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A review of dynamic voltage support for power grids with large-scale penetration of renewable generation

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Dynamic voltage stability analysis and control of power systems with large-scale penetration of renewable energy have gained significant attention in relevant fields. This article provides the latest development of dynamic voltage support technology under such a scenario, covering the following four main aspects. Firstly, the mechanism and challenges of dynamic voltage analysis with the development of large-scale renewable energy are described, and the state-of-the-art status and problems of dynamic voltage support are discussed. Second, the aggregation modeling method suitable for dynamic voltage support of both photovoltaic (PV) and wind farms is analyzed, considering the dynamic voltage response characteristics and control technologies. Then, the innovation of multi-types reactive power sources coordinated control based on autonomous decentralized control and its realization are discussed. Finally, the key problems of dynamic voltage support technology to be solved in the renewable energy-penetrated power grids are described, and the future research and development work is outlined.

KEYWORDS

dynamic voltage stability, large-scale penetration of renewable energy, dynamic voltage support, multi-type reactive power sources, coordinated control

1 Introduction

The large-scale penetration of renewable energy is deeply changing the operation characteristics of the traditional power grids. Renewable generations are characterized by stochasticity, decentralization, low inertia, and low immunity (Wu et al., 2023a; Zhang et al., 2023; Zhang et al., 2024; Huang and Xu, 2024). Both the steady-state operation and dynamic process of the grids, as well as the frequency and voltage characteristics, will change to significantly with the high penetration of renewable resources (Huang et al., 2024; Shang et al., 2022).

The frequency and power angle problems essentially result from the imbalance of the active power, which is determined by the frequency support of renewable-penetrated power grid as discussed in Reference (Chen et al., 2024). Thus, this article focuses on the dynamic voltage problem and the relevant control technologies of the renewable generations.

The emergence of dynamic voltage problem in large-scale renewable-penetrated power systems is brought about by the following intrinsic properties: 1) Fluctuating output power of renewable energy units will exacerbate the power imbalance of the system, thereby causing voltage fluctuations; 2) The transmission and consumption of large-scale renewable generations are usually based on high-voltage direct current (HVDC)

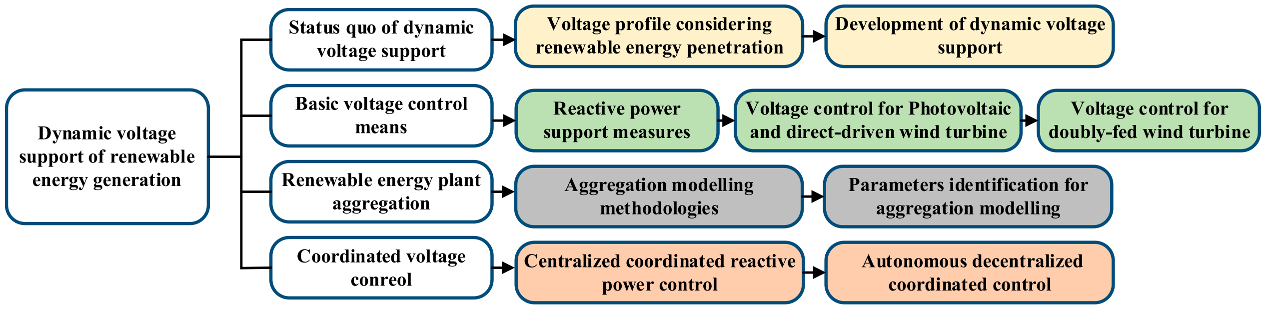

FIGURE 1
Flowchart of the article.

devices, which may face challenges such as power regulation, commutation failure, and unipolar/bipolar blockages, leading to active/reactive power variations and aggravating dynamic voltage issues; 3) With increasing renewable penetration, the grid strength dominated by conventional synchronous generators weakens, making the system more prone to dynamic voltage fluctuations. In practice, voltage problems caused by high-proportion renewable-penetrated grids have occurred in power supply centers (e.g., Xinjiang, Qinghai, Ningxia Province) and load centers (e.g., Shandong, Jiangsu Province) in China (Chow, 2023; He et al., 2021). While multiple factors contribute to grid stability, the low voltage support capabilities of some wind and PV generation systems have played a significant role in recent notable grid stability disturbances, such as the "9.28" South Australia blackout in 2016 (Australian Energy Market Operator, 2016) and the "8.9" United Kingdom blackout in 2019 (National Gid ESO, 2019).

On the other hand, renewable energy generations provide foundational support for grid regulation and control, despite their operational challenges. The operation of PV and wind generation systems is enabled by multiple types of converters, which offer advantages such as flexible control, rapid response, and decentralized deployment. Consequently, dynamic voltage control at the point of common coupling (PCC) can be achieved through well-designed control strategies.

Therefore, as shown in Figure 1, this paper first discusses the mechanism and technologies of dynamic voltage support for the renewable energy power generations in Section 1. Second, the basic control means of voltage profile are summarized and analyzed in Section 2. Then, the aggregated modelling method used for dynamic voltage support of PV and wind power plants is explored, followed by a description of decentralized coordinated control of multiple reactive sources. Finally, the paper concludes by pointing out the key issues that need to be further addressed for large-scale renewable-penetrated power grids.

2 State of art in dynamic voltage support of renewable energy power plant

Voltage problem is one of the basic problems in power system operation and control, which can be divided into steady-state and dynamic stage. In both stages, the voltage stability and voltage quantity are both significant. It should be noted that the voltage problem has great diversity in different time-scale in terms of description and solution.

Table 1 summarizes the voltage problem from the perspective of time-domain. The dynamic voltage problem is usually discussed in terms of root mean square (RMS), which refers to the characteristics of voltage changes during the transient process on time-scales of milliseconds to minutes, including voltage dips and rises, voltage variations in Table 1, all of which are dynamic voltage phenomenon (Hatziargyriou et al., 2021). These dynamic voltage phenomena may be caused by fluctuations in loads and power resources during the normal operation of the grid, or due to various types of faults. Dynamic voltage process and voltage stability are two closely related concepts: On the one hand, voltage stability is embodied through the process of dynamic voltage evolution; On the other hand, the control of voltage dynamics is the basic means to realize voltage stability control (Blaabjerg et al., 2023). Dynamic voltage support is defined to reduce voltage fluctuations and maintain a stable voltage level by providing "timely" and "appropriate" dynamic reactive power.

From the perspective of frequency domain, after the renewable energy generation is connected to the grid through the converters, the nonlinear behavior of the converter leads to harmonics in the voltage dynamics. At the same time, as a large number of renewable energy generations are connected, the power grid presents a smaller short-circuit ratio and damping ratio. Thus, the renewable energy plants and the power grid is prone to oscillation, the frequency of which ranges in tens to thousands of Hertz (Hatziargyriou et al., 2021), bringing about voltage fluctuations and stability problems. These issues have been systematically discussed in other references and will not be analyzed in depth in this article.

From the early stage of power systems, researchers have analyzed and studied the voltage problem and proposed systematic solutions. However, the large-scale penetration of renewable energy resources represented by PV and wind power has brought a series of essential changes to the operation and control of the grid, and the attributes of the voltage problem and its control strategy have also presented new features at multiple levels (Huang et al., 2024). During the decades of development of PV and wind power, the grid-connected technology has been continuously developed and progressed (He et al., 2021). Before 2010, the core of the technology lay in the maximum power

TABLE 1 Description of voltage problems based on time-scale.

Voltage phenomena	Time scale	Description	Solution
Voltage pulse/Voltage transient	<10 ms	Instantaneous value	Suppression from source
Temporary drop/rise	10~500 ms	Instantaneous/valid value	Dynamic voltage regulation (DVR)
Voltage fluctuation/flicker	10 ms~1 min	Valid value (rapid change)	Static var compensation (SVC)
Undervoltage/overvoltage	>1 min	Valid value (differential equation)	Source and load adjustment
Voltage deviation	0.5~10 min	Valid value (algebraic equation)	Capacitors/reactance switching

tracking, which operates according to the fixed power factor, and is manifested as "unsupported and low disturbance" (Wu et al., 2023b). After 2010, with the increasing proportion of renewable energy capacity, these units have had a significant impact on the traditional power grids, and the voltage control strategy has also presented new characteristics at various levels.

With the more and more prominent impact of renewables on the power system operation, the industry has begun to carry out research and application of "grid-friendly" units, generally realizing reactive power regulation, low-voltage ride-through (LVRT) (Liu et al., 2014; Gong et al., 2023; Garcia and Santana, 2024; Martínez-Treviño et al., 2021; Fang and Zhang, 2022), and reactive power control in steady-state operation at the plant level (Cheng et al., 2023).

According to the national standards for energy industry, the requirement of converters used for connection of PV and wind power in normal operating conditions are as follows: When the output active power of inverter is greater than 50% of its rated power, the power factor should not be less than 0.98 (forward or lagging); The output active power at 20%~50% of the rated power, the power factor should not be less than 0.95 (forward or lagging) (Fang and Zhang, 2022). It can be seen that the converter can provide 20%–30% of the rated capacity of reactive power under normal operation. For converters with grid support capability, 48% of the rated capacity of the reactive power can be dynamically supplied (Naz et al., 2021). In fact, the output reactive power can play an important role in voltage control.

The reactive power control modes can be adopted in different ways according to the needs of grid operation (Jiao et al., 2022), including constant voltage control, Q-V sag control, constant power factor control and constant reactive power control, etc. The converter is capable of accepting commands from the control system to output reactive power and switching between various control modes online (Tamboli and Jadhav, 2018).

2.1 Steady-state voltage control at renewable energy plant and the correlation with dynamic voltage support

For the reactive power/voltage control in the steady-state operation of the power grid, PV and wind farms have formed a mature control technology (Keskes et al., 2021; Chen et al., 2023; Djalal et al., 2023; Pal et al., 2023; Khan et al., 2021; Rajeev and Agarwal, 2020; Wang et al., 2021; Richard et al., 2020; Liu et al., 2023). So far, PV inverters, doubly-fed wind turbines (DFIG) and direct-driven wind turbines have generally adopted vector control technology, which realizes the decoupling control of active and reactive power, and lays the foundation for the reactive power support of PV and wind power plants to the power grid (Hadavi et al., 2022; Li et al., 2020; Qi et al., 2020; Fang et al., 2021; Ikram et al., 2023; Hadavi et al., 2022; Gui et al., 2024; Bhyri et al., 2024).

The automatic voltage control (AVC) system set up in renewable energy plant can maintain the voltage at the PCC within the required range by coordinating and controlling all the local reactive power resources using an optimization algorithm. The AVC system control strategy of a renewable energy plant is mainly carried out by coordinating the distribution of reactive power output from each reactive power resource in the plant. Reactive power allocation among units mainly includes: Equal power factor allocation, equal margin allocation, capacity sag allocation and optimal allocation. Optimized allocation is carried out by establishing an objective function and applying an optimization algorithm to calculate the reactive power output of each unit with reactive power regulation capability in the plant. The optimization objectives can be various, such as minimizing active losses, minimizing voltage fluctuations at the PCC of the wind farm, and minimizing operating costs, etc. The commonly used optimization algorithms are traditional optimization methods, such as interior point method and intelligent algorithms such as genetic algorithm and particle swarm algorithm.

The steady state reactive power regulation of renewable energy plants has been generally realized worldwide (Xu et al., 2021; Ahn et al., 2014; Ahn et al., 2013; Wu and Wang, 2021; Zhang et al., 2021). Wind farms from GE could realize reactive power/voltage control with a delay time of 100 ms and a response time of 400 ms in 2004 (Liu et al., 2014). In China, the research of reactive power/voltage control strategies and the development of devices for PV and wind farms started around 2006 (Zhao et al., 2023). Nanrui, Xuji and other electrical equipment companies have developed advanced AVC systems, which have been successfully applied to the voltage control of renewable energy plants (Liu and Wang, 2021).

The relevant departments of China have jointly launched a specification for reactive power configuration for wind power plants (Xia et al., 2016), which sets out clear requirements for the configuration and control of reactive power. Although the steady-state voltage problem is very different from the dynamic voltage problem in terms of time-scale, measurement indicators and control measures, the two are also closely related.

On the one hand, PV and wind power converters have fast reactive power regulation capability, and various reactive power compensation devices configured in renewable energy plants, such as static reactive power compensator (SVC) and static var generator (SVG) are capable of achieving dynamic voltage regulation (Palanimuthu et al., 2023). These devices involved in steady-state voltage regulation are also the basis of the equipment to achieve dynamic voltage support. On the other hand, the steady-state operating state of the converter determines the static operating point of reactive power regulation, which is related to the range and margin of dynamic reactive power regulation (Ibrahim et al., 2022).

The steady-state reactive power control process should also enable the renewable power plants to have sufficient reactive power reserve capacity to cope with system faults and provide effective voltage support during the transient process. The following section focuses on the dynamic voltage support of PV and wind farms and discusses the dynamic voltage support of different types of standalone devices, the aggregation response characteristics at the plant level and the coordinated control strategies between different reactive power resources.

2.2 The research of the dynamic voltage support at renewable energy plant

With the development and implementation of the renewable-penetrated power systems, when the proportion of renewables is greatly increased to become the main body of power systems or even the main body of power quantity, the dynamic voltage support from the renewable units has become critical, and has become one of the common concerns of the power system (Tong et al., 2015).

Active support based on auxiliary devices, including crowbar protection, is commonly applied in DFIGs to limit over currents in the rotor, thereby protecting the converters (Naderi et al., 2019). However, activating crowbar protection places the DFIG in asynchronous operation, consuming significant reactive power, and deteriorating the wind farm voltage, which is detrimental to voltage recovery in wind power grid-connected systems (Firouzi and Gharehpetian, 2018). Utilizing a DC-link chopper can effectively suppress internal over voltages within wind turbine generators (WTGs) and enhance the wind turbine's voltage disturbance rejection capability (Dong et al., 2021). Implementing fault current limiters (FCLs) is an effective solution for addressing fault current exceeding limits in wind power systems. This device can significantly improve the WTG's LVRT capability, providing strong support for the application of DFIG transient voltage active support technologies (Ahmidi et al., 2012). Current research indicates that applying FCLs during grid faults has a positive effect on maintaining the WTG's reactive power voltage support capability.

The Dynamic Voltage Restorer (DVR) is an effective device for mitigating grid voltage sags, enabling wind power transient voltage active support, and enhancing the LVRT capability of WTGs and wind farms. In practical applications, the DVR is typically connected in series between the WTG and the grid via an injection transformer. It serves to isolate grid faults, rapidly restore voltage, and improve the WTG's LVRT performance (Torkaman and Keyhani, 2018). Its topology and typical control scheme are illustrated in Figure 2. Literature (Chen et al., 2018) demonstrates that a DVR can maintain the wind turbine's terminal voltage under fault conditions and achieve voltage sag compensation for the wind power grid-connected system. The combination of FCLs and DVRs, as explored in (Flannery and Venkataramanan, 2008), effectively enhances the WTG's immunity to disturbances and increases the unit's voltage support capability during faults. Integrating a DVR with an energy storage system (ESS), as presented in (Kanjiya et al., 2014), can effectively suppress wind power fluctuations and compensate for grid voltage disturbances.

Furthermore, some scholars have proposed modifying the topology of wind turbine generators to improve their fault ride-through performance and active voltage support capabilities. Literature (Ambati et al., 2015) proposes a WTG topology based on series converter compensation of grid voltage to support the voltage at the wind power grid-connection point under fault conditions. Through the improvement of the DFIG grid-side converter structure, wind farms can meet the reactive power needs of the grid-connected system and eliminate the influence of grid voltage changes on the wind power system operating voltage, as demonstrated in (Zhu et al., 2017). Active transient voltage support technology of DFIGs based on auxiliary devices relies on the correct and effective operation of external devices. This technology can not only improve the LVRT performance of wind turbine generators, but also enable the wind farm to inject reactive power into the grid-connected system during grid faults, realizing active support for the grid transient voltage support of the wind farm.

Active support methods based on wind power's own control strategy are important measures to maintain voltage stability of new power systems with wind power as the core power source. Transient voltage active support technology based on wind power's own control strategy can realize the safe grid connection operation of wind power from the control perspective and make full use of the available reactive power capacity of the unit to implement voltage support for the grid-connected system under fault conditions. Low voltage ride-through control technologies, such as rotor current control (Zhou and Blaabjerg, 2018), de-excitation control (Xie et al., 2013), and improved speed control (Li et al., 2018), can improve the wind turbine's operating control to achieve the purpose of suppressing the unit's overcurrent and overvoltage. This type of control can effectively protect operating equipment, improve and enhance the transient operating characteristics and LVRT capability of wind turbines, and lay the foundation for the implementation of active support technology in DFIG wind farms. Transient voltage active support technology based on the WTG's own control strategy can actively provide reactive power to the grid and assist in restoring system voltage during grid voltage dips by adjusting the control structure, improving the control strategy, and optimizing the control algorithm. In terms of adjusting the control structure, current research mostly adopts the method of adding control links to achieve active support. In terms of optimizing control algorithms, multiple types of optimization methods are used to improve the control performance of the unit. Based on the coefficient of variation method, literature (Huang et al., 2019) proposes a multi-machine reactive power support allocation method and reactive power control method considering the operating differences within the wind farm. A typical control schematic diagram of transient voltage

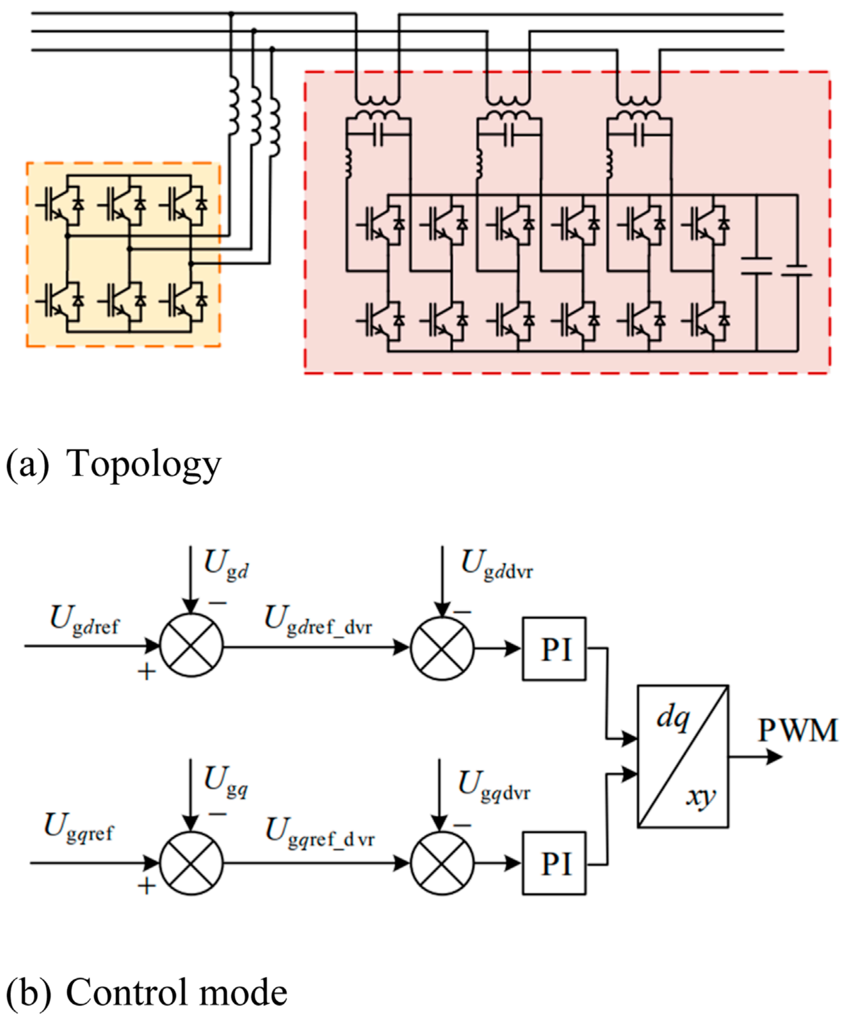

FIGURE 2
Topology and typical control of dynamic voltage restorer. **(a)** Topology. **(b)** Control mode.

active support technology based on the unit's own control strategy is shown in Figure 3.

The role of PV and wind turbines in supporting the dynamic voltage of the power grids starts with the importance, development and application of low/high voltage ride-through (LVRT/HVRT) technologies of the units (Du et al., 2021). The LVRT standard specifies the fault ride-through capability for magnitude and time durations of different voltage dips as well as the response time of dynamic reactive current and the relationship between different voltage dips and the dynamic reactive current provided (Xia et al., 2016).

The application of these technologies and the implementation of the standards have improved the support of renewable units for dynamic voltage to a certain extent (Joseph et al., 2020; Lee et al., 2021). However, up to now, the LVRT and HVRT technologies are still limited to the fault ride-through of single units, and the research hotspots mainly focus on the negative sequence current control under asymmetrical fault at the level of single units, high voltage ride-through, and continuous ride-through realization.

Virtual synchronous generator (VSG) technology can improve the voltage stability in the weak grid (Mohiuddin and Qi, 2022), but due to the overload capacity limitations, low-voltage process is usually switched to phase-locked synchronous current source control mode, which cannot present a real characteristic of dynamic voltage source (Alonso et al., 2022).

In recent years, some enterprises and research institutions in China have carried out new support technologies: Nanrui has piloted fast power regulation technology for PV plants in Tibet, Inner Mongolia, Gansu, Yunnan and other places since 2018, adopting GOOSE communication protocol to greatly reduce communication delay. Therefore, the response time of active and reactive power control can be reduced to 30 ms in non-fault conditions (Chen et al., 2023).

In conjunction with the actual situation in China, China Electric Power Research Institute has researched the technology to improve the dynamic stability and consumption capacity of PV and wind power plants through the dynamic control strategy and parameter optimization, which and has achieved good performance (Aboshady et al., 2023). However, these techniques

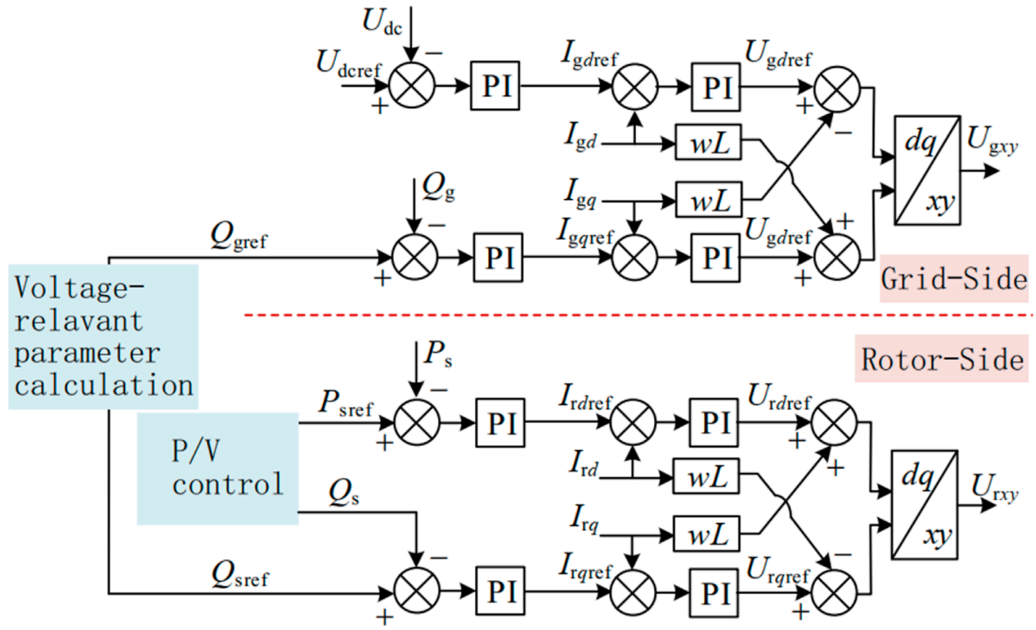

FIGURE 3
Typical control diagram of transient voltage active support technology based on the control of unit.

focus on the initiative regulation of PV and wind power plants, emphasizing the role of centralized control.

The above analyses show that the problem of voltage support for PV and wind farms in steady state and small disturbance scenarios for a high proportion renewable penetrated power grids has been basically solved. However, the support for dynamic processes considering large disturbances is still limited to fault ride-through at the single-unit level.

In the future, renewable energy will play a dominant role in the security and stability of the power system, and there is an urgent need to expand the support scenario of PV and wind power from steady state and small disturbances to dynamic and large disturbances, and to expand the support mode from single-unit response to single unit-plant-grid cooperative.

3 Basic means of dynamic voltage control

In response to the fluctuation of voltage, renewable energy plants need to compensate enough reactive power to ensure the stability of voltage (Qiao et al., 2009). At present, China has put forward relevant specifications for the reactive power compensation capability of renewable energy plants, requiring wind farms and PV plants to be equipped with reactive power compensation devices, and requiring wind turbines to be equipped with reactive power control systems and PV inverters to have reactive power compensation capability (Tong et al., 2015).

This section first introduces typical dynamic reactive power regulation measures, and then introduces voltage control techniques for PV inverters and wind turbine converters. Relevant reactive power control characteristics at the plant level will be discussed in Section 4.

3.1 Typical dynamic reactive power regulation measures

Typical dynamic reactive power regulation means include synchronous condenser, SVC, SVG, and direct current reactive power modulation, etc. (Qi et al., 2020). The advantages and disadvantages are listed in Table 2. Among them, the most common mechanical rotating reactive power compensation device: the synchronous condenser, is the earliest equipment applied to power system for dynamic reactive power regulation and voltage control. The synchronous condenser can be equivalently regarded as a synchronous generator with zero active power output. During normal operation, it works at synchronous speed and regulates the voltage by over-excitation or under-excitation according to the demand of the power grid (Richard et al., 2020; Liu et al., 2023; Hadavi et al., 2022; Li et al., 2020).

Because the synchronous condenser is a rotating device, the response process requires hundreds of milliseconds, which leads to high operation and maintenance cost, and necessitates investment in supporting starting and protection equipment. Thus, it was once regarded as an obsolete technology (Gui et al., 2024) However, in recent years, with a high proportion of renewable energy resources integrated into the power grid, new requirements on the inertia and dynamic voltage support of the system, synchronous condenser has gained favor again with a certain degree of rotational inertia support and characteristics of the dynamic reactive power compensation.

Static reactive power compensator (SVC) is a kind of static reactive power compensator that uses thyristors as the switching

TABLE 2 Comparison of typical dynamic reactive power regulation measures.

Measure	Advantages	Disadvantages
Synchronous condenser	1.Overloaded capacity 2. Rotation inertia 3. Dynamic reactive power supply 4. Suitable for variable scenario	1. Rotating device 2. High cost
SVC	1. Low cost 2. Steady reactive power 3. Large capacity of capacitor	1. Limited by voltage profile 2. Resonance risk
SVG	1. Low cost 2. Flexible control mode 3. Fast response speed	1. Failed in imbalanced fault 2. Small capacity of capacitor
HVDC	1. Flexible control mode 2. Fast response	1. Complex structure 2. Limited to specified scenario 3. High cost

device composed of inductors, fixed or variable capacitors in parallel. The main SVC devices are thyristor switched capacitor (TSC), and thyristor controlled reactor (TCR)+fixed capacitor (FC), etc. A TSC can achieve zero voltage input and zero current withdrawal of reactive power compensation. A TCR + FC can continuously regulate the reactive power between output and absorption, so that the voltage can be quickly and dynamically regulated, with a response time between 50 and 100 ms.

Static reactive generators (SVG) are based on fully controlled devices that constitute the voltage-type or current-type grid-connected inverters, which can regulate reactive power quickly, stably and continuously, among these, voltage-source three-phase bridge inverters are the most widely used devices. SVG has two reactive output modes: Fixed reactive power control or specified voltage control of the PCC.

Compared with SVC, which requires large capacity capacitors or reactors, SVG only requires small capacity capacitors on the DC side and can both supply and absorb reactive power (Li et al., 2022). Moreover, due to the limitation of impedance of inductance and capacitance, the maximum current compensated to the grid by a traditional SVC decreases with the voltage reduction, while the SVG can adjust the AC voltage amplitude and phase by switching the device, and its maximum current compensation is not affected by the voltage magnitude (Xia et al., 2016).

In addition, SVG has a fast response speed, the response time from zero reactive power output to maximum reactive power output is about 20 ms (Ibrahim et al., 2022), which meets the requirement of national standard "Reactive Power Compensation Response Speed Less Than 30 ms", and the harmonics are small, so it is gradually replacing SVC as the mainstream reactive power compensation device.

Conventional LCC-type HVDC transmission can be used to regulate the voltage of AC power grid by reactive power modulation (Lee et al., 2021). Especially when overvoltage occurs in the grid, the overvoltage can be suppressed by increasing the trigger angle and increasing the reactive power consumption.

In addition, in recent years, the rapid development and application of voltage-sourced converter (VSC) HVDC transmission technology, large-scale energy storage technology, etc., rely on the SVC, due to its active-reactive decoupling characteristics (Mohiuddin and Qi, 2022). The principle is similar to that of PV inverters and will be specifically discussed in the next Section.

3.2 Dynamic voltage control methods for PV and direct-driven wind power

Both PV and direct-driven wind farms use VSC-type converters with similar reactive voltage response characteristics among all the renewable energy plants. The control modes of VSC converters can be divided into grid-following (GFL) control and grid-forming (GFM) control (Zhang et al., 2021). The GFL requires a phase-locked loop to phase-lock the voltage at the PCC and to achieve synchronous grid connection (Zhao et al., 2023); the GFM actively constructs the grid voltage and frequency according to the output power of the converter.

Renewable energy plants in China require a certain period of time and a certain amount of reactive power support when a high/low voltage fault occurs in the system, and the grid-connected inverter switches the control mode and adopts an open-loop control strategy with a single current loop. When a high-voltage fault occurs in the system, the grid-connected inverter needs to switch the control mode without taking off the grid for a certain period of time, however, in contrast to LV faults, HVRT ability requires the grid-connected inverter to absorb reactive power, and at the same time, an increase of the voltage reference in the DC-side is usually used to stabilize the fluctuations in the DC-side voltage during the HVRT period (Palanimuthu et al., 2023).

In renewable energy plants, the generation unit usually executes after receiving the command issued for the plant. At this time, the fastest reported reactive power response time can already be comparable to SVG, which is about 23–27 ms (Lee et al., 2021). When high/low voltage faults occur, the voltage detection delay will be increased before the command is issued. The command issued at this time is usually difficult to meet the reactive power support demand during the fault period, so to improve the dynamic reactive power support capacity of the renewable energy plant, the high/low voltage control needs to be further studied.

Because of the stability problem in the weak power network, the converter should adopt the control mode in the grid with small short-circuit ratio and low system inertia (Alonso et al., 2022). At present, some scholars refer to the virtual synchronous machine control and have applied it to the PV and wind power to improve the stability of the system in low inertia and weak power grids (Aboshady et al., 2023).

In addition, commonly used GFM control also includes sag control and virtual oscillator control (Ghosh et al., 2023). The sag control can realize global power distribution without communication by simulating the sag curves of active power-frequency and reactive power/voltage of the synchronous generator (Camal et al., 2023). However, due to the influence of line impedance, accurate power distribution is difficult to achieve (Wang et al., 2024).

Virtual oscillator control obtains a sinusoidal voltage to the oscillator, which is used as a reference voltage to control the output of the inverter (Ghosh et al., 2023). Because the converter external characteristics are represented by the physical characteristics of the oscillator, the synchronization between different converters and power distribution can be achieved through the resonance principle of the oscillator (Camal et al., 2023).

It is important to note that VSC converters usually use insulated gate bipolar transistor (IGBT) fully controlled switching devices to achieve commutation, and the IGBT's current flow capability has limitations (Palanimuthu et al., 2023). Therefore, when the system has a serious fault, even if the VSC converter uses a GFM control strategy, the VSC converter may degenerate into a fixed power control because of current limiting.

3.3 Reactive-voltage control methods for doubly-fed wind turbines

DFIG is currently the mainstream model for wind power generation. The stator of DFIG is directly connected to the grid-connected transformer; the rotor is connected to the grid-connected transformer through the rotor side converter (RSC) and the grid-side converter (GSC) (Chang et al., 2020). Controlled by RSC, the stator side outputs the maximum active power and inductive reactive power to maintain the voltage. GSC controls the rotor power output, similar to PV converters. When there is a transient voltage drop, the unit provides reactive power to the system to help restore the grid voltage.

The maximum reactive power output capacity of DFIG can reach more than 30% of the rated capacity. Based on the existing control strategy, the dynamic reactive response speed of the DFIG is about 60 ms (Bhyri et al., 2024). Compared with PV units, wind turbines are more prone to large-scale off-grid due to high voltage during voltage recovery. At present, some countries have required wind turbines to have HVRT ability. Literature (Du et al., 2021) proposes a method of realizing the HVRT through the collaborative control of the main control system and the converter of wind turbine. However, the existing research has not considered the influence of overvoltage on the electromagnetic characteristics of the unit, and HVRT technology must be studied further.

In addition, a virtual synchronous control strategy applied to DFIG has been proposed to simulate the rotor equation of synchronous generators, including active power control, reactive power control, damping control, etc. Virtual impedance control of DFIG is applied to RSC, while GSC still adopts voltage-oriented vector control based on phase-locked synchronization. However, when a voltage drop occurs in the power grid, virtual synchronous control will cause the RSC to be impacted by strong electromagnetic stress and rotor overcurrent, and the unit will face the risk of off-grid.

4 Aggregation characteristics of dynamic reactive power support for renewable power units

4.1 The requirement of aggregation modelling

The PV and wind turbine units are dispersed with random and fluctuating output (Camal et al., 2023). Thus, their active/reactive output characteristics and voltage response characteristics are mainly determined by the control mode of power electronic devices. Existing research on renewable energy units has provided a mature summary for response characteristics at equipment level (Wang et al., 2024).

However, as the proportion of PV and wind units connected to the system increasing year by year, the role of renewables is gradually changing from auxiliary power supply to the dominant power supply of the power system (Li et al., 2022). Therefore, it is inevitable to set the maximum power tracking as the basic control objective of the controlled current source characteristics to support the voltage and frequency stability of the power system (Wang et al., 2016). The dynamic voltage control of power plants has become an important technical bottleneck restricting the development of renewable energy.

Based on the characteristics of voltage response at the PCC, it is difficult to achieve the analysis of dynamic characteristics through the model of the single unit when designing the dynamic voltage regulation strategy (Ibrahim et al., 2022). In order to accurately grasp the voltage response characteristics of renewable energy plants and fully reflect the dynamic reactive power support capability of PV and wind power plants under different control strategies and topologies, it is urgent to explore and establish of a dynamic voltage support research direction. The research on aggregation model for dynamic reactive power support should be able to fully reflect the autonomous decentralized response characteristics of the units under transient disturbances on the one hand, and characterize the overall effect and multi-time-scale dynamics of voltage support for the PCC in the plants on the other hand.

Providing an accurate analytical model for the dynamic voltage stability analysis of the power plants through an aggregation modelling is a prerequisite for the subsequent analysis of dynamic reactive power support and the design of reactive power compensation strategies, and is also the theoretical basis for the research of the coordinated control of renewable energy units and dynamic reactive power compensation equipment at the plant level.

4.2 Aggregation modelling methodologies

In view of the above modelling requirements, the aggregation modelling should take into account the external natural resources conditions and focus on the response characteristics of the aggregation model to the power system voltage fluctuation. However, there is still little literature on the aggregation modeling of dynamic voltage response characteristics at plant level, and the commonly used aggregation modelling methods for renewable energy plants mainly include mode equivalence method, Singular perturbation method and dynamic aggregation method.

According to the aggregation results, the commonly used aggregation modelling methods include aggregated single-machine modelling and grouped multi-machine aggregation modelling (Shang et al., 2022), which can be flexibly selected according to the analysis scenarios such as the size of the plants and the flexibility of the operating state. This type of modelling method essentially provides a method of simplification and downgrading model. In order to facilitate the design of control parameters, it is usually necessary to retain the mapping relationship between the overall characteristics of the plants and the parameters. Then, the parameter estimation or parameter aggregation is used to group the system to one unit.

The detailed description of the dynamic characteristics of renewable energy resources are still rarely taken into account in the existing aggregated modeling literatures (Camal et al., 2023). In fact, the difference of terminal voltage at different locations in actual operation will directly affect the working mode of the units, and whether they will enter the fault ride through mode.

In view of the research objectives of dynamic characteristics of voltage response, the clustering should consider the relevant indicators including the selection of natural resources, output characteristics, operating environment, the critical value of HVRT/LVRT and control parameters (Palanimuthu et al., 2023), so as to characterize the dynamic voltage response characteristics of the unit and reflect the influence of location dispersion. The hierarchical clustering method is not affected by the initial setting value and can avoid the local optimal characteristics, obtaining a widely application in power systems.

To meet the requirements of dynamic voltage analysis and control, the trade-off between accuracy and complexity should be balanced in modeling (Xia et al., 2016). The applicability of the model should be evaluated through errors and characteristic differences.

4.3 The parameter identification of aggregation model

In order to improve the dynamic equivalence performance of the aggregation model, it is necessary to analyze the factors causing the error of the model, considering the influence of the LVRT strategy on the external characteristics under typical operating conditions and the quantitative relationship between the capacity of the plant and the error of the aggregation model (Martínez-Treviño et al., 2021).

For the estimation of aggregation parameters, capacity weighting method and equal power loss method have been well applied (Qiao et al., 2009). The equivalent aggregation model of the plant utilizing the equivalent admittance method has been evaluated time-consuming and heavy calculation burden.

The parameters of the aggregated model established by the state-space model method can achieve a better parameter fitting in the optimized equations, and can guarantee the accuracy of the model (Wang et al., 2022). However, all the state-space equations of large wind farms or PV plants in the optimization solutions will lead to high computational burden, and the efficiency of parameter identification needs to be improved.

From the perspective of engineering application, the parameter identification method based on phasor measurement unit (PMU) can further improve the model accuracy. By comparing with actual engineering operation data, PMU-based methods can guarantee the reliable parameter identification results and can be widely used in the parameter identification of aggregate models (Qiao et al., 2009).

5 Coordinated dynamic reactive power control for renewable energy plants

5.1 Basic problems confronted with coordinated control of multi-type reactive power

The output characteristics of renewable units are completely different due to the different device attributes and control strategies of the multi-type reactive power resources in the plants (Asadollah et al., 2020). From the perspective of topology, DFIG is connected to the grid through the multiple energy paths of generators and converters and full-power direct-driven wind turbines are connected through VSC converters (Zhang et al., 2021). PV inverters, whether centralized or serial, are connected to the grid through VSC converters. Different types of renewable energy devices and different connection methods lead to great differences in the reactive power regulation characteristics of these renewable energy units. Therefore, the voltage regulation cannot be achieved by controlling a single reactive power resource.

In the context of high-proportion of renewable energy penetration, especially under weak grid and AC/DC fault conditions, the grids need more reactive power to support the dynamic voltage profile of renewable energy plants, and improper coordination and control may cause reactive power circulation and reactive power oscillation. This puts forward high requirements for the coordinated control of multi-type reactive power sources.

The existing HVRT/LVRT strategies cannot match the demand of voltage support at the PCC, and the control mode mainly relies on the traditional automatic voltage control (AVC) (Nguyen et al., 2021), which uses centralized control as the adjustment method, and its reactive power adjustment time is on the minute level, thereby failing to meet the multi-time scale control demand of voltage support of renewable energy plants.

TABLE 3 Comparison of plant-level reactive power compensation equipment.

Equipment	Response speed	Dynamic voltage support ability	Cost
Condenser	Middle	Strong	Middle
SVG/STATCOM	Fast	Middle	Low
Fixed capacitor	Slow	Weak	Low
Synchronous generator	Middle	Strong	High

According to the current national standard in China, PV and wind turbine inverter is an important reactive power resources compared to SVG and other devices (Lu et al., 2023). How to coordinate and utilize the reactive power compensation capability of renewable energy equipment and solve the problem of insufficient dynamic control capability is the basic challenge of dynamic voltage control of renewable energy plants.

When designing the control strategy, it is necessary to coordinate the response time and capacity of the various types of reactive power compensation equipment according to the different response characteristics of reactive power compensation devices in actual engineering operation. Otherwise, the compensation equipment may be taken off the grid earlier than the renewable energy units during the fault due to the electrical limitation of the equipment (Wang et al., 2013).

As synchronous rotation equipment, generators and condensers can also provide short circuit capacity for the system and dynamic voltage support through excitation (Hadavi et al., 2022). At the same time, the operating characteristics of condensers meet the needs of dynamic reactive power in HVDC transmission and the dynamic process of large-scale renewable energy plants. Compared with SVC, STATCOM and other reactive power compensation devices, the new-type condensers have stronger dynamic reactive power support and dynamic voltage regulation capabilities, which is more suitable for practical application (Ge et al., 2022).

As shown in Table 3, different types of reactive power resources considering the characteristics, response time scale, support capacity, and cost, etc., are summarized and compared.

5.2 Centralized control

The existing technologies that widely used in the industry includes AVC, dynamic automatic voltage control (DAVC) (Lu et al., 2023), whose main control objectives are to optimize voltage deviation, improve static voltage stability and reactive power margin. The static voltage control system of the power grid is mainly designed based on the concept of "voltage control zone" and "central bus voltage", which has been widely used. However, to meet the voltage regulation requirements of renewable penetrated power systems, it is still necessary to further study dynamic voltage regulation technology to overcome the problems as follows: 1) AVC systems need to adjust each other among multi-level dispatching centers; 2) The overall voltage control quality is low; 3) The dynamic voltage support ability is insufficient. Literature (Wang et al., 2013) put forward the collaborative voltage control technology of network-provincial-ground multi-level control center, which realized the cooperation among multi-level AVC systems through the interaction of a few key variables. Literature (Ge et al., 2022) proposed a preventive control method aiming at the safety and stability of power grid, where representative serious faults were selected from fully anticipated fault sets and dynamic voltage partitions were formed correspondingly to achieve global optimal control through coordination. Literature (Yang et al., 2019) improved the dynamic support performance of wind farms on voltage through the coordinated control of AVC and wind turbines designed with constant voltage control mode.

When the voltage is disturbed during the fault, the reactive power response of the renewable energy units is completely determined by its own control system design, thus, it is impossible to realize the cooperative control of each unit by means of communication in this time range since the duration of the disturbance is short. Therefore, the characteristic of unit autonomous response determines the fluctuation of voltage profile and the distribution of reactive power. The control parameters and operation mode are the key to the response characteristics of the voltage support, and this characteristic determines whether it will cause cascading failures or expand the accident scope.

The existing control strategy is mainly based on the idea of control mode switching to achieve reactive power voltage control in the fault stage. Thus, the smooth switching control methods is essential for ensuring the stable operation of the control system. After the fault is cleared, where the voltage recovery stage comes, the purpose of collaborative control of renewable energy units should give priority to how to adjust the reactive power distribution of each unit, output power limiting and the influence of active and reactive power coupling on system stability, so as to provide the reactive power to the system to help the voltage recovery. Literature (Heming et al., 2013) discussed the mechanism of the influence of active and reactive power coupling on voltage stability in detail. Literature (Wang et al., 2020) discussed the mechanism of overvoltage and put forward suggestions for optimization of wind turbine to effectively suppress the system overvoltage level during voltage recovery process.

The above dynamic voltage regulation method based on the preset strategy is convenient to implement and easy to operate, and it is an important development direction of the preventive voltage control of the power plants. However, there is still much room for improvement in the optimization dynamic process and the collaborative control of voltage recovery after failure. How to coordinate the reactive power resource at plant level and make full use of reactive power compensation capability of the renewable energy units to reshape the dynamic response characteristics of reactive power on multiple time scales and effectively improve the dynamic voltage support capability of the plant remains to be explored.

5.3 Autonomous decentralized control

In view of the shortcomings of the existing centralized control at the plant level, it is urgent to explore the autonomous decentralized control of multiple reactive power resources at the plant, which is different from the centralized control, so as to realize the full coverage of the process of voltage control from steady state to dynamics, and the control mode change from passive response of single-unit to active support of the plant (Mudaliyar et al., 2020).

Decentralized response-aggregate support is the basic goal of multi-reactive power resource autonomous decentralized control (Derakhshan et al., 2023). Autonomous control uses the active response characteristic of the reactive power resource unit. When detecting the voltage fluctuation, it operates autonomously according to the preset control strategy, and actively adjusts the reactive power output in response to the voltage fluctuation to achieve the control purpose using decentralized response from the device (Samende et al., 2021).

Aggregate support is a basic requirement for dynamic reactive power response (Sun et al., 2020). Based on the obtained global information, multi-objective optimization can be carried out. The aggregate model of the plant discussed in Section 4 is used to analyze the reactive power adjustment margin and the operating state of the operating point, then the dynamic reactive power compensation demand of the plant can be calculated (Xu et al., 2020).

According to the operation mode of power grids and the characteristics of faults, the occurrence, development and recovery process of voltage can be predicted. Then, the distribution of reactive power and control parameters are sent to the units according to refresh cycle, so as to achieve the purpose of aggregate support by dispersed response of the plants.

In device level, the control objects include reactive power compensation devices such as renewable energy units, SVC and SVG, which are mainly responsible for voltage profile detection and uploading, operation mode switching, and online adjustment of control parameters. Based on the above ideas of autonomous decentralized control, the global information of the plant is obtained and the reactive power margin, voltage support capacity and reactive power demand are analyzed first based on the aggregate model, then, multi-objective including network loss and voltage stability indicators are optimized. Based on the optimization results, the reasonable operating point and control parameters of each unit at the current operating point can be given, and the parameters are sent to each unit for adjustment.

When the large disturbance occurs, each unit realizes the quick support of the dynamic reactive power based on the operating point and control parameters in an autonomous control mode. After the disturbance, the unit continues to dynamically adjust the operating parameters according to the received instructions.

Compared with the traditional centralized control mode, the autonomous decentralized control mode has a more flexible adjustment mode, and can improve the collaborative support ability of dynamic voltage. The upper layer control mainly includes (Sun et al., 2020): 1) Dynamic optimization based on the unit operating point and power network operating state obtained by global information, reactive power distribution determination and reactive power compensation margin reservation, which is required in advance to cope with possible disturbances; 2) Adjustment of action parameters and limits, such as whether to participate in voltage regulation, entry conditions, withdrawal conditions, etc.; 3) The adjustment of sag parameters and control parameters is based on the operating state of the power grid, such as the adjustment of short-circuit ratio. The optimization algorithm based on global information can effectively avoid the local optimal solution and make full use of the reactive power regulation ability of the plant.

The lower layer is the equipment layer, which is mainly responsible for: 1) Communicating with the upper layer and providing the basic operation information of the equipment; 2) Implement upper-layer delivery control policies; 3) Sent adjustment instructions of the control parameters delivered by the upper layer during steady state operation. The architecture of the proposed autonomous decentralized voltage control is illustrated in Figure 4.

The hierarchical coordination can ensure the continuous of dynamics, and the rapid autonomous reactive power response of a single unit can be realized based on the preset operating mode and control parameters (Derakhshan et al., 2023). After the fault is cleared, the adjustment of the single unit based on the global information optimization results helps the system voltage recovery, so that the plant switches to the steady-state operation mode, thereby improving the dynamic reactive power adjustment capability of the renewable energy plant and the voltage support capability of the PCC.

5.4 Future development trend

Although the voltage stability challenges of power systems with large-scale renewable energy have received significant attention, the research and implementation of dynamic voltage support are still in their early stages. This paper discusses the main achievements in voltage support, progressing from individual equipment to plant-level and coordinated control strategies, as presented in the first four sections.

However, due to the inherent complexity of power systems, the stochastic nature of disturbances, and the spatio-temporal multi-scale characteristics of the system response, several significant technical challenges remain to be explored:

1) The 10 ms Problem after Disturbance Clearing: As indicated by the analyses presented in the preceding sections, the response times of various reactive power resources differ considerably. The dynamic response time of PV converters and direct-drive wind turbines is typically greater than 20 ms, while that of DFIGs is approximately 60 ms (Wu and Zhang, 2022). The response time of static VAR generators (SVGs) is also more than 20 ms, and that of static VAR compensators (SVCs) is around 60 ms, whereas the response time of synchronous condensers exceeds 100 ms (Z. Rafiee et al., 2022). Consequently, within the initial 10 ms following a voltage transient, insufficient reactive power is typically provided by existing voltage support devices. Therefore, how to effectively leverage renewable energy converters and SVG devices to provide dynamic voltage support represents a crucial area for further investigation.
2) Equivalence of Deterministic Controllable Reactive Power Resources: As discussed previously, the dynamic reactive

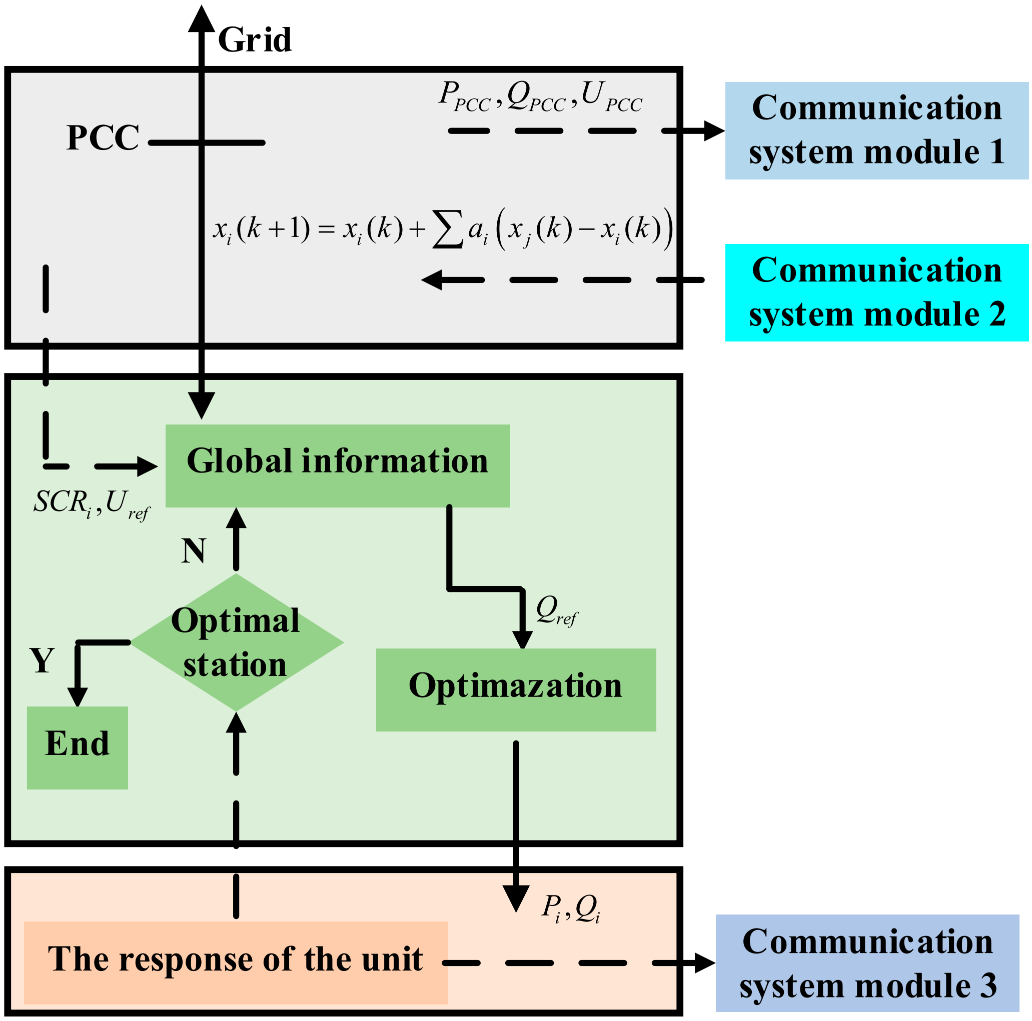

FIGURE 4
The architecture of the autonomous decentralized voltage control.

power compensation performance of PV and wind power converters within renewable energy plants is highly dependent on factors such as device type, operating state, and control strategy (Zhao et al., 2023), resulting in considerable randomness in the overall compensation effect. This inherent variability introduces significant uncertainty into the dynamic voltage support capabilities (Ghosh et al., 2023). An ideal approach involves organically integrating reactive power compensation equipment at the plant level, such as SVGs and synchronous condensers, with the distributed reactive power compensation provided by PV and wind power units, and achieving equivalent deterministic controllable reactive power through coordinated control strategies. Key research areas include accurately characterizing the reactive power compensation characteristics of renewable energy units and coordinating the capacity and response times of various compensation devices.

3) HVRT/LVRT Technology and Control Delay: Historically, HVRT and LVRT strategies have often been discussed in isolation. However, low-voltage and high-voltage faults can occur in rapid succession, with alternating intervals potentially spanning tens of milliseconds. Given that the typical response time of reactive power sources ranges from 20 ms to 30 ms, poorly coordinated control strategies can exacerbate voltage fluctuations, potentially leading to voltage instability [59]. Therefore, future research should focus on addressing the phenomenon of alternating low/high voltage conditions in renewable energy systems and enhancing the response speed of various reactive power resources.

4) Autonomous Decentralized Control for Dynamic Voltage Support in Renewable Energy Plants: This control technology necessitates the rapid acquisition and dynamic updating of global information within the plants, the application of multi-objective optimization algorithms incorporating global information, and the development of device-level cooperative control strategies. While global information from renewable energy units is obtained at the substation level, the impact of communication delays and the frequency of information exchange remains unclear. Furthermore, in terms of multi-objective optimization algorithms, establishing a

comprehensive objective function that effectively combines system stability with dynamic reactive power capabilities presents a valuable area for future research.

6 Conclusion

Focusing on dynamic voltage control in power systems with high penetration of renewable energy, this paper *examines* the research focus of reactive power/voltage regulation technologies, from renewable energy converters to auxiliary equipment. The development of dynamic voltage support technology within renewable energy plants is also *reviewed*, and the basic objectives and requirements of dynamic voltage support are defined. The basic idea of *an* autonomous decentralized control approach for multi-reactive power resources is proposed for dynamic voltage support.

According to the dynamic voltage support requirements of renewable energy plants, the article *identifies* the direction of further research work, *spanning* four key aspects. *Given* the increasing proportion of renewable energy in power systems, dynamic voltage support is a *critical* endeavor with strong engineering application potential. From the theoretical analysis of dynamic voltage support to its practical application, it is essential to integrate the advancements in renewable energy converters, reactive power compensation equipment, and the information systems of power plants to achieve effective dynamic voltage support and ensure the stability of power systems.

Author contributions

SG: Conceptualization, Data curation, Investigation, Methodology, Writing – review and editing. HZ: Conceptualization, Funding acquisition, Writing – original draft. XM: Investigation, Resources, Software, Writing – original draft. YZ: Formal Analysis, Investigation, Visualization, Writing – review and editing.

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References

Aboshady, F. M., Pisica, I., Zobaa, A. F., Taylor, G. A., Ceylan, O., and Ozdemir, A. (2023). Reactive power control of PV inverters in active distribution grids with high PV penetration. *IEEE Access* 11, 81477–81496. doi:10.1109/ACCESS.2023.3299351

Ahmidi, A., Guillaud, X., Besanger, Y., and Blanc, R. (2012). A multilevel approach for optimal participating of wind farms at reactive power balancing in transmission power system. *IEEE Syst. J.* 6, 260–269. doi:10.1109/JSYST.2011.2163003

Ahn, S. H., Gong, J. W., Jang, S. R., and Ryoo, H. J. (2013). "Design of high voltage DC power supply using asymmetric three phase resonant," in 2013 Abstracts IEEE International Conference on Plasma Science (ICOPS) (San Francisco, CA, USA: IEEE), 1. doi:10.1109/PLASMA.2013.6635185

Ahn, S.-H., Ryoo, H.-J., Gong, J.-W., and Jang, S. R. (2014). Low-ripple and high-precision high-voltage DC power supply for pulsed power applications. *IEEE T Plasma Sci.* 42, 3023–3033. doi:10.1109/TPS.2014.2333813

Alonso, A. M. S., Arenas, L. D. O., Brandao, D. I., Tedeschi, E., and Marafao, F. P. (2022). Integrated local and coordinated overvoltage control to increase energy feed-in and expand DER participation in low-voltage networks. *IEEE T Sustain Energ* 13, 1049–1061. doi:10.1109/TSTE.2022.3146196

Ambati, B. B., Kanjiya, P., and Khadkikar, V. (2015). A low component count series voltage compensation scheme for DFIG WTs to enhance fault ride-through capability. *IEEE T Energy Conver* 30, 208–217. doi:10.1109/TEC.2014.2351799

Asadollah, S., Zhu, R., and Liserre, M. (2020). Analysis of voltage control strategies for wind farms. *IEEE T Sustain Energ* 11, 1002–1012. doi:10.1109/TSTE.2019.2915667

Australian Energy Market Operator (2016). *Preliminary report-blacksystem event in South Australia on 28 september 2016*.

Bhyri, A. K., Senroy, N., and Saha, T. K. (2024). Enhancing the grid support from DFIG-based wind farms during voltage events. *IEEE T Power Syst.* 39, 733–744. doi:10.1109/TPWRS.2023.3239503

Blaabjerg, F., Yang, Y., Kim, K. A., and Rodriguez, J. (2023). Power electronics technology for large-scale renewable energy generation. *Proc. IEEE* 111, 335–355. doi:10.1109/JPROC.2023.3253165

Camal, S., Michiorri, A., and Kariniotakis, G. (2023). Reliable provision of ancillary services from aggregated variable renewable energy sources through forecasting of extreme quantiles. *IEEE T Power Syst.* 38, 1–15. doi:10.1109/TPWRS.2022.3198839

Chang, Y., Hu, J., and Yuan, X. (2020). Mechanism analysis of DFIG-based wind turbine's fault current during LVRT with equivalent inductances. *IEEE J. Em Sel. Top. P* 8, 1515–1527. doi:10.1109/JESTPE.2019.2956085

Chen, D., Hong, W., Zhang, S., Shen, X., Lin, Y., and Lin, H. (2023). A high power density low voltage static var generator based on wide band gap semiconductor devices. *IEEE Access* 11, 141753–141763. doi:10.1109/ACCESS.2023.3338366

Chen, Q., Bu, S., and Chung, C. Y. (2024). Small-signal stability criteria in power electronics-dominated power systems: a comparative review. *J. Mod. Power Syst. Cle* 12, 1003–1018. doi:10.35833/MPCE.2023.000526

Chen, X., Yan, L., Zhou, X., and Sun, H. (2018). A novel DVR-ESS-embedded wind-energy conversion system. *IEEE T Sustain Energ* 9, 1265–1274. doi:10.1109/TSTE.2017.2781287

Cheng, R., Shi, N., Maharjan, S., and Wang, Z. (2023). Automatic self-adaptive local voltage control under limited reactive power. *IEEE T Smart Grid* 14, 2851–2862. doi:10.1109/TSG.2022.3224463

Chow, J. H. (2023). Enabling inverter-based resource stability control in power systems with high renewable penetration. *CSEE J. Power Energy* 9, 1248–1250. doi:10.17775/CSEEJPES.2022.08000

Derakhshan, S., Shafiee-Rad, M., Shafiee, Q., and Jahed-Motlagh, M. R. (2023). Decentralized robust LMI-based voltage control strategy for autonomous inverter-interfaced multi-DG microgrids. *IEEE T Power Syst.* 38, 1–12. doi:10.1109/TPWRS.2022.3204625

Djalal, M. R., Robandi, I., and Prakasa, M. A. (2023). Stability enhancement of sulselrabar electricity system using mayfly algorithm based on static var compensator and multi-band power system stabilizer PSS2B. *IEEE Access* 11, 57319–57340. doi:10.1109/ACCESS.2023.3283598

Dong, Z., Li, Z., Du, L., Liu, Y., and Ding, Z. (2021). Coordination strategy of large-scale DFIG-based wind farm for voltage support with high converter capacity utilization. *IEEE T Sustain Energ* 12, 1416–1425. doi:10.1109/TSTE.2020.3047273

Du, K.-J., Ma, X.-P., Zheng, Z.-X., Hu, W., and Dong, K. (2021). LVRT capability improvement of DFIG-based wind turbines with a modified bridge-resistive-type SFCL. *IEEE T Appl. Supercon* 31, 1–5. doi:10.1109/TASC.2021.3091114

Fang, H., and Zhang, X. (2022). Improvement of low-voltage ride-through capability for wave energy conversion system. *IEEE T Power Electr.* 69, 8123–8133. doi:10.1109/TIE.2021.3109536

Fang, T., Zhou, Q., Ding, F., Wu, X., Li, Z., and Tang, H. (2021). Response time of reactive power based on different definitions and algorithms. *J. Mod. Power Syst. Cle* 9, 440–449. doi:10.35833/MPCE.2019.000085

Firouzi, M., and Gharehpetian, G. B. (2018). LVRT performance enhancement of DFIG-based wind farms by capacitive bridge-type fault current limiter. *IEEE T Sustain Energ* 9, 1118–1125. doi:10.1109/TSTE.2017.2771321

Flannery, P. S., and Venkataramanan, G. (2008). A fault tolerant doubly fed induction generator wind turbine using a parallel grid side rectifier and series grid side converter. *IEEE T Power Electr.* 23, 1126–1135. doi:10.1109/TPEL.2008.921179

Garcia, I., and Santana, R. (2024). Unified framework for the analysis of the effect of control strategies on on-load tap-changer's automatic voltage controller. *IEEE T Autom. Sci. Eng.* 21, 1539–1548. doi:10.1109/TASE.2023.3244606

Ge, H., Wang, B., Guo, Q., Sun, H., Lin, Y., Zhao, W., et al. (2022). Dynamic automatic voltage control system for ac-dc hybrid power grid with high proportion of renewable energy: design and application. *Proc. CSEE* 40, 5170–5178. doi:10.13334/j.0258-8013.pcsee.200375

Ghosh, R., Tummuru, N. R., and Rajpurohit, B. S. (2023). A new virtual oscillator-based grid-forming controller with decoupled control over individual phases and improved performance of unbalanced fault ride-through. *IEEE T Power Electr.* 70, 12465–12474. doi:10.1109/TIE.2023.3236069

Gong, X., Wang, X., and Cao, B. (2023). On data-driven modeling and control in modern power grids stability: survey and perspective. *Appl. Energ* 350, 121740. doi:10.1016/j.apenergy.2023.121740

Gui, Y., Nainar, K., Dimon Bendtse, J., Diewald, N., Florin, L., Yang, Y., et al. (2024). Voltage support with PV inverters in low-voltage distribution networks: an overview. *IEEE J. Em Sel. Top. P* 12, 1503–1522. doi:10.1109/JESTPE.2023.3280926

Hadavi, S., Rathnayake, D. B., Jayasinghe, G., Mehrizi-Sani, A., and Bahrani, B. (2022). A robust exciter controller design for synchronous condensers in weak grids. *IEEE T Power Syst.* 37, 1857–1867. doi:10.1109/TPWRS.2021.3110504

Hatziargyriou, N., Milanovic, J., Rahmann, C., Ajjarapu, V., Canizares, C., Erlich, I., et al. (2021). Definition and classification of power system stability – revisited and extended. *IEEE T Power Syst.* 36, 3271–3281. doi:10.1109/TPWRS.2020.3041774

He, X., Geng, H., and Mu, G. (2021). Modeling of wind turbine generators for power system stability studies: a review. *Sust. Energ Rev.* 143, 110865. doi:10.1016/j.rser.2021.110865

Heming, L., Shuhui, D., Yi, W., and Yazhao, R. (2013). Coordinated control of active and reactive power of PMSG-based wind turbines for low voltage ride through. *Trans. China Electrotech. Soc.* 28, 73–81. doi:10.19595/j.cnki.1000-6753.tces.2013.05.010

Huang, J., and Xu, Y. (2024). Multi-timescale coordinated control of wind power plant for supporting power system operation. *IEEE T Power Syst.* 40, 355–367. doi:10.1109/TPWRS.2024.3387537

Huang, L., Wang, D., Wang, X., Xin, H., Ju, P., Johansson, K. H., et al. (2024). Gain and phase: decentralized stability conditions for power electronics-dominated power systems. *IEEE T Power Syst.* 39, 7240–7256. doi:10.1109/TPWRS.2024.3380528

Huang, S., Wu, Q., Guo, Y., and Rong, F. (2019). Hierarchical active power control of DFIG-based wind farm with distributed energy storage systems based on ADMM. *IEEE T Sustain Energ* 11, 1528–1538. doi:10.1109/TSTE.2019.2929820

Ibrahim, T., Rubira, T. T. D., Rosso, A. D., Patel, M., Guggilam, S., and Mohamed, A. A. (2022). Alternating optimization approach for voltage-secure multi-period optimal reactive power dispatch. *IEEE T Power Syst.* 37, 3805–3816. doi:10.1109/TPWRS.2021.3133358

Ikram, M. K., Amrr, S. M., Asghar, M. S. J., Islam, T., and Iqbal, A. (2023). Voltage independent reactive current based sensor for static VAr control applications. *IEEE Sens. J.* 23, 10023–10031. doi:10.1109/JSEN.2023.3258696

Jiao, W., Chen, J., Wu, Q., Li, C., Zhou, B., and Huang, S. (2022). Distributed coordinated voltage control for distribution networks with DG and OLTC based on MPC and gradient projection. *IEEE T Power Syst.* 37, 680–690. doi:10.1109/TPWRS.2021.3095523

Joseph, A., Smedley, K., and Mehraeen, S. (2020). Secure high DER penetration power distribution via autonomously coordinated volt/VAR control. *IEEE T Power Deliv.* 35, 2272–2284. doi:10.1109/TPWRD.2020.2965107

Kanjiya, P., Ambati, B. B., and Khadkikar, V. (2014). A novel fault-tolerant DFIG-based wind energy conversion system for seamless operation during grid faults. *IEEE T Power Syst.* 29, 1296–1305. doi:10.1109/TPWRS.2013.2290047

Keskes, S., Salleem, S., Chrifi-Alaoui, L., and Ali Kammoun, M. B. (2021). Nonlinear coordinated passivation control of single machine infinite bus power system with static var compensator. *J. Mod. Power Syst. Cle* 9, 1557–1565. doi:10.35833/MPCE.2019.000173

Khan, M. A., Haque, A., and Kurukuru, V. S. B. (2021). Dynamic voltage support for low-voltage ride-through operation in single-phase grid-connected photovoltaic systems. *IEEE T Power Electr.* 36, 12102–12111. doi:10.1109/TPEL.2021.3073589

Lee, G.-S., Hwang, P.-I., and Moon, S.-I. (2021). Reactive power control of hybrid multi-terminal HVDC systems considering the interaction between the AC network and multiple LCCs. *IEEE T Power Syst.* 36, 4562–4574. doi:10.1109/TPWRS.2021.3056565

Li, G., Ma, F., Wang, Y., Weng, M., Chen, Z., and Li, X. (2020). Design and operation analysis of virtual synchronous compensator. *IEEE J. Em Sel. Top. P* 8, 3835–3845. doi:10.1109/JESTPE.2019.2943723

Li, H., Zhang, N., Fan, Y., Dong, L., and Cai, P. (2022). Decomposed modeling of controllable and uncontrollable components in power systems with high penetration of renewable energies. *J. Mod. Power Syst. Cle* 10, 1164–1173. doi:10.35833/MPCE.2020.000674

Li, X.-M., Zhang, X.-Y., Lin, Z.-W., and Niu, Y. G. (2018). An improved flux magnitude and angle control with LVRT capability for DFIGs. *IEEE T Power Syst.* 33, 3845–3853. doi:10.1109/TPWRS.2017.2788438

Liu, J.-H., Chu, C.-C., and Lin, Y.-Z. (2014). Applications of nonlinear control for fault ride-through enhancement of doubly fed induction generators. *IEEE J. Em Sel. Top. P* 2, 749–763. doi:10.1109/JESTPE.2014.2330358

Liu, T., and Wang, X. (2021). Transient stability of single-loop voltage-magnitude controlled grid-forming converters. *IEEE T Power Electr.* 36, 6158–6162. doi:10.1109/TPEL.2020.3034288

Liu, X., Xin, H., Zheng, D., Chen, D., and Tu, J. (2023). Transient stability of synchronous condenser Co-located with renewable power plants. *IEEE T Power Syst.* 39, 2030–2041. doi:10.1109/TPWRS.2023.3271025

Lu, J., Zhang, B., Hou, X., and Guerrero, J. M. (2023). A distributed control strategy for unbalanced voltage compensation in islanded AC microgrids without continuous communication. *IEEE T Power Electr.* 70, 2628–2638. doi:10.1109/TIE.2022.3169841

Martínez-Treviño, B. A., Aroudi, A. E., Valderrama-Blavi, H., Cid-Pastor, A., Vidal-Idiarte, E., and Martinez-Salamero, L. (2021). PWM nonlinear control with load power estimation for output voltage regulation of a boost converter with constant power load. *IEEE T Power Electr.* 36, 2143–2153. doi:10.1109/TPEL.2020.3008013

Mohiuddin, S. M., and Qi, J. (2022). Optimal distributed control of AC microgrids with coordinated voltage regulation and reactive power sharing. *IEEE T Smart Grid* 13, 1789–1800. doi:10.1109/TSG.2022.3147446

Mudaliyar, S., Duggal, B., and Mishra, S. (2020). Distributed tie-line power flow control of autonomous DC microgrid clusters. *IEEE T Power Electr.* 35, 11250–11266. doi:10.1109/TPEL.2020.2980882

Naderi, S. B., Negnevitsky, M., and Muttaqi, K. M. (2019). A modified DC chopper for limiting the fault current and controlling the DC-link voltage to enhance fault ride-through capability of doubly-fed induction-generator-based wind turbine. *IEEE T Ind. Appl.* 55, 2021–2032. doi:10.1109/TIA.2018.2877400

National Gid ESO (2019). *Technical report on the events of 9 august 2019*.

Naz, M. N., Imtiaz, S., Bhatti, M. K. L., Awan, Q., Siddique, M., and Riaz, A. (2021). Dynamic stability improvement of decentralized wind farms by effective distribution static compensator. *J. Mod. Power Syst. Cle* 9, 516–525. doi:10.35833/MPCE.2018.00422

Nguyen, H. M., Torres, J. L. R., Lekić, A., and Pham, H. V. (2021). MPC based centralized voltage and reactive power control for active distribution networks. *IEEE T Energy Conver* 36, 1537–1547. doi:10.1109/TEC.2021.3054844

Pal, A., Pal, D., and Panigrahi, B. K. (2023). A current saturation strategy for enhancing the low voltage ride-through capability of grid-forming inverters. *IEEE T Circuits-II* 70, 1009–1013. doi:10.1109/TCSII.2022.3221134

Palanimuthu, K., Mayilsamy, G., Lee, S. R., Jung, S. Y., and Joo, Y. H. (2023). Fault ride-through for PMVG-based wind turbine system using coordinated active and reactive power control strategy. *IEEE T Power Electr.* 70, 5797–5807. doi:10.1109/TIE.2022.3194638

Qi, J., Zhao, W., and Bian, X. (2020). Comparative study of SVC and STATCOM reactive power compensation for prosumer microgrids with DFIG-based wind farm integration. *IEEE Access* 8, 209878–209885. doi:10.1109/ACCESS.2020.3033058

Qiao, J., Lu, Z., Yong, M., Liu, J., Xie, Z., and Wang, H. (2009). New dynamic equivalence method for grid-connected wind farm. *Trans. China Electrotech. Soc.* 24, 209–213. doi:10.19595/j.cnki.1000-6753.tces.2009.04.033

Rafiee, Z., Heydari, R., Rafiee, M., Aghamohammadi, M. R., and Blaabjerg, F. (2022). Enhancement of the LVRT capability for DFIG-based wind farms based on short-circuit capacity. *IEEE Syst. J.* 16, 3237–3248. doi:10.1109/JSYST.2022.3153887

Rajeev, M., and Agarwal, V. (2020). Low voltage ride-through capability of a novel grid connected inverter suitable for transformer-less solar PV–grid interface. *IEEE T Ind. Appl.* 56, 2799–2806. doi:10.1109/TIA.2020.2979134

Richard, L., Al-Masood, N., Saha, T. K., Tushar, W., and Gu, H. (2020). Optimal allocation of synchronous condensers in wind dominated power grids. *IEEE Access* 8, 45400–45410. doi:10.1109/ACCESS.2020.2977941

Samende, C., Gao, F., Bhagavathy, S. M., and McCulloch, M. (2021). Decentralized voltage control for efficient power exchange in interconnected DC clusters. *IEEE T Sustain Energ* 12, 103–115. doi:10.1109/tste.2020.2984920

Shang, L., Dong, X., Liu, C., and He, W. (2022). Modelling and analysis of electromagnetic time scale voltage variation affected by power electronic interfaced voltage regulatory devices. *IEEE Tran. Power Syst.* 37, 1102–1112. doi:10.1109/TPWRS.2021.3100606

Sun, L., Sun, K., Hou, Y., and Hu, J. (2020). Optimized autonomous operation control to maintain the frequency, voltage and accurate power sharing for DGs in islanded systems. *IEEE T Smart Grid* 11, 3885–3895. doi:10.1109/TSG.2020.2992802

Tamboli, A. S., and Jadhav, H. T. (2018). "Hybrid STATCOM for reactive power compensation," in 2018 International Conference on Current Trends towards Converging Technologies (ICCTCT) (Coimbatore, India: IEEE), 1–5. doi:10.1109/ICCTCT.2018.8550889

Tong, N., He, S., Lin, X., Zheng, P., and Li, Z. (2015). RBFNN-based adaptive crowbar protection scheme designed for the doubly fed induction generator in large-scale wind farms. *IEEJ T Electr. Electr.* 10, 644–652. doi:10.1002/tee.22131

Torkaman, H., and Keyhani, A. (2018). A review of design consideration for Doubly Fed Induction Generator based wind energy system. *Electr. Pow. Syst. Res.* 160, 128–141. doi:10.1016/j.epsr.2018.02.012

Wang, B., Guo, Q., Sun, H., Li, H., Luo, J., Zhang, B., et al. (2013). Research on generation and execution of coordination strategy for Bi-directional and interactive coordinated voltage control between provincial and district levels. *Power Syst. Technol.* 37, 3426–3432. doi:10.13335/j.1000-3673.pst.2013.12.004

Wang, C., Li, Z., Liang, J., Wang, J., Yang, M., and Dong, X. (2016). "A dynamic equivalent method of wind farm considering wind farm dispersity and wind turbine difference," in 2016 IEEE Industry Applications Society Annual Meeting (Portland, OR, USA: IEEE), 1–6. doi:10.1109/IAS.2016.7731945

Wang, M., Guo, J., Ma, S., Zhang, X., Wang, T., and Luo, K. (2024). A novel decentralized frequency regulation method of renewable energy stations based on minimum reserve capacity for renewable energy-dominated power systems. *IEEE T Power Syst.* 39, 3701–3714. doi:10.1109/TPWRS.2023.3286459

Wang, S., Duan, J., Shi, D., Xu, C., Li, H., Diao, R., et al. (2020). A data-driven multi-agent autonomous voltage control framework using deep reinforcement learning. *IEEE T Power Syst.* 35, 4644–4654. doi:10.1109/TPWRS.2020.2990179

Wang, Y., Wang, L., and Jiang, Q. (2021). Impact of synchronous condenser on sub/super-synchronous oscillations in wind farms. *IEEE T Power Deliv.* 36, 2075–2084. doi:10.1109/TPWRD.2020.3019481

Wang, Y., Yan, G., Mu, G., and Yang, C. (2022). Research on aggregation modeling of grid connected VSC under AC current control scale. *Proc. CSEE* 42, 2900–2909. doi:10.13334/j.0258-8013.pcsee.220294

Wu, H., and Wang, X. (2021). Passivity-based dual-loop vector voltage and current control for grid-forming VSCs. *IEEE T Power Electr.* 36, 8647–8652. doi:10.1109/TPEL.2020.3048239

Wu, Q.-H., Bose, A., Singh, C., Chow, J. H., Mu, G., Sun, Y., et al. (2023a). Control and stability of large-scale power system with highly distributed renewable energy generation: viewpoints from six aspects. *CSEE J. Power Energy* 9, 8–14. doi:10.17775/CSEEJPES.2022.08740

Wu, Q.-H., Lin, Y., Hong, C., Su, Y., Wen, T., and Liu, Y. (2023b). Transient stability analysis of large-scale power systems: a survey. *CSEE J. Power Energy* 9, 1284–1300. doi:10.17775/CSEEJPES.2022.07110

Wu, Y., and Zhang, P. (2022). Online monitoring for power cables in DFIG-based wind farms using high-frequency resonance analysis. *IEEE T Sustain Energ* 13, 378–390. doi:10.1109/TSTE.2021.3113017

Xia, A., Qiao, Y., Lu, Z., and Ruan, J. (2016). Effects of aggregated PMSG wind farm model error on transient stability analysis of power systems. *Power Syst. Technol.* 40, 341–347. doi:10.13335/j.1000-3673.pst.2016.02.002

Xie, D., Xu, Z., Yang, L., Ostergaard, J., Xue, Y., and Wong, K. P. (2013). A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support. *IEEE T Power Syst.* 28, 3302–3310. doi:10.1109/TPWRS.2013.2240707

Xu, Q., Xu, Y., Zhang, C., and Wang, P. (2020). A robust droop-based autonomous controller for decentralized power sharing in DC microgrid considering large-signal stability. *IEEE T Ind. Inf.* 16, 1483–1494. doi:10.1109/TII.2019.2950208

Xu, S., Xue, Y., and Chang, L. (2021). Review of power system support functions for inverter-based distributed energy resources- standards, control algorithms, and trends. *IEEE Open J. Power Electron.* 2, 88–105. doi:10.1109/OJPEL.2021.3056627

Yang, C., Peng, S., Chen, X., Qiao, Y., Wang, X., and Liu, J. (2019). "Wind farm active voltage regulation strategy of transient support improvement," in 8th Renewable Power Generation Conference (RPG 2019) (Shanghai, China: IET), 1–4. doi:10.1049/cp.2019.0394

Zhang, H., Xiang, W., Lin, W., and Wen, J. (2021). Grid forming converters in renewable energy sources dominated power grid: control strategy, stability, application, and challenges. *J. Mod. Power Syst. Cle* 9, 1239–1256. doi:10.35833/MPCE.2021.000257

Zhang, N., Jia, H., Hou, Q., Zhang, Z., Xia, T., Cai, X., et al. (2023). Data-driven security and stability rule in high renewable penetrated power system operation. *Proc. IEEE* 111, 788–805. doi:10.1109/JPROC.2022.3192719

Zhang, X., Wu, Z., Sun, Q., Gu, W., Zheng, S., and Zhao, J. (2024). Application and progress of artificial intelligence technology in the field of distribution network voltage Control: a review. *Sust. Energ Rev.* 192, 114282. doi:10.1016/j.rser.2024.114282

Zhao, F., Wang, X., Zhou, Z., Sun, Y., Harnefors, L., and Zhu, T. (2023). Robust grid-forming control with active susceptance. *IEEE T Power Electr.* 38, 2872–2877. doi:10.1109/TPEL.2022.3223511

Zhou, D., and Blaabjerg, F. (2018). Optimized demagnetizing control of DFIG power converter for reduced thermal stress during symmetrical grid fault. *IEEE T Power Syst.* 33, 10326–10340. doi:10.1109/TPEL.2018.2803125

Zhu, D., Zou, X., Deng, L., Huang, Q., Zhou, S., and Kang, Y. (2017). Inductance-emulating control for dfig-based wind turbine to ride-through grid faults. *IEEE T Power Syst.* 32, 8514–8525. doi:10.1109/TPEL.2016.2645791