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TOPICAL REVIEW

Promising Grid-Forming VSC Control Schemes Toward Sustainable Power Systems: Comprehensive Review and Perspectives

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ABSTRACT Driven by environmental and economic aspects, the proliferation of renewable energy sources (RES) has been expanded in power systems worldwide. In this regard, the intermittent generation of such RESs (e.g., photovoltaic and wind farms) can cause several operational and stability problems in such low-inertia power systems. To handle these issues, great interest in the literature has been directed to develop feasible grid-forming voltage source converters (VSC) control schemes that have voltage/frequency regulatory functions. Accordingly, an inclusive review is presented in this paper for these promising grid-forming VSC control schemes which will be the backbone of sustainable converter-dominated power systems. Specifically, control structures, smart grid-support functionalities, stability issues, and fault current mitigations are compared considering the existing grid-forming VSC control schemes. Besides, the applications of grid-forming VSC along with their benefits and drawbacks are investigated for both isolated and bulk power systems. The evaluation aspects are also explored for assessing the performance of the existing VSC control schemes in the grid. Finally, the current challenges that face VSC in forthcoming applications and existing gaps are highlighted while corresponding perspectives for future research studies are defined for stable sustainable low-inertia power systems.

INDEX TERMS Grid-forming VSC, control schemes, low-inertia power systems, renewable energy sources, energy storage systems.

I. INTRODUCTION

A. BACKGROUND

Recently, great interests have been focused to integrate diverse renewable energy sources (RESs) into power systems throughout the world. In this regard, Paris Agreement endorses all parties to contribute in innovative scientific ways to mitigate crucial risk carbon emissions for accomplishing sustainable development and lessening climate change [1], [2], [3], [4]. The European Union (EU) follows a strategy to utilize a 64% to 97% renewable energy share in 2050 [5], [6], [7], [8]. Further, the application of solar and wind energy sources is expanding in several areas with high solar irradiance and wind speed profiles. Promising RESs can provide considerable technical benefits to the grid, besides environmental benefits [9], [10], [11]. To allow such expansion, new research and development are required to be feasibly realized where distributed energy sources will be integrated into diverse power system levels, including distribution systems and transmission systems [12], [13], [14], [15], [16].

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B. MOTIVATION

Incidentally, uncertain and intermittent renewable generations can greatly affect the performance and economic condition of power systems [17], [18], [19], [20], [21]. Most importantly, frequency deviations due to lack of inertia are common operational problems with high RES penetrations [22], [23], [24], [25]. To lessen these technical issues, power utilities and system operators have established administrative codes in the case of integrating RESs into the main grid (transmission and distribution system levels). Besides, various research efforts have been directed to optimize renewables' hosting capacity without degrading system performance while avoiding high energy curtailment [26], [27], [28], [29], [30]. A combination of various approaches has been intensively studied for improving the performance of such sustainable power systems, e.g component upgrades and planning and managing RES units, energy storage devices, and flexible loads [31], [32], [33], [34], [35].

However, one of the main challenges of a power system with a high penetration of RES comes from the fact that the majority of RES, including photovoltaic and wind farms, as well as battery storage systems and high-voltage direct-current (HVDC) linkages, are linked to the power grid via a converter-based interfacing device. The different generators are classified in Fig. 1 based on their interfacing devices and ability to manage the voltage and frequency of the grid. Importantly, only electrical generation systems with synchronous generators indicated in Fig. 1 have the natural inertia while can manage the voltage and frequency of grids [36], [37], [38]. The induction generator, current source converters, and most of the voltage source converters can only inject power into an already constructed network.

In turn, modern VSC technologies, known as grid-following, are managed by software to work as a current source to follow the grid voltage [39], [40], [41] and, like current source converters (CSC), are incapable of controlling voltage. Specifically, they employ a phase lock loop (PLL) unit and perform best in a power supply with almost constant voltage [42], [43], [44].

In grid-following mode, VSC requires a strong power system, which is already built by other generators such as synchronous generators [45], [46], [47]. As a result, in power systems without a significant amount of synchronous generators (i.e., converter-dominated systems), an additional control mode of the converter called grid-forming needs to be used to form/support system voltage and frequency.

In a VSC, the output frequency is equal to the frequency of the input carrier signal [48], [49], [50], which is not associated with the active power balancing, and the swing equation. Therefore, the grid-forming mode requires a new control paradigm to maintain synchronization with other generators and balance production and consumption. Fully VSC interfaced generation systems are in use in low or medium-voltage electricity supplies (i.e., microgrids) [51], [52], such as offshore wind farms and uninterruptible power supplies [53], [54], [55]; However, few research studies have been conducted on transmission system applications to date due to high risks and uncertainties.

Many papers have reviewed the relevant literature on the diverse features of grid-forming converters. The authors of [56] have examined several virtual synchronous generator control approaches, their drawbacks, prospective directions for future research, and their application to grid frequency management. Other grid-forming control varieties, nevertheless, are not described in [56]. Various approaches and their typologies, such as synchronous generator model-based, swing equation-based, frequency-power response-based, and droop-based control methods have been described in [57], along with a discussion of virtual inertia and associated concerns. In [58], a literature review of diverse forms of virtual synchronous machine control approaches has been introduced for wind turbines while not covering the other grid-forming control types. A classification and review of VSC grid forming control techniques have been conducted in [59]. In [60], three control methodologies have been summarized as grid-forming control categories. As noticed in the literature, most of the review papers on this topic focus on a single type or specified types of grid-forming control varieties. In this regard, this paper will contribute to expanding the literature review by providing a recent summary of the VSC grid-forming control varieties which are classified into five categories.

C. CONTRIBUTION AND PAPER ORGANIZATION

To address these challenges and requirements, there has been a lot of interest in the literature in developing practical grid forming VSC control systems with voltage/frequency regulating functions. As a result, this study provides a comprehensive assessment of these prospective grid-forming VSC management techniques, which will serve as the foundation of long-term low-inertia power systems. Control structures, smart grid-support functions, stability difficulties, and fault current mitigations are specifically compared while taking into account the existing grid-forming VSC control systems. Furthermore, the applications of grid forming VSC, as well as their advantages and disadvantages, are examined for both isolated and bulk power systems. The assessment criteria are also investigated for analyzing the performance of the grid's existing VSC control methods. Finally, the present issues that VSC will encounter in future applications, as well as existing gaps, are emphasized, while corresponding plausible solutions and future visions for reliable, sustainable low-inertia power systems are proposed.

The next sections of the paper are organized as follows. Section II describes the development of power systems toward low-inertia features. In Section III, VSC modeling and control techniques are reported. The evaluation aspects are explored in Section IV for assessing the performance of the existing VSC control schemes. In Section V, the current challenges. Finally, Section VI concludes this paper and provides the corresponding recommendations are defined for stable sustainable low-inertia power systems with VSC.

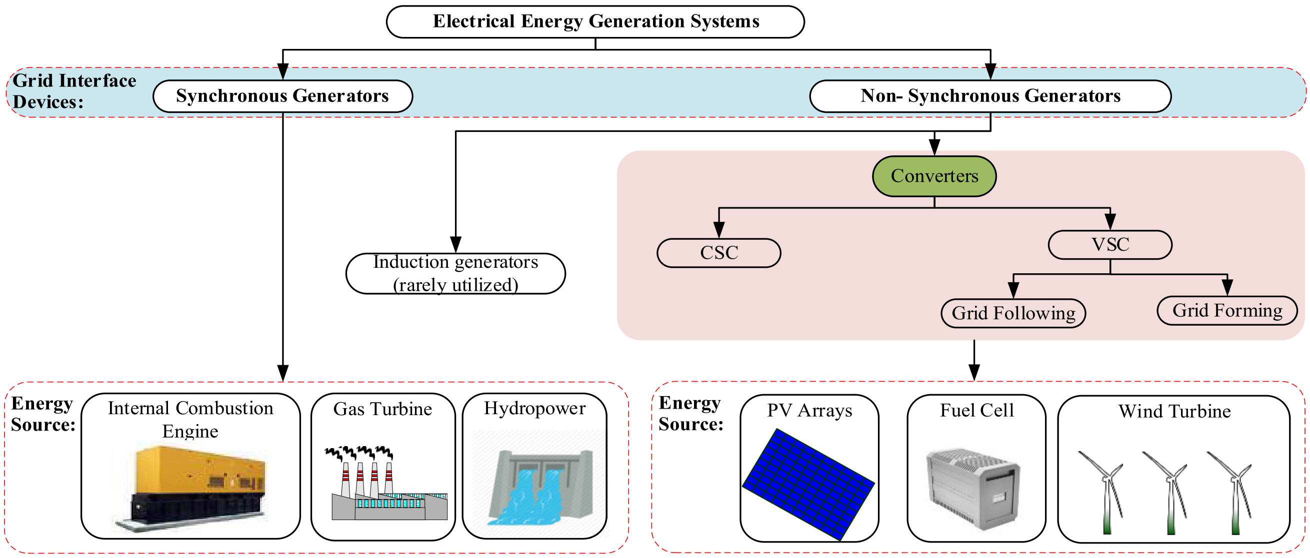

FIGURE 1. Classifications of electrical generation systems according to the interfacing devices and energy sources.

II. DEVELOPMENT OF POWER SYSTEMS TOWARDS LOW-INERTIA FEATURES

RESs are being used inequitably, however, there is a definite trend toward investment in this promising energy industry. The effectiveness of capturing a certain type of energy is determined by factors such as geographical location, available space, capital expenses, operational costs, and environmental issues [61], [62], [63]. At the moment, the cost of energy obtained by capitalizing on renewable energies is generally higher than the cost of energy obtained by capitalizing on depletable energy resources, and the current trend is to gradually increase renewable energy recovery systems, in tandem with technological evolution. Such RES technologies are introduced in various power system levels, including transmission systems, distribution systems, and buildings [64], [65], [66]. At various scales, energy consumption is mostly documented in the form of thermal and electrical energy gained through the use of nonrenewable resources, with relatively substantial issues, which is why there are attempts to progressively replace these systems.

Because of the increased usage of RES, traditional power systems are being changed into sustainable ones all over the world. In this regard, the EU has created an ambitious goal to become the world leader in RES use by 2030 [67], [68], [69]. According to the road map to 2050 reported in [70], to satisfy the Paris Agreement's decarbonization and climate mitigation targets, renewable energy usage must have globally been scaled up at least 6 times rapidly. For instance, Fig. 2 compares the past and future penetration levels of RES in various countries [70], [71], where a massive increase in the RES share is noticed by 2050. Further, the worldwide electricity generation from 2010 till 2050 by different energy sources (coal, oil, natural gas, nuclear, and renewables) is shown in Fig. 3 [72]. Interestingly, the share of electricity generation by renewables is rising; in turn, the share of other

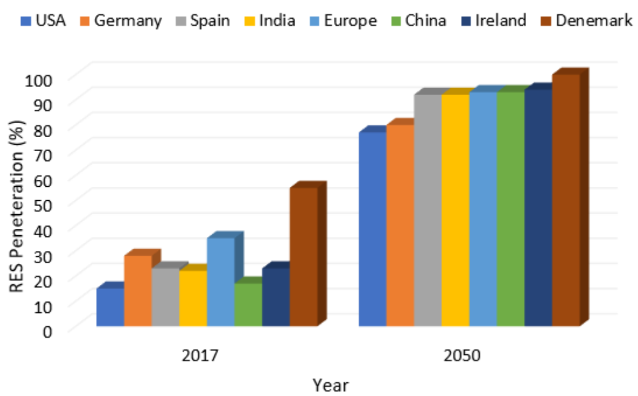

FIGURE 2. Past and future penetration levels of RES in various countries [70], [71].

traditional energy sources, especially the cool, is going down worldwide.

Aside from reducing RES emissions toward a carbon-neutral society, these RES may deliver significant technical improvements to distribution networks, such as energy loss reduction, flexible voltage control, enhancing grid resilience, and improving grid power quality [73], [74], [75]. Wind power generating systems and photovoltaic (PV) is the most promising RES categories based on current industrial growth because they provide an adaptive and flexible structure that can be linked to the system by operators, entrepreneurs, and even residential users [76], [77]. Surprisingly, the watt-var control characteristics of their inverters are a defining feature of these two RES categories, providing for local regulatory options. These alternate possibilities, however, come at the price of severe power curtailment in highly penetrated RES systems [78], [79], [80]. Furthermore, substantial technological, economic, and regulatory penalties may constrain future

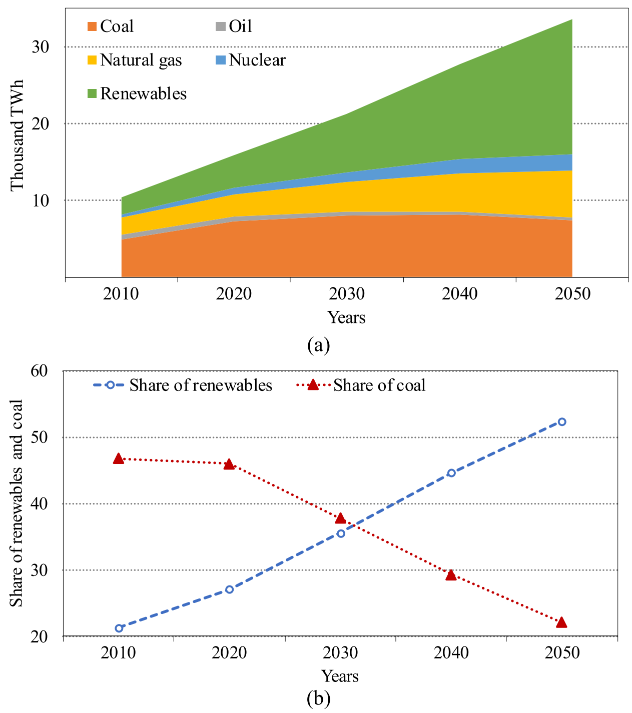

FIGURE 3. Worldwide electricity generation by different energy sources from 2020 till 2015. (a) Electricity generation, (b) the percentage of share of renewable and coal [72].

worldwide efforts to increase projected RES accommodating capacity [27], [81], [82], [83], [84]. Parallel to the rising trend of wind power and PV technologies, the use of energy storage devices, including charging stations for electric vehicles, has lately expanded [85], [86], [87], [88].

The frequency of the power system is a common measure of the instantaneous power balance between production and consumption, as well as power exchange, whereas frequency performance is an important sign of robust system security. In this regard, frequency variations outside the desired region can put the security of the entire system at risk by lowering the available balancing reserves to deal with disruptions, especially with RES generation intermittency. Fig. 4 illustrates an example of the development of power systems from the traditional to the future power system structures. Traditional power systems are demonstrated with synchronous generators at high-voltage transmission levels as well as distribution system levels. In turn, future power system structures will move towards adopting more renewables in which the converters are utilized to interface them to the grid. In general, such RESs do not have the ability to provide a natural inertial response to a grid, unlike synchronous generators. In other words, as the penetration of RES grows, the inertia of the power grid reduces [72], [89], [90]. Under power imbalances, the lower inertia in the power system causes a rise in the amount of change of frequency and frequency deviations in a relatively short period, affecting the frequency system stability. In such a future scenario, promising grid-forming converters can play a vital role to enhance system stability, which is reviewed in the next section.

III. VSC MODELING AND CONTROL SCHEMES

A. GENERAL STRUCTURE

Typically, a power electronic converter is a device that has the ability to transform direct current (DC) electricity from a typical energy source type (e.g. wind power, PV units, or battery systems), into alternating current (AC) form to be synchronized with the main grid. A basic power electronic inverter model, as illustrated in Fig. 5, includes three main terms: 1) DC side with a connection to the energy source, 2) series of switching semiconductor devices, and 3) grid-side passive filter [91], [92], [93]. It is important to note that the input side of the DC-link could have two forms; the first form is to be connected with the energy source, such as wind and PV, directly while the second form is to be linked to extra power electronic devices, so-called DC-to-DC converters that can yield the maximum power point tracking [94], [95], [96], [97]. To interface such a unit to the grid, a power transformer is normally exploited, allowing to match its terminal voltage to the grid voltage.

Basically, a closed-loop control scheme is essential for the power converters which mainly consist of multiple controllable switches. Accordingly, a considerable proportion of closed-loop controllers in current converters take the form of a digital controller. Because digital-based control units are totally programmable, they have the ability to provide a high degree of algorithmic elasticity and allow for a relatively simple mixture of modern controllers. There are two control schemes for the inverter, which are grid-forming and grid-following modes. To illustrate them, Fig. 6 shows the major features of the grid-forming mode and the grid-following mode of the converter-dominated system in terms of representations as well as active/reactive power generation characteristics. From the perspective of their representations, grid-following-based controllers behave similarly to current sources with respect to the grid with fixed active and reactive generation (i.e., P and Q) due to terminal voltage (V) and frequency (F) real-time variations. The most obvious difference in the grid following converters is that it requires to be synchronized to the existing grid and its operation is based on current control with current, the active and reactive powers can be adjusted. In turn, grid-forming-based controllers behave similarly to voltage sources in which their output power can be adjusted dependent on droop rules for active and reactive power. In this review paper, we will focus on the grid-forming control schemes that can maintain a healthy grid, which are given in the next subsection.

B. GRID-FORMING CONTROL SCHEMES

In the literature, several grid-forming techniques for converter-based generators have been developed to date. In this context, the term grid-forming has widely been utilized to refer to any controller of converters that has the function to

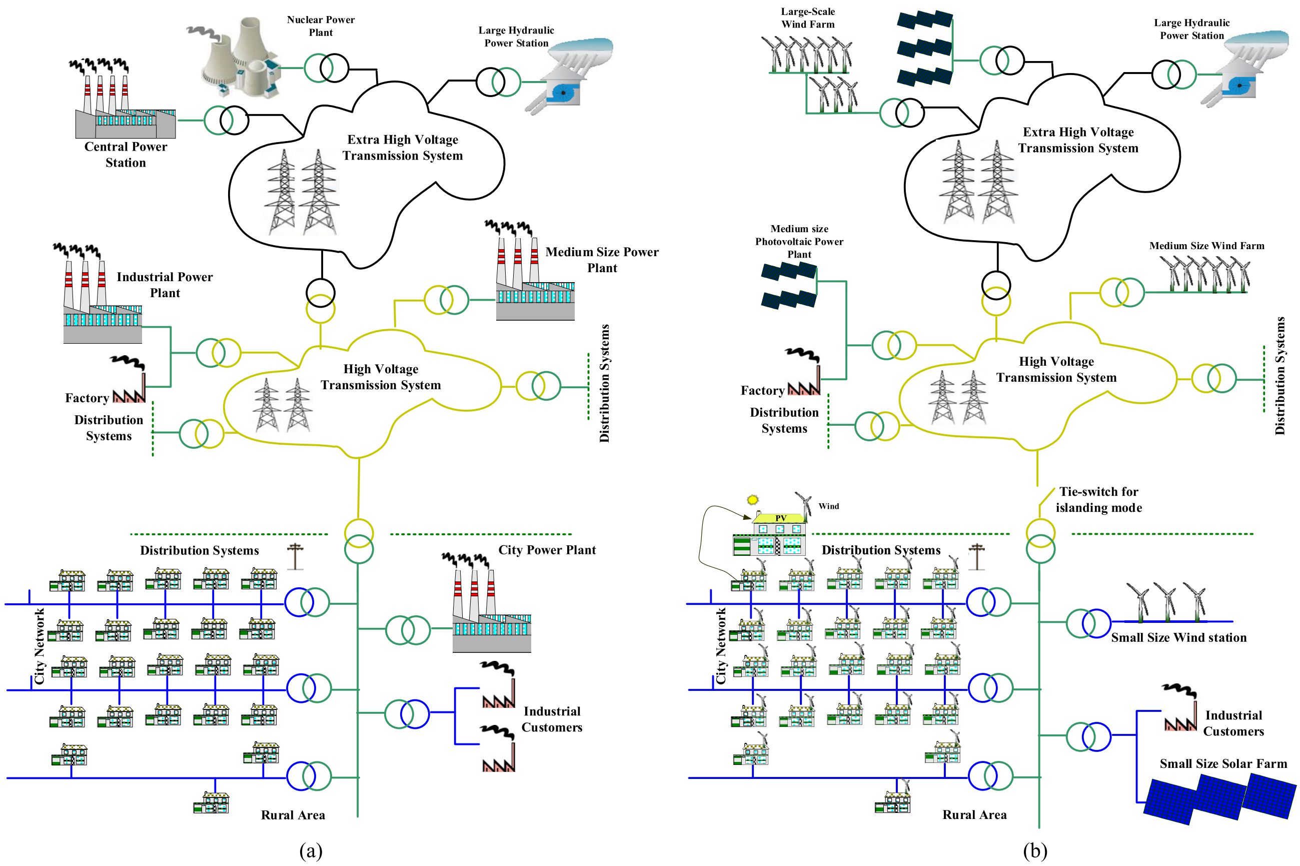

FIGURE 4. Traditional and future power system structures. (a) traditional power system with synchronous generators; (b) future power system structures with converter-based RES generators.

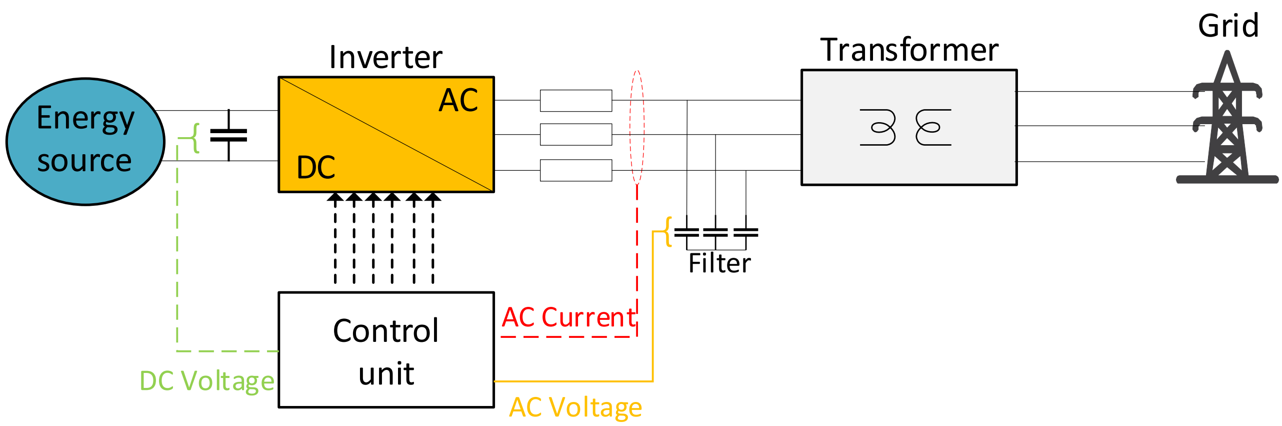

FIGURE 5. Overall structure of a grid-connected inverter-based generation system with a control unit.

control the real-time frequency and terminal voltages and that does not necessitate the use of a PLL. Another notice about grid-forming techniques is that the multiple units naturally operate in a decentralized manner (i.e., without requiring communication infrastructure) with respect to the voltages and frequency, similar to synchronous machines. In other words, the grid-forming control schemes aim to emulate the natural response of synchronous machines while considering the operational limits and regulations of its power electronic-based components.

Existing grid-forming controllers, as illustrated in Fig. 7 (a, b, c, d, and e), can be roughly classified as droop based (DB) control schemes, virtual synchronous machine-based (VSMB) control schemes, matching based (MB) control

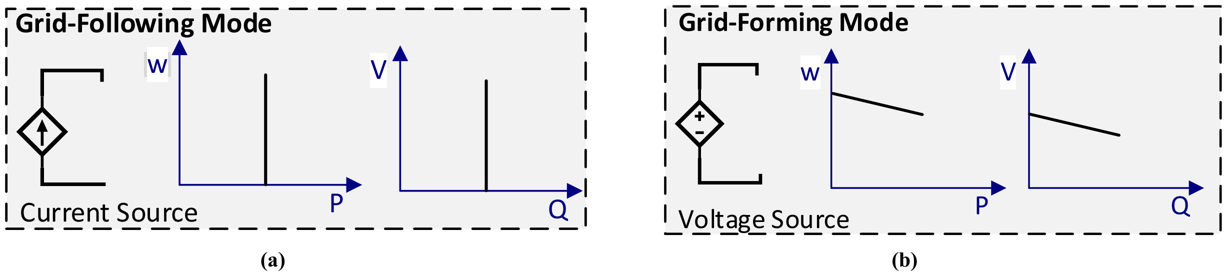

FIGURE 6. Major features of (a) the grid-forming mode and (b) the grid-following mode of inverter-based generations in terms of representations as well as active/reactive power generation characteristics.

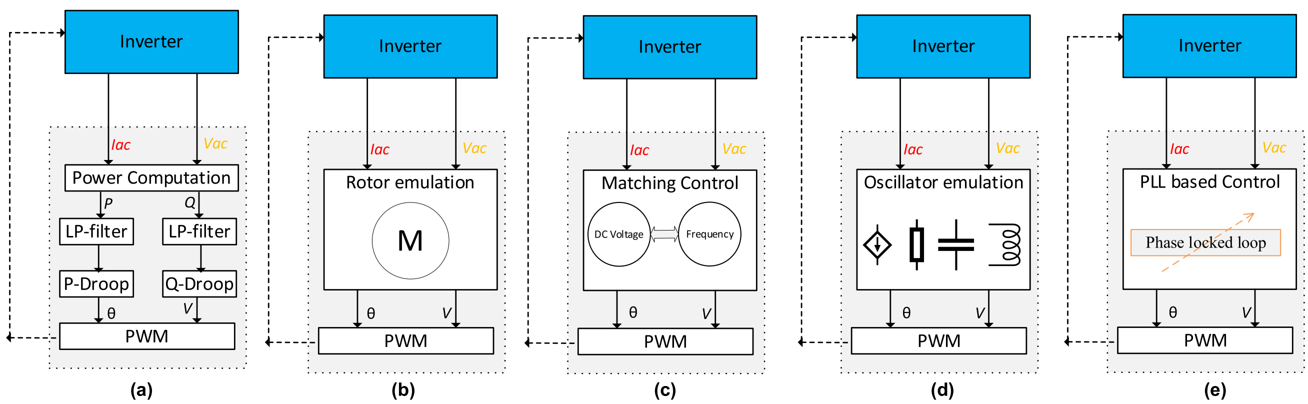

FIGURE 7. Classifications of the various grid-forming based control schemes. (a) DB control schemes, (b) VSMB control schemes, (c) MB control schemes, (d) VOB control schemes, and (e) PLLB control schemes.

schemes, virtual oscillator based (VOB) control schemes, and PLL based (PLLB) control schemes. These controllers are described as given below:

1) DB CONTROL SCHEMES

DB control, which has been initially presented two decays earlier, is the most well-established grid-forming inverter control approach in standalone AC power systems [98]. Another variant of the DB control scheme has been proposed in [99] and [100] that does not require a communication connection, taking into account the main source impact. Fig. 10 shows the DB control scheme block diagram in which the controller consists of voltage, current, and power controller models. As shown in Fig. 12, the power controller model involves frequency droop control and voltage droop control. The frequency droop control looks like the speed droop feature of the synchronous machine while trading off deviations of the active power output (P) with respect to its rated value (P^*) and frequency deviations of measured frequency (ω) from the nominal frequency (ω_r), where D_f signifies the gain of the governor speed droop. Similarly, the voltage droop control simulates the synchronous machine AVR where Q is the reactive power output and Q^* its rated value; D_q signifies the droop gain.

The authors of [101] have provided a stability-constrained adaptive droop control strategy for autonomous power-sharing in an AC-multiterminal DC (MTDC) grid after a

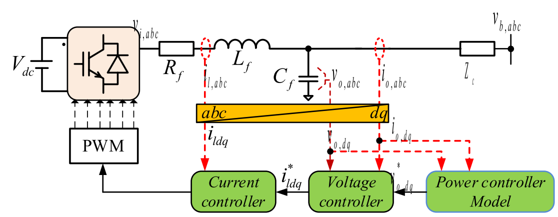

FIGURE 8. Block diagram of the VSMB control scheme [107].

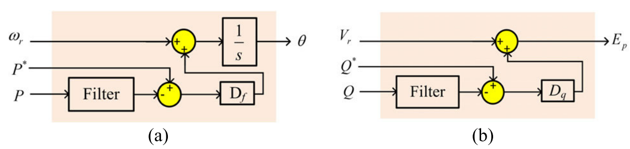

FIGURE 9. Block diagram of the power control model in the DB control scheme [93], [94], [95], [96], [97], [98], [99], [100]. (a) Frequency droop control, (b) Voltage.

converter outage. The use of model predictive control has been introduced in [102] to coordinate all droop-based controllers. This new model can decrease the grid DC voltage variations and eliminate control mode changes in order to retain the capability of droop VSC to manage DC voltages. A decentralized adaptive droop-based control scheme has been proposed in [103] for active power sharing across parallel inverters in autonomous microgrids. DB methods

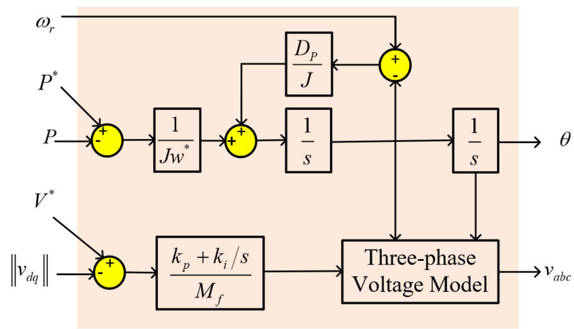

FIGURE 10. Block diagram of the VSMB control scheme [107].

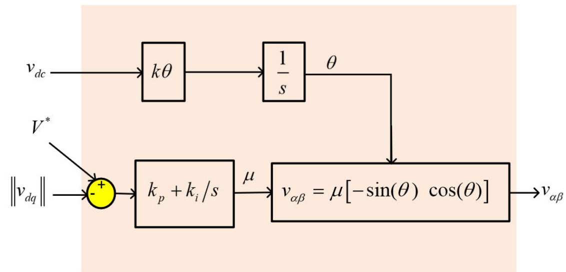

FIGURE 11. Block diagram of the MB control scheme [116].

having ancillary control loops to improve the steady-state voltage and frequency regulation, active and reactive power-sharing, and small-signal stability introduced in [104] and [105].

The distinguishing characteristic of such a control scheme variant is that similar to a normal synchronous machine in the steady-state condition, it displays a linear relationship between frequency and active power as well as voltage and reactive power. Such linear relations (i.e., droop laws) are known as the real power-frequency (P-F) and reactive power-voltage (Q-V) relationships. As a result, all interconnected units to the power system will diverge to an identical frequency after load variations. Another property is that each interconnected unit shares a certain amount of the additional load levels according to its adjusted droop slope, besides its nominal rating.

2) VSMB CONTROL SCHEMES

This control scheme is constructed based on emulating a synchronous machine inside the confines of the interfacing inverter. Specifically, this control scheme provides both phase angle and frequency references to the inner control loops for operating the VSC. There are various variants of this control scheme as follows. The authors of [106] have introduced a virtual synchronous machine in which a power electronics-based technique enables grid-compatible incorporation of mostly RES electricity producers even in ill networks, giving them the appearance of common electromechanical synchronous apparatuses. As shown in Fig. 11, it involves virtual damping, represented by $D_f(\omega^* - \omega)$,

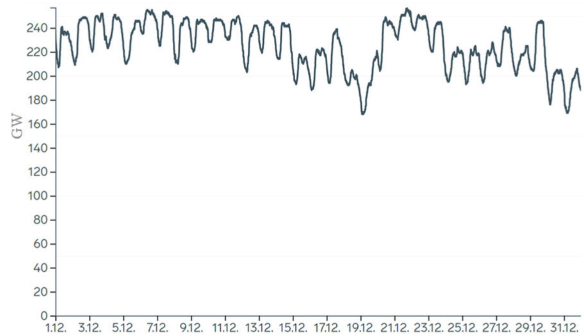

FIGURE 12. Inertia of the Nordic power system during December 2021 (Fingrid, [144]).

which is inspired by the speed droop response of synchronous machines [107]. J represents the inertia constant of the virtual rotor; M_f is the magnitude of the virtual mutual inductance. In [108], an enhanced grid-connected inverter control paradigm has been proposed which is based on duplicating the positive properties of conventional generators. The fundamental limits of the standard droop control system have been revealed in [109]; after that, an improved droop control approach has been given in order to provide precise proportional load sharing for standalone microgrids. The authors of [110] have proposed a virtual synchronous control scheme for VSC which can utilize the dynamics of the capacitor on the DC side to apprehend self-synchronization. For such control schemes, the real-time data from the current and voltage sensors of the inverter are passed to a digital synchronous machine model. The main duty of this digital synchronous machine model is to mimic nonlinear dynamics. The virtual machine's complexity might range from comprehensive electromechanical paradigms to basic swing forms. In general, virtual inertia control schemes are considered simple approaches, and they capture merely the dynamics of an imitated rotor and its stable P-F relations. Using comparable modeling, the research proposed in [111] has offered a robust secondary frequency control design technique for the VSM-based low voltage microgrid cluster based on VSMB.

The emulation of rotor dynamics could introduce new oscillatory modes into the power systems for the VSMB control. To handle this issue, a control scheme based on the alternating moment of inertia has been proposed in [112] with experimental validations with promising stabilizing impacts. In [113], a parameter alternating VSMB control scheme has been introduced to enhance the damping performance and reduce the negative influence on the DC side voltage stability. The authors of [114] have introduced self-adaptive inertia combined with a damping control technique to enhance the frequency stability of VSMB.

3) MB SCHEMES

MB control schemes are considered one of the grid-forming control variants that take the use of operational likenesses between synchronous machines and power converters. As an example of this control scheme, in [115], it has been explained in detail how to control power converters by way of synchronous machines in the d-q coordinate domain while illustrating the relations between power converter parameters with respect to the ones of isotropic synchronous machines. In general, their concept is based on the notion that voltage on the DC side can be used as an implication for imbalances in power, like frequency in synchronous machines. Consequently, the voltage at the DC side is employed to push the converter frequency up to a certain setting. The converter differential formulae are reformulated so as to match the ones of the synchronous machine. Besides, the current in the DC side is utilized to adjust the power on the AC side in the same way as the machine input torque is. The authors of [116] have considered the topic of developing grid-forming converter control techniques for weak-grid settings based on the concept of matching control, in which the critical coupling between the voltage at the DC side and the corresponding frequency on the AC side is accomplished via feedback. Accordingly, in a coordinate frame coupled to the virtual oscillator angle, this method can offer an appropriate condition ensuring the uniqueness, presence as well as global asymptotic stability of driven equilibria. As shown in Fig. 11, the dynamics of the matching control angle are signified as $\theta = k_\theta v_{dc}$ where $k_\theta = \omega^*/v_{dc}^*$. Note that the magnitude of the voltage is managed by the modulation factor μ *with* a PI control [116]. In [117], to precisely match the dynamics of the synchronous machine, the dc-bus integrator is proposed to be added to provide unhindered power flow from AC to the DC side while combining the features of the machine and inverter.

4) VOB CONTROL SCHEMES

Alternative inverter control scheme based on nonlinear oscillator simulation has evolved recently [118]. VOB is a time-domain-based controller that allows linked RES interfacing inverters to stabilize any beginning circumstances to a synchronized sinusoidal limit cycle, as opposed to the DB control schemes, which are only adequately characterized in sinusoidal steady-state. In this scheme, the measured real-time data are analyzed by a digital paradigm, which modulates the inverter power stage in the same way as a virtual synchronous machine would. The essential distinction is that the paradigm takes the form of an oscillator circuit with a natural frequency that coincides with the rated frequency of the power system; in turn, the other parameters are set to manage the controller bandwidth as well as the terminal voltage. In [119], it has been investigated a novel method for synchronizing linked oscillators, which does not operate in polar coordinates and does not reflect oscillations of static magnitude, in contrast to the well-known models. Both synchronization and dispatch-ability features have been confirmed in [120] by simulations and experimental validations, suggesting that VOB control schemes are efficient for upcoming smart grids. It is a fact that the structure of this inverter control scheme has a significant difference compared to the other three aforementioned schemes; however, they also have similar characteristics in the settled condition by following the droop laws.

5) PLLB GRID-FORMING CONTROL SCHEMES

As illustrated above, the controller emulates the swing equation of a synchronous machine in grid-forming control, thereby forming frequency droop characteristics. However, it has recently been demonstrated that a PLL, which is ordinarily grid following, can be utilized in a way to simulate a generic power controller and so yield a grid-forming control scheme. The authors of [121] have examined the possible capability of VSCs that are empowered by the PLL unit to play a role in islanded power systems with including inertia response and frequency control. Based on the experimental implementation in [122], the finding of the PLLB grid forming control schemes has exhibited near-identical performance compared with the PLL-free grid forming control schemes.

C. COMMON FEATURES OF VARIOUS CONTROL SCHEMES

Tables 1 and 2 provide a summary of DB control schemes, VSMB control schemes, MB control schemes, VOB control schemes, and PLLB control schemes. It is clear that different schemes are investigated in the literature with different control features. Several test systems are used for this topic where most of the studies use only simulations, thereby more experimental verifications are required for future studies.

Despite the different dynamic properties of the five control schemes, they have unified properties in steady-state behavior with slight variations. Specifically, the voltage and frequency behavior when adopting any of such grid-forming control schemes will be similar to the characteristic of common voltage sources in which frequency and voltage vary with active and reactive power, respectively. This feature enables grid-forming control schemes to modify output power almost instantly to balance generation and demand (frequency control) and manage the terminal voltage magnitude. In [123], a comparative study of some of the grid-forming control strategies has been established on the 9-bus test system. This study has shown the importance of considering AC and DC current limitations; however, further technical issues in VSC are still required more investigations. The performance of diverse applications of grid-forming converters throughout significant transient disturbances has been investigated in [59]. Further, the functionalities of the main subsystems have been classified, which has led to a generic control structure while providing possible solutions for these subsystems considering the transition from island to grid-connected operation.

A detailed overview of grid-forming converters for power system applications has been provided in [124] where a functional comparison of grid-forming converters and grid-following inverters has been made to demonstrate the potential of grid-forming inverter technologies in supporting power system stability. Furthermore, sophisticated control methodologies incorporated into grid-forming inverters

TABLE 1. Summary of DB and VSMB control schemes.

Control Scheme	Ref.	Year	Theme	Features	Test System	Exp. /Sim.
DB	[98]	1993	Control of parallel connected inverters in standalone ac supply systems	It solely employs feedback on variables that may be monitored locally at the inverter and does not require control signal connection between the inverters.	Standalone system with 2 inverters	Sim.
	[99], [100]	2012	Decentralized cooperative control of microsources for stabilizing autonomous microgrids	A new control technique without a communication connection is suggested, along with a unique hybrid model of generators that takes into account the main source impact.	Microgrid with 4 VSCs	Sim.
	[104], [105]	2012	Comprehensive analysis of power sharing, voltage and frequency regulation, and stability in DB control method	It suggests ancillary control loops to improve the steady-state voltage and frequency regulation, active and reactive power-sharing, and small-signal stability	37 bus-test system with 3 VSCs	Sim.
	[101]	2019	Stability-constrained adaptive droop for power sharing in AC-MTDC grids	The proposed method can be used as part of the power system operators' dynamic security assessment while ensure the stability of the surrounding AC systems.	Bipole MTDC grid	Sim.
	[102]	2018	Coordinated design of droop control in MTDC grid based on model predictive control	It decreases the grid DC voltage variations and eliminates control mode changes in order to retain the capability of droop VSC to manage DC voltages.	MTDC grid with 6 VSCs	Sim.
	[103]	2021	Adaptive droop-based control in autonomous microgrid for improved transient performance	A decentralized adaptive droop-based control scheme has been proposed for active power sharing across parallel inverters in autonomous microgrids.	Autonomous microgrid with 2 VSC	Sim. & Exp.
VSMB	[106]	2007	Virtual synchronous machine	It can enable grid-compatible incorporation of mostly RES electricity producers even in ill networks, giving them the appearance of electromechanical synchronous apparatuses.	Exp. set-up	Exp.
	[108]	2012	Generator emulation controls for photovoltaic inverters	An enhanced grid-connected inverter control paradigm has been proposed where it is based on duplicating the positive properties of conventional generators.	Two test Beds	Sim. & Exp.
	[109]	2013	Robust droop controller for accurate proportional load sharing among parallel inverters	An improved droop control approach has been given in order to provide precise proportional load sharing for standalone microgrids.	Two single-phase inverters	Sim. & Exp.
	[110]	2017	virtual synchronous control for VSCs utilizing dynamics of dc-link capacitor	It can utilize the dynamics of the capacitor in the DC side to apprehend self-synchronization.	VSC system	Sim. & Exp.
	[111]	2021	Robust secondary frequency control for VSMB microgrid cluster using equivalent modeling	It provides a robust secondary frequency control design technique for the VSM-based low voltage microgrid cluster based on VSMB.	4 CIGRÉ benchmark microgrids	Sim. & Exp.

under diverse operating situations are provided by evaluating current research and practical implementations. While grid-following inverters have received a lot of attention in both research and practical implementations, grid-forming control schemes have developed mainly theoretically, while their practical implementations are limited to small-scale power systems, e.g., micro-grids and isolated power networks.

Here, we provide some realistic projects with grid-forming converter techniques. In Jamestown, South Australia, a grid-forming control has replaced the pre-existing grid-following control for a station with a 150 MW / 193.5 MWh power reserve and 315 MW wind farm [125]. Other realistic examples are established by General Electric (GE) where a funding of 4.2 million dollars funding is assigned to advance grid-forming solar converter control [126]. Furthermore, a wind farm-based grid-forming control with the black-start capability is established in Dersalloch Windfarm - National Grid UK, Scottish Power Renewables [127].

IV. PERFORMANCE EVALUATION METRICS

The development of the power systems toward converter-dominated systems creates new technical challenges. In this regard, the grid forming technology is supposed to mitigate these challenges. Therefore, it is required to evaluate different technologies from these aspects. The energy source of VSC can be classified into grid-connected RES (PV and wind power) and energy storage systems [128], [129], [130], [131], [132]. The inertial of PV and wind power are functions of MPP control and the rotating mass, respectively. In turn, the inertial of energy storage systems is related to its

TABLE 2. Summary of MB, VOB, and PLLB control schemes.

Control Scheme	Ref.	Year	Theme	Features	Test System	Exp. /Sim.
MB	[115]	2015	Modeling and control of grid-connected VSCs emulating isotropic and anisotropic synchronous machines	It provides the procedure to control power converters by way of synchronous machines in the d-q coordinate domain while illustrating the relations between power converter parameters with respect to the ones of isotropic synchronous machines.	grid-interface converter	Sim.
	[116]	2018	Grid-forming control for power converters based on matching of synchronous machines	in a coordinate frame coupled to the virtual oscillator angle, this method can offer an appropriate condition ensuring the uniqueness, presence as well as global asymptotic stability of driven equilibria.	Parallel inverters	Sim.
	[117]	2020	The electronic realization of synchronous machines	It can precisely match the dynamics of the synchronous machine by the dc-bus integrator.	two-inverter system	Exp.
VOB	[118]	2016	Synthesizing virtual oscillators to control islanded inverters	It allows linked RES interfacing inverters to stabilize any beginning circumstances to a synchronized sinusoidal limit cycle, unlike DB control schemes.	single-phase inverter	Exp.
	[119]	2019	Global phase and magnitude synchronization of coupled oscillators	It does not operate in polar coordinates and does not reflect oscillations of static magnitude.	three grid-connected inverters	Sim.
	[120]	2019	Dispatchable virtual oscillator control for decentralized inverter-dominated power systems	Both synchronization and dispatchability features have been confirmed in by simulations and experimental validations, suggesting that VOB control schemes are efficient.	Inverter-dominant grid	Sim. & Exp.
PLLB	[121]	2018	Inertia and primary frequency Provisions of PLL-synchronized VSC	It can play a role in islanded power systems with including inertia response and frequency control with the PLL unit.	large-scale wind farm	Sim.
	[122]	2022	Generic PLL-based grid-forming control	PLLB grid forming control schemes has exhibited near-identical performance compared with the PLL-free grid forming control schemes.	grid-forming converter	Sim. & Exp.

charging/discharging features and the state of charges. The main challenge in PV is to attain the MPPT while managing the DC side while the wind generation requires a specified control scheme for each type. Regarding the energy storage systems with their V2G capabilities, they are relatively expensive and require intensive integration studies considering the various types (e.g. supercapacitors, Li-ion batteries, and flywheels) [133], [134]. Other general planning and control issues to be considered for all energy source types are the cost assessment, sizing and locating these energy sources, grid codes and market features, and the efficiency of the control scheme with respect to the operational requirements [135], [136].

The evaluation aspects will be explored here for assessing the performance of the existing VSC control schemes concerning the main grid, as follow:

A. FREQUENCY PERFORMANCE

It is demonstrated that reduced inertia with RES causes a quicker RoCoF and additional unstable system dynamics, which requires faster control measures to alleviate frequency deviations. For instance, Fig. 12 shows the inertia of the Nordic power system during December 2021 while the corresponding frequency of this power system is given in Fig. 13. It is clear that the system inertial varies during the month, according to the number of synchronous-based generators and the renewable generations, where the frequency also varies during this period. This feature is not a specified feature for the Nordic system, but for any other power system. Accordingly, frequency stability is a critical issue with sustainable power systems. To assess such index, frequency nadir ($\|\Delta\omega\|_{\infty}$) and RoCoF ($R$) are utilized, which can be expressed as follows:

$$\|\Delta\omega\|_{\infty} = \max_{t \geq t_s} |\omega - \omega(t)| \tag{1}$$

$$R = \frac{|\omega(t_f) - \omega(t_s)|}{t_f - t_s} \tag{2}$$

in which t_s and t_f represent the starting time and ending time of the evaluation window of the frequency, respectively.

In these circumstances, forming the grid and providing frequency by VSCs is important. Different control methods of grid-forming may have different impacts, and so assessment studies are required to compare their frequency performances, which is lifted for a future study.

B. REACTIVE POWER SUPPORT FOR VOLTAGE CONTROL

Voltage control typically denotes generation control functions that are accomplished by tuning the reactive power support so as to keep the terminal voltages within an allowable

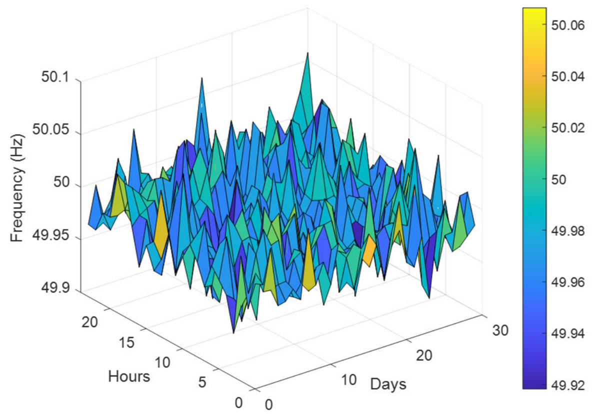

FIGURE 13. Frequency of the Nordic power system during December 2021 (Fingrid, [144]).

threshold. The automated voltage controller of synchronous generators controls the terminal voltage value by regulating reactive power output through the main field. In turn, grid-forming converters can provide voltage regulation functions using their preset droop rules. Here, the converter's reactive power is typically controlled using q-axis current control when the converter is aligned according to the grid voltage. The limitations for the reactive power control come from the operational current limitation. The current limit is based on the chosen power semiconductors' current rating. The next formula represents the formula for calculating the local voltage deviations (VD) at the point of common connection:

$$VD_i(t) = \frac{(V_i(t) - V_n)^2}{V_n} \tag{3}$$

where $VD_i(t)$ is the voltage deviations at the terminal bus i during time t, $V_i(t)$ and V_n are the voltage magnitudes at the terminal bus i during time t and nominal voltage, respectively. It is important to note that the spare capacity of the inverter after considering its rated capacity ($S_{Inv,i}^2$) the active power generation ($P_{Inv,i}^t$) can be employed for reactive power support where the upper and lower bounds of the reactive power output can be formulated as in (4), respectively.

$$\begin{cases} Q_{Inv,i}^{max}(t) = \sqrt{S_{Inv,i}^2 - \left(P_{Inv,i}^t(t)\right)^2} \\ Q_{Inv,i,s}^{min,t}(t) = -\sqrt{S_{Inv,i}^2 - \left(P_{Inv,i}^t(t)\right)^2} \end{cases} \tag{4}$$

C. FAULT RIDE-THROUGH (FRT) AND VOLTAGE RECOVERY

Risky interruptions, e.g. short-circuit and open-conductor faults as well as the rapid disconnection of large generation stations, can produce instability issues to the overall system components. During such events, generators are required to remain on duty to assist the grid to guarantee that the grid finds a suitable operative equilibrium. Fault ride-through (FRT) refers to an inverter-based generation's capability to continue connected while enduring irregular voltage [59]. VSCs are interconnected to the grid in accordance with a profile throughout time even during faults. In such scenarios, the VSC will reach its current boundary because of voltage sag throughout faults. Because the time constant at the DC side is modest), the direct voltage can rapidly climb to undesirable high levels. VSCs can also help to support grid voltage by injecting an additional reactive current considering its constraints (4) on top of the pre-fault level.

D. CONVERTER CONTROL LIMITATIONS

When developing a converter controller in the modern grid, it is critical to consider its corresponding dynamic interface with the entire grid. In a traditional grid, the rapid dynamics of electrical transmission lines are conquered by the comparable dynamics of sluggish electro-mechanical of synchronous machines, and hence essentially inconsequential. In contrast to synchronous machines, the physical VSC dynamics are on comparable time scales to the dynamics of the transmission line, and their controls are far quicker than the controls of synchronous machines, up to milliseconds in duration [137]. Such a rapid reaction seems to be advantageous; however, the quicker the converter controllers, the higher dynamic interaction levels with the grid, which can lead to stability issues in practical situations [138], [139], [140]. Further, the added blocks for emulating the inertial can provide temporal delays caused by sensing and processing AC values rendering the benefits of power converter management worthless in such comparable systems [56], [141], [142], [143]. The limitations can be summarized as follow:

- Converters cannot be overloaded, and therefore typically higher nominal power converters need to be invested if higher powers are needed.
- Response speed when no inertia. Measurement and conversion delays due to the frequency measurement chain?
- Harmonics.
- Lifecycle expectancy and Reliability
- The tendency towards oscillations when parallel controlled

E. PROTECTION FUNCTIONS

It is obvious that the protection of entire power system components is vital to detect diverse abnormal conditions (short circuit faults, voltage sags, etc.) and so apply mitigation responses, thereby reducing grid outage. The protection schemes are constantly changing due to the rising trend of utilizing VSC-based generations. In the microgrid levels, it has been established in [34], [116], [145], [147], [148], [149], [150], and [151] that significant penetrations of RES result in the possibility for traditional protective measures to operate incorrectly mainly due to the bidirectional power flows. Particularly, the requirement for synchronous machine protection is well understood in the literature and implemented practically. These, on the other hand, are rather sluggish and are frequently delayed since the machine can withstand significant over-currents for a limited period of time. In turn, emphasize the necessity of modeling saturation bounds [152], [153], [154], such as over-currents, in converters, particularly for studying post-contingency performance.

V. CONCLUSION AND FUTURE RECOMMENDATIONS

RESs have proliferated in power systems across the world, owing to environmental and economic considerations. In this context, the intermittent generation of such RESs (for example, solar and wind farms) can generate a number of operational and stability issues. To address these challenges, there has been a lot of interest in the literature in developing practical grid-forming VSC control systems with voltage/frequency regulating functions. As a result, this study provides a comprehensive assessment of these potential grid-forming VSC management techniques, which will serve as the foundation of sustainable converter-dominated power systems. Control structures, smart grid-support functions, stability difficulties, and fault current mitigations are specifically compared while taking into account the existing grid-forming VSC control systems. Furthermore, the applications of grid-forming VSC, as well as their advantages and disadvantages, are examined for both isolated and bulk power systems. The assessment criteria are also investigated for analyzing the performance of the grid's existing VSC control methods. Finally, the present issues that VSC will encounter in future applications, as well as existing gaps, are emphasized, while corresponding plausible solutions and future visions for reliable, sustainable low-inertia power systems are investigated. The future work will be directed to a comparative simulation study of the different control schemes of grid-forming converters while qualifying their benefits compared to grid-following techniques.

The following are some of the recommendations for further development and coming studies in grid-forming converters for sustainable power grids based on the paper sections:

- Investigate if a mixture of dissimilar grid-forming control schemes (i.e., DB, VSMB, MB, VOB, and/or PLLB control schemes) in the grid can effectively work together.
- Identifying the shares of grid forming VSC which can guarantee sufficient power system stability.
- Identifying standard grid codes by which the feasible combinations of grid-forming converters, grid following converters, and synchronous generators can be accomplished.
- Studying in detail the effect of interaction between synchronous generator excitation system and several grid-forming converters in voltage and frequency regulation.
- Revising stability measures and protection functions to cope with the updated converter-dominated grids with different time scales and dynamics.
- Proposing planning studies that can determine the best locations, sizes, and control schemes of grid-forming converters to provide better support to the grid.
- Introducing new grid-forming control schemes that ensure the best voltage and frequency grid response.
- Investigating the positive roles of some devices in cooperation with grid-forming converters, such as HVDC, super-capacitors, FACTS, and superconducting energy storage technology-based systems.

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