

Overview of Coordinated Control Strategies of Wind Farm Integrated MMC-HVDC

Jingyi Zhang, Huiru Yang, Zhen Tian, *Member, IEEE*, Meng Huang, Pan Feng, Fei Liu, Zhe Chen, Ruanming Huang, *Member, IEEE*, and Xiaoming Zha, *Senior Member, IEEE*

Abstract—With the development of onshore power grid projects in desert, Gobi and desertified regions as well as offshore wind power projects, electric energy requires long-distance transmission due to insufficient local consumption. Modular multilevel converter based high-voltage direct current (MMC-HVDC) has become the mainstream transmission technology for large-scale remote wind farm integration. However, MMC-HVDC electrically decouples wind farms from the main grid, and its interaction with wind farms can trigger various oscillations. In addition, the MMC-HVDC connected wind farm system differs from single-converter grid-connected systems in structure, equipment complexity, and fault evolution, leading to problems such as low inertia, wideband oscillations and poor fault ride-through. To address these issues, coordinated control strategies considering dynamic interactions between wind farms and MMC-HVDC have been widely studied. This paper thus reviews such coordinated control strategies from three aspects: first, introducing common engineering symmetrical monopole/bipolar MMC-HVDC system structures; second, summarizing grid frequency sensing methods and inertia support control strategies for MMC-HVDC and wind farms; third, discussing coordinated oscillation suppression and fault ride-through control strategies, considering direct current (DC)-side faults, alternating current (AC)-side grid faults, and wind farm area faults. Finally, it summarizes deficiencies of existing studies for each challenge and prospects future research directions for *MMC-HVDC connected wind farm systems*.

Index Terms—Wind farm, Modular multilevel converter based high-voltage direct current (MMC-HVDC), Coordinated control, Dynamic interactions.

Manuscript received October 29, 2024; revised November 20, 2025 and February 18, 2026; accepted March 18, 2026. Date of publication June 25, 2026. Date of current version April 29, 2026.

This work was supported by Smart Grid-National Science and Technology Major Project (Novel Grid-Integrated Transmission System for Far-Offshore Wind Power, No. 2024ZD0801300).

Jingyi Zhang, Huiru Yang, Zhen Tian, Meng Huang, Pan Feng, Fei Liu, Xiaoming Zha are with School of Electrical Engineering and Automation, Hubei Key Laboratory of Power Equipment & System Security for Integrated Energy, Wuhan University, Wuhan 430072, China (e-mail: zhjydyx@whu.edu.cn, 2025282070100@whu.edu.cn, ztian.ee@whu.edu.cn; meng.huang@whu.edu.cn; 2023202070069@whu.edu.cn; lf_dyj@whu.edu.cn; xmzha@whu.edu.cn).

Zhe Chen is with State Grid Shanghai Electric Power Company, Shanghai 200122, China (e-mail: jennychen_0212@163.com).

Ruanming Huang is with Economic and Technology Research Institute, State Grid Shanghai Electric Power Company, Shanghai 200122, China (e-mail: hrmjobhrms@163.com).

(Corresponding Author: Zhen Tian)

Digital Object Identifier 10.30941/CESTEMS.2026.00015

I. INTRODUCTION

In recent years, the new energy generation technology has been developing rapidly. Among them, wind power generation technology has been widely used due to its low cost, large storage capacity, mature technology, etc. As wind farm scale and transmission distance increase, the transmission technology of wind power has also changed. High-voltage alternating current (HVAC) systems exist with high cost, limited transmission capacity, high loss, and other issues. Line commutated converter based high voltage direct current (LCC-HVDC) system is prone to commutation failure, and successive commutation failures can affect the safe and stable operation of the system. In contrast, the modular multilevel converter based high-voltage direct current (MMC-HVDC) system has become an ideal way for wind power long-distance transmission due to its strong controllability, fast response speed, and more economical long-distance transmission [1]-[3].

With conventional control schemes, wind turbines and the MMC-HVDC cannot respond to the grid's frequency deviations by releasing or absorbing energy [4]. Moreover, the MMC-HVDC system isolates the wind farm from the grid, which makes the wind farm also unable to sense the frequency change. The above reasons make the inertia of the MMC-HVDC connected wind farm system low, so that the frequency stability problem of the system is serious. The importance of inertia and damping to maintain the system's frequency stability was demonstrated by the blackout in the UK on August 9, 2019 [5]. Therefore, there is an urgent need to utilize the frequency regulation capability of the wind farm and the MMC-HVDC system and change the existing control methods to realize the frequency support of the MMC-HVDC connecting the wind farm system to the power grid. To improve the frequency stability of the system, there is an urgent need to change the existing control strategy to coordinate the frequency regulation capability of the wind farm and the MMC-HVDC system. Frequency regulation control strategies that consider coordinating the wind farm and MMC-HVDC must be proposed.

Current research also focuses on the oscillation suppression and fault ride-through problem for the MMC-HVDC connected wind farm. The interaction between the wind farm and MMC-HVDC causes multiform oscillation problems, so it is necessary to clarify this interaction. The corresponding

coordinated oscillation suppression methods are investigated according to the oscillation mechanism. As for transient analysis, the system structure, equipment complexity, and fault development characteristics of MMC-HVDC connected wind farms differ from those of a single converter grid-connected system. Failure in any position will affect the operation of the whole system and the safety of the equipment. So, it is necessary to develop a new type of fault ride-through scheme. However, most literature only studies grid-connected wind farms or the MMC-HVDC system connected to active networks [6]-[11]. For the MMC-HVDC connected wind farm system, one party only responds when the other sends a command. If the response is not made in time or the command is sent too late, the system's operation will be affected. Therefore, it is necessary to coordinate the wind farm and MMC-HVDC, reasonably arrange their control timing, and study the coordinated control strategy for the MMC-HVDC connected wind farm.

There have been a number of overviews of the wind farm or the MMC-HVDC. Although [12]-[14] detail the oscillation analysis methods and suppression strategies for wind turbines and the MMC-HVDC system, respectively, the analysis of the interaction between them is missing. Ref. [15] focuses on the aspects of frequency regulation, oscillation suppression, and fault protection of the MMC-HVDC connected wind farm, but lacks a detailed description of the coordinated control.

Based on the preceding analysis, it is clear that while several excellent reviews have explored the system of MMC-HVDC connecting with wind farm, and others have provided in-depth analysis on specific issues like subsynchronous oscillation or frequency regulation, a critical gap in the literature remains. There is a lack of a systematic review centered on coordinated control strategies as a framework for managing the complex "dynamic interactions" between wind farm and MMC-HVDC systems. Furthermore, many emerging methods and new insights from the rapid technological advancements in recent years have yet to be systematically summarized. We argue that the fundamental challenge in this domain lies not in controlling each subsystem in isolation, but in coordinating them to achieve system-level stability and efficiency. The key issues of frequency regulation, oscillation suppression, and fault ride-through are not independent challenges; rather, they are physically coupled phenomena rooted in the same dynamic interaction process.

To fill this gap, this paper presents a comprehensive review from a unified perspective of coordinated control. We uniquely structure our analytical framework around the three key challenges, and systematically summarize the state-of-the-art coordinated control strategies for each challenge. Meanwhile, based on in-depth discussion, we identify the limitations of existing studies and point out future research directions for each field. This paper aims to provide a clear and logical framework for researchers and engineers to understand and address the core issues of MMC-HVDC connected wind farm systems, as well as to present the

deficiencies of current research and future development trends.

II. SYSTEM STRUCTURE AND BASIC CONTROL STRATEGY FOR MMC-HVDC CONNECTED WIND FARM

A. Structure of MMC-HVDC connected wind farm System

The basic structure of the MMC-HVDC connected wind farm is shown in Fig. 1. According to the connection mode of the converter in the system, the MMC-HVDC connected wind farm projects are mainly divided into symmetrical monopole structure (pseudo-bipolar structure) and symmetrical bipolar structure (true bipolar structure) [16]. The two systems' internal structure is the same: Each phase of the bridge arm adopts the structure of cascaded modular multilevel converter (MMC) with bridge arm inductance. Symmetrical monopole systems typically employ cables as direct current (DC) transmission lines, whereas symmetrical bipolar systems typically employ overhead lines as DC transmission lines. In addition, the symmetrical monopole system has no real ground loop, and only one MMC for one side exists. The symmetrical bipolar system has a real ground loop at the neutral point and two MMCs on the same side. If one pole is blocked due to a fault, the other pole still can provide half of the transmission capacity, enhancing the system's reliability and flexibility [17]. The overall MMC-HVDC connected wind farm projects are given in Table I.

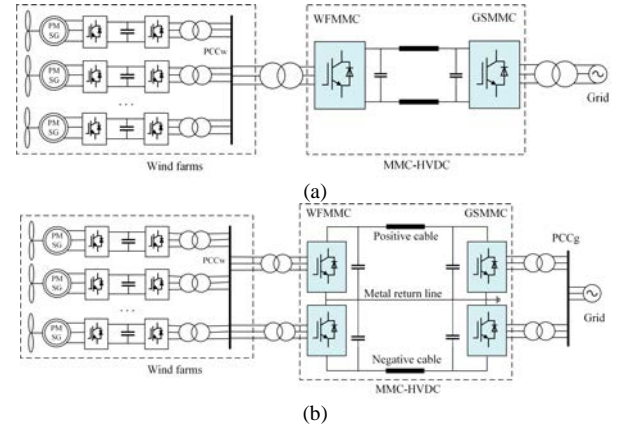


Fig. 1. The system structure of the MMC-HVDC connected wind farms. (a) Schematic of symmetrical monopole MMC-HVDC connected wind farm. (b) Schematic of symmetrical bipolar MMC-HVDC connected wind farms

B. The Basic Control Strategy for MMC-HVDC connected wind farm

The basic control for the MMC-HVDC connected wind farm system can be divided into two parts: the control for the MMC-HVDC and the control of the wind farm. The MMC-HVDC system includes the wind farm side MMC (WFMMC) and grid side MMC (GSMMC). Since the wind farm is a passive system, the control goal of WFMMC is to provide a stable AC voltage and frequency for the wind farm to connect to the grid. Therefore, the WFMMC generally adopts a voltage-frequency (V/f) control strategy to control the voltage and frequency of the AC collection line of the wind farm [4].

TABLE I
MMC-HVDC CONNECTED WIND FARM PROJECTS [15]-[16]

Project	Investment time	Wiring method	Cables/overhead lines	Voltage level (kV)	Capacity (MW)
Rudong MMC-HVDC System	2021	Symmetrical monopole structure	Submarine cables	± 400	1100
German BorWin1	2010	Symmetrical monopole structure	DC cable	± 150	400
Yangjiang Qingzhou Offshore Wind Power Transmission Project	Expected to be commissioned in 2024	Symmetrical monopole structure	Submarine cables	± 500	2000
German BorWin6	Expected to be commissioned in 2027	Symmetrical monopole structure	DC cable	± 320	1030
Xiamen MMC-HVDC Project	2015	Symmetrical bipolar structure	DC cable	± 320	1000
Zhangbei MMC-HVDC Project	2020	Symmetrical bipolar structure	Overhead line	± 500	3000

The main control goal of GSMMC is to establish a stable DC voltage to meet the stable access of WFMMC. GSMMC usually utilizes the voltage and current double closed-loop control structure to control DC voltage/reactive power (U_{dc}/Q) or active power/reactive power (P/Q) [4]. The symmetrical monopole system usually uses DC voltage as the control target because there is only one converter station at the receiving end. In comparison, the symmetrical bipolar system can use master-slave control mode [15]. One GSMMC is the main grid converter station and works in constant DC voltage mode. The other GSMMC works in constant power mode. Assuming GSMMC1 as the master station and GSMMC2 as the slave station, the operational characteristics of master-slave control are shown in Fig. 2.

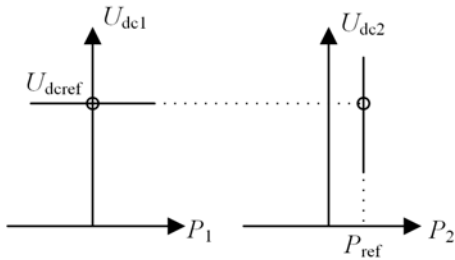


Fig. 2. Operation characteristics of master-slave control mode [15].

The control objective of wind turbines is to deliver stable, active, and reactive power to the grid. Therefore, the grid-side converter (GVSC) of a wind turbine usually adopts the same U_{dc}/Q control mode as the GSMMC to provide a constant DC voltage to the machine-side converter (WVSC). The WVSC usually operates in maximum power point tracking (MPPT) mode by controlling the generator torque and making the wind turbine run at a variable speed to capture the maximum wind energy [4].

As the existing literature [18]-[19] has provided detailed introductions to MMC-HVDC-integrated wind farm systems and MMC topologies, these aspects will not be repeated in this paper.

C. Control Problems and Challenges for MMC-HVDC connected wind farm

In the process of building a new power system dominated by renewable energy, the coordinated operation of MMC-HVDC systems with large-scale wind farms will encounter problems and challenges primarily in three core areas: inertia support, fault ride-through, and wideband oscillation.

In the inertia support domain, the MMC-HVDC system,

lacking rotating mass, needs to emulate the inertia response characteristics of synchronous generators through power electronic control. The core problem lies in the significant time delay present in the virtual inertia response, primarily originating from power command calculation, communication transmission, and the cumulative effects of control cycles. Simultaneously, the random fluctuations of wind power further increase the difficulty of frequency regulation, making traditional active power-frequency (P-f) droop control inadequate for dynamically matching system inertia requirements. In multi-source coordination scenarios, the inertia support capability of the wind farm and the MMC is constrained by operating points, and response mismatch among units under a distributed control architecture can trigger power counter-regulation phenomena. The key challenge focuses on the uncertainty of dynamic stability boundaries: In high-penetration renewable energy systems, virtual inertia control parameters exhibit strong coupling characteristics with grid strength, and universal design guidelines are currently lacking. Furthermore, inertia support requires the rapid release or absorption of substantial energy within a short period, while the limited capacity of DC capacitors and wind turbine DC-link capacitors constitutes an energy storage bottleneck.

In the fault ride-through domain, during DC-side faults, the discharge of MMC submodule capacitors causes fault current rise rates exceeding 5 kA/ms, and traditional blocking strategies easily induce DC overvoltage risks. Blockage of power transfer paths during bipolar short-circuit faults can trigger AC-side over-frequency issues. When asymmetrical faults occur in the AC grid, phase power imbalance in the MMC leads to conflicts between negative-sequence current suppression objectives and active power support requirements. Notably, the interaction between wind turbine converter low-voltage ride-through control and MMC fault response strategies can excite subsynchronous oscillations, forming a chain-fault mechanism. More severe compound fault scenarios expose response mismatch defects in existing hierarchical control architectures. The core challenge in this domain lies in the dynamic maintenance of power balance during faults, necessitating rapid power deficit compensation under safety constraints while avoiding maloperation of protection devices.

In the wideband oscillation domain, MMC and wind turbine converters exhibit multiple resonance points within the 10 Hz to 1 kHz frequency band; overlapping impedance

characteristics readily induce subsynchronous oscillation or high-frequency resonance. The interaction between phase-locked loop (PLL) bandwidth and grid strength significantly impacts system stability: Reduced PLL frequency under weak grid conditions may excite low-frequency oscillations. Concurrently, the distributed structure of wind farm clusters and the MMC obscures oscillation propagation paths, making it difficult for traditional FFT analysis methods to accurately identify the dominant oscillation source. The technical challenge in this area centers on the limitations of small-signal impedance models: These models neglect nonlinear characteristics such as insulated gate bipolar transistor (IGBT) switching transients, while the dimensionality of the system impedance matrix across multiple operating points complicates stability analysis. Active damping control has potential side effects: Damping injection may alter the phase characteristics of the system impedance, thereby inducing new resonance points. Therefore, suppressing wideband oscillations requires coordinated consideration of coupling mechanisms across different frequency bands and the design of synergistic control strategies to avoid the amplification of power fluctuations.

Deep coupling mechanisms exist simultaneously among the above three domains: Power fluctuations induced by inertia support may trigger wideband oscillations, subsequently weakening fault ride-through capability and creating a risk of cascading failure. Multi-timescale coordination constitutes a key challenge: The control objectives for inertia response, oscillation suppression, and fault ride-through exhibit temporal conflicts. Current standardization systems have not yet covered comprehensive “inertia-oscillation-fault” performance assessment, and standards lack unified testing procedures targeting system-level resilience.

III. COORDINATED FREQUENCY CONTROL FOR MMC-HVDC CONNECTED WIND FARM

With the increased use of renewable energy sources such as wind power, the problem of frequency stability of the power system is becoming more and more prominent. Relevant regulations on MMC-HVDC connected wind farm systems are as follows [20]: 1) The system does not go off-grid under ± 2.5 Hz/s frequency change; 2) the system can provide inertia support in response to grid frequency change; 3) the system has the ability of automatic adjustment. The system can automatically adjust the active power reference value when the grid frequency deviation reaches the specified value. To meet the grid-connected frequency requirements, frequency control strategies are required to coordinate the MMC-HVDC with the wind farm to provide inertia response or frequency regulation support [21]. To make the existing projects in operation also have the ability of frequency regulation, under the condition that no additional energy device is installed, the control of additional virtual inertia is usually used to improve the frequency support capacity. The inertial support energy source of the MMC-HVDC system is the capacitor of the submodules (SMs). The inertial support energy of the wind farm is derived from the rotor kinetic energy and wind energy [22].

A. Frequency Regulation Methods for MMC-HVDC

Currently, the frequency regulation methods of MMC-HVDC can be divided into two types: PLL-based frequency and DC voltage droop control, and phase-locked loop-less frequency response control strategy. Although the two control structures are different, both use the energy of the capacitors of the SMs of the receiving end converter station as the energy source for frequency regulation.

1) PLL-based frequency and DC voltage droop control

The control block diagram for PLL-based frequency and DC voltage droop control is shown in Fig. 3. The principle of this control strategy is as follows: After the grid frequency receives a perturbation, the DC voltage of the MMC-HVDC system changes accordingly, which makes the MMC submodule capacitor release or absorb energy immediately. The WFMMC establishes the wind farm side frequency based on the DC voltage deviation. Then, the wind farm responds to the GSMMC side’s frequency change and provides frequency support for the grid [22]-[24].

The equation of the GSMMC DC voltage control is expressed as:

$$U_{\text{dcref}} = \Delta U_{\text{dc}} + U_{\text{dcN}} = K_{\text{dc}} \Delta f + U_{\text{dcN}} \quad (1)$$

The WFMMC frequency control equation is:

$$f_{\text{WFref}} = K_{\text{wf}} \Delta U_{\text{dc}} + f_{\text{WFN}} \quad (2)$$

where U_{dcref} is the DC voltage reference of the GSMMC constant DC voltage control loop; ΔU_{dc} is the DC voltage fluctuation; U_{dcN} is the DC voltage rated value; Δf is the frequency fluctuation of the power grid; f_{WFref} and f_{WFN} are the frequency reference and frequency rated value of the WFMMC; K_{dc} and K_{wf} are the constants. K_{dc} can be artificially selected based on the inertia time constants provided by the GSMMC.

Combining (1) and (2), it can be seen that $\Delta f_{\text{wf}} = K_{\text{dc}} K_{\text{wf}} \Delta f$. The larger the values of K_{dc} and K_{wf} , the larger the MMC-HVDC DC voltage deviation and the frequency deviation of the WFMMC, and the larger the active power support provided by the MMC-HVDC system and wind farm. It is important to note that both DC voltage and wind farm frequency fluctuations should be limited to a specific range to maintain system stability. Refs. [25]-[26] propose a frequency regulation control strategy considering that the DC voltage is stable. This method can automatically adjust the frequency droop coefficient and moderately adjust the active power reference value to reduce the overshooting of the DC voltage in the regulation process.

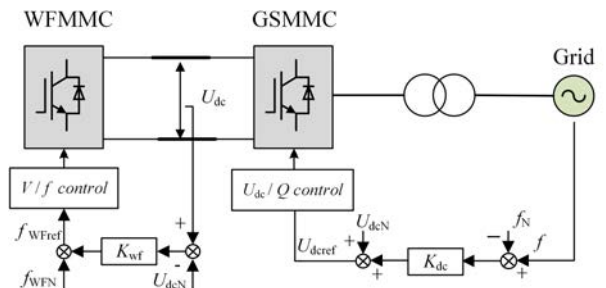


Fig. 3 PLL-based frequency and DC voltage droop control.

2) Frequency response control without PLL

There are two types of frequency response control strategies that are not PLL-based: virtual synchronous machine (VSG) control [27] and capacitor-inertia-based PLL-less control [28]. Both control methods give the converter voltage source characteristics without needing phase locking to external voltages. It can provide active power support capability to the grid and is suitable for weak grids.

3) Virtual synchronous generator control

The control block diagram for virtual synchronous generator control is shown in Fig. 4. The VSG control simulates the rotor equations of motion of the synchronous generator (SG) as shown in (3), and generates a reference phase for the Park transformation, which simulates the primary frequency regulation characteristics of the generator.

$$\begin{cases} J \frac{d\omega}{dt} = \frac{P_{\text{ref}}}{\omega_N} - \frac{P_{\text{grid}}}{\omega_N} - D(\omega - \omega_N) \\ \frac{d\delta}{dt} = \omega - \omega_N \end{cases} \quad (3)$$

where J is the virtual inertia; D is the virtual damping coefficient; P_{ref} and P_{grid} are the active power reference and active power output, respectively; ω and ω_N are the actual angular speed and rated angular speed angular frequency, respectively; θ is the phase angle reference of the output voltage.

The reactive power loop is based on the reactive power-voltage droop characteristic and simulates the excitation regulation system of a generator, as shown in (4). The reactive output power can be controlled by changing the output AC voltage.

$$Q_{\text{ref}} - Q_e = -k_q (U_N - E) \quad (4)$$

where k_q is the reactive loop droop coefficient; Q_{ref} and Q_e are the reactive power reference and output reactive power, respectively; U_N is the rated voltage value; E is the voltage reference amplitude for the GSMMC.

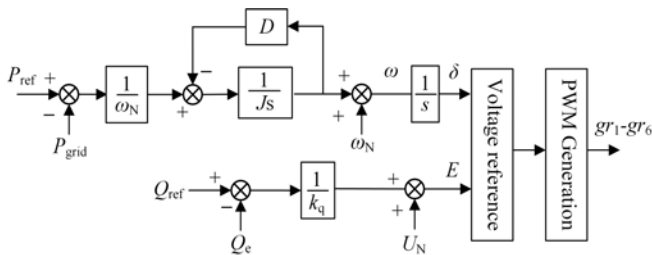


Fig. 4. Virtual synchronous machine control.

4) Capacitor-inertia-based control

The control block diagram for capacitor-inertia-based PLL-less control is shown in Fig. 5. Neglecting the damping term, the rotor equation of the SG can be rewritten as:

$$P_m - P_e = J_m \omega_m \frac{d\omega_m}{dt} \quad (5)$$

The expression for the active power output of an SG is (6):

$$P_e = \frac{3E_f U_g}{X_g} \sin\delta = \frac{3\psi\omega_m U_g}{\sqrt{2}X_g} \sin\delta \quad (6)$$

where P_m and P_e are the mechanical power and electromagnetic power of the SG, respectively; J_m is the inertia of the SG; ω_m is the rotor speed; E_f is the induction voltage; U_g is the RMS voltage value for the grid-connection point; ψ is the air gap flux of the SG; δ is the phase angle difference between the grid voltage and the GSMMC output voltage; X_g is the equivalent reactance between the converter station and the grid-connection point.

The synchronous generator has a self-synchronisation capability using the kinetic energy stored in the rotor of the synchronous machine. When the grid frequency decreases, the power angle difference increases, and the synchronous generator's output active power P_e will increase. Because of the unbalanced torque, the rotor of the synchronous machine will decelerate. According to the proportionality between rotor speed and output frequency, the output frequency of the synchronous machine will also decrease until it is equal to the grid's frequency.

For the MMC-HVDC system, the GSMMC sub-module capacitance can be equated to the capacitance connected in parallel to the DC side of the GSMMC. Assuming that each sub-module capacitance value is C_{sm} , the equivalent capacitance value is $6C_{\text{sm}}/N$ [29]. The relationship between the dynamic process of energy storage of the equivalent capacitor and the DC voltage can be expressed as (7):

$$P_{\text{WF}} - P_{\text{grid}} = C_{\text{eq}} U_{\text{dc}} \frac{dU_{\text{dc}}}{dt} \quad (7)$$

P_{grid} can be expressed as:

$$P_{\text{grid}} = \frac{3U_{\text{rec}} U_g}{X_g} \sin\delta = \frac{3mU_{\text{dc}} U_g}{2\sqrt{2}X_g} \sin\delta \quad (8)$$

where P_{WF} is the output active power of the wind farm; U_{dc} is the DC voltage for the GSMMC; U_{rec} is the output AC voltage root-mean-square (rms) value of GSMMC; m is the modulation ratio of the GSMMC.

Based on (5)-(8), the GSMMC also has a self-synchronisation capability similar to that of a synchronous machine if the DC voltage output from the GSMMC is equated to the rotor speed of the synchronous generator.

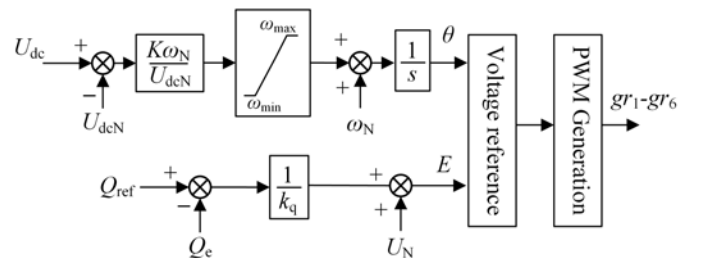


Fig. 5. Capacitor-inertia-based control.

Because of the strong correlation between the DC voltage and the MMC submodule voltage in the conventional control of the MMC-HVDC system, it is impossible to set aside the DC voltage and control the MMC energy independently to achieve stronger power support. Much of the literature extends on the basis of the capacitor-inertia-based PLL-less control.

TABLE II

COMPARISON OF EXISTING COORDINATED FREQUENCY CONTROL METHODS			
Ref.	Converter engaged in frequency regulation	Is the U_{sm} decoupled from the U_{dc}	Method of using the stored energy of the converter
[27]	GSMC	No	Establish the relationship between active output power and output frequency.
[28]	GSMC	No	Establish the relationship between U_{dc} and output frequency f .
[30]	GSMC	Yes	Establishes the relationship between W_{total} and the output frequency f .
[31]	GSMC, WFMMC	Yes	Establishes the relationship between W_{total} and the output frequency f .
[32]	GSMC, WFMMC	Yes	Large capacitor voltage's operating range by decreasing the inserted number N of SMs.

Refs. [30]-[32] decouple the DC voltage from the submodule capacitor voltage to avoid DC voltage fluctuation beyond the rated range caused by capacitor charging and discharging. Ref. [30] eliminates the connection between the DC voltage U_{dc} and the grid frequency and directly establishes the relationship between the total energy W_{total} of the submodules' capacitance and the output frequency of the GSMC. This improves the dynamic characteristics of the DC voltage loop and the fault ride-through capability of the system. The above strategy only utilizes GSMC's frequency regulation capability. It does not exploit the frequency regulation capability of WFMMC, which is only used as a medium for transmitting grid frequency signals to the wind farm. Ref. [31] improves the nearest level modulation (NLM) method by introducing the DC modulation index M_{dc} . Combined with the energy synchronisation control, a dual grid-forming MMC control scheme with active energy management is proposed, which enables autonomous grid synchronisation and precise energy regulation independent of DC voltage. In [32], to fully utilize the capacitors' energy margin, the capacitor voltage's operating range is expanded by decreasing the number of inserted SMs. Under the condition that the DC voltage fluctuation range is limited, this method realizes an effective decoupling of the capacitive voltage from the DC voltage, where the DC voltage change is only a signal to the wind farm to transmit the grid frequency change. The MMC-HVDC frequency regulation control strategies mentioned in the above literature [27]-[32] are summarized in Table II.

B. Frequency Regulation Methods for Wind Farm

The above control strategies focus on the MMC-HVDC system. It is considered that wind turbines, like MMC submodule capacitors, can simulate synchronous machines to provide virtual inertia. Therefore, it can be utilized to improve the MMC-HVDC connected wind farm system's frequency support to the grid by utilizing its frequency regulation capability [33]-[34]. The frequency control strategy for wind farm mainly involves changing the active power control loop in the converter so that the active output of the wind turbine

can respond to the system's frequency change in real time. The frequency control is mainly divided into rotor kinetic energy control and power reserve control.

Frequency control utilizing rotor kinetic energy includes frequency droop control of wind turbines [35]-[38] and virtual inertia control of the wind turbines [39]. The frequency droop control of wind turbines simulates the primary frequency regulation process of synchronous machines, where the input is the frequency deviation, and the active output power reference is changed according to the input. The virtual inertia control output of the wind turbine is the same as the frequency droop control; both are active output power changes. However, it uses the rate of frequency change as the input signal and can provide frequency support faster in the initial stage of frequency response when the frequency rate of change is more significant, and the value of frequency change is minor. Ref. [40] combines frequency droop control and virtual inertia control. Changing the blade pitch angle increases the active power output of the wind turbine. Furthermore, virtual inertia control linked to the rate of grid frequency variation and frequency droop control associated with grid frequency deviation magnitude are integrated into the GSVSC to emulate the frequency response characteristics of synchronous generators.

Wind turbines generally have a certain amount of reserve power to have the same frequency regulation characteristics as synchronous machines. The overspeed control and pitch angle control can obtain the reserve power [41]-[42]. Under normal conditions, when the grid frequency rises, increasing the turbine speed to a speed greater than the corresponding speed at the maximum power point or increasing the pitch angle can reduce the wind power captured by the turbine. When the grid frequency decreases, the output power increases by reducing the speed or decreasing the pitch angle. The pitch angle control with virtual inertia control and voltage droop control is shown in Fig. 6.

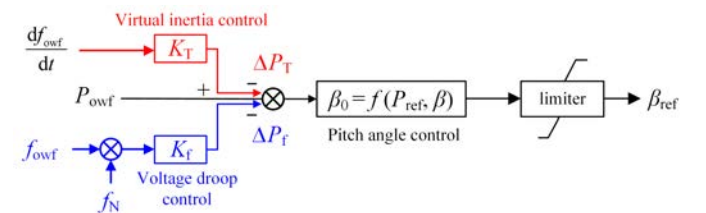


Fig. 6. Pitch angle control using rotor kinetic energy.

In addition to utilizing the wind turbine, the active frequency support of the wind farm can be increased by employing an additional energy storage device. Ref. [43] proposes an integrated inertia control strategy using supercapacitors in the DC link of a double fed induction generator (DFIG). However, the energy utilization efficiency of the supercapacitor is limited due to the limitation of the DC voltage variation range. Ref. [44] incorporates a bidirectional DC/DC converter between the supercapacitor and the DC bus of the wind turbine. The bidirectional DC/DC converter improves the range of variation of the supercapacitor voltage so that the energy stored in the supercapacitor can be better

utilized. The common frequency regulation strategies for wind farm are categorized, as shown in Fig. 7.

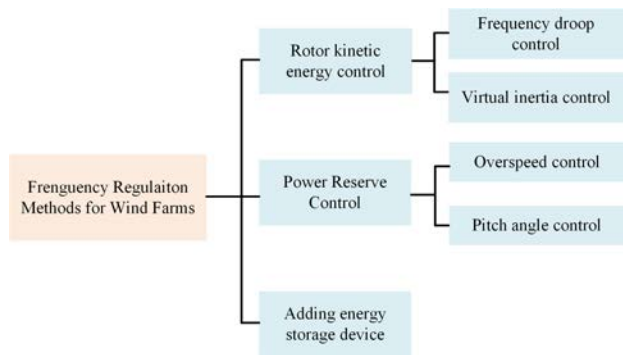


Fig. 7. Classification of frequency regulation control strategies for wind farm.

C. Grid Frequency Sensing Methods

Although both the wind farm and the MMC-HVDC system have certain frequency regulation capabilities, the decoupling effect of the MMC-HVDC DC transmission makes it impossible for the wind farm to provide frequency support for the grid. To improve the system's stability, it is better to utilize the frequency modulation capability of both the wind farm and the MMC-HVDC system. This requires coupling the onshore grid frequency to the wind farm in a certain way so that the wind turbines can sense the frequency changes. Frequency sensing can generally be realized in a communication or non-communication way.

1) Communication-based frequency sensing methods

The grid frequency can be transmitted directly to the wind farm by supervisory control and data acquisition (SCADA) or other fast communication methods [45]. The communication system makes it easier for the wind farm to sense the frequency and act accordingly. However, as the transmission distance becomes longer, the communication delay increases. The delay for a wind turbine to provide frequency support is about 50 ms-1 s [46]. The long delay makes it difficult to use this method because the system requires a fast response [47]. So, there is a need to minimize the transmission delay as much as possible.

2) Frequency sensing method without communication

Failing to avoid the effect of time delay in long-distance communication, [48]-[51] modify the control of the WFMMC so that the reference frequency of the WFMMC varies with the change of the onshore grid frequency. In this way, the wind turbine can sense the change of the onshore grid frequency by monitoring the change of the WFMMC frequency, thus realizing a fast response. Refs. [52]-[54] establish the coupling relationship between the frequency of the onshore grid and the DC voltage of the MMC-HVDC system, and the wind turbine can obtain the frequency regulation signal by directly detecting the DC voltage. However, the output power variations of the wind farm, in return, lead to the dynamic fluctuation in the DC voltage of the MMC-HVDC system. This can affect the accuracy of the communication-free frequency transfer and the precision of the inertia support.

However, most existing studies on inertial support for wind

farm grid-connected systems only focus on the virtual inertia control of wind turbines themselves, with insufficient attention paid to the role and coordination mechanism of flexible DC transmission systems in inertial support, which limits the applicability of research conclusions in power grids with high-proportion MMC-HVDC. The current inertia support schemes are limited in response speed and support capacity, making it difficult to provide sufficient and rapid frequency support during grid faults, which may lead to a sharp drop in system frequency and further threaten the frequency stability and safe operation of the power grid. Therefore, it is necessary to further explore novel multi-coordinated and fast-response inertia support technologies. Meanwhile, most inertia control strategies do not fully consider the system damping characteristics, which may result in insufficient damping and oscillation induced by inertia response. Thus, the coordinated optimization of inertia support control and low-frequency oscillation suppression is urgently required. In addition, a unified and comprehensive quantitative evaluation system and key indicators for inertia support performance have not yet been established, leading to the lack of objective and comparable evaluation criteria for different inertia control strategies, which restricts the engineering application and popularization of such technologies.

IV. COORDINATED CONTROL FOR OSCILLATION

SUPPRESSION OF MMC-HVDC CONNECTED WIND FARM

A. Interactions between Wind Farm and MMC-HVDC

At present, many projects have experienced oscillation instability during the commissioning process. For example, sub-synchronous oscillation (SSO) of voltage and current has been observed during the gradual increase of wind farm output in the Nanhui HVDC Project, Nan'ao HVDC Project, and Xiamen HVDC Project in China [14]. In addition, the German North Sea wind farm through the VSC-HVDC transmission project has occurred in the 250-350 Hz medium-frequency oscillation; the oscillation current reaches more than 40% of the base wave current [55]. At the same time, there was a high-frequency oscillation of 1270 Hz when the domestic LUXI back-to-back VSC-HVDC transmission project was connected to the weak AC system [56]. A high-frequency component trip occurred at a converter station in the Zhoushan Five-terminal Project during the transition from the networked operation mode to the islanded operation mode [57].

It has been shown that there is an interaction between the wind farm and the MMC-HVDC converter, leading to oscillatory destabilization of the system. The destabilizing link may exist in the wind farm or the MMC-HVDC system. Therefore, studying the interaction and destabilization mechanism between the wind farm and the MMC-HVDC system is necessary.

Ref. [58] analyzes the coupling between the wind farm and the voltage source converter based high-voltage direct current transmission (VSC-HVDC) system using the eigenvalue

analysis method and finds multiple oscillation modes (low-frequency, subsynchronous, and high-frequency). Ref. [59] uses the impedance analysis method to analyze the cause of oscillation between the wind farm and the VSC-HVDC system. It points out that the interaction between GVSC and WFMMC causes oscillation. Ref. [60] studies the mechanism of the subsynchronous oscillation based on the root trajectory analysis method. It is believed that the more the output active power of the wind farm, the higher the risk of subsynchronous oscillation. In [61]-[62], it is found that the PLL of GVSC and the WFMMC AC voltage control affect the degree of coupling between the wind farm and the MCC-HVDC system. An increase in the PLL bandwidth of the converter of the wind turbine will decrease the feasible region of the AC voltage control parameters of the WFMMC. So, to keep the system stable, the system needs to increase the proportional gain of the AC voltage control. Ref. [63] establishes the single-input single-output (SISO) transfer function model of direct-drive wind turbine connected VSC-HVDC system and utilizes the Nyquist criterion to study the interaction between the wind farm and the VSC-HVDC. Ref. [63] considers that the larger the bandwidth of the voltage loop of the VSC-HVDC wind farm side converter (WFVSC), the weaker the interaction between the VSC-HVDC and the PLL of the wind turbine's inverter, and the smaller the impact on system stability received. Conversely, the smaller the bandwidth, the greater the impact on system stability. When the bandwidth of the current loop of the WFVSC is smaller than the bandwidth of the current loop of the wind turbine and the voltage loop of the WFVSC, it is not beneficial to the system's stability. Ref. [64] uses impedance analysis to explain the mechanism of medium-frequency oscillations in direct-drive wind turbine-connected VSC-HVDC systems, which thinks that it is the reduced DC voltage control bandwidth of the GVSC that causes the resonance peak in the medium-frequency range.

Also, for DFIG-based wind farm integrated into the grid through the VSC-HVDC system, [65] analyzes the interaction based on impedance analysis and finds that the DFIG operating in an under-synchronized state behaves as an inductive reactance with negative resistance. Its interaction with WFVSC, which is considered a resistive capacitor, forms a negative resistance equivalent resonant circuit. The power oscillation will appear due to the negative damping. Ref. [66] investigates the mechanism of high-frequency oscillation of the system using impedance analysis. It is considered that the control delay of the VSC-HVDC is the cause of system destabilization. Ref. [67], based on the eigenvalue analysis method, concludes that the increase in active power output from the wind farm will lead to a decrease in the system stability margin. Adjusting the control parameters of the circulating current suppressor controller of the WFMMC can effectively improve the stability margin of the system and is more economical.

Ref. [68] analyzes the impact of wind farm access on the MMC-HVDC grid and finds that wind power access will not destroy the original mode of the MMC-HVDC grid and only

add wind farm-related and WFMMC-related modes. However, wind power access will weaken the damping ratio of the coupled modes between the MMC stations, which is not conducive to the system's stability.

Most of the above papers utilize the impedance analysis method or the eigenvalue analysis method to analyze the causes of oscillations. By establishing the impedance function of the system and utilizing the Nyquist curve or the positive or negative resistance at the zero crossing point frequency, the impedance analysis method is combined with the closed-loop interconnection model of the system and the Nyquist criterion to analyze the oscillations of the system. This method gives the oscillation mechanism at the physical level from the point of view of contributing negative resistance.

The eigenvalue analysis method is based on the system's oscillation modes. By establishing an overall state-space linearization model of the power system and performing mode analysis on the state-space matrix, the information about the dominant oscillation mode, such as eigenvalues, eigenvectors, and participation factors is obtained, which can be used to evaluate the degree of participation of each dynamic element of the system in this mode. The impedance analysis method suggests that the oscillations originate from negative resistive effects resulting from interactions between wind farm and the MMC-HVDC system. In contrast, the eigenvalue analysis method suggests that mode damping decreases cause the oscillations [69]. In general, the interaction between wind farm and the MMC-HVDC system is mainly generated by the coupling of GVSC and WFMMC. The influencing factors include various converter control parameters, the operational parameters of wind farm, and so on.

B. Coordinated Oscillation Suppression Control

The oscillations caused by the interaction between wind farm and the MMC-HVDC system seriously affect the power system's safe and stable operation. Therefore, it is necessary to research oscillation suppression strategies. The current control methods for the suppression of oscillations caused by MMC-HVDC connected wind farms can be classified into controller parameter optimization, passive damping suppression, and active damping suppression [70].

1) Controller parameter optimization

Ref. [71] reduces the risk of sub-synchronous oscillations in the system by changing the wind turbine inverter PLL design and optimizing the control parameters of the voltage loop of the HVDC rectifier. For the low-frequency oscillation caused by the virtual synchronous generator-permanent magnet synchronous generator (VSG-PMSG) wind farm via the MMC-HVDC system, [72] suggests that increased active power transmitted by the wind farm will lead to the risk of oscillation. By reasonably adjusting the controller parameters of the active loop of the VSG and the voltage loop of the WFMMC, it is beneficial to reduce the risk of low-frequency oscillations when the active power increases. Ref. [73] suggests that it is simpler to change the control parameters of the WFMMC than to change the converter parameters of the wind turbines in projects under operation. At the early design

stage, it should be noted that the larger the submodule capacitance or bridge arm inductance, the larger the stability margin of the system.

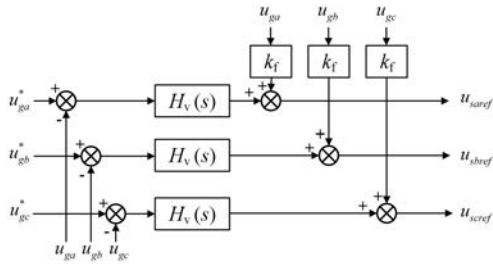


Fig. 8. The control block diagram of WFMMC in [73].

2) Passive damping control

Passive damping suppression control effectively suppresses oscillations by adding additional hardware equipment. Most systems containing wind farm utilize series flexible ac transmission systems (FACTS) devices such as thyristor-controlled series capacitors (TCSC), static synchronous series compensators (SSSC), gate-controlled series capacitors

(GCSC), or subsynchronous damping controllers (SSDC), etc., to suppress oscillations [74]. In addition, [75] builds a robust static synchronous compensator (STATCOM) controller based on H_∞ theory to suppress the subsynchronous oscillations. Ref. [76] proposes that the impedance reshaping of the wind farm is achieved by adding a shunt-VSC subsynchronous damping controller, which changes the aggregated impedance characteristics of the system and suppresses the subsynchronous oscillations. The controller parameters are also optimized in [76] to suppress the oscillations effectively.

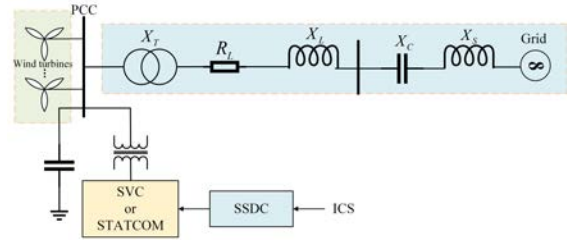


Fig. 9. Passive damping control block diagram [74].

TABLE III
COMPARISON OF OSCILLATION SUPPRESSION METHODS FOR MMC-HVDC CONNECTED WIND FARM

Ref.	Causes of oscillations	Types of oscillation suppression methods	Methods for suppressing oscillations
[71]	Poor stability margin Unreasonable controller parameters	Optimize the control parameters	Optimize the wind turbine inverter PLL design and the control parameters of the HVDC rectifier voltage loop
[72]-[73]	Too much power output from wind farm	Optimize the control parameters	Optimize the parameters of the wind turbine active loop and WFMMC constant AC voltage loop
[75]	Unreasonable controller parameters of the wind turbine / VSC-HVDC transmission lines introduce negative damping to the wind turbine	Passive damping suppression control	Build a robust static synchronous compensator (STATCOM) controller based on H_∞ theory at the wind farm side
[76]	The wind farm and the MMC-HVDC system form an RLC oscillator circuit with negative resistance.	Passive damping suppression control	Wind farm in parallel with a Shunt-VSC Subsynchronous Damping Controller
[60]	Too much power output from the wind farm	Active damping suppression	Adding a series of virtual resistors to the WFMMC outer loop controller
[64]	Decrease in constant DC voltage loop bandwidth of GVSC	Active damping suppression	Propose the virtual impedance-based impedance reshaping control in WFVSC
[77]	Increase in wind farm output power or GVSC PLL parameters	Active damping suppression	Setting up a virtual parallel impedance control strategy in the q-axis of the MMC
[78]	Too much power output from wind farm or too small grid short-circuit ratio	Active damping suppression	Sub-synchronous oscillation suppression based on capacitance energy

3) Active damping control

Active damping suppression has developed rapidly compared to passive damping suppression because it does not require additional equipment and has advantages such as flexible control. Essentially, active damping control is a virtual impedance method. Ref. [60] proposes a damping control strategy, adding a series of virtual resistors to the WFMMC outer loop controller to improve the system's stability. Aiming at the oscillation problem of the PMSG-based wind farm connected VSC-HVDC, [64] and [77] propose an oscillation suppression control strategy based on virtual impedance adding to the WFVSC and clarifies the design method of the controller parameters. Ref. [78] proposes a sub-synchronous oscillation suppressing method based on capacitance energy control. The method modulates the capacitive energy stored in the MMC by controlling the zero-sequence component of the loop current so that the capacitive energy damps the sub-synchronous oscillations according to the common connection

point frequency. Conventional damping controllers get the damping energy from the power side. Compared to the conventional damping control, the capacitance energy damping control directly uses the energy from the converter station, which is faster. Damping of sub-synchronous oscillations values the rapidity of the energy more than the amount of energy. Therefore, the method for suppressing capacitor energy oscillation has an advantage in suppressing the sub-synchronous oscillations. The oscillation suppression methods for MMC-HVDC connected wind farm mentioned in the above literature are summarized in Table III.

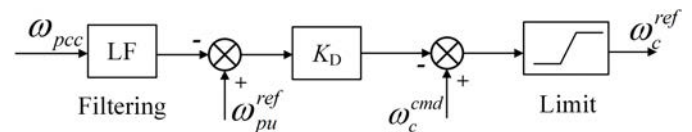


Fig. 10. Structure of damping controller based on energy control [78].

While this section has focused on the suppression of small-signal oscillations, the system's stability under large-signal disturbances, such as faults, presents a different set of challenges. These transient stability issues, which are critical for ensuring system resilience, will be systematically reviewed from a coordinated control perspective in Section V.

Nevertheless, current research mainly focuses on the grid-side converters of wind turbines and the sending-end converters of MMC-HVDC, while ignoring the machine-side converters of wind turbines and the receiving-end converters of MMC-HVDC. As a result, a full-link and high-precision analysis model for wideband oscillation has not yet been formed. Furthermore, the research on oscillation mechanism is mostly based on the typical scenario of grid-following units connected to weak power grids. The investigation on the oscillation initiation mechanism, propagation paths, and suppression strategies under the coordinated control of multiple converters in grid-forming-based power grids is still in the exploratory stage.

V. COORDINATED FAULT RIDE-THROUGH CONTROL FOR MMC-HVDC CONNECTING THE WIND FARM

When the system failure occurs, because of the low voltage and current tolerance and rapid dynamic processes of the power electronic devices in MMC-HVDC connecting the wind farm, a series of fast over-voltage and over-current phenomena will be generated. Therefore, traditional protection methods can no longer meet the requirements of fast and complex fault ride-through problems. The system fault can be divided into DC area faults and AC area faults, depending on the type of fault. Not only do different fault types correspond to different fault ride-through control strategies, but different wiring methods of the MMC-HVDC system also correspond to fault ride-through strategies. For the symmetrical bipolar MMC-HVDC, when one-pole converters are blocked due to the fault, converters of the other pole can continue operating as in conventional DC transmission systems [79]. However, the symmetrical monopole MMC-HVDC system cannot be operated like that because it has only one pole. The following content describes the corresponding fault ride-through strategies for the MMC-HVDC system's different fault types and different wiring methods.

A. DC-side Fault Ride-through control

1) Fault clearing method

When a fault occurs in the DC side of the MMC-HVDC system, the capacitance of the SMs and the alternating current (AC) grid are discharged to the short-circuit point at the same time. Due to the small impedance of the fault circuit, the fault has no natural over-zero point. The fault current rises quickly and with a high peak. Therefore, to ensure the stable operation of the power grid and the safety of the system's key equipment, it is necessary to limit the fault current. Two basic ways to isolate short-circuit faults in the DC line are an MMC submodule topology with DC fault clearing capability and the DC circuit breaker.

a) MMC submodule with DC fault self-cleaning ability

Refs. [80]-[82] propose new types of SMs with DC fault isolation and clearing capability, which can effectively block DC faults. Currently, most projects still use Half-Bridge SMs, which do not have fault-clearing capabilities, so this method cannot be applied to the existing projects.

b) DC circuit breaker

The DC circuit breaker isolates the DC short circuit fault point when a fault occurs. The fault current will be transferred to the energy-absorbing branch for discharge [85]. Because DC circuit breakers can quickly cut off the fault current and do not affect the power transmission of the non-fault line, DC circuit breakers have received more and more attention as a powerful tool for dealing with high-voltage DC faults. It has been utilized in many flexible DC transmission system projects such as Nan'ao project, Zhoushan project, and Zhangbei MMC-HVDC project [84].

2) DC fault ride-through control for wind farm via bipolar MMC-HVDC system

For the MMC-HVDC system with symmetrical bipolar structures, the wind farm energy is transmitted from the non-fault pole after the fault pole is blocked. If a large amount of wind farm energy is transferred to the non-faulted pole, a DC overvoltage may be caused, jeopardizing the safety of the entire system. At this time, it is necessary to coordinate the wind farm and the MMC-HVDC system and new DC fault ride-through methods must be explored to realize the reasonable allocation of unbalanced power and fault current limitation.

For permanent DC faults caused by DC submarine cable breakage, [85] proposes a multilevel coordinated control (MLCC) scheme utilizing the fault pole, the non-fault pole, and wind farm. After a fault occurs, the fault pole WFMMC utilizes the energy storage capability of the submodule (SM) capacitors to absorb the wind farm energy before the converter station is blocked, buying time for the control activation of the non-fault pole. When the fault line current is detected to drop to 0, the non-fault pole GSMC actively raises the DC voltage to reduce the DC current to avoid overcurrent protection action. After receiving the blocking signal from the fault-pole WFMMC, the non-fault pole WFMMC increases the received energy through active energy control (AEC) to absorb the wind energy. When communication is allowed, the wind farm receives the fault pole command and reduces the delivered active reference to 0.5 per unit (p.u.) AEC will be maintained for a while, which usually depends on the time required for power reduction at the wind farm. After the internal energy returns to its rated value, the non-fault pole WFMMC will deliver the received energy to the non-fault pole GSMC. The idea of [86] is similar to that of [85], which also divides fault ride-through into two phases: before fault isolation and after fault isolation. The DC current rise rate is limited by reducing the number of inserted SMs before fault isolation. After fault isolation, the fault pole WFMMC works in STATCOM mode to maintain the stability of the wind farm AC bus voltage. At the same time, the reactive power reference value of the non-fault pole WFMMC is set to 0 to improve the active power transfer

capability. Compared to [85], [86] describes the coordinated control of wind turbines in more detail. Successively, overspeed load shedding and pitch angle control methods are utilized in [86] to reduce the output power of the wind farm.

For the permanent DC fault, [85] suggests that overspeed load shedding of the wind farm is unable to meet the requirement of power balance. Cutting the wind turbines to

reduce the active power output is necessary. At this time, an energy storage system is required, which cooperates in absorbing the excess power until the wind farm completely reduces power. Meanwhile, the MMC-HVDC system is running at full load. Compared with the energy consumption resistor, the energy storage system absorbs power more smoothly, with a power fluctuation of only 2.5%.

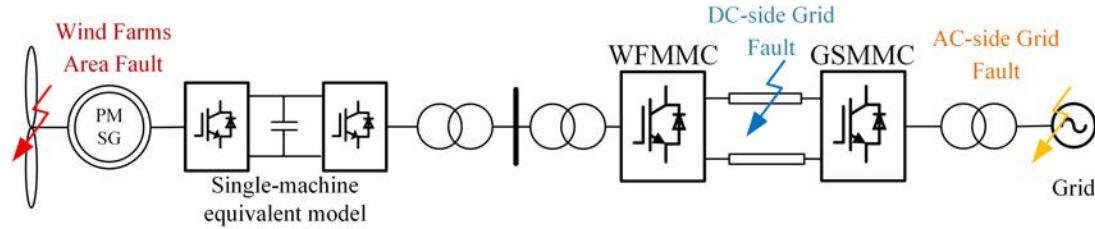


Fig. 11. Diagram of faults in the MMC-HVDC grid-connected system of wind farm.

B. AC-side Grid Fault Ride-through Control

When the grid AC-side fault causes the transmission interruption of wind power, the excess power accumulates on the DC transmission lines, rapidly increasing the DC voltage like DC-side faults. The current coordination methods for grid-side fault ride-through combine the improvement of the MMC-HVDC control strategy or the energy consumption resistor and the reduction of the wind turbine output power.

Refs. [88]-[89] propose a communication-based coordinated method. After a voltage drop in the grid, the wind farm can receive the instruction via communication and quickly reduce the output power. However, the protection is triggered by DC overvoltage within tens of milliseconds after the fault. It is difficult to ensure the wind farm can complete the load shedding at the required time when the communication delay is large. Therefore, [90] applies energy consumption resistors in GSMMC submodules to absorb the unbalanced power during the wind farm response after the fault occurs. This energy consumption resistor only needs to operate in the early stages of wind turbine load shedding (< 200 ms) and does not take up additional station space. However, energy-consumption resistors installed in the submodules will heat the submodules. Therefore, additional costs for heat dissipation in the converter station need to be considered.

To avoid all the surplus energy from being consumed in the form of thermal energy, [91] proposes active energy control using the energy margin of the submodule capacitance. First, the decoupling control strategy for MMC based on the DC modulation ratio is proposed. The energy utilization algorithm is added to the current loop of WFMMC and GSMMC, respectively. The energy is released after the DC voltage drops to the rated value, which can reduce the working time of DC energy dissipation devices.

Considering the cost and delay of communication methods, [92]-[95] propose ride-through control strategies without communication. The WFMMC generally transmits a signal to the wind farm based on the DC voltage using either the frequency rise method or the voltage drop method. The wind turbine changes the active power reference value based on the

WFMMC instruction. However, since wind turbines are frequency-sensitive, improper control may result in large-scale off-grid. The voltage drop method may also cause the voltage to exceed the safe operating range, leading to system protection actions. Ref. [96] uses harmonic injection instead of communication. When the WFMMC detects the DC overvoltage, it reduces the AC line voltage of the wind farm and actively injects different sequence harmonics into the AC line according to the DC voltage rise rate. When the GVSC of the wind turbine detects the corresponding harmonics, the output active power is reduced by updating the d-axis current reference value. To speed up the system power balancing time, while reducing the wind farm output, [97] decreases the amplitude of the GSMMC bridge arm modulation wave. This increases the equivalent capacitance on the DC side and reduces the average capacitance voltage. The maximum energy the GSMMC absorbs is greater than that of conventional fault ride-through methods. And the more severe the fault, the more energy is absorbed. The grid area AC fault ride-through control strategies are categorized, as shown in Fig. 12.

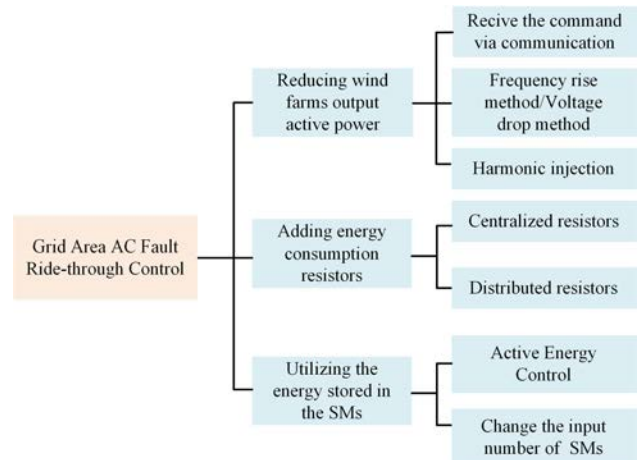


Fig. 12. Classification of grid AC area fault ride-through control.

C. Wind Farm Area Fault Ride-through Control

Research on coordinated control for AC side faults of wind farm is still in its early stages. AC faults on the wind farm

side usually include single-phase grounded short-circuit faults, two-phase short-circuit faults, and three-phase grounded short-circuit faults. Among them, single-phase grounded short-circuit faults and two-phase short-circuit faults can cause serious overvoltage problems [98]. A novel coordinated control strategy is proposed in [99]. DFIG wind turbines apply synchronized control, which can make the wind turbine work as a voltage source to regulate the voltage magnitude and phase of the AC system amplitude, and angle to the AC grid voltage. On the contrary, WFMMC works as a current source with constant power control. During the fault, the wind turbine is switched to the fault ride-through state, and the active power of the WFMMC quickly drops to 0. The GSMC is not affected due to the isolation of the DC line.

Three-phase grounded short-circuit faults are usually permanent, so the wind turbines on the line need to be removed. Restricted by the AC circuit breaker operation time and fault removal time (60-100 ms), the low voltage ride-through (LVRT) problem of the wind farm and WFMMC needs to be considered during this time. The WFMMC enters the current limiting mode to control the fault current. Due to the voltage drop on their AC side, the wind turbine submodules (SUBMs) will switch to the LVRT mode.

Existing studies have not fully investigated the transient response characteristics and differentiated influence laws of the system under different fault locations and fault types. The overcurrent tolerance limits of power devices in converters are not fully considered in fault analysis, and the research on the prevention and control mechanism of device damage and secondary fault cascading reactions caused by overcurrent shocks during fault transients is insufficient. Meanwhile, most studies focus on the system stability control during faults, while the research on the voltage and power transient regulation characteristics and instability risk prevention in the fault recovery stage is relatively weak. A fault support control system covering the whole process of fault “occurrence-duration-recovery” has not been established. In addition, the fault response speeds of wind turbines and MMC-HVDC are different during faults, so the response characteristics of the whole fault process at multiple time scales should be considered. Furthermore, most existing studies adopt the simplified topology of a single wind turbine, lacking consideration of complex practical engineering conditions such as multi-terminal access of wind farms and the combined operation of converters and energy storage systems. Therefore, the engineering adaptability and practical application value of the research results need to be further improved.

VI. FUTURE TRENDS

To summarize, the technology of the MMC-HVDC connected wind farm has become more and more mature. However, the improvement of related standards and the emergence of hot issues still cause this system to have many urgent problems, which motivate us to explore further.

A. Future Development of Inertial Support

Future research will break through the limitation of focusing only on the virtual inertia control of wind turbines. It will focus on exploring the coordinated inertial support mechanism between wind farms and MMC-HVDC systems to improve the inertia support capacity. Meanwhile, novel inertia support technologies with faster response speed and larger support capacity will be developed. These technologies will address the insufficient frequency support and sharp frequency drop during grid faults to ensure the safe and stable operation of the power grid. In addition, the system damping characteristics will be fully considered in the design of inertia control strategies. Coordinated optimization between inertia support control and low-frequency oscillation suppression will be implemented to avoid oscillation caused by insufficient damping. A unified and complete quantitative evaluation system and key indicators for inertia support performance will also be established. This will provide an objective standard for the performance comparison of different inertia control strategies and promote the engineering application and large-scale popularization of related technologies.

B. Future Development of Oscillation Suppression

In the future, a full-link and high-precision wideband oscillation analysis model will be constructed. It will be used to comprehensively characterize the influence of the interaction among multiple converters on oscillations. Besides, the research will go beyond the traditional scenario of grid-following converters connected to weak grids. The inherent mechanism of wideband oscillations induced by the interaction between grid-forming wind farms and MMC-HVDC will be revealed. Systematic oscillation suppression strategies will be formed accordingly. The research will be upgraded from local oscillation analysis to system-level stability prevention and control. It will provide technical support for the wideband stable operation of high-proportion power electronics-dominated power systems.

C. Future Development of Fault Ride-through Control

Future research on fault ride-through technologies will focus on improving system fault handling capability and enhancing the engineering practicability of related techniques. The transient response characteristics and differentiated influence laws of the system under different fault locations and fault types will be thoroughly investigated. The overcurrent tolerance limits of power devices in converters will be fully considered. Protection schemes against overcurrent shocks during fault transients will be improved to prevent device damage and cascading failures caused by secondary faults. Meanwhile, a comprehensive fault support and control framework covering the entire fault process of occurrence, duration and recovery will be constructed. It will take into account voltage and power transient regulation as well as instability risk prevention during the fault recovery stage, so as to enhance the full-process fault handling capability of the system. Furthermore, the response speed

differences between wind turbines and MMC-HVDC systems during faults will be fully considered. The multi-time-scale response characteristics in the whole fault process will also be taken into account. In addition, the research will break through the limitation of the simplified topology of a single wind turbine. It will be carried out in combination with practical engineering conditions such as multi-terminal access of wind farms, reactive power allocation and energy storage configuration. This will further improve the engineering adaptability and practical application value of fault ride-through strategies.

VII. CONCLUSION

This paper presents a comprehensive review of the MMC-HVDC connected wind farm system from a unified perspective of coordinated control. Firstly, the issues faced by the MMC-HVDC connected wind farm system are classified into three categories: inertia control, wideband oscillation, and fault ride-through. A unique and clear analytical framework is established, and the state-of-the-art coordinated control strategies for each challenge are systematically summarized. Based on in-depth analysis, the deficiencies and limitations of existing studies for each challenge are concluded as follows:

1) Current research on inertial support for wind farm grid-connected systems mainly focuses on the virtual inertia control of wind turbines, with insufficient attention to the coordination mechanism of MMC-HVDC, leading to limited applicability. Existing support methods suffer from slow response and insufficient capacity, which can hardly guarantee frequency security under faults. The lack of consideration for damping in control strategies tends to induce oscillations. Moreover, the absence of a unified quantitative evaluation system severely restricts the engineering application of related technologies.

2) Current studies on wideband oscillation mostly neglect the machine-side converters of wind turbines and the receiving-end converters of MMC-HVDC, and a full-link high-precision analysis model has not yet been established. The oscillation mechanism is mostly studied based on the scenario of grid-following converters connected to weak grids. The oscillation mechanism, propagation paths, and suppression strategies under the coordinated control of multiple converters in grid-forming-based power grids still need to be further investigated.

3) Existing studies are insufficient in the aspects of fault transient response laws, converter overcurrent protection, full-process fault control, multi-time-scale response characteristics, and complex engineering conditions. A complete fault support control system covering the whole process of fault "occurrence-duration-recovery" and adapting to practical engineering has not been formed, and the engineering applicability of the research results needs to be further improved.

This paper aims to provide a clear and logical framework for researchers and engineers to understand and solve the core problems of the MMC-HVDC connected wind farm system, present the deficiencies of existing research, and

indicate future research directions and development trends for each field.

REFERENCES

- [1] N. Flourentzou, V. G. Agelidis, and G. D. Demetriades, "VSC-based HVDC Power Transmission Systems: an Overview," *IEEE Transactions on Power Electronics*, vol. 24, no. 3, pp. 592-602, Mar. 2009.
- [2] S. M. Muyeen, R. Takahashi, and J. Tamura, "Operation and Control of HVDC-connected Offshore Wind Farm," *IEEE Transactions on Sustainable Energy*, vol. 1, no. 1, pp. 30-37, Apr. 2010.
- [3] K. H. Xu, Z. Zhang, and Q. H. Lai *et al.*, "Study on Fault Characteristics and Distance Protection Applicability of VSC-HVDC Connected Offshore Wind Power Plants," *International Journal of Electrical Power & Energy Systems*, vol. 133, pp. 107252, Dec. 2021.
- [4] Z. X. Lu, H. Y. Tang, and Y. Qiao *et al.*, "The Impact of Power Electronics Interfaces on Power System Frequency Control: a Review," *Electric Power*, vol. 51, no. 1, pp. 51-58, Jan. 2018.
- [5] National Grid ESO, (2019, Aug.), Technical Report on the Events of 9 August 2019. [Online]. Available: <https://www.neso.energy/document/152346/download>
- [6] S. Sang, C. Zhang, and X. Cai *et al.*, "Voltage Source Control of Wind Turbines with Full-scale Converters (Part I): Control Architecture and Stability Analysis Under Weak Grid Conditions," *Proceedings of the CSEE*, vol. 41, no. 16, pp. 5604-5616, Aug. 2021.
- [7] D. Groß, E. Sánchez-Sánchez, and E. Prieto-Araujo *et al.*, "Dual-port Grid-forming Control of MMCs and Its Applications to Grids of Grids," *IEEE Transactions on Power Delivery*, vol. 37, no. 6, pp. 4721-4735, Dec. 2022.
- [8] C. Collados-Rodríguez, M. Cheah-Mane, and F. Cifuentes-García *et al.*, "Integration of an MMC-HVDC Link to the Existing LCC-HVDC Link in Balearic Islands based on Grid-following and Grid-forming Operation," *IEEE Transactions on Power Delivery*, vol. 37, no. 6, pp. 5278-5288, Dec. 2022.
- [9] W. Xiang, S. Z. Yang, and G. P. Adam *et al.*, "DC Fault Protection Algorithms of MMC-HVDC Grids: Fault Analysis, Methodologies, Experimental Validations, and Future Trends," *IEEE Transactions on Power Electronics*, vol. 36, no. 10, pp. 11245-11264, Oct. 2021.
- [10] Y. T. Xiao, and L. Peng, "A Novel Fault Ride-through Strategy based on Capacitor Energy Storage Inside MMC," *IEEE Transactions on Power Electronics*, vol. 35, no. 8, pp. 7960-7971, Aug. 2020.
- [11] Q. Xie, Z. X. Zheng, and C. J. Huang *et al.*, "Coordinated Fault Ride Through Method for PMSG-based Wind Turbine Using SFCL and Modified Control Strategy," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 8, pp. 1-5, Nov. 2021.
- [12] C. Chen, W. J. Du, and H. F. Wang, "Review on Mechanism of Sub-synchronous Oscillations Caused by Grid-connected Wind Farms in Power Systems," *Southern Power System Technology*, vol. 12, no. 1, pp. 84-93, Jan. 2018.
- [13] H. P. Li, H. Nian, and B. Hu *et al.*, "Review of Analysis and Suppression Methods for Wide-band Oscillation in Wind Power Grid-connected Systems," *New Type Power Systems*, vol. 1, no. 3, pp. 237-255, Dec. 2023.
- [14] C. Q. Yin, X. R. Xie, and H. Liu *et al.*, "Analysis and Control of the Oscillation Phenomenon in VSC-HVDC Transmission System," *Power System Technology*, vol. 42, no. 4, pp. 1117-1123, Apr. 2018.
- [15] R. X. Yang, G. Shi, and X. Cai *et al.*, "Present Situation and Prospect of the Control and Protection Technology for Flexible DC Intergration of Wind Farm," *Southern Power System Technology*, vol. 13, no. 3, pp. 48-57, Mar. 2019.
- [16] Y. M. Zhang, W. X. Zhang, and B. H. Li *et al.*, "Influence Mechanism of MMC-HVDC Grid Topology on Fault Current," *Electric Power Engineering Technology*, vol. 41, no. 5, pp. 94-102, Sept. 2022.
- [17] S. De Boeck, P. Tielens, and W. Leterme *et al.*, "Configurations and Earthing of HVDC Grids," in *Proc. of 2013 IEEE Power & Energy Society General Meeting*, Vancouver, BC, Canada, Jul. 2013, pp. 1-5.
- [18] X. Y. Li, Q. Zeng, and Y. H. Wang *et al.*, "Control Strategies of

- Voltage Source Converter based Direct Current Transmission System,” *High Voltage Engineering*, vol. 42, no. 10, pp. 3025-3037, Oct. 2016.
- [19] X. Cai, R. X. Yang, and J. Q. Zhou *et al.*, “Review on Offshore Wind Power Integration via DC Transmission,” *Automation of Electric Power Systems*, vol. 45, no. 21, pp. 2-22, Nov. 2021.
- [20] H. Yu, Z. M. Zhang, and S. Peng *et al.*, “Comparative Analysis of Technical Standards for Offshore Wind Power via VSC-HVDC,” *Journal of Shanghai Jiao Tong University*, vol. 56, no. 4, pp. 403-412, Apr. 2022.
- [21] C. H. Lin, and Y. K. Wu, “Overview of Frequency-control Technologies for a VSC-HVDC-integrated Wind Farm,” *IEEE Access*, vol. 9, pp. 112893-112921, Aug. 2021.
- [22] A. E. Leon, “Short-term Frequency Regulation and Inertia Emulation Using an MMC-based MTDC System,” *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2854-2863, May 2018.
- [23] Y. Phulpin, “Communication-free Inertia and Frequency Control for Wind Generators Connected by an HVDC-link,” *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 1136-1137, May 2012.
- [24] B. Silva, C. L. Moreira, and L. Seca *et al.*, “Provision of Inertial and Primary Frequency Control Services Using Offshore Multiterminal HVDC Networks,” *IEEE Transactions on Sustainable Energy*, vol. 3, no. 4, pp. 800-808, Oct. 2012.
- [25] Y. P. Liu, Q. Xie, and H. P. Liang, “Frequency Regulation Control Strategy for Flexible DC Transmission System based on Adaptive Virtual Inertia,” *Automation of Electric Power Systems*, vol. 45, no. 5, pp. 129-136, Mar. 2021.
- [26] Z. G. Dong, Q. H. Xu, and Q. Chen *et al.*, “Improved Droop Control Strategy Involved in Power Grid Frequency Regulation for VSC-MTDC Transmission Systems,” *Southern Power System Technology*, vol. 18, no. 3, pp. 146-155, Mar. 2024.
- [27] M. Y. Guan, W. L. Pan, and J. Zhang *et al.*, “Synchronous Generator Emulation Control Strategy for Voltage Source Converter (VSC) Stations,” *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3093-3101, Nov. 2015.
- [28] R. X. Yang, C. Zhang, and X. Cai, “Control of VSC-HVDC with Real-time Frequency Mirroring and Self-synchronizing Capability for Wind Farm Integration,” *Proceedings of the CSEE*, vol. 37, no. 2, pp. 496-505, Jan. 2017.
- [29] R. X. Yang, “Research on Key Technologies of Grid Connection Control and Protection of VSC-HVDC System with Wind Farm Integration,” Ph.D. dissertation, Shanghai Jiao Tong University, Shanghai, China, 2020.
- [30] R. X. Yang, G. Shi, and C. Zhang *et al.*, “Internal Energy based Grid-forming Control for MMC-HVDC Systems with Wind Farm Integration,” *IEEE Transactions on Industry Applications*, vol. 59, no. 1, pp. 503-512, Jan.-Feb. 2023.
- [31] H. B. Zhang, W. Xiang, and J. Y. Wen, “Dual Grid-forming Control with Energy Regulation Capability of MMC-HVDC System Integrating Offshore Wind Farms and Weak Grids,” *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 261-272, Jan. 2024.
- [32] S. Q. Jiang, H. B. Wang, and G. Q. Li *et al.*, “A Novel Coordinated Control Strategy for Frequency Regulation of MMC-HVDC Connecting Offshore Wind Farms,” *IEEE Transactions on Sustainable Energy*, vol. 15, no. 2, pp. 1028-1038, Apr. 2024.
- [33] X. Zhang, Y. L. Chen, and S. Yue *et al.*, “Retrospect and Prospect of Research on Frequency Regulation Technology of Power System by Wind Power,” *Power System Technology*, vol. 42, no. 6, pp. 1793-1803, Jun. 2018.
- [34] X. S. Tang, F. F. Miao, and Z. P. Qi *et al.*, “Survey on Frequency Control of Wind Power,” *Proceedings of the CSEE*, vol. 34, no. 25, pp. 4304-4314, Sept. 2014.
- [35] G. Ramtharan, J. B. Ekanayake, and N. Jenkins, “Frequency Support from Doubly Fed Induction Generator Wind Turbines,” *IET renewable power generation*, vol. 1, no. 1, pp. 3-9, Mar. 2007.
- [36] J. F. Conroy, and R. Watson, “Frequency Response Capability of Full Converter Wind Turbine Generators in Comparison to Conventional Generation,” *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 649-656, May 2008.
- [37] D. Gautam, L. Goel, and R. Ayyanar *et al.*, “Control Strategy to Mitigate the Impact of Reduced Inertia Due to Doubly Fed Induction Generators on Large Power Systems,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 214-224, Feb. 2011.
- [38] S. Ghosh, S. Kamalasan, and N. Senroy *et al.*, “Doubly Fed Induction Generator (DFIG)-based Wind Farm Control Framework for Primary Frequency and Inertial Response Application,” *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 1861-1871, May 2016.
- [39] J. Morren, S. W. H. de Haan, and W. L. Kling *et al.*, “Wind Turbines Emulating Inertia and Supporting Primary Frequency Control,” *IEEE Transactions on Power Systems*, vol. 21, no. 1, pp. 433-434, Feb. 2006.
- [40] M. Kayikci, and J. V. Milanovic, “Dynamic Contribution of DFIG-based Wind Plants to System Frequency Disturbances,” *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 859-867, May 2009.
- [41] J. Lee, E. Muljadi, and P. Srensen *et al.*, “Releasable Kinetic Energy-based Inertial Control of a DFIG Wind Power Plant,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 279-288, Jan. 2016.
- [42] L. Ding, S. Y. Yin, and T. X. Wang *et al.*, “Integrated Frequency Control Strategy of DFIGs based on Virtual Inertia and Over-speed Control,” *Power System Technology*, vol. 39, no. 9, pp. 2385-2391, Sept. 2015.
- [43] J. B. Zhu, J. B. Hu, and W. Hung *et al.*, “Synthetic Inertia Control Strategy for Doubly Fed Induction Generator Wind Turbine Generators Using Lithium-ion Supercapacitors,” *IEEE Transactions on Energy Conversion*, vol. 33, no. 2, pp. 773-783, Jun. 2018.
- [44] J. B. Zhu, M. Q. Shi, and L. Zhang *et al.*, “Supercapacitor-based Coordinated Inertia Support Strategy for Offshore Wind Farms Integration via VSC-HVDC,” *Power System Technology*, vol. 46, no. 8, pp. 2938-2947, Aug. 2022.
- [45] Y. Pipelzadeh, B. Chaudhuri, and T. C. Green, “Inertial Response from Remote Offshore Wind Farms Connected Through VSC-HVDC Links: a Communication-less Scheme,” in *Proc. of 2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, USA, Jul. 2012, pp. 1-6.
- [46] S. Ray, and G. K. Venayagamoorthy, “Real-time Implementation of a Measurement-based Adaptive Wide-area Control System Considering Communication Delays,” *IET generation, transmission & distribution*, vol. 2, no. 1, pp. 62-70, Jan. 2008.
- [47] F. Wilches-Bernal, D. A. Schoenwald, and R. Fan *et al.*, “Analysis of the Effect of Communication Latencies on HVDC-based Damping Control,” in *Proc. of 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Denver, CO, USA, Apr. 2018, pp. 1-9.
- [48] J. Tang, J. T. Su, and Y. G. Yao *et al.*, “Technical Analysis of Power System Frequency Regulation by Wind Power for New Power System,” *Thermal Power Generation*, vol. 51, no. 7, pp. 1-8, Jul. 2022.
- [49] S. H. Li, and G. W. Zhu, “Capability and Effect of Primary Frequency Regulation by Wind Turbine Generators with Active Power Reserve,” *Advanced Technology of Electrical Engineering and Energy*, vol. 34, no. 10, pp. 28-33+50, Oct. 2015.
- [50] H. Z. Liu, and Z. Chen, “Contribution of VSC-HVDC to Frequency Regulation of Power Systems with Offshore Wind Generation,” *IEEE Transactions on Energy Conversion*, vol. 30, no. 3, pp. 918-926, Sept. 2015.
- [51] K. Jose, T. Joseph, and J. Liang *et al.*, “Auxiliary Dead-band Controller for the Coordination of Fast Frequency Support from Multi-terminal HVDC Grids and Offshore Wind Farms,” *IET Renewable Power Generation*, vol. 12, no. 13, pp. 1444-1452, Oct. 2018.
- [52] Q. Zhang, J. D. McCalley, and V. Ajjarapu *et al.*, “Primary Frequency Support Through North American Continental HVDC Interconnections with VSC-MTDC Systems,” *IEEE Transactions on Power Systems*, vol. 36, no. 1, pp. 806-817, Jan. 2021.
- [53] S. Q. Jiang, Y. N. Xu, and G. Q. Li *et al.*, “Coordinated Control Strategy for Improving Frequency Stability of MMC-HVDC Connecting Offshore Wind Power,” *Electric Power Automation Equipment*, vol. 43, no. 9, pp. 194-201, Sept. 2023.
- [54] H. H. Chen, W. B. Qi, and T. Jiang *et al.*, “Integrated Control Strategy for Improving Frequency Stability of Low Inertia System Connecting to Offshore Wind Power via VSC-MTDC,” *Electric Power Automation Equipment*, vol. 42, no. 8, pp. 103-110, Aug. 2022.

- [55] C. Buchhagen, C. Rauscher, and A. Menze *et al.*, "BorWin1-first Experiences with Harmonic Interactions in Converter Dominated Grids," in *Proc. of International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age*, Bonn, Germany, Nov. 2015, pp. 1-7.
- [56] S. Q. Yang, K. P. Liu, and L. Qin *et al.*, "Research Progress of High Frequency Oscillation in MMC-HVDC," *High Voltage Engineering*, vol. 47, no. 10, pp. 3485-3496, Oct. 2021.
- [57] J. Wu, F. Fang, and X. M. Zhao, "Analysis on Typical Faults in Passive HVDC Startup Tests in Zhouyang VSC-HVDC Converter Station," *Zhejiang Electric Power*, vol. 35, no. 1, pp. 6-9, 2016.
- [58] B. B. Shao, S. Q. Zhao, and B. F. Gao *et al.*, "Inside-wind-farm/Wind-farm-grid Sub-synchronous Oscillation Characteristics Analysis in Multiple D-PMSGs Interfaced with VSC-HVDC System," *Proceedings of the CSEE*, vol. 40, no. 12, pp. 3835-3846, Jun. 2020.
- [59] M. Amin, and M. Molinas, "Understanding the Origin of Oscillatory Phenomena Observed Between Wind Farms and HVdc Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 1, pp. 378-392, Mar. 2017.
- [60] X. S. Guo, Y. F. Li, and X. T. Xie *et al.*, "Sub-synchronous Oscillation Characteristics Caused by PMSG-based Wind Plant Farm Integrated via Flexible HVDC System," *Proceedings of the CSEE*, vol. 40, no. 4, pp. 1149-1160, Feb. 2020.
- [61] Y. F. Wang, C. Y. Zhao, and C. Y. Guo, "Transfer Function Model and Low-frequency Stability Analysis for PMSG-based Wind Farm Interconnected with Flexible-HVDC System," *Proceedings of the CSEE*, vol. 40, no. 5, pp. 1485-1497, Mar. 2020.
- [62] Y. J. Luo, P. Huang, and X. C. Duan *et al.*, "Equivalent Impedance Modeling Method for MMC-HVDC Considering Coupling of Offshore Wind Power and MMC Impedance," *Proceedings of the CSEE*, vol. 44, no. 7, pp. 2655-2669, Apr. 2024.
- [63] R. Yin, Y. Y. Sun, and S. S. Wang *et al.*, "The Interaction Mechanism Analysis Among the Different Control Loops of the Direct-drive Wind Turbine Connected VSC-HVDC Systems," *Proceedings of the CSEE*, vol. 42, no. 10, pp. 3627-3641, May 2022.
- [64] K. Sun, W. Yao, and Y. Zhou *et al.*, "Mechanism Analysis and Suppression of Medium-frequency Oscillation based on the SISO Impedance in a PMSG-based Wind Farm When Connected to a VSC-HVDC," *Proceedings of the CSEE*, vol. 43, no. 2, pp. 442-453, Jan. 2023.
- [65] K. Sun, W. Yao, and J. Y. Wen, "Mechanism and Characteristics Analysis of Subsynchronous Oscillation Caused by DFIG-based Wind Farm Integrated into Grid Through VSC-HVDC System," *Proceedings of the CSEE*, vol. 38, no. 22, pp. 6520-6532, Nov. 2018.
- [66] B. Pang, H. Nian, and Y. Y. Xu, "Mechanism Analysis and Damping Method for High Frequency Resonance Between VSC-HVDC and the Wind Farm," *IEEE Transactions on Energy Conversion*, vol. 36, no. 2, pp. 984-994, Jun. 2021.
- [67] Y. F. Wang, C. Y. Zhao, and C. Y. Guo, "Small Signal Stability and Oscillation Suppression Method for Islanded Double Fed Induction Generator-based Wind Farm Integrated by Modular Multilevel Converter based HVDC System," *Transactions of China Electrotechnical Society*, vol. 34, no. 10, pp. 2116-2129, May 2019.
- [68] B. Pang, C. Y. Guo, and X. Wang *et al.*, "Influence of Wind Power Access on Coupling Oscillation Modes Between Converter Stations in MMC-based HVDC Grid and Quantitative Evaluation of Interaction," *Power System Technology*, vol. 47, no. 8, pp. 3206-3216, Aug. 2023.
- [69] Y. J. Wang, W. J. Du, and H. F. Wang, "Review on Small Signal Stability Analysis of Large-scale Wind Power Collection System," *Power System Technology*, vol. 46, no. 5, pp. 1934-1946, May 2022.
- [70] N. W. Xiang, S. L. Wang, and B. B. Shao *et al.*, "Research Status and Challenges of Wide-band Oscillation in Flexible Low-frequency Transmission System," *High Voltage Engineering*, vol. 50, no. 5, pp. 1967-1977, May 2024.
- [71] H. C. Liu, and J. Sun, "Voltage Stability and Control of Offshore Wind Farms with AC Collection and HVDC Transmission," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 4, pp. 1181-1189, Dec. 2014.
- [72] Y. G. Li, W. C. Chu, and H. Z. Liu, "Low-frequency Oscillation Characteristic Analysis of Grid-connected VSG-PMSG via MMC-HVDC System," *Electric Power Automation Equipment*, vol. 43, no. 9, pp. 186-193, Sept. 2023.
- [73] J. Lv, and X. Cai, "Controller Parameters Optimization Design for Enhancing the Stability of Wind Farm with VSC-HVDC System," *Proceedings of the CSEE*, vol. 38, no. 2, pp. 431-443, Jan. 2018.
- [74] J. Shair, X. R. Xie, and G. G. Yan, "Mitigating Subsynchronous Control Interaction in Wind Power Systems: Existing Techniques and Open Challenges," *Renewable and Sustainable Energy Reviews*, vol. 108, pp. 330-346, Jul. 2019.
- [75] Y. T. Zhou, L. L. Hao, and H. H. Wang *et al.*, "Analysis and Suppression of SSO at Sending/receiving End in VSC-HVDC System Connected Large-capacity Wind Farms," *Electric Power Automation Equipment*, vol. 40, no. 3, pp. 100-106, Mar. 2020.
- [76] H. Z. Li, J. Y. Li, and J. J. Yang *et al.*, "Shunt-VSC Subsynchronous Damping Controller to Suppress SSO in Wind Power Connected by Flexible DC Sending System," *Electric Power Automation Equipment*, vol. 42, no. 8, pp. 133-139, Aug. 2022.
- [77] Y. F. Li, W. G. Zhao, and M. Kong *et al.*, "Virtual Paralleled-impedance Control Strategy of Flexible HVDC Connecting to the PMSG-based Wind Farm for Sub-synchronous Oscillation Suppression," *Proceedings of the CSEE*, vol. 42, no. 17, pp. 6326-6337, Sept. 2022.
- [78] S. Zhu, K. P. Liu, and Q. Wang *et al.*, "Sub-synchronous Oscillation Suppression of Modular Multilevel Converter based on Capacitance Energy and Its Impedance Analysis," *Proceedings of the CSEE*, vol. 41, no. 6, pp. 2230-2244, Mar. 2021.
- [79] Z. Xu, Y. L. Xue, and Z. R. Zhang, "VSC-HVDC Technology Suitable for Bulk Power Overhead Line Transmission," *Proceedings of the CSEE*, vol. 34, no. 29, pp. 5051-5062, Oct. 2014.
- [80] C. Wang, K. D. Tan, and Y. Wang *et al.*, "Topology of MMC Oblique-connection Full-bridge Sub-module with Capability of DC Fault Clearing and Voltage Self-balancing," *Automation of Electric Power Systems*, vol. 44, no. 24, pp. 151-160, Dec. 2020.
- [81] Y. Y. Luo, Y. H. Wang, and R. H. Song *et al.*, "Improved Capacitive Sub-module with DC Fault Self-clearing Capability," *High Voltage Engineering*, vol. 47, no. 12, pp. 4510-4517, Dec. 2021.
- [82] H. C. Shu, W. T. Wang, and Y. X. Jiang *et al.*, "Novel MMC Sub-module Topology with DC Fault Clearing Capability," *Electric Power Automation Equipment*, vol. 42, no. 5, pp. 75-81, May 2022.
- [83] X. G. Wei, C. Gao, and X. Luo *et al.*, "A Novel Design of High-voltage DC Circuit Breaker in HVDC Flexible Transmission Grid," *Automation of Electric Power Systems*, vol. 37, no. 15, pp. 95-102, Aug. 2013.
- [84] S. B. Song, D. B. Zhou, and W. Peng *et al.*, "Comparisons and Application Prospect Analysis of High-voltage DC Circuit Breakers," *Guangdong Electric Power*, vol. 34, no. 12, pp. 38-47, Dec. 2021.
- [85] H. Y. Zhou, W. Yao, and K. Y. Sun *et al.*, "A Multi-level Coordinated DC Overcurrent Suppression Scheme for Symmetrical Bipolar MMC-HVDC Integrated Offshore Wind Farms," *International Journal of Electrical Power & Energy Systems*, vol. 147, pp. 108880, May 2023.
- [86] S. Q. Jiang, Y. C. Xin, and G. Q. Li *et al.*, "A Novel DC Fault Ride-through Method for Wind Farms Connected to the Grid Through Bipolar MMC-HVDC Transmission," *IEEE Transactions on Power Delivery*, vol. 35, no. 6, pp. 2937-2950, Dec. 2020.
- [87] Y. F. Sun, Y. Z. Lu, and Y. H. Liu *et al.*, "Coordinated Control Strategy of DC Fault Ride-through for Flexible DC Grid-connected System of Wind Power based on Energy Storage," *Automation of Electric Power Systems*, vol. 47, no. 3, pp. 122-132, Feb. 2023.
- [88] C. Feltes, H. Wrede, and F. W. Koch *et al.*, "Enhanced Fault Ride-through Method for Wind Farms Connected to the Grid Through VSC-based HVDC Transmission," *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1537-1546, Aug. 2009.
- [89] D. Tzelepis, A. O. Rousis, and A. Dysko *et al.*, "Enhanced DC Voltage Control Strategy for Fault Management of a VSC-HVDC Connected Offshore Wind Farm," in *Proc. of 5th IET International Conference on Renewable Power Generation*, London, UK, Sept. 2016, pp. 1-6.
- [90] X. H. Wang, R. X. Yang, and Z. H. Shi *et al.*, "Coordinated Low Voltage Ride-through of MMC-HVDC Transmission System and Wind Farm with Distributed Braking Resistors," *IEEE Access*, vol. 10, pp. 87860-87869, Aug. 2022.

- [91] H. B. Zhang, W. Xiang, and J. Y. Wen, "Active Energy Control of Offshore Wind Power MMC-HVDC System to Handle AC Faults of Receiving-end Power Grid," *Proceedings of the CSEE*, vol. 43, no. 12, pp. 4600-4613, Jun. 2023.
- [92] R. Teixeira Pinto, P. Bauer, and S. F. Rodrigues *et al.*, "A Novel Distributed Direct-voltage Control Strategy for Grid Integration of Offshore Wind Energy Systems Through MTDC Network," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2429-2441, Jun. 2013.
- [93] A. Kirakosyan, M. S. E. Moursi, and V. Khadkikar, "Fault Ride Through and Grid Support Topology for the VSC-HVDC Connected Offshore Wind Farms," *IEEE Transactions on Power Delivery*, vol. 32, no. 3, pp. 1592-1604, Jun. 2017.
- [94] O. D. Adeyi, M. Cheah-Mane, and J. Liang *et al.*, "Preventing DC Over-voltage in Multi-terminal HVDC Transmission," *CSEE Journal of Power and Energy Systems*, vol. 1, no. 1, pp. 86-94, Mar. 2015.
- [95] S. I. Nanou, and S. A. Papathanassiou, "Grid Code Compatibility of VSC-HVDC Connected Offshore Wind Turbines Employing Power Synchronization Control," *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 5042-5050, Nov. 2016.
- [96] K. Jia, X. Z. Dong, and Z. W. Wen *et al.*, "Harmonic Injection based Fault Ride-through Control of MMC-HVDC Connected Offshore Wind Farms," *IEEE Transactions on Sustainable Energy*, vol. 14, no. 3, pp. 1796-1806, Jul. 2023.
- [97] K. Jia, X. Z. Dong, and T. S. Bi *et al.*, "A Grid Side Fault Ride-through Method based on Precise Matching Power for Offshore Wind Farms Connected MMC-HVDC," *Proceedings of the CSEE*, vol. 43, no. 2k, pp. 84-93, Aug. 2023.
- [98] X. H. Wang, L. G. Yang, and B. Lin *et al.*, "Mechanism and Restraining Strategy of the Sending-end Grid Overvoltage in Offshore Wind Farm-flexible HVDC Transmission System Under Grid Faults," *High Voltage Engineering*, vol. 47, no. 8, pp. 2688-2697, Aug. 2021.
- [99] M. Hong, H. H. Xin, and C. B. Xu *et al.*, "Coordinated Control Strategy of Offshore Wind Farms and VSC-based HVDC Transmission Systems," *Automation of Electric Power Systems*, vol. 40, no. 21, pp. 53-58+65, Nov. 2016.



Jingyi Zhang was born in Henan, China, in 2000. She received the M.S. degree in electrical engineering from Wuhan University, Wuhan, China, in 2025.

She is currently with the Research Institute of NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing, China. Her research

interests include power electronics, offshore wind power, and modular multilevel converters (MMC).



Huiru Yang was born in Hubei, China, in 2003. She received her bachelor of engineering degree in electrical engineering from Wuhan University, Wuhan, China, in 2025.

Currently, she is pursuing her master's degree in Electrical Engineering with the School of Electrical Engineering and

Automation, Wuhan University. Her research interests include the modeling, control and inertial response characteristics of wind power generation.



Zhen Tian (Member, IEEE) received the B.S. degree in electrical engineering from Wuhan University, Wuhan, China, in 2014, and the Ph.D. degree in control science and engineering from Shanghai Jiao Tong University, Shanghai, China, in 2019.

During 2017–2019, he was a visiting scholar with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, USA. He is currently a Postdoctoral Fellow with the School of Electrical Engineering and Automation, Wuhan University. His research interests mainly include modeling, control and stability analysis of renewable energy generation, microgrid, and power-electronics-enabled power systems.



Pan Feng was born in Xingtai, Hebei Province, China, in 2002. He received the B.Eng. degree in electrical engineering from Sichuan University, Chengdu, China, in 2023.

He is now working towards the Ph. D. degree in electrical engineering with Wuhan University, Wuhan, China. His research interests include the modeling and stability analysis of virtual synchronous generator-based and DC-link voltage-synchronized-based grid-forming converters.



Fei Liu (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China, in 2008.

He is currently a professor and doctoral supervisor with the School of Electrical Engineering and Automation, Wuhan University, Wuhan, China. His research interests include distributed photovoltaic (PV)-storage-charging access to DC distribution systems, multi-converter interaction and coordinated control of grid-forming PV power stations, power electronic technology in smart grids and new energy generation, and PV-storage energy conversion & information fusion in intelligent buildings.



Zhe Chen received the M.S. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2022.

She is currently an engineer with State Grid Shanghai Electric Power Research Institute. Her research interests include HVDC power transmission, renewable energy integration, and the application of power electronics in power systems.



Ruanming Huang is a senior expert with the State Grid Shanghai Electric Power Company. He serves as an enterprise master supervisor of Shanghai Jiao Tong University, Shanghai, China, a part-time master supervisor of Wuhan University, Wuhan, China, and a distinguished teacher of Harbin Institute of Technology

and Shanghai University of Electric Power, Shanghai, China.

He has presided over major national scientific and technological projects, won more than 30 scientific and technological progress awards, obtained over 40 invention patents, published more than 130 academic papers, and presided over the development of an internationally leading offshore wind power three-dimensional (3D) virtual reality (VR) device, with his deeds reported by mainstream media.



Xiaoming Zha (Member, IEEE) was born in Huaining, China, in 1967. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Wuhan University, Wuhan, China, in 1989, 1992, and 2001, respectively.

He was a Postdoctoral Fellow with the University of Alberta, Canada, from 2001 to 2003. He has been a Faculty Member with Wuhan University since 1992, and became a professor in 2003. He is currently the Deputy Dean with the School of Electrical Engineering, Wuhan University, Wuhan, China. His research interests include power electronic converter, the application of power electronics in smart grid and renewable energy generation, the analysis and control of microgrid, the analysis and control of power quality, and frequency control of high-voltage high-power electric motors.



Meng Huang (Member, IEEE) received the B.Eng. and M.Eng. degrees in electronic science and technology from the Huazhong University of Science and Technology, Wuhan, China, in 2006 and 2008, respectively, and the Ph.D. degree in electrical engineering from the Hong Kong Polytechnic University, Hong

Kong, in 2013.

He is currently a Professor with the School of Electrical Engineering and Automation, Wuhan University, Wuhan, China. His research interests include nonlinear analysis of power converters and power electronics reliability.

Dr. Huang was the recipient of the best paper award of the IEEE Transactions on Power Electronics in 2016. He is the Guest Associate Editor for the IEEE Journal of Emerging and Selected Topics of Power Electronics, IEEE Journal of Emerging and Selected Topics of Circuits and Systems, and the Associate Editor for the IEEE Access.