Fault Ride-Through and Recovery Strategy for Offshore Wind Power MMC-HVDC System Directly Feeding Urban Centers Against Urban Grid AC Faults

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***Abstract*—Offshore wind power delivered via MMC-HVDC systems to urban centers is vulnerable to AC grid faults, which can cause DC overvoltage and grid voltage instability. This paper proposes a fault ride-through strategy that ensures system stability during such faults. The method prioritizes reactive power support to the urban grid while utilizing the wind turbines' rotor kinetic energy to absorb excess active power. Post-fault, a recovery strategy smoothly restores power delivery. Simulations confirm the strategy's effectiveness in stabilizing both DC and AC voltages, enhancing the system's resilience.**

***Index Terms*—Offshore Wind Power MMC-HVDC System, fault ride-through and recovery, wind turbines' rotor kinetic energy, DC voltage.**

I. INTRODUCTION

Against the backdrop of the deepening global energy transition, far-reaching offshore wind power, with its prominent advantages such as abundant resource reserves[1], and offers higher consistency and capacity factors compared to onshore wind, has emerged as a pivotal energy form to address the constraints of traditional fossil fuels and achieve the "dual carbon" goals. The large-scale development and utilization of far-reaching offshore wind power has become a critical direction in the new energy strategies of various countries[2]. Meanwhile, China's urbanization process continues to accelerate. As the core carriers of economic and social development, urban load centers are experiencing rigid growth in electricity demand[3], with increasingly stringent requirements for power supply reliability and voltage stability.

In traditional offshore wind power grid integration modes, AC transmission faces challenges such as extensive land requirements for transmission corridors and difficulties in controlling short-circuit currents, while conventional DC transmission is susceptible to the risk of commutation failure. Both modes struggle to adequately meet the demand of urban load centers for the efficient integration of clean electricity. Modular Multilevel Converter based High-Voltage Direct Current (MMC-HVDC) technology provides an ideal solution for directly delivering offshore wind power to urban load centers. Compared to the AC integration mode, the MMC-HVDC system can significantly reduce the land area required for transmission corridors, offers easier control of short-circuit current levels, and avoids the issue of excessive short-circuit currents associated with reinforcing AC grid infrastructure[1]. Compared to conventional DC integration, it does not require commutation support, fundamentally avoiding the risk of commutation failure. Furthermore, leveraging its flexible control characteristics, it possesses dynamic reactive power regulation capability, enabling it to directly provide voltage support for the urban power grid and address the shortage of reactive power supply in urban grids.

The urban power grid, characterized by highly concentrated loads and densely interwoven transmission lines, is significantly more susceptible to instantaneous AC line faults due to factors like lightning strikes and temporary equipment abnormalities compared to remote area grids[3]. This substantially increases the suddenness and uncertainty of on-shore AC grid faults, thereby imposing a mandatory requirement on the offshore wind power MMC-HVDC direct delivery system[4]: "it must possess fast and reliable strategies to handle urban AC faults." However, this model currently faces severe challenges: during faults, power transmission at the receiving-end converter station is hindered, preventing the absorption of offshore wind power[5]. This leads to power surplus on the DC side and a rapid rise in DC voltage, potentially causing converter blockades and submarine cable damage. Traditional mitigation methods relying on centralized DC choppers or energy dissipation devices not only waste green energy but also suffer from high costs and large space requirements[6][7]. Furthermore, the urban grid contains a significant amount of voltage-sensitive loads, which demand high power quality, especially voltage level. Utilizing MMC-HVDC to provide necessary voltage support is also one of the key considerations[3]. Therefore, developing fault ride-through strategies that concurrently provide reactive power support for the urban grid and maintain DC voltage stability for the MMC-HVDC system itself is an essential requirement for promoting the direct delivery of offshore wind power to urban load centers, holding significant engineering and academic value.

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This paper proposes a fault ride-through strategy for an offshore wind power MMC-HVDC system directly feeding an urban center against urban grid AC faults. The main contents are as follows:

1) The system configuration of the offshore wind power MMC-HVDC system, the typical control strategies and mathematical models of wind turbine generator.

2) A fault ride-through strategy for the offshore wind power MMC-HVDC system is formulated from both active and reactive power aspects during urban grid AC faults.

3) A post-fault recovery strategy is developed from both active and reactive power perspectives following fault clearance.

4) The proposed fault ride-through and recovery strategies are validated through simulations in a test system.

II. Overview of the Offshore Wind Power MMC-HVDC System for Direct Delivery to Urban Centers

The offshore wind power MMC-HVDC system for direct delivery to load centers primarily consists of two parts: first, the MMC-HVDC system that performs wind power AC collection, DC transmission, DC-to-AC conversion, and finally integration into the urban center power grid; second, the offshore wind turbines responsible for capturing wind energy and converting it into AC electrical energy.

A. Main Structure and Control Scheme of the Offshore Wind Power MMC-HVDC System

The structure of the offshore wind power MMCHVDC grid integration system is shown in Fig. 1. The electrical energy collected from the AC bus of the offshore wind farms is fed into the offshore converter station via step-up transformers, rectified, then transmitted to the onshore converter station via submarine cables, and finally inverted into AC power to be fed into the receiving-end grid.

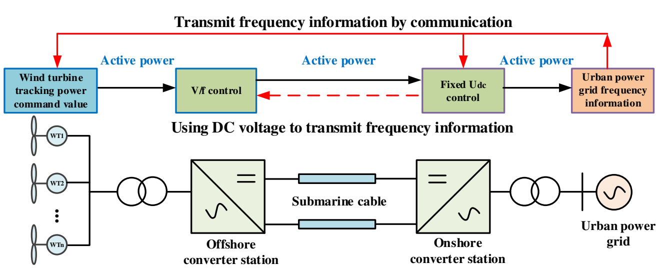

Fig. 1. Structural diagram of offshore wind power MMC-HVDC grid-connected system.

Since most wind turbine generators operate in grid-following mode, the offshore converter station needs to provide voltage and frequency references for them, thus requiring V/f control; while the DC system voltage needs to be controlled by the onshore converter station. When a frequency dip occurs in the receiving-end grid, communication systems, utilizing optical fiber or other media, can be employed to transmit the receiving-end's frequency signal to the offshore wind turbine side. If no communication equipment is available, the DC voltage can be utilized as a transmission medium to convey the frequency information of the receiving-end grid.

There are various types of wind turbines, which can be broadly categorized into three main types based on the form of the main drive train: direct-drive wind turbines, doubly-fed induction generator wind turbines, and semi-direct-drive wind turbines. Among them, the direct-drive wind turbine has gained favor due to its relatively simpler unit structure and control scheme.

B. Main Structure and Control Scheme of the Direct-Drive Wind Turbine

The basic structure of the direct-drive wind turbine is shown in Fig. 2.

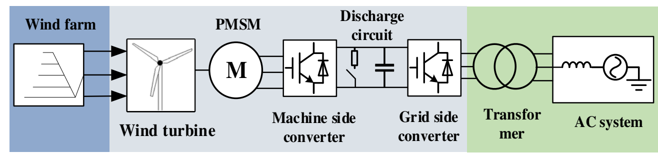

Fig. 2. Structural diagram of direct-drive wind turbine generator.

The wind turbine captures wind energy. The permanent magnet synchronous generator is directly coupled to the wind turbine. The electrical power generated is fed through a pair of back-to-back converters, stepped up by a transformer, and then supplied to the AC system. Typically, the machine-side converter employs zero d-axis current control and fixed active power control (the active power reference is generated by the MPPT module); the grid-side converter employs fixed DC voltage control and unity power factor control.

The wind energy capture equation for the wind turbine is:

$$P_\omega = \frac{1}{2P_B}\rho\pi R^2 v^3 C_p(\lambda,\beta) \tag{1}$$

$$C_p(\lambda,\beta) = 0.22(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{-\frac{12.5}{\lambda_i}} \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

$$\lambda = \frac{\omega\omega_B R}{v} \tag{4}$$

where P_B is the rated output power of the wind turbine; P_ω is the per-unit value of the power captured by the wind turbine; ρ is the air density; R is the rotor radius; v is the wind speed; C_p is the power coefficient, which is related to the pitch angle β and the tip speed ratio λ of the generator; ω and ω_B are the per-unit value of the rotational speed and the rated actual value, respectively.

Neglecting control delays, the actual output power of the wind turbine is:

$$P_{out} = P_{ref} = P_\omega - T_J\omega\frac{d\omega}{dt} \tag{5}$$

Where P_{out} is the real output power of the wind turbine; P_{ref} is the reference value of the output power; T_J is the physical inertial of the wind turbine.

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III. FAULT RIDE-THROUGH STRATEGY

Considering that during an AC grid N-1 contingency, the voltage dips require substantial reactive power support; and furthermore, considering that synchronous generators still constitute a significant portion of the AC grid and there are considerable frequency regulation resources deployed, the offshore wind power MMC-HVDC transmission system operating at reduced power or even zero active power for a short duration has minimal impact on the frequency stability of the AC grid. Therefore, a fault ride-through strategy for urban AC grid faults is formulated, which prioritizes reactive power support and utilizes the rotor kinetic energy of the wind turbines to temporarily absorb the surplus active power.

A. Reactive Power Aspect

First, based on the principle of providing sufficient reactive power/voltage support, the q-axis current of the onshore converter station during the fault is set.

For the ideal model of an offshore wind power MMC-HVDC system connected to a single-machine infinite bus AC system, the desired reactive power that the AC grid is expected to acquire is obtained:

$$Q = \frac{U_s(U_s - U_{sys}\cos\theta_s)}{X_{sys}} \tag{6}$$

Here, U_{sys} is the equivalent voltage source of the AC grid, and $R_{sys} + jX_{sys}$ is the Thevenin equivalent impedance of the AC grid (Typically, the offshore wind MMC-HVDC system is directly connected to the 525kV AC transmission network, where the resistance is far smaller than the reactance and can be neglected). θ_s is the voltage phase angle at the point of common coupling for the offshore wind farm.

It is assumed that during the AC fault ride-through period, the Phase-Locked Loop (PLL) of the onshore converter station operates normally, meaning that under the original grid voltage orientation, the q-axis component $U_{sq} = 0$ of the voltage at the converter's point of common coupling remains unchanged. According to the instantaneous power theory, the expression for the reactive power injected by the converter into the AC grid remains:

$$Q_s = \frac{3}{2}(U_{sd}i_q - U_{sq}i_d) = \frac{3}{2}U_s i_q \tag{7}$$

where U_s is the RMS value of the AC voltage at the point of common coupling. From Equation (2.1) and Equation (2.2), the reference value for the q-axis current I_{qref} of the onshore converter station can be set as:

$$i_{qref} = \min[I_{\max}, \frac{2(U_s - U_{sys}\cos\theta_s)}{3X_{sys}}] \tag{8}$$

Where, I_{max} is the current limit value of the onshore converter station.

According to the reactive power priority principle, after satisfying the iq requirement, the reference value for the d-axis current component is then set based on the converter current limit.

$$I_{\max}^2 \geq i_q^2 + i_d^2 \tag{9}$$

From Equation (2.3) and Equation (2.4), the following can be obtained:

$$i_d = \sqrt{I_{\max}^2 - i_q^2} \tag{10}$$

According to the instantaneous power theory, the active power injected by the converter into the AC grid is given by:

$$P_s = \frac{3}{2}U_s i_d = \frac{3}{2}U_s\sqrt{I_{\max}^2 - i_q^2} \tag{11}$$

Compared to the initial active output power P_0, the surplus power resulting from the AC grid fault and the configured fault ride-through strategy is:

$$P_{sur} = P_0 - P_s \tag{12}$$

When accurate communication means are available, the power adjustment command can be directly transmitted to the offshore wind turbines, modifying their power reference value to:

$$P_{ref} = P_s \tag{13}$$

When reliable communication equipment is unavailable, the power reference value of the offshore wind turbines can be set based on the detected DC voltage deviation, which is a method of regulation with deviation. It should be noted that the rate of change of the DC voltage deviation is not used as an input variable to avoid the impact of high-frequency noise on system stability:

$$P_{ref} = P_0 - D\Delta U_{dc} \tag{14}$$

Among them, ΔU_{dc} is the DC voltage deviation detected by the offshore converter station; D is the droop control parameter. Based on the principle that the surplus power absorbed by the offshore wind turbines is maximized when the DC voltage deviation reaches its maximum value, D can be set as:

$$D = \frac{P_0 + P_{wind}}{\Delta U_{dc,\max}} \tag{15}$$

Among them, P_{wind} is the rated output power of the offshore wind turbine unit, and it is considered here that the maximum power it can absorb is also P_{wind}; $\Delta U_{dc,\max}$ is the maximum DC voltage deviation that the DC transmission system can withstand. It should be noted that the offshore wind farm model used in this paper is an equivalent model based on the single-machine aggregation method, meaning that all individual wind turbines are assumed to have identical models, parameters, and operating environments. During faults, the operating states and control effects of all turbines remain consistent, and the wind speed is assumed to be constant without fluctuations.

IV. POST-FAULT RECOVERY STRATEGY

After fault clearance, the AC voltage requires a certain period (typically around 100 milliseconds) to recover to its normal state. During this period, the MMC-HVDC converter must continue to provide voltage support, meaning the reactive power priority strategy remains in effect. Once the voltage has recovered to its normal state, the provision of reactive power support is ceased. The active power reference of the wind turbines is restored to its normal value. After maintaining this

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state for a period (indicating the urban grid has completely stabilized into a new operating state), the active power reference of the wind turbines is appropriately adjusted to deliver the surplus energy stored in the turbine rotors during the fault period to the urban grid.

A. *Reactive Power Aspect*

During the post-fault clearance voltage recovery period, the reactive power priority strategy is still adopted to facilitate the recovery of the voltage at the point of common coupling (PCC).

After the voltage recovers to its normal state, further consideration must be given to compensating for the undelivered active power during both the fault period and the post-fault voltage recovery period, aiming to maintain a constant average power output from the offshore wind power MMC-HVDC integration system over a defined timeframe.

B. *Active Power Aspect*

The system's surplus energy during the fault is determined according to the following equation:

$$E_{sur} \approx P_{sur}^{fault} \times \Delta t_{fault} \quad (16)$$

Within a certain period after fault clearance and voltage recovery to normal, the output active power is required to be appropriately increased. The active power reference value for the offshore wind turbines can be set as:

$$P_{ref} = \min\{P_0 + \frac{E_{sur}}{\Delta t_{\text{expect}}}, P_N\} \quad (17)$$

The time required to deliver all the absorbed surplus energy to the AC grid is:

$$\Delta t_{\text{real}} = \frac{E_{sur}}{P_{ref} - P_0} \quad (18)$$

V. CASE STUDY

A simulation model as shown in Fig. 1 was built in MATLAB/Simulink. The main parameters of the MMC-HVDC system are listed in Table 1. The turbine parameters of the three wind farm are given in Table 2.

TABLE I. MAIN PARAMETERS OF THE MMC-HVDC SYSTEM

Parameter Name	***Value***
Rated Capacity	1070MVA
DC Voltage	135kV
Offshore Station AC Voltage	66kV
Onshore Station Converter Transfer Voltage	230kV/66kV
Converter Current Limit	1.25pu
DC capacitance	40μF

TABLE II. MAIN PARAMETERS OF THE WIND TURBINES

Wind Farm ID	***Rated Power per Turbine (MW)***	***Number of Turbines***	***Rated Rotational Speed (rpm)***	***Rotor Inertia Time Constant***
W1	26	20	7.2	7.7354
W2	18	15	8.5	9.0398
W3	14	20	9.5	5.9116

TABLE III. THE AC VOLTAGE OF PCC

PCC Voltage	***Value***
Without proposed strategy	0.521 pu
With proposed strategy	0.516 pu

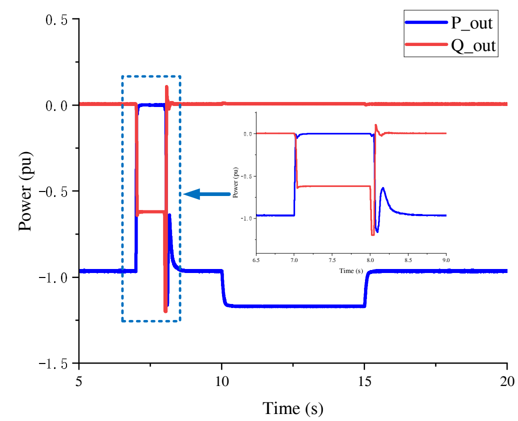

Fig. 3. Waveforms of the output active and reactive power from the onshore converter station.

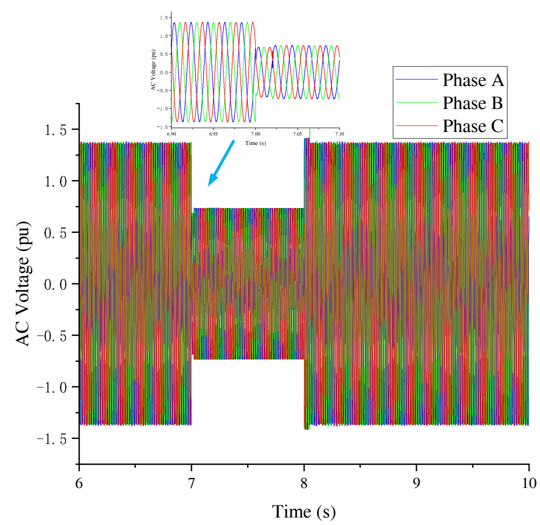

Fig. 4. Three-Phase Voltage Waveform at PCC.

Consider that an AC grounding fault occurs in the urban grid at t = 7 s, causing the voltage source of the Thevenin equivalent circuit (viewed from the PCC of the MMC-HVDC converter station towards the system) to drop to 0.5 pu. The fault is cleared after 2 seconds., a comparison is made regarding the variations in system DC voltage and PCC AC voltage under two scenarios: the offshore wind power MMC-HVDC grid integration system operating without any additional strategy, versus operating with the additional strategy proposed in this paper. It should be noted that at 3 seconds after fault clearance, i.e., at t = 10 s, the wind turbines begin to release the surplus energy accumulated during the fault period, which continues over a duration of 5 seconds.

The output active and reactive power of the onshore converter station is shown in Fig. 3.As can be seen from Fig. 3, after the strategy is applied, the onshore converter station can fully output reactive power and reduce the active power to zero during both the fault and the post-fault recovery periods. This results in a certain degree of improvement in the AC voltage at PCC, as indicated in Table 3. The three-phase voltage waveform at the PCC after the strategy application is shown in Fig. 4.

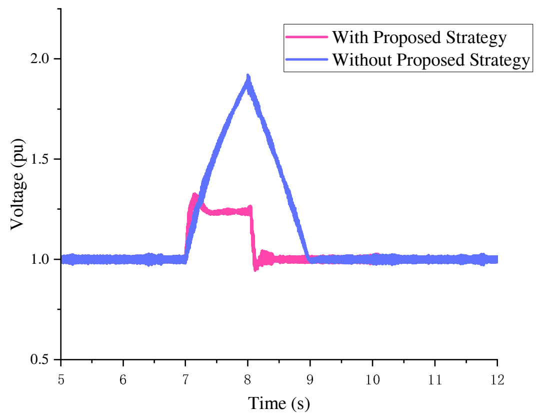

Fig. 5. DC voltage comparison.

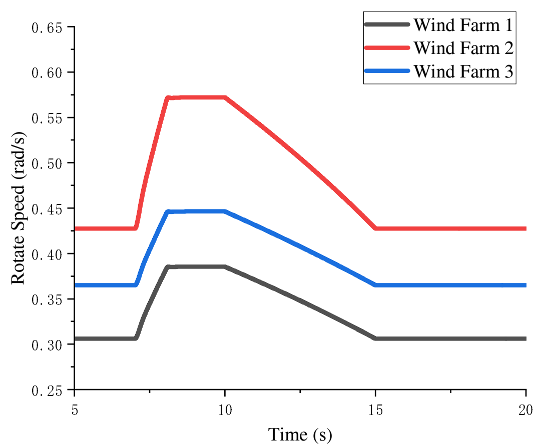

Fig. 6. Wind turbine rotor speed waveform.

Due to the adjustment of the wind turbine power reference value during the fault, which enables the absorption of part of the surplus power by the turbines, the overvoltage situation in the DC system is significantly improved, as shown in Fig. 5. Concurrently, because the wind turbines absorb a portion of the surplus power, their rotor speed increases accordingly, as depicted in Fig. 6.

VI. Conclusion

A coordinated fault ride-through and recovery strategy has been proposed, focusing on both reactive and active power management to enhance system resilience and support grid stability. The key contributions are summarized as follows:

1) A reactive power priority strategy was developed for the onshore converter station during faults, ensuring maximum reactive power injection to support the depressed AC voltage at PCC, thereby improving voltage stability.

2) An active power curtailment and absorption strategy was implemented, utilizing the rotor kinetic energy of the wind turbines to temporarily store surplus active power, thus preventing dangerous DC overvoltage and avoiding the need for expensive energy dissipation devices.

3) A post-fault recovery strategy was designed to smoothly restore active power delivery while ensuring continued reactive support during voltage recovery.

Simulation results in a MATLAB/Simulink test system validated the effectiveness of the proposed strategies. The system with the proposed strategy demonstrated significant improvement in DC voltage stability and a measurable enhancement in PCC AC voltage during fault conditions. The coordinated control between the onshore converter and offshore wind turbines proved effective in managing power imbalances and supporting grid voltage.

Future work will focus on optimizing the coordination between multiple wind farms with heterogeneous characteristics, investigating the strategy's performance under more complex grid fault scenarios, and exploring its integration with other grid-supporting services like frequency regulation.

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