · Droop control · Energy management · Frequency containment · Grid-forming converter · Inertia · Stability · Transient state

1 Introduction

Power system is going through a transitional phase from conventional generation to alternative clean generation sources. Consequently, renewable energy (RE) sources are targeted to be constituted as the main source of electricity production. The integration of REs not only introduces a higher degree of stochasticity but also reduces the inertia of the system. The globally predominant REs technologies, namely solar and wind energy source, are unpredictable, non-dispatchable, and have negligible contribution toward the system's inertia.

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Therefore, for appropriate grid integration in accordance with the grid standards the respective variable DC and AC output power of the solar and wind generation system requires a converter interface. These converter interfaces also facilitate an opportunity to appropriately mitigate the REs' variable output power as well enable controllability over the RE system.

Modern power systems must reduce system inertia, and therefore, grid-forming converters are crucial. Inertia from synchronous generators maintained electricity systems by resisting frequency shifts. However, green power integration and converter-based technologies have reduced system inertia. This problem can be solved using grid-forming converters like voltage and current source converter. By injecting synthetic inertia, these converters may mimic synchronous generators, stabilizing the grid. Grid-forming converters (GFM) can quickly adapt to frequency disturbances by actively regulating the phase and voltage angle, guaranteeing stable power supply and integrating green power sources into the grid. Understanding decreased system inertia and grid-forming converters is essential to creating modern power systems and obtaining sustainable energy.

In this respect, the grid-connected inverters, therefore, have the capability to contribute to the grid stability that is analogous to the synchronous generators. Grid-following converters are current-controlled, and they cannot perform any grid parameter formation. However, the GFM does form the voltage phasor, thereby maintaining stability and resiliency. The GFM was conceptualized in [1, 2] as a solution for stable interconnected power systems that experience large integration of converter-based generating units that would suffer from degraded inertia [3]. The provision of an inertial response to maintain rotor-angle stability or frequency stability by GFMs is essential in interconnected networks. Moreover, the reduced inertial in the converter-based networks is manifested as a stability problem that must be handled so as not to compromise network security. These stability measures are rotor-angle stability frequency stability, and voltage stability.

A viable solution for dynamic PLL that maximizes control efficiency in different grid circumstances is still lacking in the available research. This study builds on by presenting an actual application of dynamic PLL, balancing system resilience and control effectiveness through continuous assessment of the impedance-based sensitivity parameter. The system sensitivity characteristic is assessed using real-time grid-reactance observations using PRBS techniques in this article. Characterization methods provide quick detection and response to grid impedance shifts, ensuring consistency. The suggested approaches manage PLL spectrum to maintain a consistent optimum system sensitivity functional value independent of grid circumstances. This ensures system resilience by maintaining stability tolerances with the maximum PLL frequency. A more advanced and systematic adaptive control of the PLL is offered, focusing on both optimal performance and system stability. This enhances power quality and dq-domain control functionality according to diverse grid settings [4].

The operability of the GFMs to maintain stability, interface RE resources to grids, or provide ancillary services are governed by several control schemes. Conclusively, GFMs have multi-dimensional prospects of applications in the domain of RE integration, especially at high and very high RE penetration. Accordingly, many emerging solutions provided by energy storage systems in terms of power conditioning rely on appropriate control algorithms for the battery-coupled converters [5, 6]. The meta-heuristic-based solution for GFM considering gain normalization, stability enhancement with PV-STATCOM, and optimization schemes for converters was discussed in [7–12]. Therefore, the successful integration of REs will be governed based on the controller schemes of GFMs. Globally, many research propositions have been categorically formulated to provide many distinct as well as collective solutions to the challenges associated with RE integration. Hence, it is pertinent to quantify the capabilities and applications of GFM achieved so as to appropriately direct global efforts toward sustainable energy and smart grid establishment.

Indeed, the GFMs utilization requires a classification of the different control approaches implemented. These control schemes could be used for different power system applications that correspond to certain equipment in the conventional power system. In this respect, the objective of this review paper is to provide a categorized and sub-categorized applicative scope of GFMs in renewable-integrated and converter-dominated power grid. The aim is to contribute toward the efforts of researcher, power system operators, developers, and policy makers through state-of-the-art review on current and future trends of GFMs. With the overview of the impact on the system's stability with reduced inertia, this paper comprehensively expands on the numerous control architecture, control theories, and algorithms with intensive explanations on parameters that give indications of the stability performance. Accordingly, an extensive analysis, classification, and comparison is presented to highlight the importance and capabilities of GFMs toward system stabilization based on different control architectures and topologies based on their respective applications. Furthermore, different research gap areas are elaborated to have a bird-eye view of the GFMs research direction, including overcurrent protection, island mode transition, and synchronization transient stability. Finally, the GFMs control scheme future trend is presented in which artificial intelligence (AI) would be the cornerstone for the GFMs operation.

The remainder of this paper is organized as follows (Fig. 1). Section 2 describes the effects on grids as a result of

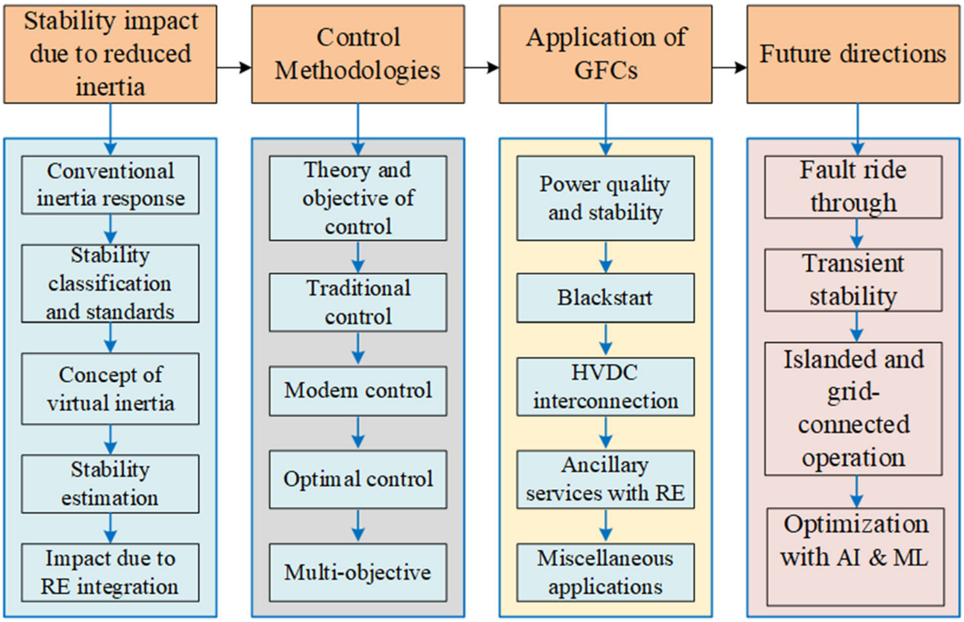


Fig. 1 Schematic overview of this paper

reduced inertia. Section 3 categorically and sub-categorically describes various control schemes of the GFMs. Section 4 presents the prevalent GFMs applications along with their respective control configurations. The GFM future trend in research is highlighted in Sect. 5. Finally, the main conclusion is presented in Sect. 6.

2 Stability Impacts of Reduced Inertia

Many factors drive the high demand of clean energy sources, REs in particular. This increasing demand causes modern power networks to gravitate toward converter-based generators that lack of mechanical inertial response that compromises networks' stability [13–16]. The evolution from the generator-based networks into the converter-based networks is depicted in Fig. 2.

REs resources are connected to grids through power converters that decouple them from the grids [17]. Consequently, the overall power system inertia is reduced if conventional-generating units are replaced by REs [18, 19]. Low inertia raises several challenges in power systems that could impede the RE utilization and growth. It is of primary objective to ensure the system operational stability at the degraded inertia scenario. The timescale of synchronous inertia is rather small, ranging from milliseconds to tens of seconds. Broadly speaking, power system stability is classified into three major classes: frequency stability, rotor-angle stability, and voltage stability. A reduction in system inertia affects transient stability as well as small-signal stability [13]. Some of the low-inertia challenges were highlighted in [20, 21], but they lack of scientific foundations to approach such issues. In [22], a thorough review was conducted on the system inertia values pertaining to power systems and wind power plants that help estimating potential inertial degradation upon adopting non-synchronous generation units.

Traditionally, stability measures in power system networks are dependent on the stored kinetic energy stored in SMs in which it is automatically extracted in case of any power imbalance. For example, a sudden load addition or loss of a generating unit would reduce the SMs speed, thereby decreasing grid frequency [22].

Two distinct approaches are used to address the power system stability issues, namely theoretical and computational. The pros and cons of each method are presented in [23], and computational (simulation-based) examples are given in [24].

The low-inertia deterioration caused by the REs grid-interfacing, virtual inertia (VI), known as artificial inertia or synthetic inertia, has received lots of research and experiments in literature. VI inverters strive to emulate the SM inertia response mathematically via modulated pulse width modulation (PWM). Some techniques used to provide VI in power system are illustrated in Fig. 3. The VI techniques are broadly classified as energy storage related or VI-based converters [25].

Although many studies provide useful understanding of the immediate stability concerns, they do not make any contribution to the instantaneous power limits of non-synchronous (i.e., REs) resources that a grid can take before losing the frequency stability. Moreover, some studies focused on the power balance aspect and simplified the problem through assumptions that ignored the stability concerns [15]. The authors, also, divided the low-inertia system

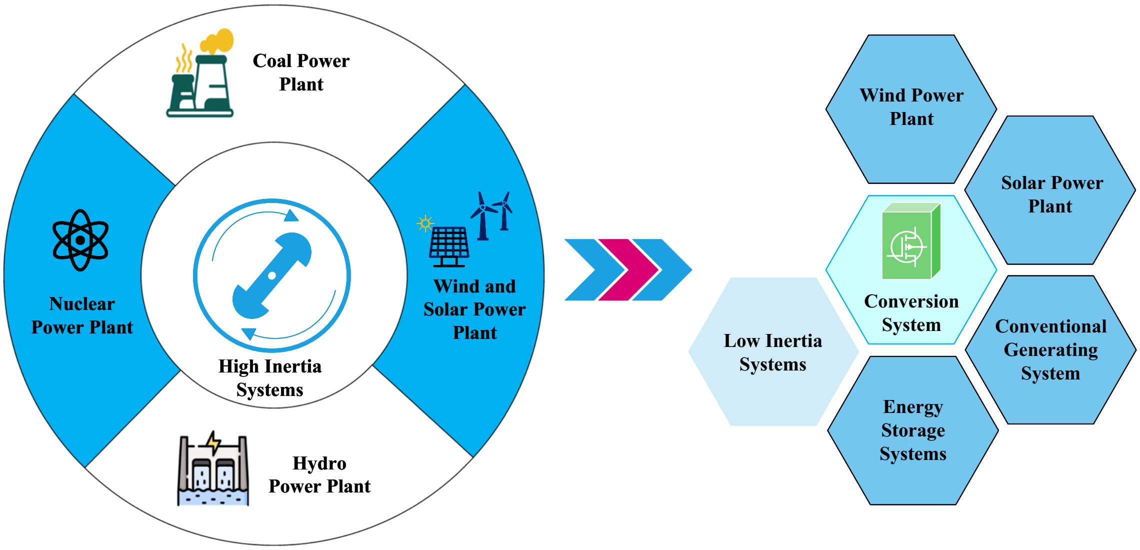


Fig. 2 Evolution toward converter-based grids [26]

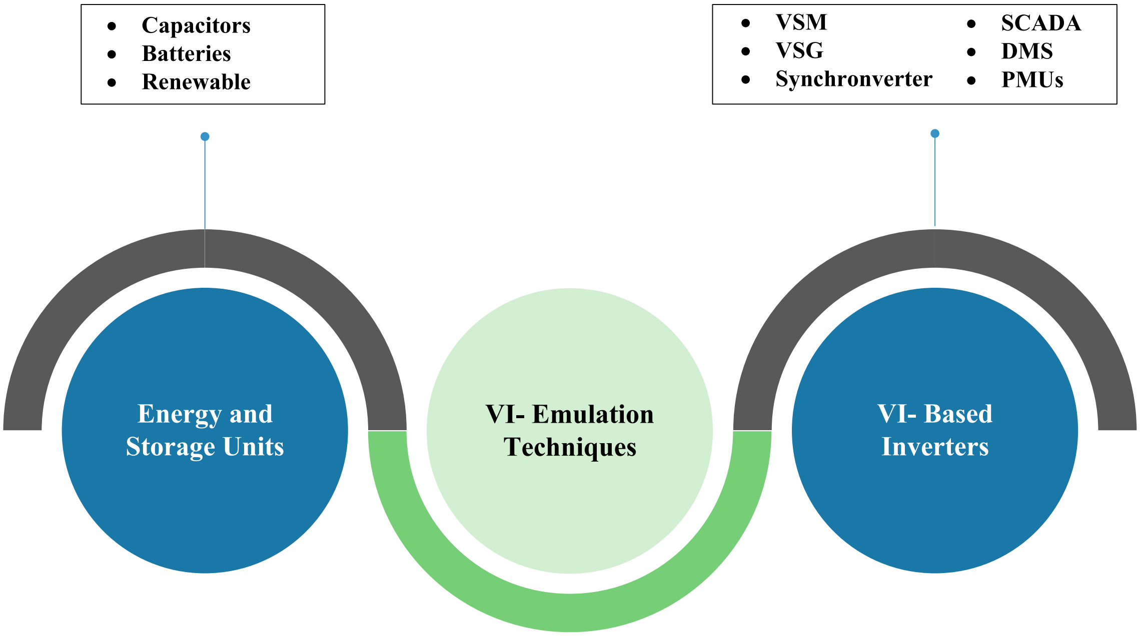


Fig. 3 Virtual inertia techniques

issue into analytical questions that cover different system levels, ranging from the device level to the whole system limitations. Besides, a thorough review of inertia enhancement approaches is discussed broadly along with potential challenges associated with them in [16].

2.1 Grid Impedance Estimation

The stability problems related to grid impedance is twofold. The small-signal stability measures are governed by tuning the control parameters at the steady-state operating point [27]. Furthermore, the active power transfer is a function of the grid impedance [28]. Normally, an excessive active power flow in weak grids raises large-signal stability issues like voltage stability [29]. Consequently, the grid impedance estimation is highly important to the controller in order to incorporate the necessary VI value for a better stability performance [28].

Different techniques of grid impedance estimation are detailed in [28] that are more stable for grid-following converters and cannot be directly applied to GFM. The reference proposed a grid estimation approach that suits GFM.

It operates in four distinct points to account for different small-signal stability conditions. The model averts the harmonic distortion and possesses accurate estimates, too. A novel approach was formulated in [30] that estimates the converter-based grids' impedance using a mapping technique that considers different converter operation modes and states. Various methodologies for grid security, impedance estimates, vehicle-to-grid applications, fast transient and voltage balancing, and fast transient and stability have been extensively discussed in references [31–38].

2.2 Renewable Energy Integration Impact on Power System Stability

Transient stability represents the system stability after large disturbances, such as faults, generation loss, line switching, etc. The classical SMs transient stability factors are elaborated in [39], and the inertia contribution to these machines transient stability is presented in [40].

REs are mainly wind power and PV, and each manifests distinct performance under transient stability. The wind power is rather similar to the conventional networks, as it was shown in [41, 42] that doubly fed induction generators (DFIG) can improve the synchronous generators transient stability margin by delivering voltage and reactive power after a fault. The anticipated pros and cons of integrating the wind power units are demonstrated in [43].

The PV, on the other hand, has received less research works on that field. Some researches addressed the benefits and adverse impacts of adopting the PVs at a large scale [19, 44]. The authors in [45] pointed that the PV fault-ride through (FRT) capability is essential in determining the PV performance during transient stability cases.

REs are characterized by intermittency in which they are interfaced to grids via fast-responding converters, so REs are considered as fast-dynamic systems. There are several grid issues associated with such fast interactions that are manifested as voltage amplitude stability, phase angle stability, and frequency stability [46]. These instability problems are aggravated during fault conditions [25].

The following subsections addresses the REs integration effect on the three stability measures: voltage stability, frequency stability, and rotor-angle stability.

2.2.1 Voltage Stability

A large PV integration is believed to affect grid voltage stability along with the effect on transmission/sub-transmission systems' stability were presented in [44, 45, 47]. In fact, the PV penetration level is the main factor in having a beneficial or detrimental effect on the system voltage magnitude [45]. Another study in [44] that was conducted on Ontario system revealed that a centralized PV plant could be less beneficial than the distributed PV arrangement in terms of voltage magnitude stability.

A physically rotating component sets the synchronous generator's (SG) angular frequency, allowing it to automatically synchronize with the power grid. However, converters' static semiconductor components allow for much customization and regulation. The GCL uses a phase-locked loop (PLL) to align voltage and synchronize grid frequency, SGs. A closed-loop converter's PLL regulates power angle and maximum time constant. The grid shows that this has far-reaching impacts on input/output dynamics. Many PLLs assume constant measured voltage and frequency. PLL dynamics may be separated from the converter system under this premise.

Wind power also contributes to the voltage stability especially at large-scale integration. The wind power impact on voltage and reactive power is investigated in [43], where two test cases in Belgium illustrated that the wind power mode of operation during voltage dip events is set according to the grid short-circuit power and the X/R ratio. Generally, it is preferred to adopt wind power for voltage control especially in remote areas that mandate additional control schemes. Voltage dips cases necessitate a coordinated control of the wind power plants in order to maintain the voltage limits. Unexpectedly, it was proven in [41] that the converter-connected generation units penetration level does not only depend on the synchronous inertia; instead, it relies on the amount of reactive power available and the grid topology. Should the reactive power value and the FRT increased, the maximum integration level can be achieved. Moreover, it was shown that classical solutions work as well, like installing conventional generation units to increase the inertia. An ultimate conclusion was drawn that a grid with distributed generation feature transmits less power than that of only conventional generators, which benefits the network transient stability.

Voltage stability, also, is supported during transient periods. A voltage dip event in Spain tripped many wind power units leading to a power imbalance [48]. This case urged utilizing FRT capability in the wind power codes [43]. That being said, this is not enough to guarantee a safe operation of wind power plants, and the reactive power support is a required service from the wind power plants [49]. The integration level of wind power at remote areas is limited by the available reactive power, so the reactive power management controls such wind power integration [50].

2.2.2 Frequency Stability

Traditionally, stability measures in power system networks are dependent on the stored kinetic energy stored in SMs in which it is automatically extracted in case of any power imbalance. The high penetration of converter-based REs introduces some network security issues as well as critical frequency stability problems [51]. For example, a sudden

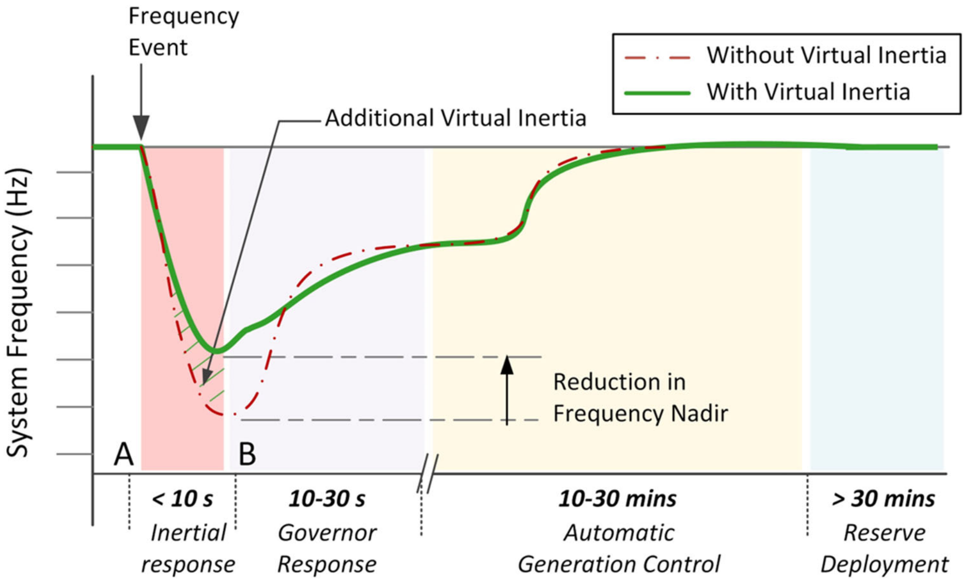


Fig. 4 Multiple time-frame frequency response in a power system following a frequency event [26]

load addition or loss of a generating unit would reduce the SMs speed, thereby decreasing grid frequency [22].

Frequency must fall in a predefined range, so the system operation security is not impaired [13, 21]. Reduced synchronous inertia degrades the system frequency, as the system cannot maintain a steady frequency in case of significant deviations between power generation and power consumption [26, 52, 53]. An independent system operator, Electricity Reliability Council of Texas (ERCOT), reported a continual inertial response decline in its system that is accompanied by a conventional-generating units power loss. The recommendation was to add more inertial responses to offset such a decline [54]. In fact, low inertia affects frequency stability in two ways: a rapid ROCOF and a large frequency deviations (i.e., low frequency nadir) [55]. These frequency deviations must be allayed to avoid unnecessary generation units tripping and/or load curtailments. Thus, techniques were devised to stabilize the frequency and then bring it back to its nominal range value [20].

Various approaches are adopted to maintain power-demand balance to keep frequency within acceptable limits as in Fig. 4. The primary frequency control (governor response) takes place in the very few first seconds (10–30 s) to reduce the frequency deviations. The frequency secondary control (automatic generation control (AGC)), on the other hand, takes over after the primary frequency control, it lasts for few minutes (usually 10–30 min), and it aims to bring the frequency back to its nominal value. The tertiary response is the emergency reserve that deploys available resources upon emergency needs. All of these actions are preceded by the kinetic energy stored in the rotor that provides the inertial response to counteract any power imbalance till the primary frequency control takes over [26].

The overall inertial response is impacted badly in a reduced synchronous inertia network. This is attributed to the matter of fact that the converters' generators are electrically decoupled from the system, which prevents the kinetic energy delivery to the grid. This kinetic energy forms the basis of the inertial response under investigation. Consequently, the ROCOF and the frequency nadir are both influenced in a way that protective devices might be adversely affected [16, 56]. Basically, synchronous units respond rapidly to the frequency variations through the physical inertia, while the non-synchronous units must be forced to emulate the inertial response by specific controllers. As a result, this inertial response is prone to delays, malfunctioning, and unforeseen coupling to system dynamics. This implies that low-inertia systems are less secure than systems with high inertial capability [15]. Furthermore, generating units are subject to physical damages when exposed to high ROCOF, like pole slipping that would occur if the ROCOF is within 1.5–2 Hz/s [57].

A simple simulated model was conducted in [58] to test the frequency response of a network that has 10% power imbalance of the total generation capacity for certain levels of converter-based generators. These converters were assumed they do not deliver any frequency support and gradually replace the synchronous generators. The results showed that an increase of the converter-based generation increases the ROCOF and decreases the nadir frequency.

Non-conventional generating units have generally a slow response time and this aggravates the nadir frequency and the ROCOF. It was stated in [20] that the increase in ROCOF value is one of the major obstacles against a safe operation of a low-inertia grid. Not only does a high ROCOF affect generating units protection schemes, but it also minimizes

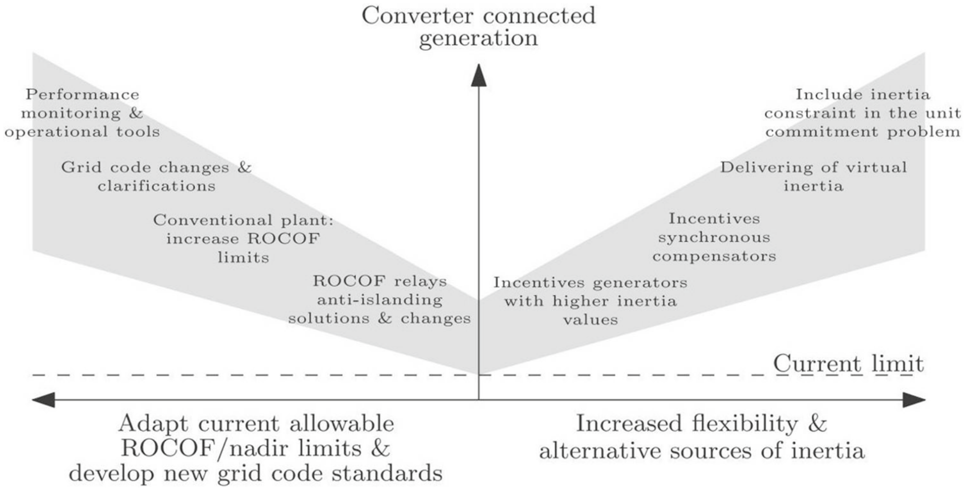


Fig. 5 Proposed solutions for low-inertia systems [20]

the governor time window to react before exceeding the frequency limits.

The frequency stability is not the only problem emerges upon low inertia systems. Frequency control-related issues also arise (e.g., high ROCOF). Many case studies in the literature tried to explore this matter to come up with operational strategies to lessen the associated low-inertia potential effects. These studies consider isolated and small systems in which their results can be generalized to larger interconnected systems. Initially, the low inertia was not seen as a problem since most of TSOs set the converter-based generation to the maximum level, which ranges between 20 and 50% [59]. Subsequently, the rising of REs shifted the attention to the low-inertia issue which forces certain precautions to be considered. For instance, Ireland suggested to limit the wind power penetration level to only 30% during the day to eschew technical and operational troubles [60].

A further increase in the penetration level introduces other low inertia related issues, one of which is ROCOF relay settings. Normally, distributed generation units are equipped with ROCOF relays to protect against islanding [61, 62]. In converter-based networks, the ROCOF relays are so sensitive to loss of mains or frequency imbalance that a disconnection of a generation unit might result in a cascaded effect that causes a widespread outage [63]. A case study was implemented in [64] concluded that ROCOF current settings in the Irish island grid must be increased to accommodate the expected wind power integration. It was stated in [65] that the converter-based generators should not exceed the set limit (65–70%). Another study on the Irish network was held in [66], to review the Ireland Grid Code ROCOF element. It was concluded that the ROCOF shall be increased from 0.5 Hz/s to 1.0 Hz/s that is measured over a 500 ms period. This aids to cope with the rising System Non-synchronous Penetration (SNSP) sources that degrade the system inertia. The technical report addresses different implications in relation with the ROCOF problem and compares the Irish case to some European countries. A UK case study studied the effect of GFM-based wind power farm on the turbine frequency stability [67].

Presumably, ROCOF and frequency nadir are directly influenced by system inertia. This is a simplification to the issue at hand, as it might yield inconsistent ROCOF results with simulations. The authors in [21] highlighted the Nordic HVDC link problem in relation with the isolated system small inertia that impacts the frequency regulation negatively. The ROCOF estimation was proven not to solely rely on the available system inertia. Several factors are addressed that would have significant effect on the ROCOF. In regard with the frequency nadir, the so-called frequency containment reserve (FCR) along with the system inertia determines the frequency nadir magnitude. Distributed generation scheme gains popularity due its reliability and flexibility in distributed generation applications despite the degraded inertial response [68].

Many solutions were proposed in the literature to tackle the low inertia problem, and they are summarized in Fig. 5. These proposed techniques boil down to two main approaches in which they aid existing grids to accommodate converter-based generating units. The first approach is to accept the high ROCOF and large frequency swings by adapting existing grids code and protection to the additional non-conventional generation sources. The second approach, on the other hand, adds different forms of inertia to the grids to counteract the low-inertia issue. This extra inertia could be a virtual inertia or an incentivized investors that can afford the required large inertia [69]. Some studies suggest to impose inertial constraints on unit commitment problem so as to reserve some inertia. The isolated mode of the GFM has limited resources available, which makes it very difficult to maintain the operation status within the same tolerance level as the grid-connected mode. The frequency nadir and

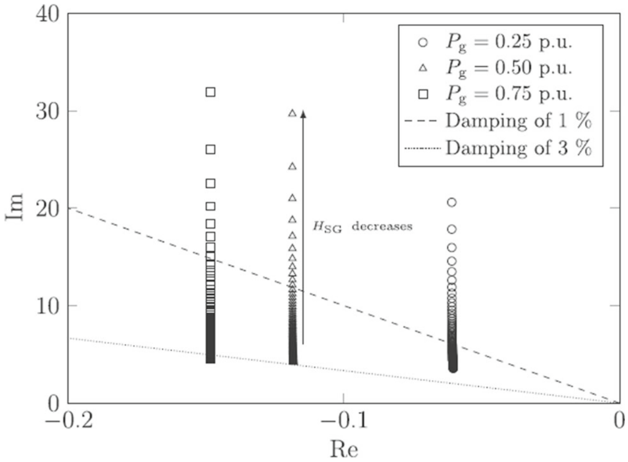


Fig. 6 Electromechanical modes for a single-machine infinite-bus system in function of inertia and operating point [20]

ROCOFs, hence, can be relaxed to account for such resource scarcity [70, 71].

2.2.3 Rotor-Angle Stability

Rotor-angle stability is defined as the ability to keep machines' synchronism when a system is subjected to disturbances. These disturbances could be small-signal or transient. The small-signal stability enables utilizing linearized system equations that facilitate the analysis [20]. Eigenvalues of a system matrix indicates the oscillatory modes and describes the system small-signal stability [58]. Hence, the low-inertia effect is easily assessed through the electromechanical oscillatory modes as shown in Fig. 6 that illustrates a single-machine infinite-bus system. The graph shows an inverse relationship between the generator inertia and the eigenvalue imaginary part. The lower the machine inertia is, the larger the imaginary eigenvalue, which corresponds to more rapid oscillations and lower damping factor.

The linearized small-signal modeling is not applicable at large signal disturbances since the linear operating point is not valid. It is essential to maintain the GFM synchronism with the grid during and after the disturbance events under such transient stability conditions [58]. The transient stability case has been receiving much attention in the literature. The voltage sag effect on GFM current saturation was investigated in [72] to analyze the droop control performance under this transient event. Also, the droop-based control in conjunction with low-pass filter (LPF), inertia term, was considered to study its transient stability with Lyapunov function [73]. The power synchronization control (PSC) behavior under different fault conditions was analyzed in [74]. A common assumption of these studies is that the transient stability is solely dependent on decoupling the active power control from the reactive power control, which functions properly in stiff grids [75]. The cross-coupling between the active control and reactive control plays a major role in determining accurate transient stability measures; thus, it has to be considered to avoid inaccuracy [76]. This cross-coupling problem is shown in Fig. 7, where the active power is not only dependent on the dynamics of the resultant, but also the reactive power dynamics are considered. This makes the transient stability analysis complex. The reactive power control was studied qualitatively by power angle curves to illustrate the link of the reactive power control and the transient stability deterioration [77]. A design-oriented analysis was conducted in [76] to address the droop control and the PSC so as to quantify the reactive power control loop effect on the transient stability.

The high penetration rate of the converter-connected units and the potential impact on the system oscillatory modes are studies in [78]. Generally, there is no agreement on the effect of the increased number of the converter-based generating units integrated to power systems on the electromechanical oscillatory modes and small-signal stability in particular. The induction motor load and SMs rotor-angle stability can be enhanced by reactive power injection by wind power plants [43].

Fig. 7 Transient stability model of GFM

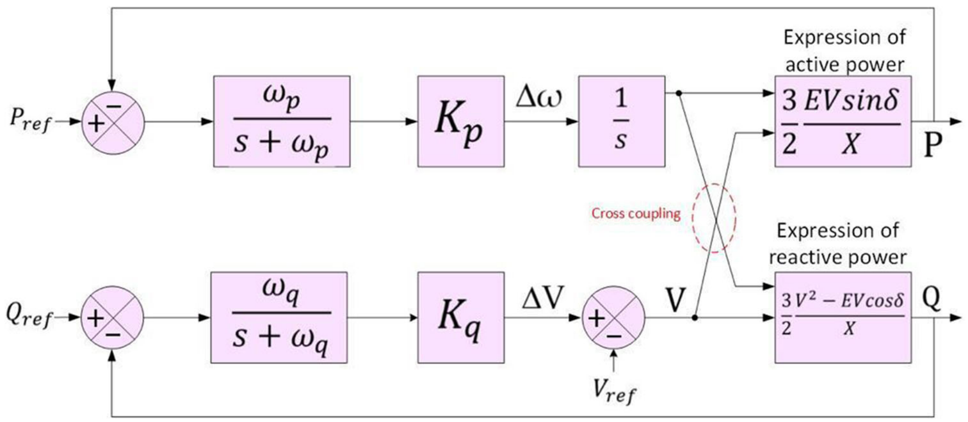


Table 1 Summary of control techniques of GFM

Control scheme	Frequency voltage regulation	Transient stability	References
Droop	Yes	Strong	[86, 87]
SPC	Yes	Weak	[88, 89]
PSC	Yes	Strong	[90–92]
Virtual inertia	Yes	Weak	[93–96]
Matching control			[97–103]
d(VOC)	Yes	Strong	[15, 104–106]
Model predictive control			[107–111]
Optimization			[112–118]

3 Control Techniques and Utilization Architecture of Grid-Forming Converters

In MGs, different DG resources (REs, oil, gas, etc.) and a broad category of converter types (grid-forming and grid-feeding) might be interconnected, and hence, a structured set of controllers should be devised so as to ensure a proper system operation under different operation modes [79]. A comparative study between the two converter types is given in [80].

Several GFM control schemes were developed to overcome the negative impacts of non-synchronous generation units, ranging from simple and basic controls (active power and reactive power controls) to grid-forming control, virtual synchronous machine (VSM), and operating electric networks with power electronic devices [81]. Other control schemes were introduced for an island mode operation. They are short-term voltage source controllers (i.e., identify how a voltage source converter reacts to events at point of common coupling (PCC)). In addition, the switched DC-link voltage value is considered as the manipulated value that is realized by a specific switching pattern of the converter legs. This is why the converter is assumed to be a controlled voltage source behind an inductive filter. In addition, other control loops could be added to handle certain problems like resonance damping and overlaid control loops. These additional control loops are detached from this specific grid-forming control scheme [82].

Some control scheme versions, like VSM, use phase-locked loop (PLL) to estimate the grid frequency so that the power control and the frequency control are decoupled. This subsequently enables controller to support frequency control compared to the PLL-free controllers that cannot do so because of the power and frequency/power coupling. A control model that decouples the power/frequency loops and not PLL-based was proposed in [83]. Furthermore, inertia-based controllers (e.g., VSM) are of a second order, while the non-inertia controllers are first-order systems. The former could experience power oscillations in weak grids, thereby degrading the GFM transient stability, while the latter shows stronger transient stability response. Nevertheless, the non-inertia controllers would endanger the frequency stability due to the lack of inertial support [84].

Aside from the cascaded PI controllers, other control techniques were proposed, such as linear quadratic regulator (LQR), sliding mode control, H2/H∞, and AI. A comprehensive review of GFMs is provided in [85] that summarizes the control schemes and applications. Table 1 lists different control techniques along with their characteristics and related main references.

3.1 A Generalized Control Structure

A general GFM control architecture, derived from different control schemes, is depicted in Fig. 8 that shows different control input signals [79]. These signals include the converter current and the current/voltage at the PCC. Another generalized control architecture incorporates different control schemes in the form of multi-variable feedback in which the AC and DC control are coupled [119]. Other control signals are the reference active power, reference reactive power, the reference frequency, and the reference voltage. These control signals are allocated into two loops—namely inner loop and outer loop, in which PI controllers form the basis for such an approach. The coupling of both loops is elaborately analyzed in [120].

The outer loop that is also referred to as the system-level control acts on a higher level to tackle the system stability measures. These controllers manage the power sharing among different power converters by adopting different controlling techniques, such as droop control and virtual inertia emulation control techniques. Also, the system-level controllers do not need any communication between the interconnected converters [1]. Basically, it computes the frequency, the angle, and the voltage source voltage magnitude. The outer loop contains two sub-systems: the frequency scheme and the angle scheme as illustrated in Fig. 8. The interconnection between these two sub-systems, however, is dependent on the adopted control scheme.

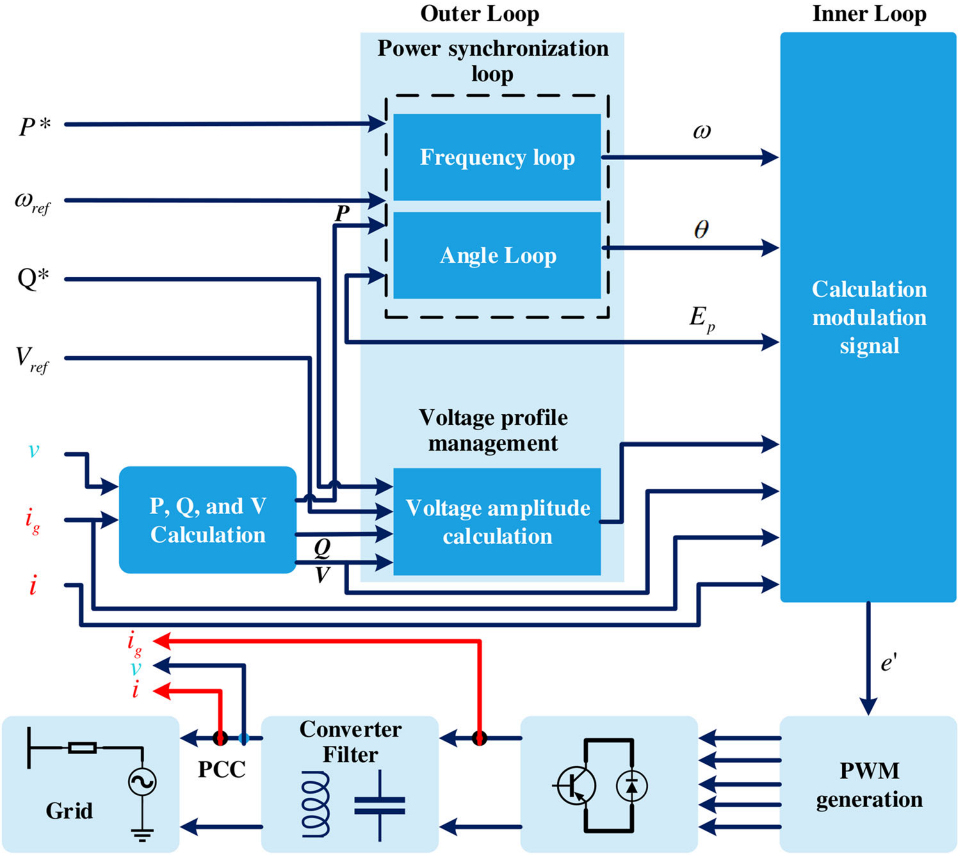


Fig. 8 General control structure of GFM [79]

On the other hand, the inner loop, known as low-level (device level) control, does other control actions to produce the modulating signal for the PWM. The inner loop controllers shall have a wide bandwidth and good performance in order to a fast time response against the different operation modes. Typically, the inner loop comprises three topologies: inner current control, inner current control and cascaded voltage control, and no inner current loop control. These topologies were contrasted in [121] in terms of grid impedance, power sharing, and electromechanical oscillations. Briefly, the inner current control with the cascaded voltage control does not perform well in weak networks due to the inner loop controllers' delay, and they are more sensitive to electromechanical oscillations opposed to the other topologies.

The cascaded PI controllers implemented in the GFM structure introduce difficulty in tuning the related parameters. A self-tuning online optimization techniques are used to tune the PI controller parameters [117]. An automatic tuning procedure is devised in [122] in which a linearized model produces parametric eigenvalues. A proportional plus resonant scheme is implemented for the outer loop and the PI scheme is for the inner loop [123]. A main disadvantage of these methods is the necessity to have a precise GFM model. Besides, they usually have a narrow-band range for stability when switching frequency is low [122]. Similarly, a voltage differential feedback controller in [124] for the outer loop necessitates an accurate system modeling to design the inner loop and the outer loop effectively. An online neural network controller uses an adaptive dynamic programming to optimize the system and minimize energy usage [125].

The LC filter is employed to counter PWM switching ripples. Should the GFM not be modeled properly, the inherent resonance of the LC filter would cause oscillation and instability in dynamic behavior [126]. Passive damping and active damping are adopted to face the LC filter resonance, but the passive damping is not efficient, while the active damping is prone to parameter uncertainties [127, 128]. The following sections address different control methods employed for the GFM application.

3.2 Droop-Based Control

Droop control is the baseline for the GFM in which it mimics the SM speed droop control. The droop controller, under the assumption that the grid is inductive, is depicted in Fig. 9 whose mathematical expression is as below:

$$\omega = \omega_{\text{ref}} + m_p(P_{\text{ref}} - P) \tag{1}$$

Fig. 9 Frequency droop control

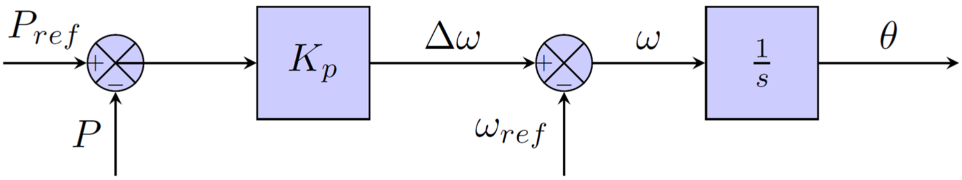
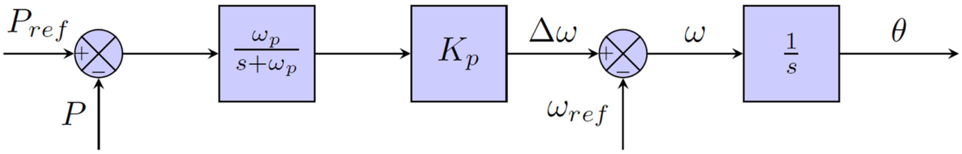


Fig. 10 Frequency droop control with LPFs



where ω is the grid frequency, ω_{ref} is the reference frequency, m_p is the active power droop coefficient, and P is the instantaneous active power.

The concept of utilizing power droops to synchronize parallel inverters was pioneered by [129]. The authors in [130] proposed the droop control of active power and frequency, and there were many modified versions as presented in [86]. The authors in [87, 131] addressed the power sharing problems that arise in specific applications. The droop gain adheres to the maximum voltage deviation implemented in the primary control and to the grid voltage characteristics that affect the system stability [132].

An important assumption behind the droop control is the availability of a stiff DC voltage source. The proportional gain value and the internal frequency dynamics have to function in harmony so as to forestall the interactions with the AC grid line dynamics; hence, the power measurement is filtered using a LPF before the droop controller [133, 134]. Furthermore, load unbalance could cause fluctuation in the measured output power, so a LPF is added into the power control loops (Fig. 10) to remove such fluctuations. Unintentionally, the LPF introduces virtual inertia similar to the voltage source generator (VSG) [135]. The DC voltage dynamics are considered in [136] to account for DC-link disturbances.

The analysis of such similarity is elaborated in [76, 82]. Indeed, the swing equation precise replication is not necessary, as the droop control with the inertia emulation is more flexible in implementation [137, 138]. In spite of that, the LPF addition has a detrimental impact on the frequency control loop in which the dynamic response is compromised once the cutoff frequency is reduced [139]. In fact, the right cutoff frequency is a trade-off between the desired dynamic response and the harmonic distortion level.

Island mode of MGs is not uncommon, and it needs a special droop control configuration. Basically, the droop control assumes an inductive grid in which the power angle/active power and the voltage/reactive power relationships hold. This is not the case, however, for the island mode since the given grid is resistive in nature. The analytical aspect is addressed in [1]. Different techniques of the droop control in isolated MGs are presented in [140]. Besides, resistive grids do have particular transfer functions that need to be adapted with the control action, which is implemented using rotational matrix T as addressed in [141]. The measured output power values are not the inputs to the droop controllers, but virtual values that result from the rotations in the complex plane in accordance with the R/X ratio of the power lines. This increases the effectiveness of the droop control scheme, but the load sharing mechanism suffers.

Other supplemental components enhance the droop control performance. Differentiators improve transient response by adjusting the corresponding reactance virtually in conjunction with the current rate of change during transient processes [142, 143]. Additionally, the combination of droop control and virtual impedance loop improves the droop load sharing while maintaining the essential control structure [144, 145]. Weak AC grids could take an advantage of incorporating a PLL into the droop control without causing any instability conditions as illustrated in [146].

3.3 Power Synchronization Control

PSC is another control scheme that was proposed in [147] in which it synchronizes the voltage source converter with the grid through a power synchronization loop. The model was elaborated later in [148]. Other sources tackled the PSC in greater details [90–92]. Figure 11 shows the control block diagram of the PSC, where the active power error is integrated into a phase increment, which in turn is added into a static phase ($\omega_0 t$); the final outcome is θ as described in equation (2).

The figure, also, illustrates the equivalence of the PSC and the droop control in terms of control law. The analysis of such equivalency is worked out in [82, 143, 149].

$$\theta = \frac{1}{s}[k_i(P_{\mathrm{ref}} - P)] + \theta_{\mathrm{ref}} \tag{2}$$

where k_i is a control parameter and θ_{ref} is the integral of ω_{ref}.

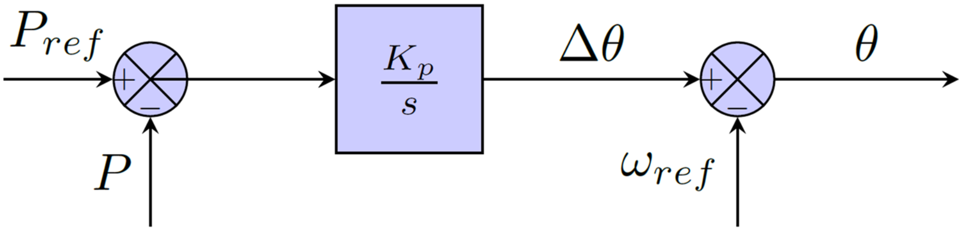


Fig. 11 Power synchronization control (PSC)

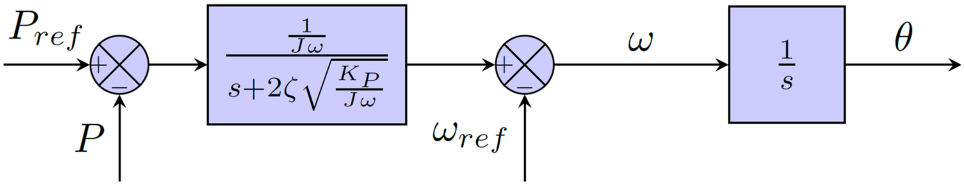


Fig. 12 Synchronous power control (SPC)

The swing equation synchronization mechanism can help to match the dynamic order with a given damping capability, which was utilized to improve the PSC performance [150].

Similar to the droop control, the PSC emulates inertia by introducing a LPF [90, 91, 137, 138, 147, 151]. Nevertheless, this makes the resultant system of a third-order type, thereby complicating the model design [88]. The second-order system analysis techniques were utilized to conduct a thorough investigation of the PSC power loop in [137, 138, 151]. The authors observed that it is quite difficult to see an enhanced performance except for a filter loop addition as proposed in [152, 153]. This is attributed to the uncontrolled zero residing in the active power loop that degenerates the dynamic response [154]. This problem was highlighted in [76], where a controller design guideline was proposed from the transient stability perspective. The second-order system overshoot is notorious for the transient stability.

3.4 Synchronous Power Control

A synchronous power controller (SPC) was proposed in [88, 89] as an alternative controller that improves the power controller performance. Unlike traditional droop/PSC control schemes that employ frequency/phase angle to regulate the active power, the SPC uses both frequency and phase angle to control the active power as illustrated in Fig. 12. The model has two distinct features that make it outperform other schemes: Virtual frequency inertia design is not linked to the power dynamic response, and the system is reduced to a first-order system. The angle (θ) is expressed as in equation (3).

$$\theta = \frac{(P_{\text{ref}} - P)\frac{1}{J\omega}}{s + 2\zeta\sqrt{\frac{K_p}{J\omega}}} + \omega_{\text{ref}} \tag{3}$$

where J is the virtual moment of inertia, and K_p is a transfer function between the varying GFM angle ($\Delta\theta$) and the injected active power (ΔP).

3.5 Virtual Inertia-Based Control

The frequency disturbances vary the grid frequency in accordance with the variant swing equation (4).

$$\frac{2H}{\omega}\frac{d\omega}{dt} = \frac{P_{\text{gen}} - P\text{load}}{S_g} \tag{4}$$

where H is the inertia constant and S_g is the system apparent power. Note the derivative term ($d\omega/dt$) that represents the system ROCOF, discussed in Sect. 2.2.2, is inversely proportional to the system inertia.

The rapid growth of REs adoption mandates the VI need, so the VI-based controllers receive significant publications and researches. Comparative studies of the different VI control schemes are limited, which encouraged exploring the potentials and applicability of different VI controllers that all make use of the swing equation with different architecture controllers. The control schemes pertaining to GFM are VSM and synchronverter [25]. Aside from the employed scheme, all of them imitate SM inertial response by a special technique [25].

Apart from the droop-based and PSC that emulate VI with LPF, all VI-based control schemes stem from the mathematical model of SM and SG [155]. Generally, SM is a term that denotes both synchronous motors as well as SG, and hence, the three VI control schemes (i.e., VSM, VSG, and synchronverter) are identical [25]. All VSM schemes use the swing equation, which emphasizes the importance of the virtual mass inertia damping. A compilation of damping techniques for VSM is given in [156].

3.5.1 Virtual Synchronous Machine

VSM is gaining attention as a solution for the degraded inertia. VSM and VISMA both stand for virtual synchronous machine, but VSM is more common. The dynamics of VSM are represented mathematically in equation (5), which is a

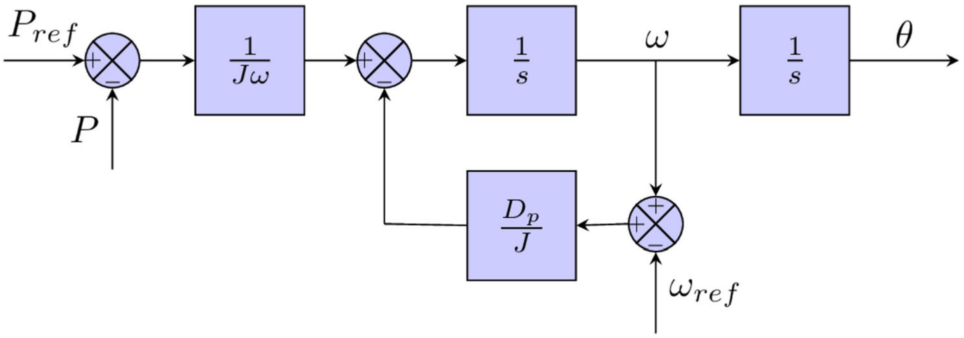


Fig. 13 Virtual synchronous machine control

modified version of the swing equation presented in (4). Additionally, both acronyms emulate SM with subtle different topologies. Basically, VSM implies either a real virtual inertia or a fast frequency response [?]. The first VSM concept was formulated in [157]. VSM zero inertia (VSM0H) is a VSM replica whose constant inertia (H) is zero, but it does not need PLL [25, 96]. A detailed description of the VSM is in [25], where different modes of operations that rely on the tracking error magnitude and their applications are highlighted. The control block diagram is illustrated in Fig. 13, where the frequency is regulated in the active power control loop and the voltage magnitude is controlled from the reactive power loop (not shown). A comparative analysis between the VSM and the droop controller showed that the overall dynamic response improves in the VSM controller although it experiences more oscillations than the droop-based controllers [158].

$$\frac{2H}{\omega}\frac{d\omega_{\text{VSM}}}{dt} = \frac{P_m - P_e - P_D}{S_g} \tag{5}$$

where P_m is the mechanical power, P_e is the electrical power, and P_D is the damping power.

The main objective of VSM is to equip grid-forming inverters with frequency droop and VI. PLL estimates frequency value to compute ROCOF [159]. The PLL function is eliminated during normal operation, as VSM can synchronize with the grid in accordance with the power balance after initiation with the PLL [160]. The ROCOF value is obtained by a derivative component that is integrated into the control architecture in different schemes to tune the VSM in real time—namely primary frequency droop-like control, heuristics, or optimization-based [161, 162]. Inspired by the same approach, the so-called interval-based control scheme emerged in which a unit mode of operation, acceleration/deceleration, is determined by the sign of the trigger signal $\wp = \Delta w(wt)$. This mode of operation heuristically determines the inertial level [163]. Nevertheless, these approaches are focused on the overall frequency enhancement regardless to the costs incurred [164].

The authors in [165] addressed this problem through incorporating an LQR adaptive virtual inertia controller that optimizes the inertial gain provided that it meets the two objectives. This work was extended in [164] to include the effect of multi-machine configuration and adaptive damping. Additionally, LQR was used to tune PID controller gains that adopt VI to limit overcurrent conditions [166]. The model of discrete LQR was formulated in [167].

Different VSM architectures had been proposed in which each type depends on the degree to which the SM is emulated [93]. In fact, some architectures implement the full set of the SM dynamic equations and some implement simplified versions [26, 95]. An underlying assumption is that the SM can generate/absorb infinite amount of power; hence, the limitation of the DC-link is usually omitted [168].

In [169], there is a comprehensive realization of VSM, whereby a combined swing equation, damping factor, and frequency droop model emulate the actual SM behavior. The model, however, suffers from some shortcomings due to the PLL, such as delays in performance and numerical instability. Also, several supplement control schemes were added to devise the full model. Apart from that, VSM still has stable performance in weak grids [170].

3.5.2 Synchronverter

Synchronverter is a variant of the VI-based control scheme whose algorithm mimics the SM operation as its control block diagram is depicted in Fig. 14. It is an inverter-based generating unit that is self-synchronizing and acts as SGs dynamic response [171]. This is due to maintaining the power system operational structure without major changes [26]. The synchronverter topology is well established in the literature as in [94, 172]. The inverter control is composed of the swing equation along with the algebraic equations to couple virtual rotor and stator of SGs, which is based on the second-order to the third-order model of the SG [82, 95]. The damping factor is achieved by taking the difference between the reference frequency and the resultant computed frequency as a feedback signal. This implies the power–frequency droop ratio like what was mentioned in the droop-based controller

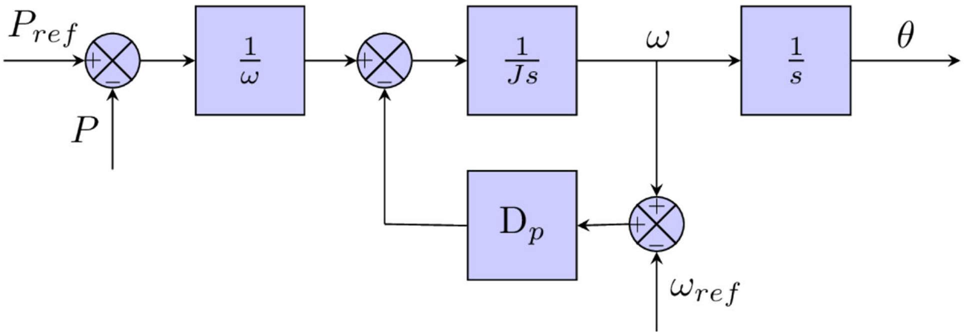


Fig. 14 Synchronverter control

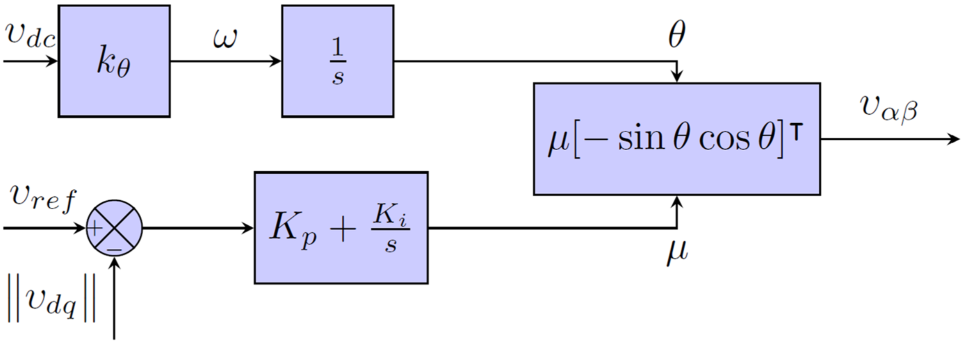


Fig. 15 Matching control

[156]. Interestingly, the damping factor approach replaces the interactive method to compute the controller parameters through the damping correction loop, thereby improving steady-state performance as well as transient performance [152]. The basic equations that govern the synchronverter control and the model is explained in [26].

The most comprehensive topology was formulated in [95] in which the model operates with PLL. The subsequent models were improved significantly, including self-synchronization capability [173] and voltage/frequency limitations [174]. The synchronverter equations is considered as an enhanced version of PLL or sinusoidal-locked loop, thereby enabling the synchronverter to support synchronism with the terminal voltage [175]. The single-phase model of the synchronverter was developed in [176]. The synchronverter needs a PLL to synchronize to the grid at first although the use of PLL introduces instability conditions [177]. The self-synchronizing synchronverter version was subsequently designed in [173]. The PLL removal enhances the development cost, the tuning complexity, and the time needed for computation [178].

The synchronverter implementation as a voltage source converter removes the frequency derivative factor, which lessens the noise significantly. The system complexity can introduce numerical instabilities that might counter the obtained benefits. Moreover, the voltage source model means there is no inherent protection so an external protection element is needed [26]. Robust control modeling can tackle the uncertainties of different grid conditions, which in turn improves the stability performance [179]. The capacitor and inductor linked to the synchronverter went virtual in [180] to make the synchronverter more robust against fault conditions.

In [181], the authors shed some light on the potential inherent problems accompanying the SG emulation. The overcurrent problem results from the post-fault response, the prolonged delay owing to the high-order nonlinear dynamics of the SG detailed model integration, and the recommended tuning of the virtual inertia to be much less than the damping ratio that effectively reduces the synchronverter control to the droop controller. The synchronverter does not have an inherent capability of current protection since it is a voltage source converter, so an overcurrent protection is added to the original model [182].

3.6 Matching Control

Matching control is derived from the similarity in structures between the two-level power converters and SMs as illustrated in Fig. 15 [98, 99]. The DC current is an equivalent to the SM input torque, thereby varying the AC power. The angle dynamics are represented in equation (6). The AC voltage magnitude is controlled by a modulating signal (μ) using a PI controller as in equation (7). The reference voltage in $\alpha\beta$ coordinates is expressed in (7).

$$\dot{\theta} = k_\theta v_{dc} \tag{6}$$

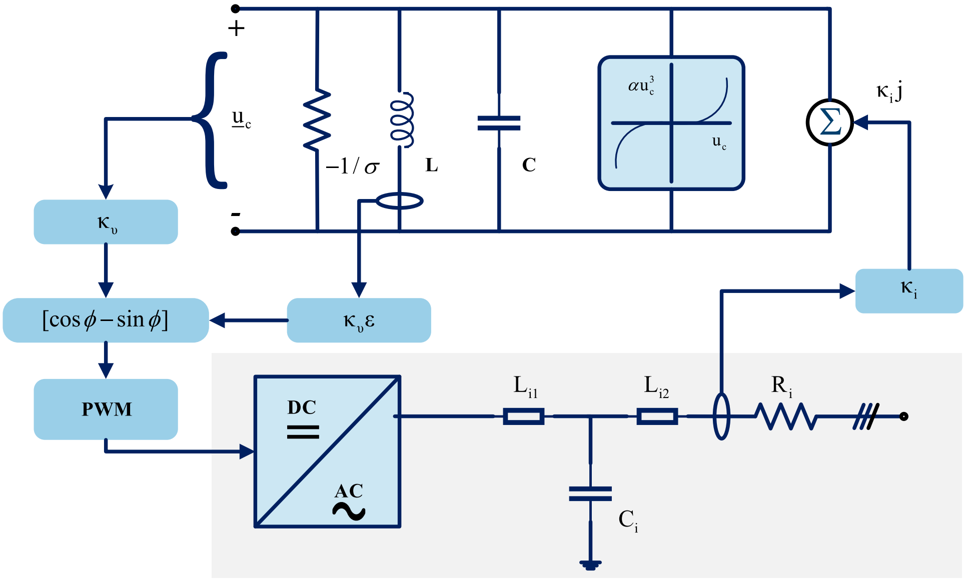


Fig. 16 Block diagram of VOC [82]

where k_θ is $\frac{\omega}{v_{dc}}$

$$\mu = K_p \left(v_{\text{ref}} - \left\| v_{dq} \right\|\right) + k_i \int_0^t \left(v_{\text{ref}} - \left\| v_{dq(\tau)} \right\|\right) \mathrm{d}\tau \quad (7)$$

$$v_{\alpha\beta} = \mu[-\sin\theta \cos\theta]^\top \quad (8)$$

Moreover, the control block diagram in Fig. 15 depicts the matching control technique. This duality reveals a relationship between the DC-link voltage and the SM rotor angular frequency in indicating power imbalances. This means the DC voltage drives the converter frequency to certain levels [100]. This control scheme requires a measurement of the DC voltage only with no other inner loop controllers, which speeds up the control processes compared to other control techniques. Furthermore, the GFM has an architectural feature that is independent of any control strategy and is exposed in the matching control approach. The converter has to have the DC voltage stabilized by a primary DC source so as to keep power balance across the converter without compromising the capacitor status. Other control techniques, on the other hand, need a stiff DC voltage control and a separate timescale [15].

Seemingly, this control technique structurally resembles the differential equations of SMs. The mathematical model and the block diagrams are explained in [97, 100, 183]?. The matching control equations can be extended to AC filter, and dynamics of generator stator as derivations are in [98, 184].

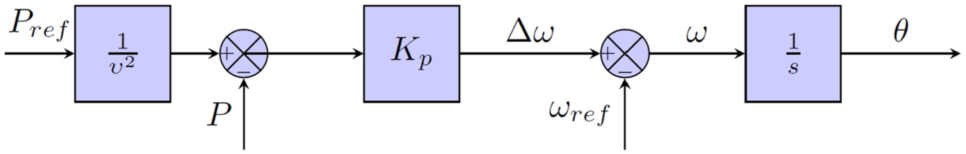
In [183], it was shown that the matching control suffers from a relatively high ROCOF due to the fact that other control approaches like droop and VSM ignore the DC-link voltage and regulate AC quantities till reaching stability, which in turn results in high transient peaks in the DC-link current in order to reach stability of the DC-link voltage. The matching control, however, does regulate the DC-link voltage through the DC source and regulated AC quantities [97, 185]. Another important finding is that the improved ROCOF in other control techniques could cause instabilities if the converter operates near its rated DC source, thereby promoting the matching control strategy. Also, the DC source saturation has no impact on the DC-link stability under this scheme.

3.7 Virtual Oscillator Control

The virtual oscillator control (VOC) is not based on a phasor representation as other control approaches (see Fig. 16). Rather, it is a time representation in a sinusoidal form, where it is related to synchronizing with other coupled oscillators in complex grids [104]. This VOC employs a van der Pol oscillator along with nonlinear differential equations to interact with the converter terminal signals and provide the virtual oscillator [15, 186]. It is suitable for networks dominated with DG units, as the VOC is intrinsically maintains synchronism and make load sharing [187]. The VOC concept has been verified and experimentally implemented in [188, 189]. Most of VOC schemes ignore high-frequency dynamics that affect the harmonic contents. This problem is resolved in [190], where the dynamics are considered to suppress harmonic currents.

The VOC was compared to the droop controller and refined further in [104, 133]. The power injection of the VOC cannot be specified accurately, but the full dispatchable VOC resolves the problem [105]. This version prespecifies an operating point, satisfying all load flow equations, and ensures synchronism of that point [191]. It is noteworthy to mention that the VOC reduces to the simple droop-based controller at quasi-steady state, but with faster and more robust convergence performance [104, 186]. Another VOC version is a

Fig. 17 Dispatchable VOC (dVOC)



unified VOC that operates in both grid-following and GFMs. It also retains synchronization with strong and weak grids without the need to PLL. The transition from island mode to grid mode is seamless [192]. A hybrid control scheme merging the matching control and the VOC was devised in [185]. The control scheme achieves global stability under certain grid conditions, and it showed an intrinsic droop behavior.

It is important to highlight the limitation of the VOC scheme in regulating active and reactive power, thereby restricting its capabilities. An alteration to the VOC has been proposed as dispatchable VOC (dVOC) in [105, 106] to resolve this limiting factor in which both active power and reactive power control follow the scheme in Fig. 17.

3.8 Model Predictive Control

Model predictive control (MPC) is capable of handling multi-objective optimization problems in constrained systems; this makes it a proper control scheme in many fields [193]. MPC regulator could optimize power flow between MGs [194]. An optimal energy management that is dependent on distributed MPC is addressed in [195], while a central MPC regulator is proposed for the dynamic optimal power flow between energy storage systems [196]. A more detailed analysis pertaining to island mode is shown in [197]. The authors in [107] developed an MPC model that controls the output voltage of converters in islanded MGs.

A simpler method was initiated in [108], where MPC prediction horizon is minimized to simplify the associated cost function. Additionally, an MPC method for the output voltage control of the GFM was considered in [109], but it has to have a precise system modeling. It struggles to tune the weighing factors in the objective function, too.

Finite control is widely used in many applications, one of which is the grid-connected application [198]. In [199], different algorithms are analyzed in terms of performance for the grid-connected applications. Basically, the finite/MPC control scheme utilizes a discrete model of power converters with filters to predict the behavior of all related input signals and select the one that yields the optimal result of the objective function [199]. Mainly, all inner control loops are limped into an algorithm that considers the converter model and its filters [200]. This structure makes the converter control more flexible and rapid response, especially for the power balance between converters. Usually, short-horizon prediction encounters difficulties in controlling high-order converters; this problem is resolved in [201] by analyzing all orders to decouple variables and control them separately, thereby eliminating the need for heavy computation as compared to long-horizon prediction. Another problem associated with finite/MPC controller is the variable switching frequency that makes it difficult to design LC filters. The authors in [202] approach this problem through obtaining a feasible solution in order to have a fixed switching frequency and a simple filter design. An enhanced finite/MPC control is proposed in [203], where it is adopted for the GFM mode along with LC filter modeling. The scheme is based on a short-horizon prediction that tracks the referenced voltage signal. The model works to reduce the harmonic distortion and prevent the variable switching experienced in other models.

An interesting strategy in [111] aims to adopt MPC to force converters act in the grid-forming mode. The authors explained the limitations of the conventional PI controllers used in the GFMs in terms of current saturation issue and the mismatch between the voltage control loop and the current control loop, which in turn hinders the overall converter operability. In addition, the conventional GFM has two control loops composed of four PI controllers, so there are eight parameters to set. In the proposed scheme, the equality and inequality constraints reduce these parameters to only three in which the controller selects the parameters in the objective function. This strategy permits the controller to define the optimal controlling action that tracks the desired reference signal within the formulated constraints. The problem formulation and validation are elaborately explained in the reference.

3.9 Optimal Control

In [112], the sliding mode control was employed to control the GFM current on a hysteresis-band method. This approach, however, results in variable switching frequency that causes undesirable stability performance [204]. This method was improved to be a variable hysteresis-band method that has a fixed switching frequency [113]. The computation cost is high, and the controller suffers with high computational burden. The proposed model in [117] overcomes these drawbacks through utilizing the sliding mode control in the d-q synchronous domain. Also, it circumvents the LC filter resonance without the passive filter or the active filter. A sliding mode controller in the inner loop and the $H2/H\infty$ optimal controller in the outer loop are adopted. The sliding mode control is known for its robustness to system parameter variations and fast-dynamic response [205]. Nevertheless, the H2 control and the H∞ control cannot support the system disturbances independently. Each control method has some drawbacks that impede the controller robustness [114, 206]. In fact, the H2/H∞ control technique does optimality and robustness into the controller [115, 116, 118, 207, 208]. The advantages and disadvantages of the different control theories are presented in Table 2.

4 Grid-Forming Converter Power System Applications

Modern energy storage systems need grid-forming converters to work inside the grid and enable a variety of applications to improve grid dependability, stability, and resilience as shown in Table 3. GFM has many applications in power system. The GFM functions as an interface between these applications and the grid. The applications include RE grid integration [209], energy storage system, MG [210], electric vehicle charger [211], static synchronous compensator (STATCOM) [212], high-voltage direct transmission (HVDC) [213], and many others. Table 4 summarizes some of GFM applications along with references.

4.1 On-Grid Renewable Energy

Distributed generation characterizes MGs that adopts REs resources. The corresponding outputs have different frequencies, phase angles, and amplitudes, thereby contributing to the overall system instability [26]. Therefore, GFM is necessary to interface the REs into grids and contribute to the system stability by regulating voltage stability and frequency stability. Ancillary services could be delivered to grids, including harmonics reduction, dynamic power support, reactive power compensation, or even a VI to stabilize the grid. The VI-based GFMs are usually used for REs resources, solar PV and wind power in particular [219]. For example, a wind power that is interfaced with the grid the GFM delivers VI to dampen oscillations [220]. The wind power source is interfaced properly to grid through GFM [221]. Currently, wind farms have to have inertial support as an ancillary service [222]. Some commercial wind turbine manufacturers like WindINERTIA and ENERCON already incorporate VI response in their products [223, 224].

PV farms are mandated in some countries to provide frequency regulations (primary or secondary), or to have an inertia support [225]. There are different technologies to achieve these requirements, but GFM shows promising results. The PV inverter providing inertia support is analyzed in [226]. Existing PV farms that utilize grid-following converters could be transformed into GFM without investing in hardware or software [227]. The references sowed that employing supercapacitor as an energy storage system can make the transformation easily.

4.1.1 High-Voltage Direct Current Transmission

HVDC with GFM is another application in which the combined system serves as standby for blackstart of onshore AC grid [228]. The HVDC/GFM formed a basic transmission infrastructure for offshore wind power plants between Denmark and Norway [229]. Additionally, it demonstrated a capability to energize Belgium from the UK side [230].A detailed UK report addressed the essential problem of HVDC system inertia support. Maintaining grid stability and inertia when renewable energy sources are integrated into the system becomes harder. The paper investigates whether HVDC systems can sustain inertia, a service normally handled by synchronous generators. The UK is taking a major step in adapting its power infrastructure to the changing energy environment to ensure a dependable and sustainable electricity supply by exploring the technical feasibility and economic viability of this novel strategy [231].

HVDC/GFM can respond to load changes and contribute to load restoration without the need for details of transformer or cable transient responses [232]. Simulations in [233] demonstrated that HVDC/GFM ability to perform blackstart whereby the HVDC/GFM sequentially energizes the AC grid, followed by the HVDC link energizing and the onshore converter pre-charging. That being said, the onshore converter pre-charging process causes considerable HVDC voltage dip and transients in the offshore and onshore converters [92].

The authors in [216] introduced the so-called synchronverter/HVDC transmission. The sending-end rectifier mimics SM functionality, while the receiving-end inverter acts as a SG. The DC-link connects the two units forming the synchronverter/HVDC transmission. Buffering AC disturbances from traversing into the DC side is critical in the HVDC application, which was formulated in [234].

4.1.2 Communication Delays Between Grid-Forming Converters

Stability and communication delays between grid-forming converters are crucial in low-inertia power systems, which cannot absorb unexpected generation or load changes. These situations depend on grid-forming converters to emulate synchronous machines and stabilize the grid. Communication delays from network congestion, signal processing, or data transfer might be significant. Delays can slow reactions, fluctuate frequency, cause voltage instability, and reduce oscillation damping. Minimizing delays, establishing adaptive control algorithms, redundancy in communication routes,

Table 2 Comparison of different control approaches

Technique	Pros	Cons
Droop-based Control [86, 87, 129–134]	Simple and easy to implement	Lack of precise voltage and frequency control
	Decentralized control for distributed systems	Inaccurate power sharing in multi-inverter systems
	Good for microgrids and small-scale systems	
Power synchronization control [82, 90–92, 143, 148, 149]	Precise voltage and frequency control	Complex and centralized control architecture
	Suitable for large-scale power systems	High communication and computational requirements
	Improved power quality and grid stability	Potential single point of failure
Synchronous power control [88, 89]	High precision in power sharing	Limited scalability for large systems
	Better transient response and stability	Complex control algorithms
	Suitable for multi-inverter systems	Requires accurate measurements and communication
Virtual inertia-based control [25, 155, 156]	Enhanced grid stability during disturbances	Requires accurate modeling and parameter tuning
	Improved frequency regulation	May introduce additional control complexity
	Adaptability to varying grid conditions	
Matching control [97, 98, 183, 184]	High power sharing accuracy	Complex control strategies
	Suitable for grid-connected converters	May require extensive parameter tuning
	Can be applied to both small and large systems	
Virtual oscillator control [15, 104, 186, 188, 189]	Improved transient response and stability	May require accurate parameter estimation
	Robust performance in varying grid conditions	Complexity increases with system size
	Reduced dependence on communication	Limited fault tolerance
Model predictive control [107, 193, 194, 196, 197]	Optimal control under varying conditions	High computational requirements
	Enhanced grid integration of renewables	Complex algorithm implementation
	Improved system efficiency and power quality	Sensitive to model inaccuracies
Optimal control [113, 117, 204, 205]	Achieves optimal system performance	Extremely complex and computationally intensive
	Highly adaptable to different system goals	Requires accurate system modeling
	Can incorporate various constraints	Limited real-time applicability

Table 3 Critical component of modern energy storage systems in grid-forming converters

Application	Description
Voltage and frequency support	During disruptions and quick load shifts, grid-forming converters can stabilize voltage and frequency. Regulating voltage and frequency within safe levels helps grid stability. This is essential for energy storage system reliability
Grid Integration	Energy storage systems are seamlessly integrated into the electrical grid via grid-forming converters. They help the grid be reliable and resilient by effectively injecting or withdrawing energy from the system
Black Start Capability	Black start capability allows grid-forming converters to resume the grid after a blackout or shutdown. They can start synchronization and progressively restore grid functionality by stabilizing voltage and frequency
Microgrid Operation	Microgrids function autonomously or with the main grid thanks to grid-forming converters. They stabilize microgrids and enable smooth grid-connected-islanded transitions
Energy Management	These converters are crucial to energy storage system energy flow management. They ensure effective storage system charging and discharging, grid compliance, energy optimization, and grid disturbance reduction

Table 4 Selected GFM applications

Application	Configuration	References
DC microgrid	VSM	[214]
Microgrid	VSM/Energy storage system	[215]
HVDC	Synchronverter	[216]
Smart grid	VSM	[169]
Renewable generation	Synchronverter	[137, 217]
Transmission system	VSC	[218]

thorough testing, and regulatory frameworks that address these difficulties can help solve these problems. Low-inertia power systems need these precautions for dependability and stability [235, 236].

4.1.3 Miscellaneous Applications

GFM applications cover a wide range in power systems. Transmission system modeling with voltage source converter was detailed in [218]. The authors divided the converter control into three levels: system control, firing control, and converter state. Then, they derived transmission system models with GFM, which in turn gave different models for different applications. These applications include shunt static synchronous compensator (STATCOM), asynchronous back-to-back interconnector, and hybrid compensators (e.g., UPFC).

GFM, moreover, can interface energy storage system to provide ancillary services in electricity market, such as frequency control and power balance regulation [25, 237]. Electric vehicles (EVs) can provide VI through their inverters using VSM control strategy [238]. Apart from some technical limitations that could be overcome with a stabilizer algorithm, the VI is provided with the bidirectional power flow concept through the EVs plug, which is also known as a vehicle-to-grid approach [239].

5 Future Research Directions

Although GFMs stability control received much attention, transient stability performance has limitations due to the reactive power control omission in some of the proposed schemes. Moreover, the PI controller-based are not robust, which limits their effectiveness. Besides, the mathematical modeling and numerical computation that form the bases for VI-based controllers suffer from instability issues that hamper their transient stability performance. The PI controllers are well established for industry, but they are not adaptive, nor do they adopt self-learning capability. This,

Table 5 Technical gaps of GFM implementation

Area	Challenge
Current limitation	Stability status during/after faults
	Accommodate different fault types
Synchronization with grid	Inner Loop outer loop interaction causing instability
	Uncertainty in stiff grid characteristics
Island-to-grid-connected transition	Frequency voltage mismatch with grid
Large-signal stability	Cross-couple of active power reactive power control loops

hence, put limitations and restrictions against utilizing the GFM capability under transient event. AI control techniques are promising in the transient stability events in which the PI controller shortcomings are likely to be overcome. The GFMs encounter difficulties in replicating the conventional power system operation, such as frequency regulation, voltage regulation, harmonics compensation, inertial response, and many others. These unexplored areas are still to be resolved.

Specifically, there are three main areas that are critical to the GFMs operation, yet they are not fully explored. These are the current limitation, synchronization stability, and island to grid-connected transition. Table 5 lists some of the technical gaps of the GFM implementation.

5.1 Current Limitation and Fault Ride Through

Intrinsic characteristics of voltage source converter behind impedance make GFM sensitive to network disturbances that might provoke unwanted overcurrent conditions. Many current-limiting techniques were proposed in the literature [240–243]. The easiest technique is to switch the GFM into a vector-controlled mode during fault conditions [147].

Mainly, two main solutions were suggested to resolve the high current problem: current saturating algorithm [240, 242] and virtual impedance implementation [244, 245]. The latter is an effective approach in which the virtual impedance limits the generation of high current in the inner current control or limits the reference AC voltage in case of omitting the inner control loop [95, 173, 180].

This current-limiting concept seems simple, but it is challenging to maintain the GFM stability during this faulty condition, especially when paralleling with SM [246]. Furthermore, post-fault synchronization of the GFM is an important concept that needs elaborate analysis. The current-limiting strategies effect against transient stability receives little attention in the literature [72, 76, 247, 248].

VSM has techniques to implement fault-ride through for GFMs that are mainly related to synchronverter [249]. A control strategy in [250] modified the synchronverter control structure by adding an inner current generator as well as an inner current control loop to compute the GFM current value during normal operation and during fault conditions. This approach does not exploit the GFM capabilities, as there is no consideration for fault type or magnitude. This problem was overcome in [251] that accounts for symmetrical fault and asymmetrical faults in which the model abides by published codes.

5.2 Synchronization Transient Stability

GFMs makes synchronized status with grids in accordance with the output active power, resembling the SGs behavior. This synchronization technique and the voltage control at PCC enable GFMs to maintain synchronism in grids with low short-circuit ratio (SCR) [147]. In contrast, stiff grids (high SCR), there is a tendency of GFMs to lose synchronism due to the fact that a large active power variation can result from a small phase difference between the GFMs and the grid [252]. Consequently, an urgent need to adopt a robust control for GFMs that operate in networks is characterized with large SCR [91]. The line impedance characteristics are important in stability topic, which was analyzed in [253]. Reactive power synchronization is also employed as elaborated in [254].

The GFMs synchronism transient stability has been receiving much attention in the literature [255, 256]. The PSC shows a superior performance under such conditions owing to its first-order dynamic behavior. In fact, system stability is guaranteed provided that an equilibrium point exists after disturbances [74]. In case there is not an equilibrium point, the critical clearing time can be easily computed. It was shown in [257] that dVOC is more superior to droop-based control schemes since it can re-synchronize after fault events even if the fault clearing time exceeds that of the critical clearing time. The response of VI-based control scheme compared to non-VI control schemes is compared in [84]. Although the non-VI controllers are stronger than their counterpart VI-based controllers, the need for the VI-based controllers is essential due to the lack of inertial support in which the frequency stability is jeopardized.

Furthermore, the inner control loop interaction with the outer control loop could adversely affect the GFMs synchronization stability because of the timescale coupling of both control loops. Two factors could lead to this coupling:

strength of the grid and the inner current control scheme [258].

5.3 Islanded Mode to On-grid Mode Transition

Technical problems might arise upon transition between island mode and grid-connected mode. The frequency and voltage magnitude mismatches cause deviations and oscillations in the transition from island mode to grid-connected mode, while a significant value of through power would impair the GFM during the grid-connected mode to island mode transition [259]. It is required to design the GFMs control scheme so that they perform the transitional phases smoothly. Particularly, the GFMs shall make an automatic connection and have stable frequency and voltage measures in the island mode. In grid-connected mode, on the other hand, the GFMs should control the injected power into grid as per demand. It is extremely important to guarantee the stability of GFMs before/after transitional periods. The droop control scheme was used to perform such transitional process [260]. However, the disadvantages of the droop control outweigh its utilization.

5.4 Artificial Intelligence and Optimization Control

The increasing complexity of power system raises uncertainty and data magnitude substantially, leading to a transformation into smart grids. The bidirectional power flow and information flow between end-users, system operators, and aggregators characterize the smart grid concept [261]. The two main problems arisen are the uncertainty resulted from the RE penetration and the difficulty in finding optimal solutions due to complexity of deregulated electricity market [262–264]. The decision-making process thus is more difficult compared to conventional control methods [265].

Therefore, more effective methods are needed to face these challenges. Data-driven control methods that are based on AI are proposed to determine power system states accurately and efficiently [266]. Particularly, the system variables and the stability parameters relationships are modeled to forecast the system states after disturbances [267]. The authors in [268], used recurrent neural network, used for the same purpose, that is based on long short-term memory cells for training. Besides, the damping state is predicted with decision tree [269].

The VI-based controllers have variant AI algorithms imposed to encounter the uncertainty conditions [88]. Self-adaptive VI control is addressed in [163], whereas fuzzy-VI controller and hold-filter VI controller are proposed in [153]. A fuzzy neural network control for the GFM with an output LC filter was suggested; however, the learning rate parameters are difficult to tune, which in turn impact the system performance adversely [270]. A combined AI techniques are employed to capitalize on the strengths of the combined techniques. The authors in [271] used an adaptive fuzzy logic controller that is based on differential evolution algorithm to regulate frequency.

A more efficient machine learning technique is the deep reinforcement learning (DRL) [272]. Reinforcement learning method has become popular owing to its effectiveness in sequential problems [273]. Hence, the DRL is well suited to many of power system applications provided that they are transformable into sequential domain. The DRL is a derivative method that combines the deep learning with the reinforcement learning that excelled in games [274], natural language processing [275], robotics [276], finance and business management [277]. In [278], a comparative analysis is accomplished between DRL and the conventional optimization methods mentioned earlier. Fundamentally, DRL does not require an exact objective function expression. Rather, it uses the reward function to assess the decision scenario. Compared to the convex optimization method, DRL can take higher-dimensional data. In relation to the programming methods, DRL uses the current state to make decision, thereby making real-time decisions. The DRL convergence is more stable and robust than its heuristic methods [279]. A thorough description of the DRL and its power system applications are reviewed in [279]. Many references in the literature focus on the small-signal stability, but only few consider the large-signal (transient) stability cases. The cross-coupling between the active/reactive power loops has not received much attention because it is difficult to acquire analytical solutions due to high nonlinearity of the resulted equations that govern this cross-coupling case. The authors in [280] developed a model to address quantitative analysis. The AI techniques could contribute effectively and efficiently to improve the transient stability controlling and obtain enhanced performance.

Mathematical modeling of optimization problems take several forms—namely convex optimization, programming, and heuristic approaches [279]. These traditional methods have their shortcomings. The traditional convex optimization methods like Lyapunov algorithm have an advantage that their mathematical representation is so rigorous that the real-time problems could be realized easily [281, 282]. Despite that, they need explicit cost function to be expressed well, which is fairly difficult in many application decision. The Lyapunov condition is far-fetched in complicated and high-dimensional problems [279].

The programming methods, including mixed integer programming [283], stochastic programming [284], and dynamic programming [285], are good tools for solving sequence optimization models, but they do the computation process of each iteration from the beginning. Consequently, the computation cost is too high to realize for real-time applications. Other programming methods are dependent on accurate modeling and prediction of renewable generation/load, which is infeasible [279].

The heuristic methods like particle swarm [286], genetic algorithm [287], and ant colony [288] are capable of finding local optima for non-convex problems, so they suit problems that are large scale. Nevertheless, they are not robust enough to tackle complex real-time problems and cannot be proven mathematically [279].

6 Conclusion

This paper provides a comprehensive review of the inertia reduction resulted from integrating distributed energy resources, which is manifested as the frequency stability, the rotor-angle stability, and the voltage stability. The GFM does contribute into stabilizing electric networks using appropriate control schemes. The paper, also, discusses different control techniques that are tweaked to the GFM applications. The applicability, advantages, and disadvantages are elaborated critically. A selected topics of the GFM applications are presented, such as HVDC, REs integration, and STATCOM. Some of challenges related to the GFM implementation are addressed like overcurrent protection, synchronization stability, and island-to-on-grid transition stability. The GFM has the potential to increase the practical controllability over the challenges related to RE sources. Moreover, the solutions facilitated through GFM form the potential viability of many domains of upcoming research, especially virtual inertia. The estimation of virtual inertia that is non-constant as opposed to conventional power grids is a pertinent topic. Seemingly, with the commercialization of distributed generation and the emergence of prosumers, virtual inertia as an ancillary service and its subsequent incorporation with the market structure will be highly dependent on the degree of controllability and security the GFM provides. Similarly, the cross-coupling of the transient stability events is an interesting topic that is open for new techniques using AI-based schemes. This review paper has given a detailed conceptual understanding of GFMs, their categorized applications, control theories, and future research directions, which will serve as an insight for upcoming researchers, industrial experts, power system planners, prosumers, and policymakers toward addressing and utilizing the potentiality of GFM toward the global efforts of viable renewable energy integration.

Acknowledgements The authors would like to acknowledge the support provided by the Center of Renewable Energy and Power Systems at KFUPM under Project No. INRE2321 and SDAIA-KFUPM Joint Research Center for Artificial Intelligence (JRC-AI). In addition, the authors would like to express their profound gratitude to King Abdullah City for Atomic and Renewable Energy (K.A.CARE) for their financial support in accomplishing this work.

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