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Grid-Forming Control Strategies for Inverter-Based Renewable Energy Systems: A Review

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Abstract

With the development of inverter-based renewable energy, synchronous generators in power systems are being replaced one by one. With the increase in the share of electricity supply from converter-interfaced wind and photovoltaic power plants, both the rotational inertia and the short-circuit strength of synchronous machines have decreased; thus, conventional grid-following (GFL) control can no longer maintain voltage and frequency in weak-grid and islanded states. Therefore, grid-forming (GFM) control has been introduced in the first stage to make converter-dominated systems act as self-synchronising voltage sources rather than current sources. Review of the State of the Art of GFM Control Strategies for Inverter-Based Renewable Energy Systems. First, the control of GFL and GFM is compared, and then a functional taxonomy is developed to organise the existing schemes into droop-based, synchronous-machine-emulation, oscillator-based families, as well as hybrid and emerging methods. All families are judged by how well they are managed, the degree of inertia and voltage support, and their stability in weak grids. Based on the comparison of several indices, none of them is better; rather, they have different compromises in terms of inertia support, transient response ability, accuracy of power sharing and implementation difficulty. Then, the review will present the main problems of transient stability, multi-converter interaction, fault ride-through and protection coordination, standardisation and data-driven control. Therefore, the field needs to establish common benchmarks, standardise verification procedures, coordinate the control of multiple converters and promote the spread of GFM technology in the system.

Keywords

Grid-Forming Control, Inverter-Based Resources, Virtual Synchronous Generator, Droop Control, Virtual Oscillator Control, Low-Inertia Power

Systems, Renewable Energy Integration

1. Introduction

The structure of power systems around the world is changing, and now synchronous generators are gradually being replaced by converter-interfaced renewable energy sources, such as wind power, solar power and battery energy storage. This will decrease carbon emissions, but at the same time, the rotational inertia and the stiff, low-impedance voltage reference of the traditional network will also be reduced. When the instantaneous penetration of inverter-based resources (IBRs) is large, the system will lose the physical coupling of mechanical rotation and electrical frequency that has long regulated frequency dynamics [1]. Therefore, the frequency of the power system is more sensitive to disturbances and its voltage is not well-regulated; this state is often referred to as a weak-grid condition. It is no longer a problem of theory; research on transmission systems with large-scale GFM integration has shown that the stability margin of the network is determined by the joint behaviour of converters and is not constrained by any synchronous machines [2].

Given the above circumstances, the main control idea inherited from the converter era, grid-following control, has certain deficiencies. A PLL is used in the GFL converter to lock onto the grid voltage and regulate the output current. The design assumes that there is a good grid voltage and a lockable converter. As the strength of the grid decreases and the number of GFL units increases, the stability of PLL-based synchronisation is reduced [3], and therefore interaction between converters and the grid may result in oscillatory instability [4]. Grid-Forming Control solves the above problem. A GFM converter is used to replace the external voltage reference; both the voltage and frequency at its terminals can be set to be controlled voltage sources with impedance, and it can operate independently of a strong external grid [1] [5]. The above functions are the basis for black start operation, islanded mode and synthetic inertia.

The literature on GFM control has grown rapidly, and now there is a large number of works at the device level, system level and in grid-code requirements. Some of the above have been mentioned in some reviews, including the general GFM control and stability [1], GFM application in wind turbine generators [5], converter control methods for high-renewable systems [1] and virtual oscillator methods [6]. However, a single accounting system has not yet been developed to organise the main strategy groups according to a common set of performance indicators and pay more attention to the practical problems of protection coordination and grid-code compliance. This paper will fill the above deficiency.

The three contributions of this paper are: First, according to the principle of synchronisation, a systematic classification of GFM strategies is provided, and it is explained why superficially different controllers have the same behaviour. Sec-

ond, there are many other requirements that the system operators need to meet in the selection, such as inertia provision, transient stability, accuracy of power sharing, ease of implementation, etc. Third, it has pointed out many research deficiencies in transient stability, multi-converter interaction, fault ride-through and standardization, and has also found some areas where this technology is converging.

2. Review Methodology

The structure of this review is systematic, but the data are qualitative and not numerical (see Table 1). Literature was obtained from IEEE Xplore, Web of Science, Scopus, ScienceDirect, Google Scholar and arXiv preprints for work that has not yet been officially published. The range of the coverage is 2015-2025, and a few foundational earlier works have been kept because they still define a concept in use. Combine device-level and system-level words in the search terms, such as "grid-forming control", "grid-forming inverter", "virtual synchronous generator", "virtual synchronous machine", "droop control", "virtual oscillator control", "dispatchable virtual oscillator", "inverter-based resources", "low-inertia power system", "weak grid" and "fault ride-through".

Records were screened in two stages. Title-and-abstract screening excluded papers that were not about GFM control or did not address the operating problems of GFM. Next, the three inclusion criteria for full-text review will be used: 1) Clear statement of the control principle or stability result; 2) Quantitative or simulation evidence; and 3) Publication in a peer-reviewed journal, conference or established preprint server. Weight will be given to peer-reviewed journal and conference papers, new achievements, and works that have been verified by performance or experiment. As the assembled evidence has different model assumptions and test systems, the synthesis will be presented as a thematic comparison based on the principle of synchronisation and not through quantitative pooling or meta-analysis; this choice will be mentioned again in Section 5 under the list of conditioning factors for cross-study comparison.

Table 1. Review method: sources, scope and synthesis process.

Item	Specification
Databases	IEEE Xplore, Web of Science, Scopus, ScienceDirect, Google Scholar; arXiv (preprints)
Coverage window	2015-2025 (selected foundational works earlier)
Search terms	grid-forming control; grid-forming inverter; virtual synchronous generator; virtual synchronous machine; droop control; virtual oscillator control; dispatchable virtual oscillator; inverter-based resources; low-inertia power system; weak grid; fault ride-through
Inclusion criteria	clear control principle or stability finding; quantitative or simulation evidence; peer-reviewed or established preprint
Exclusion criteria	subject unrelated to GFM control; purely descriptive without evidence; non-accessible full text
Screening	two-stage: title/abstract, then full-text assessment
Synthesis	qualitative, thematic comparison by synchronization principle (not quantitative pooling)

3. From Grid-Following to Grid-Forming Control: Basics and Categories

3.1. Limitations of Grid-Following Control

The current source of the converter is grid-following control. Convert the reference for active and reactive power into a current command, and then a PLL is used to track the grid voltage angle for synchronization. The first kind has a high-strength grid; that is to say, it has a low-impedance network and a stable voltage waveform. Under weak-grid conditions, the equivalent impedance is large and the short-circuit ratio is small; thus, the dynamics of the PLL will be influenced by network impedance and may be unstable. One of the well-documented failure modes is a loss of synchronisation; that is, the PLL can no longer keep up with changes in the grid angle, and the converter loses control [3] [4].

The above are some of the deficiencies. State-space models of GFL and GFM converters have shown that in GFL systems, as the strength of the grid decreases, the eigenvalue trajectories move to the unstable half-plane; GFM systems are stable over a wide range of short-circuit ratios [1]. Robust stability analysis of mixed networks has also found that the interaction between GFL and GFM units introduces extra coupling modes that are not present [7] in networks with only one type of control. Side-by-side comparisons of weak-AC systems have reached the same conclusion: the stability margin of GFL converters is lower for a small short-circuit ratio, and GFM units keep a bounded positive margin over the same range [1]. All of the above show that GFL control is not only not optimal in weak grids but also lacks a synchronization mechanism when there is no strong voltage reference.

3.2. Characteristics of Grid-Forming Control Definition

The other is the GFM control method. GFM Converter can change the scale and position of the internal voltage reference it produces, and then act as a voltage source at a controlled-impedance place. The key is that the source of the synchronisation reference is internal; it creates an own voltage phasor for the converter and does not need to determine the operating point based on a measured external angle via a PLL. It should be noted that setting up an internal reference is not the same as not taking a measurement; generally, GFMs are still used to obtain measured voltage and current feedback for the outer-loop regulation of voltage and current, virtual-impedance emulation and current limiting, and some variations use a PLL or a similar device for secondary or auxiliary purposes, such as synchronization upon reconnection. Based on the qualifications above, the four general abilities of GFM behaviour are: the ability to independently set voltage and frequency; the capacity to provide inertial and damping support for the system; the capability for stable operation in weak-grid and islanded modes; and the ability to assist in black-start operation [1].

It is necessary to distinguish between grid-forming behaviour and the general concept of grid-supporting behaviour. Many GFL-based schemes can offer ancil-

lary services such as frequency droop and reactive power support, but they are still dependent on an existing voltage source for synchronisation [5]. The defining feature of GFM control is that the converter is a voltage source itself. It will affect the system plan and the grid code, and it will be decided whether the converter can be relied upon to provide a reference during a disturbance. Distinction is also a kind of regulation, and although the requirements for GFM capability and synthetic inertia have been added to the national grid code, their general definitions are not unified, and verification is difficult [8].

3.3. A Functional Taxonomy

Based on the principle of synchronisation, the GFM strategies presented in the literature can be divided into three main categories. The first is droop control; that is, active power is related to frequency and reactive power is related to voltage magnitude via a set of fixed characteristics. The second is synchronous machine emulation control; that is, a converter mimics the swing dynamics of a synchronous generator using a virtual synchronous machine or virtual synchronous generator (VSG) model. The third is oscillator-based control; that is, an internal oscillator produces the voltage waveform and is synchronised with the grid via coupling [6]. Hybrid and new methods, such as unified GFM-GFL frameworks and learning-based controllers, do not fit well into the above categories and are dealt with separately [9].

This taxonomy is based on function rather than history, and it should be viewed as a set of areas in a continuous Design Space rather than an absolute division. It is to show the reasons why each family is in sync and what good points and shortcomings this synchronisation has for the family. The families are not mutually exclusive. A low-pass filter can be added to the measured power, and then a droop controller is used to obtain a first-order dynamic that is formally equivalent to the power loop of a VSG; in this case, the two will converge in small-signal behaviour for suitable inertia and damping values, and conversely, as the virtual inertia of a VSG approaches zero, it will reduce to a static droop characteristic. Matching control is at the intersection of the oscillator and machine-emulation families, so it has the inherent-dynamics philosophy of oscillator control and uses a swing-like internal model. Therefore, families can be considered to be regions of a continuous Design Space, and a controller labelled “droop-based” may have inertia-like characteristics after considering its filter, outer loops and current limiter. Droop control is a kind of power-frequency relationship that can achieve good steady-state sharing but has weak transient inertia. Machine emulation control adds the explicit dynamics of a rotating mass; therefore, there is inertia, but there are also oscillatory modes characteristic of synchronous machines. Oscillator control puts the synchronization inside the nonlinear dynamics of the oscillator, and it has fast and stable transient response, but it is relatively difficult to design and tune [6]. The following are the details of each family.

4. Main Grid-Forming Control Strategies

4.1. Droop Control

Droop control is the most popular GFM strategy because it is simple and has a decentralized structure. The controller is connected linearly to relate the active power error with the frequency deviation and the reactive power error with the voltage magnitude deviation. Only the local measurements of each unit are used, so these units can distribute the load independently without communication, and this scheme is still relatively stable even after adding or removing units. Therefore, droop control has been employed in microgrids and for distributed renewable energy generation [1].

The main problem of traditional droop control is that there is a steady-state frequency error because frequency is directly proportional to power. Without a second control loop in islanded mode, there will be an offset that gradually increases. Inertia provision is also small because the droop characteristic is a fixed relation and not a change over time. Recently, some researchers have modified the droop characteristics to solve the problems mentioned above. Exponential droop is a non-linear function of power and frequency, and it has been shown that under some conditions, changing the system's response to disturbances can improve frequency stability and maintain autonomous power sharing [5]. Frequency shaping control can be employed to reduce the transient droop response and improve the frequency stability of low-inertia systems [10]. Fractional-order PI controllers in the droop-control loop have been studied for their effect on the transient response, and thus the dynamic shaping of droop control is still a problem to be solved [1]. Generalized three-phase droop control has also been extended to black-start operation under unbalanced conditions, and thus a restoration function better than that of steady-state sharing can be achieved [1]. Another line of research is to classify droop-based schemes according to their dynamic structure and evaluate their suitability for high-voltage DC applications; it has been found that there are variations in the transient response [1] of the droop family itself.

4.2. Virtual Synchronous Generator Control

Control of Virtual Synchronous Generator explicitly models the electro-mechanical dynamics of a synchronous machine. A swing equation is employed in the converter to relate the virtual rotor angle and power imbalance, and a virtual excitation loop is used to regulate voltage. It can provide a true inertial response and damping, and it is in line with the physical intuition that system operators already have about synchronous machines [11] [12]. As the inertia constant and damping coefficient are software parameters and not actual values from a real machine, VSG control is also relatively easy to tune. Commercial applications of VSG-based GFM operation have begun to emerge, and the concept is now being developed into deployable equipment [11].

Many recent papers have studied the stability of VSG control in weak grids. According to the frequency and voltage stability analysis, it has been determined that

the synchronizing capacity of VSGs is reduced when grid stiffness is low; thus, inertia-damping-strengthened control has been added to restore this margin [13]. Based on the Design-Oriented Analysis, the conditions for asymptotic stability of VSG control and corresponding controller gains have been obtained; thus, case-by-case tuning is not required [14]. Transient angle stability, which is the analogue of the rotor-angle stability problem in traditional systems, has been given more attention, and control schemes have been developed to improve the transient angle behaviour of VSG-based GFM converters when connected to weak grids [15]. To increase the support of inertia and damping and improve the separation of active and reactive power, Virtual Inductance Control has been added [16]. Adaptive Virtual Synchronous Machine methods have been used to change the parameters of the power-control loop dynamically to improve decoupling and stability in weak-grid conditions [17]. Fractional-order VSG control has increased the Design Space, and small-signal analysis has shown that it is stable in weak-grid conditions [18]. All of the above have a single reason: the standard VSG model is based on synchronous machine oscillations, so a large number of studies have been conducted to reduce these oscillations without losing the inertia advantage.

It is necessary to distinguish between the emulated inertial response resulting from the swing equation and the guaranteed transmission of inertial energy. The swing equation gives a control-level inertial response; that is, it is a power reference that varies with the rate of change of frequency. Whether that response is actually realised depends on the energy in the DC source, the power headroom of the converter, and the limits imposed by the rating of the semiconductor and the current limiter. When it reaches this limit, the converter will be unable to meet the demand for response, and the swing equation will continue to require power that the hardware cannot provide. Therefore, emulated inertial response is a control-level feature, and inertial support is a system-level effect that needs to be achieved through combined action of the energy source, converter ratings and current-limiting schemes.

4.3. Virtual Oscillator Control

Virtual oscillator control is based on the idea of putting synchronisation in the nonlinear dynamics of an oscillator. Dispatchable virtual oscillator control (dVOC) is an oscillator that regulates the operation of a converter and sets the shape of its internal voltage, and it can be locked to the grid frequency by coupling with the grid. Synchronization is an inherent property of the oscillator dynamics, so a PLL does not need to be employed, and its transient response is generally faster than that of droop or VSG control [6]. Many studies have collected the development of oscillator-based methods and compared them with machine emulation and droop schemes [6].

Oscillator control has the advantages of a faster transient response and a different harmonic composition for the generated voltage, and it is known to have strong synchronization stability. To improve the stability of synchronisation, passive forms

of virtual oscillator control have been employed to change the input-output characteristics of the converter in a dissipative manner [6]. Unified oscillator controllers have been developed that support both GFM and GFL operation in the same framework; thus, the idea of the oscillator method has shown good flexibility [6]. Recently, some studies have employed coordinated adaptive virtual oscillator control to reduce subsynchronous oscillations, and the family of this work has been extended to the problem of multi-converter dynamics [1]. The main reasons for not using oscillator control are that the technology is relatively immature, it is difficult to map oscillator parameters to conventional performance specifications, and one must be careful to avoid other nonlinear phenomena. For the above reasons, oscillator methods are not often used in actual systems; instead, droop and VSG schemes have been employed. It should be noted that a fast, well-damped synchronisation response is not, in itself, proof of inertial support; an oscillator can be synchronised quickly without an extended inertial power response, but an energy buffer and sufficient headroom are still necessary.

4.4. Hybrid and New Methods

A large number of works have begun to combine the strengths of different families or apply new analytical tools to GFM control. A single framework has been developed to combine dVOC with traditional control, and it is possible to switch between GFM and GFL modes freely; thus, it can be operated in either mode according to the grid conditions [9]. Hybrid-compatible GFM inverters with coordinated regulation have been developed to meet the requirements of grid codes and maintain stability [5] in low-inertia and mixed-generation grids. Another way to have a controller that can change its synchronisation strategy according to the current network conditions [19] is to combine the control design of GFM, GFL and the intermediate mode in a single structure.

Data-driven and Physics-informed methods are now popular fields. Physics-informed neural network control has been used to solve the problem of instability in GFM converters under overload conditions; that is, the governing physical relations are employed to constrain the learned controller and improve its robustness compared with [1] purely data-driven methods. The reasons for this are that they can deal with the non-linearity and parameter uncertainty issues of model-based design, but they are also difficult to interpret, verify and certify, and have not been addressed in the current grid codes. Thus, learning-based GFM control is thought to have good prospects but has not been applied to date.

5. Comparison Analysis and Performance Trade-Offs

The three main groups can be organised according to the needs of the system operator, such as inertial support, transient and fault performance, small-signal and transient stability in weak grids, power-sharing accuracy, implementation complexity and technology maturity, as shown in **Table 2**. Before presenting the comparison, one qualification is necessary. The assessments below are based on the behav-

iour observed under the conditions of each study and should not be considered a general ranking of all networks and tunings. The main reasons for conditioning are network strength and impedance, controller bandwidth and damping [1], and the active current-limiting scheme [5]. Comparisons under different operating conditions cannot show an all-around advantage, and the following statements are only trends and not an absolute order.

Table 2. Qualitative comparison of the main grid-forming control families.

Criterion	Droop-based	VSG/VSM	Virtual oscillator (VOC/dVOC)
Inertial support	Limited, dynamic shaping dependent	Explicit and tunable (control law)	Not inertial support by itself
Transient stability (weak grid)	Moderate	Enhanced with adaptive schemes	Strong
Power-sharing accuracy (active)	High (steady state)	Moderate to high	Moderate
Power-sharing accuracy (reactive)	Impedance-dependent	Impedance-dependent	Impedance-dependent
Implementation complexity	Low	Moderate	High
Technology maturity	High	High	Lower
PLL requirement (primary sync)	None	None	None
Principal weakness	Steady-state frequency offset	Oscillatory modes	Parameter tuning, nonlinear phenomena

Note: The above qualitative indices are based on network impedance, controller tuning and current-limiting assumptions. They are the trends mentioned in the cited studies, not general attributes.

In terms of inertial support, VSG control has a very explicit and adjustable inertia; that is, the swing equation directly contains the inertia constant and damping coefficient [5] [11]-[13]. Droop control can provide virtual inertia by modifying the dynamic shape of the power-frequency curve, but the traditional type is not very good at transients [10]. Oscillator control is a kind of inertial response that is not very exposed; its dynamics are contained within the oscillator and not directly expressed as parameters [6]. In all cases, this assessment refers to the inertial response of the control law and does not guarantee the supply of inertial energy; rather, it is dependent on source energy, headroom and current limits [20].

Based on the above case studies, both the oscillator-based and the improved VSG schemes are better than the traditional droop control method for weak-grid transient stability. Oscillators have an internal synchronisation mechanism and are therefore very stable [6] in the transient state, so adaptive and virtual-inductance VSG schemes can improve the transient angle stability of the standard VSG

model [15] [16]. Although the old droop control is still suitable for strong grids, its transient margin will be small in weak grids.

Power-sharing accuracy is the division of active and reactive power. Active power sharing is achieved by droop control in steady state; that is, the power-frequency characteristics are connected so that all units have the same frequency [5] and distribute the active power among themselves [1]. Reactive-power sharing is based on a different relationship between reactive power and voltage magnitude, and it is affected by unequal feeder impedances and voltage drops. Therefore, even if there is coordination of droop characteristics, physical mismatches and line-impedance imbalances will cause reactive-power mismatches unless additional measures are taken, such as virtual impedance or secondary compensation. VSG and oscillator schemes have good complementarity [5] [16], but some extra Design is needed to prevent steady-state errors or reactive-power mismatches.

Droop control has the lowest implementation difficulty and is the most mature; VSG control is next and has also been well-developed in academia and industry [21]. Oscillator Control is the least developed, and there is no standard parameter mapping. Hybrid and learning-based methods have a high cost of implementation and verification.

The main finding of the above comparison is that these are trade-offs among mechanisms, not an ordered list. Each family achieves coordination through a different way, and the way that is strong in one direction usually has a cost in another. Droop control is simple and precise for active-power sharing, but it lacks transient inertia; VSG control has inertia and tunability, but there are oscillatory modes that need to be actively damped; oscillator control has good transient robustness, but it is complex to design and still immature. Therefore, the choice of a GFM strategy should be based on the main requirement of the application, such as steady-state load sharing in a microgrid, inertial support for a low-inertia transmission network, or fast transient response in a converter-dominated island. The lack of a single dominant strategy is why many different approaches have been proposed in the literature, and recently, context-dependent and coordinated design [1] has begun to attract attention.

6. Main Problems and Future Work

6.1. Transient Stability and Current Limitation

The first problem of GFM control is that it has a voltage-source characteristic and a current-limitation conflict. A GFM converter is a voltage source, and in the event of a fault, the resulting current would be limited only by the network impedance and would not exceed the semiconductor rating. The actual converter should limit the output current, otherwise it will lose the voltage-source characteristic and have poor transient stability. Many studies have been conducted to determine how to limit the growth of GFM after a fault. To correct the problems of the previous plan [1] [22], better voltage regulation and current-limiting control have been added

to improve the fault-ride-through capacity of the converter [1] [23]. A full review of fault ride-through techniques has gathered the methods listed above and found that they still do not meet the demands of real-world conditions; therefore, efforts have been made to improve the dynamic response of current-limited GFM converters during faults [1]. The problem is not technical but one of definition; the basic current-limiting characteristic of a GFM converter is different from the fault-current contribution of a synchronous machine, so protection coordination is difficult.

6.2. Multi-Converter Interaction and Oscillation

As the number of converters in the network increases, interactions among them and with the network will also occur, and thus oscillatory phenomena may arise that cannot be predicted by studying a single device. Sub-synchronous oscillations have occurred in systems with a high amount of IBR, and now people are actively trying [24] to find and reduce these oscillations. Research on Multi-GFM systems connected to low-impedance grids has found that strong coupling among voltage sources can lead to sub-synchronous oscillation instability even when each converter is stable [1]. A good adaptive control method has been employed to reduce the oscillations [25] of synchronous condensers caused by IBR. Based on the analysis of the interaction between GFM converters and synchronous machines, it has been found that both types of devices can exchange power in network mode without isolation [26], and recent stability studies have investigated the effect of non-minimum-phase characteristics on synchronization when converters are connected to weak grids [27]. Therefore, it is necessary to strengthen coordination at the system level, and not only to optimise individual devices. A long time ago, people developed a scalable model that is relatively accurate but easy to compute; however, now large networks are too complex for this type of model.

6.3. Protection Coordination and Fault Ride-Through

The protection system for the old network is based on the fault-current characteristics of synchronous machines; these are relatively large and decrease slowly with the degree of the fault. Inverter-based resources have a low current, and the kind of fault depends on the control method. Therefore, neither the distance nor the overcurrent protection device will be employed. Grid-forming converters are not good in this regard, as their current-limiting characteristics are based on voltage control; thus, a fault-ride-through scheme that meets the protection requirements of the converter may also reduce the fault-detection ability of the network. Recently, some scholars have raised the problem of building fault-ride-through control that meets the protection-interoperability requirements [5] for both converters and networks, and based on the analysis of the impact of GFM fault control on relay protection, some adaptation measures [1] have been developed. Research on the distance protection of GFM inverters has determined how much to adjust the incremental-quantity-based elements when the fault-current source is a current-

limited converter and not a synchronous machine [5]. Coordinating converter control and network protection has not yet been done; it is still a problem.

6.4. Standardisation and Grid-Code Compliance

Set Specific and Measurable Objectives for the Scale-up of GFM Technology. Transmission System Operators have started to specify GFM capabilities in grid codes, but the definitions and verification procedures are not the same in all areas. Function Specifications and Test Requirements for the new GFM Offshore Wind standard performance index have been published. Although the general plan of requirements [28] in China provides a framework to meet the goal of stability and ensure the safety of the system, it is also very difficult to verify whether these goals have actually been achieved. Surveys in Europe have provided some details on the control methods and application [8] of synthetic inertia, identified certain issues that need to be addressed, and pointed out that, in most cases [5], the necessity of synthetic inertia has not been established by transmission system operators. Unified Benchmarks should be set for inertia response, voltage support, fault ride-through and multi-converter stability to compare the different schemes and verify compliance.

6.5. Data-Driven and Adaptive Control

Finally, data-driven and adaptive methods have begun to be employed to deal with the nonlinearity and parameter uncertainty of model-based GFM design. Physics-informed learning is employed to add physical constraints to the learned controller and thus improve its robustness and interpretability [1]. Adaptive Schemes that change the control parameters in real time have been used to increase the range of the stability margin under all kinds of grid conditions [5] [17]. Input-output specifications and data-driven verification methods have been put forward to check whether a GFM function has the properties stated without building the whole model [29]. The primary reasons they have not been applied yet are verification and certification; it is difficult to prove that the learned or adaptive controller will operate safely in all actual circumstances, and the current testing system does not support controllers that change parameters during operation. The research and standardisation institutions should collaborate to solve the problems mentioned above.

7. Conclusions

With the decrease in system inertia and grid strength due to the replacement of synchronous generators with inverters, grid-forming control methods for inverter-based renewable energy systems are being developed in this paper. It has distinguished between grid-forming control and grid-following control, established a functional taxonomy of droop-based, machine-emulation and oscillator-based families, and compared these families according to inertial support, transient stability, power-sharing accuracy, implementation complexity and maturity. As shown in

the comparison, no single strategy is superior; rather, the conflict among families is due to problems with coordination mechanisms among them.

The review has also collected the main problems in the field, such as the conflict between voltage-source behaviour and current limitation during faults, the oscillatory interaction that occurs in multi-converter systems, the mismatch between converter fault behaviour and conventional protection, the lack of unified standardization and verification, and the verification pressure of data-driven and adaptive control. Another problem is that emulated inertial response should not be confused with guaranteed energy delivery, and at the device level, control performance must be judged in conjunction with source energy, headroom and current limits. The progress of the above areas will be less reliant on the invention of new control laws and more on coordinated system-level design, unified benchmarking and alignment of grid codes with the reliable capabilities [1] provided by grid-forming technology. Power systems with abundant renewable energy resources, the scale of construction or the speed of expansion will be determined by the conditions of the whole system and top-level institutions, rather than by improvements in device-level control.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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