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FREQUENCY STABILITY STRATEGY FOR OFFSHORE WIND POWER FLEXIBLE DC TRANSMISSION NETWORK BASED ON VSFR

Xiangsheng Lei,* Yanfeng Wang,* Xinghua Wang,* Fan Yang,** and Hanxuan Liu**

Abstract

Due to the advantages of environmental protection and economy in offshore wind power generation, the installed capacity has been increasing year by year. However, offshore wind power generation is a fluctuating new energy source that is not limited by plans, and its output has randomness and volatility. After power is connected to the active distribution network through power converters, it cannot directly respond to frequency changes caused by active distribution network parameters, resulting in frequency instability. This article conducts research on this issue. Firstly, the current research status of frequency response in offshore wind power generation was analysed, and the reasons for frequency fluctuations were discussed in depth. A mathematical model of frequency response in offshore wind power generation was established. A frequency stabilisation strategy based on virtual system frequency response (VSFR) was proposed, and the algorithm flowchart and implementation method of the strategy were provided. Numerical analysis shows that the VSFR frequency stabilisation strategy can stabilise the frequency of the grid-connected system at 50.02 Hz. This strategy has been successfully applied to the world's largest and longest transmission distance offshore wind power project. Practical applications have shown that the frequency modulation performance of the offshore wind power grid-connected system based on this strategy is superior to traditional thermal power units.

Key Words

Offshore wind power, active distribution network, frequency response, invested system frequency response, response time

1. Introduction

Since 2010, clean, low-carbon and sustainable energy has been widely developed and utilised worldwide, and is gradually replacing traditional fossil energy. Offshore wind power has large sea area, high and stable offshore wind speed, high utilisation rate and small environmental impact [1]. Therefore, offshore wind power is the focus of research and application currently.

Offshore wind power generation is affected by marine climate, geographical location and other factors, and its output is characterised by randomness and intermittence, so the output of offshore wind power generation fluctuates greatly. In practical projects, the installed capacity of offshore wind farms is relatively large, generally greater than 200 MW. If such a large capacity of power generation is directly connected to the active distribution network, it will have a huge impact on the power grid. In addition, the offshore wind power connected to the active distribution network through the converter is decoupled from the power grid and cannot directly respond to the frequency change of the power grid [2]. The offshore wind power units connected to the active distribution network through the voltage source converter based-high voltage direct current (VSC-HVDC) cannot sense the frequency of the onshore receiving power grid, decouple from the frequency of the receiving power grid, and cannot provide frequency support for the receiving power grid [3]. With the continuous increase of offshore wind power grid-connected capacity, the proportion of synchronous power sources in the receiving end grid gradually decreases, resulting in the reduction of the inertia level of the receiving end grid, the reduction of the frequency modulation reserve capacity, and the reduction of the active-frequency regulation capacity. Under the same load disturbance, the frequency of access to active distribution network changes faster and the frequency deviation is large, which seriously affects the safe and stable operation of access to active distribution network.

Reference [4] adopts a quasi-opposition harmony search (QOHS) algorithm, which is based on a centralised control scheme of a PID controller and can achieve good frequency adjustment results. Reference [5] proposes a hybrid butterfly optimisation algorithm (BOA) to minimise and maximise load when used in hybrid and hybrid markets. Reference [6] proposes a marine predator algorithm based on opposition (OMPA) and Harris Hawkes optimisation algorithm (HHO). The experimental results

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show that this algorithm can achieve good results in reactive power planning and achieve good frequency modulation performance. Reference [7] proposed a hybrid method of grey wolf optimisation and particle swarm optimisation (GWO–PSO) to solve the optimal reactive power dispatch (ORPD) problem within the power grid. This method reduces the power loss in the transmission system and the voltage deviation on the load bus. Reference [8] proposes a GWO–PSO method that utilises the FVSI method to detect weak buses, reducing the operating cost of IEEE 30 buses by 4.25%.

To sum up, studying the frequency stability method of offshore wind power generation connected to the active distribution network can strengthen the robustness and robustness of the system of offshore wind power generation at the receiving ending, improve the energy reserve and power interaction ability of offshore wind power generation connected to the active distribution network, and solve the frequency stability problem of offshore wind power generation connected to the active distribution network, which can make the application scope of offshore wind power generation wider and the installed capacity larger.

However, existing research mainly focuses on the impact of fluctuations in new energy generation on grid frequency, or the impact of transmission line faults on grid frequency. There is relatively little research on the impact of long-distance and high-power transmission system characteristics on grid frequency. This study fills this gap. At present, the mainstream offshore wind power gathering and transmission technologies mainly include power frequency AC transmission and flexible DC transmission. Flexible low-frequency AC transmission is a new efficient and economical AC transmission technology, which is a beneficial supplement to power frequency AC and DC transmission, and can improve transmission capacity, flexible control, and flexible networking. By collaborating and optimising the reactive voltage control of AC converters and wind turbines, the utilisation rate of submarine cables and system stability can be further improved.

2. Frequency Stability Problem

2.1 Large-scale Wind Power Frequency Fluctuation

Power system frequency is an important index to measure the power quality of power grid. Its essence is whether the supply and demand of active power in the power system is balanced. Power system frequency fluctuation refers to the disturbance that occurs when the frequency is affected by some factors. The ideal power system frequency is stable and can maintain or quickly recover to the allowable range in case of interference without frequency oscillation or collapse. Power system frequency stability can be divided into small disturbance frequency stability and large disturbance frequency stability. Large disturbance frequency stability can be divided into short-term process and long-term process. The time scale of the short-term process varies from a few seconds to tens of seconds, and its influence factors are the inertial response of the system and the primary frequency modulation; The time scale of the long-term process varies from a few minutes to a few hours, and its influence factors are secondary frequency modulation and tertiary frequency modulation.

The offshore wind power generation system connected to the active distribution network through flexible DC is essentially to connect large new energy, DC transmission and other power electronic equipment to the power system. At this time, the inertia level of the power system is reduced, and it does not have the ability to quickly adjust and maintain frequency stability [9]. When the random fluctuation of PV and wind power output and sudden load disturbance cause the system active power to lose balance, the system frequency change rate increases rapidly, which seriously affects the safe and stable operation of the grid system.

In practical engineering, in addition to small periodic fluctuations, the frequency can also delay the frequency decline trend, and its structure is shown in Fig. 1. For high power loss accidents, the highest priority is the lowest point of frequency fluctuation in a wide range. Although the time of primary frequency modulation process is short, as long as the process can improve the speed and degree of frequency response, it can also greatly alleviate the frequency decline transient process under severe faults for the emergency control that counts for every second. Therefore, the effect of frequency response (primary frequency modulation) is the key to determine whether the frequency is stable or not, which has attracted the attention and research of academia.

2.2 Research Status

The existing research technology route is as follows: when the offshore wind power is connected to the active distribution network through VSC-HVDC, the turbine of the wind turbine is the main reason for the frequency instability, and the VSC-HVDC frequency modulation capability is the secondary reason, so the frequency stability should be improved from the above two aspects. The manuscript first analyses the frequency support capabilities of VSC-HVDC and wind turbines [10], and concludes that wind turbines have powerful frequency support functions, but the response speed is slow, and proposes a coordinated control strategy to release the energy of DC capacitors and accelerate the frequency modulation speed of wind turbines, but this strategy will lead to the step change of DC voltage and increase the electrical stress of power electronic devices. The manuscript establishes the electromechanical transient simulation model of VSG inertial support and primary frequency modulation function [11], and deeply analyses the impact of VSG on the dynamic change of system frequency and the response characteristics in frequency accidents. The manuscript proposes a frequency stabilisation method [12], which considers both the overspeed load of wind turbine power generation price and the rotor kinetic energy. Practice has proved that this method can improve the inertia response performance of power grid and optimise

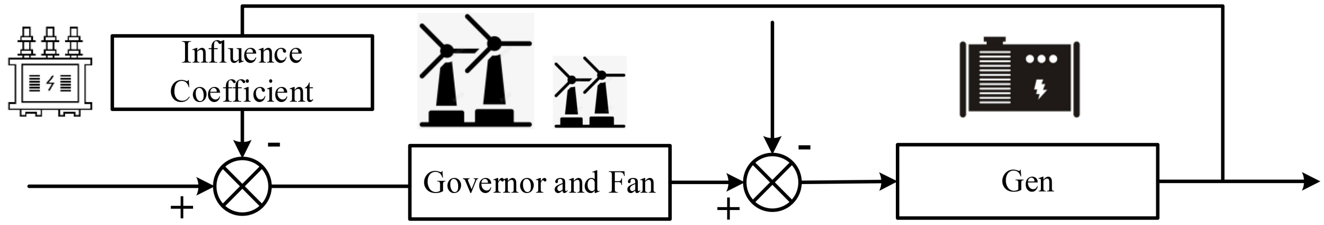

Figure 1. Frequency response transfer function model.

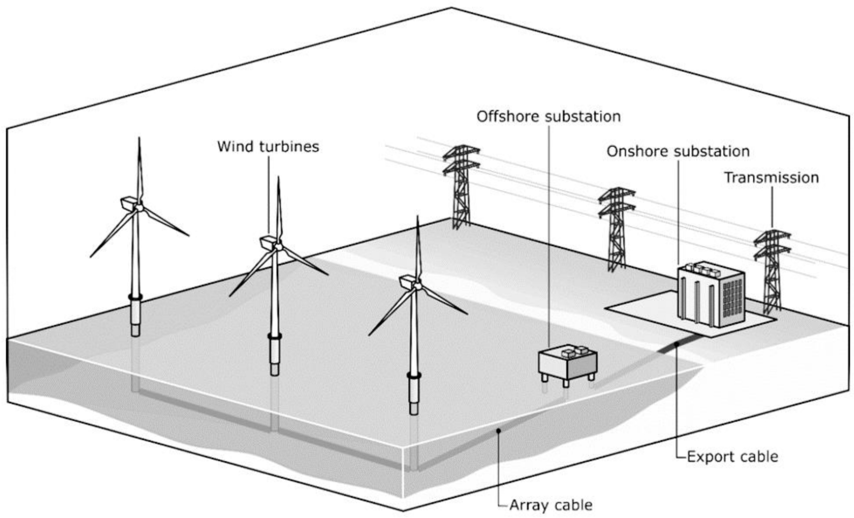

Figure 2. Topological model of offshore wind power system.

the frequency modulation stability performance. On this basis, the manuscript uses the logistic constraint function to analyse and adjust the control parameters of the converter station to ensure that the DC voltage will not exceed the limit during the change process and ensure the safe and stable operation of VSC-HVDC [13].

To sum up, the existing research mostly uses the rotor kinetic energy of wind turbine and VSC-HVDC capacitor energy storage to improve the frequency transient process of the receiving power grid, and fails to consider the standby capacity of wind turbine to improve the frequency steady-state value of the receiving power grid. Considering the above effects. This study proposes a new frequency stability strategy, which is based on VSFR and can improve the frequency stability of offshore wind power generation connected to active distribution network through coordination and coupling mechanism.

3. Frequency Response Analysis

3.1 System Topology

The topology of the offshore wind power generation system is shown in Fig. 2, which consists of three parts: offshore wind farm, VSC-HVDC and active distribution network. The three parts are equipped with frequency stability control module. The control method of WFVSC module is AC voltage control and stable frequency control; The control method of GSVSC module is constant DC voltage control and constant reactive power control. In order to prevent sudden change of power, the internal unit adopts the load-shedding control method of overspeed – pitch coordination, and reserves 20% of the standby power.

3.2 Analysis of Influencing Factors

The offshore wind turbine generator is a synchronous generator. The characteristic of synchronous generator is that the generated power and load power can maintain real-time balance, finally, the goal of stabilising the frequency of the power system is achieved. However, because offshore wind turbines are vulnerable to interference, especially sudden changes in the external environment such as sea winds, their power output fluctuates greatly, the inertia of the system is also large, the change rate of mechanical power is relatively large, and the change rate of electromagnetic power is relatively small. When the generated power is greater than the load power rate, the frequency of the transient process will rise rapidly; When the generating power is less than the load power, the frequency of the transient process will rapidly decrease [14]. To sum up, if there is load fluctuation caused by strong wind and other disturbances in the system, the power output of power generation can be increased or decreased through inertial output. When the system power is unbalanced, the power output of power generation can be increased through primary frequency modulation and secondary frequency modulation, so as to achieve the

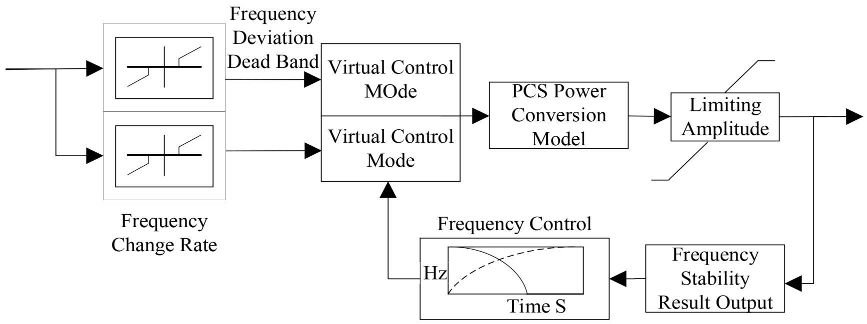

Figure 3. Schematic diagram of load frequency response model.

purpose of maintaining the dynamic stability of power system frequency.

Energy conversion process of generator shaft is modelled and analysed, and the time-domain relationship between power and speed variation in complex frequency domain is obtained as follows:

$$\Delta P_m S - \Delta P_e S = \omega_0 I \omega_s \tag{1}$$

In (1), ΔP_m is active distribution network input power, ΔP_e is wind power generation output power, S is the generator slip, ω is palstance of generator, and I is wind power generation output current.

For the load, it is composed of multiple loads with different power of frequency. The active load changes synchronously with the frequency of the active distribution network. After frequent fluctuations in the system, the active power of the system will be reduced. On the contrary, when the frequency of the system is stable, the active load of the system will increase. Therefore, it can be concluded that the frequency of active distribution network is positively correlated with active power. This load frequency characteristic is called the load frequency regulation characteristic, and the load frequency response model can be expressed as Fig. 3.

4. Frequency Stability Control Strategy

4.1 Stability Control Structure

System frequency response (SFR) model can accurately describe the frequency response process of access to active distribution network after disturbance. Assuming that the wind turbine generator and the deceleration system are equivalent to a special synchronous generator, the load of the active distribution network is a single-machine single-load model, and the inertia link time constant of the active distribution network is very small and can be ignored [15]. This paper proposes a VSFR method, and designs a VSFR controller that can make the converter station accurately simulate the frequency modulation characteristics of synchronous generator set.

VSFR control is a voltage source control with grid construction function, that is, the SFR model is embedded in the control layer of the converter station to replace the phase-locked link to output the phase angle required for the operation of the converter station, so that the converter

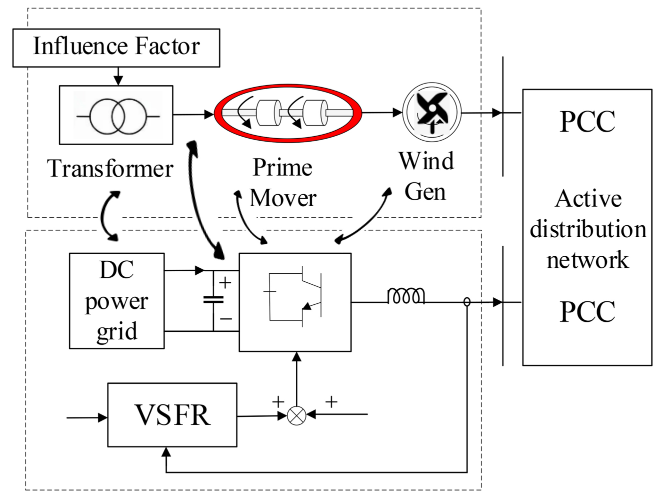

Figure 4. Schematic diagram of stability control structure.

station can simulate the frequency response characteristics of the synchronous generator, provide frequency support for the low inertia power grid connected with the converter station, and improve the frequency stability of the low inertia power grid.

As shown in Fig. 4, based on the role of each element in the frequency response process, the converter station with VSFR function can be equivalent to the traditional generator set. If the frequency response process of the grid is determined by the generator, prime mover and governor, the VSFR converter station can directly output the reference frequency for the grid, so the generator, prime mover and governor correspond to the VSFR converter station.

4.2 Frequency Regulation Control Method

According to the frequency transfer function model in Fig. 4, the closed-loop transfer function is obtained as publicity (2):

$$G(s) = \frac{1}{2H} \frac{s + \frac{1}{T_{\mathrm{RH}}}}{s^2 + (\frac{1}{T_{\mathrm{RH}}} + \frac{D}{2H} + \frac{KF_{\mathrm{HP}}}{2\mathrm{HR}})s + \frac{DR+K}{2\mathrm{HR}T_{\mathrm{RH}}}} \tag{2}$$

Where D is the load damping coefficient, R is the static adjustment parameter of the governor, $K$is the average generating power factor of offshore wind turbines,H is the inertia time constant of offshore wind turbine

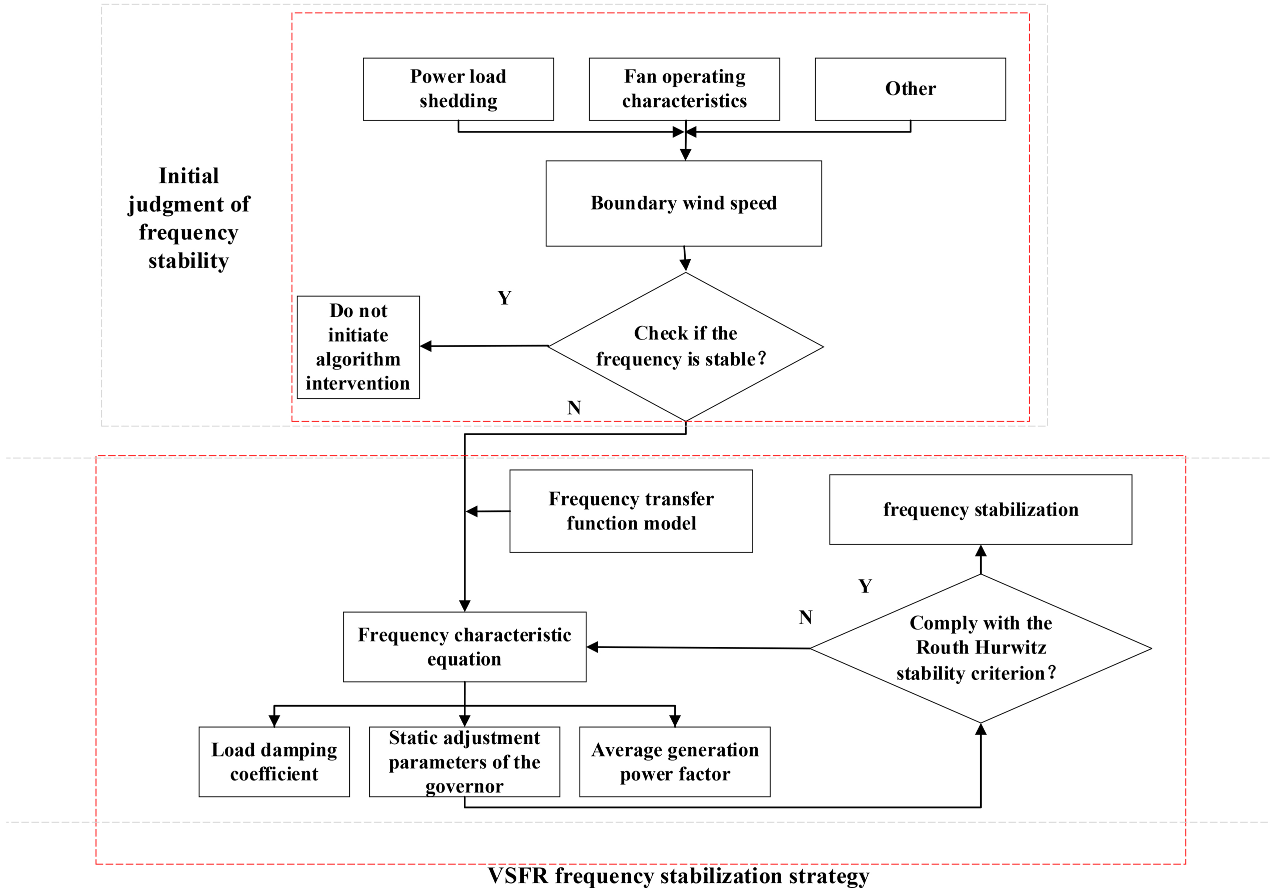

Figure 5. Algorithm flow chart.

generator, and $T_{\mathrm{RH}}$is time constant of connecting to active distribution network.

Its characteristic equation is (3) and (4):

$$s^2 + 2\zeta\omega_n + \omega_n^2 = 0 \tag{3}$$

$$\begin{cases} \omega_n^2 = \frac{DR+K}{2\mathrm{HR}T_{\mathrm{RH}}} \\ \zeta = \frac{1}{2\omega_n}\left(\frac{1}{T_{\mathrm{RH}}} + \frac{D}{2H} + \frac{KF_{\mathrm{HP}}}{2\mathrm{HR}}\right) \end{cases} \tag{4}$$

In (4), ω_n is the angular velocity of the system's inertia, and ζ is the angular velocity of the wind power generation system.

According to the Routh–Hurwitz stability criterion, the necessary and sufficient conditions for the stability of the closed-loop system are (5):

$$\begin{cases} \omega_n^2 = \frac{DR+K}{2\mathrm{HR}T_{\mathrm{RH}}} > 0 \\ 2\zeta\omega_n = \left(\frac{1}{T_{\mathrm{RH}}} + \frac{D}{2H} + \frac{KF_{\mathrm{HP}}}{2\mathrm{HR}}\right) > 0 \end{cases} \tag{5}$$

All the above parameters are positive. Since the wind turbine generator $0<F_{\mathrm{RH}}<1$, the closed-loop system is always stable [16]. The workflow of frequency stability strategy for offshore wind power flexible DC transmission network based on VSFR is shown in Fig. 5.

5. Simulation and Analysis

5.1 Simulation Parameter Setting

The above algorithm simulation runs on Matlab2016a software, and the environment and parameter settings are as follows: Set the simulation object as the active distribution network with low inertia, and the power transformer and converter station adopt three control methods: VSFR control, reactive power control, and constant active power control. And the frequency support ability of VSFR control is verified by changing the load in the low inertia power grid. In the low inertia grid, the capacity of synchronous generator is 1000 MVA, and the initial active power is 700 MW; The capacity of the converter station connected to the low inertia power grid is 700 MW, and it transmits 300 MW active power; The initial load is 900 MW; The VSFR controls the parameters of the prime mover, speed control system and generator link of the typical thermal power generation system, as follows: $F_{\mathrm{PH}} = 0.2$, $T_{\mathrm{RH}} = 7$s, $R = 0.04$, $H = 7$s, $D = 1.5\%$. When $t = 5$ s, the set load of simulation 1 increases by 100 MW; Simulation 2 sets random load disturbance with a period of 10 s, and the load range is 700–990 MW.

5.2 Results and Analysis

Assuming that the system is under operating conditions and the offshore wind turbine operates in the maximum

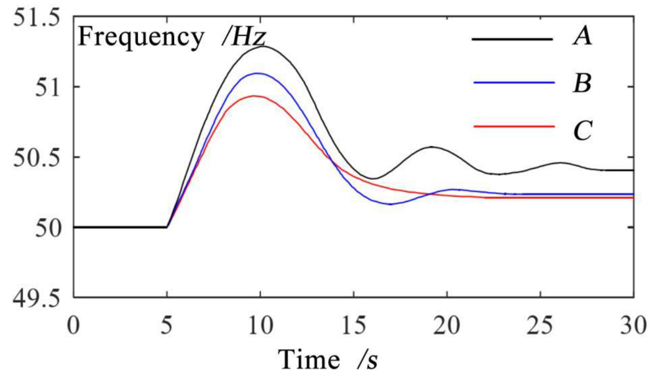

Figure 6. Frequency stability simulation results of different strategies.

power tracking mode, three simulation operating conditions are set: scenario A uses the frequency stability strategy, scenario B uses the energy storage frequency stability strategy, and scenario C uses the VSFR frequency stability strategy. The frequency change curve of the grid-connected system is shown in Fig. 6.

The active load of the power grid suddenly increased by 40 MW. Offshore wind farm system frequency rose to 52.01 Hz, and the system steady-state frequency was 51.7 Hz, the maximum frequency change rate reached 0.57 Hz/s, and the steady-state recovery time was 32.40 s; If the energy storage frequency stabilisation strategy is used, the system frequency deviation and frequency change rate will be significantly reduced. The system frequency will rise to 51.07 Hz at the highest, the system steady-state frequency will be 50.01 Hz, the maximum frequency change rate will be 0.41 Hz/s, and the system recovery time will be 21.26 s; After using the VSFR frequency stabilisation strategy proposed in this paper to configure energy storage for offshore wind farms and participate in frequency modulation, the frequency characteristics of the grid-connected system are significantly improved. The maximum value of system frequency fluctuation reaches 50.09 Hz, and the final steady-state frequency of the power grid is maintained at 50.02 Hz. The maximum frequency change rate can be calculated as 0.11 Hz/s. The whole condition time from system fluctuation to final stability is 17.51 s. The parameter of A is the best, and the result is the best. The parameters of B are good and the results are good. Because C did not use a control strategy, the parameter performance was the worst, and the quality of its results deteriorated to an unacceptable level. The system frequency modulation evaluation index under step load disturbance is shown in Table 1.

In practical engineering applications, the VSFR frequency stability strategy has a better effect on reducing the maximum frequency variation difference of the system. VSFR frequency stability strategy can greatly optimise the frequency stability of the active distribution network by large-scale direct grid connection of offshore wind turbines. The VSFR frequency stability strategy of the grid-connected is significantly optimised than that of the grid-connected system of offshore wind farms without energy storage. Obviously, the VSFR frequency stability strategy can control the frequency stability at an ideal level [17], even slightly better than the performance of traditional non-volatile thermal power units.

This algorithm is applied to the first offshore wind power flexible DC transmission project in Asia – the wind power flexible DC transmission project in Rudonghai, Jiangsu, China. The annual online electricity consumption of this project will reach 3.3 billion kilowatt hours, which can meet the annual electricity consumption of approximately 1.4 million households. Compared with coal-fired power plants of the same scale, it can save about 1 million tons of standard coal and reduce carbon dioxide emissions by about 2.5 million tons per year.

6. Conclusion

This paper proposes a frequency stability control strategy based on VSC-HVDC, which is suitable for the application of large-capacity offshore wind power generation connected to active distribution network. The manuscript draws the following conclusions: (1) The principle of this strategy is to simulate the inertia characteristics of the synchronous generator of the wind turbine and eliminate the frequency fluctuations generated by the system through VSC-HVDC. When the power grid is disturbed, the strategy adjusts the controller parameters and selects the appropriate inertia parameter value to achieve frequency stability. (2) The manuscript establishes a coupling model. The model shows the mathematical relationship between DC voltage and frequency of active distribution network and has good frequency stability. (3) This strategy is current source control, which has inherent delay and is essentially different from the instantaneous inertia response of the synchronisation unit. It cannot improve the maximum frequency change rate at the beginning of load disturbance and is not suitable for low inertia power grid.

Table 1
Measured Frequency Index of the Project

	$\lvert\Delta f(x)\rvert$	$(\frac{\mathrm{df}}{\mathrm{dt}})max$	$\Delta f(s)$	Δt
A uses the frequency stability	1.21 Hz	0.51 Hz/s	0.57 Hz	32.40 s
B uses the energy storage frequency stability strategy	1.14 Hz	0.40 Hz/s	0.41 Hz	21.26 s
C uses the VSFR frequency stability strategy	0.72 Hz	0.17 Hz/s	0.11 Hz	17.51 s
The algorithm with the best metrics	C	C	C	C

Because the algorithm used in this article uses a two-level flexible DC transmission system for simulation, the popular future application is modular multi-level systems. (4) Low-frequency grid connection of new energy is one of the prerequisites for the application of flexible low-frequency transmission systems in the collection and transmission of new energy. Offshore wind power often adopts direct drive/semi-direct drive wind turbines, which all use full power commutation and can be modified or redesigned to existing wind turbines. By changing the control, filtering, and energy harvesting circuits of the wind turbine converter, low-frequency power can be directly output to achieve low-frequency grid connection, which will not have a significant impact on the cost of the wind turbine. Therefore, in subsequent research, it is necessary to effectively test the applicability of this method in modular multi-level systems.

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Data Availability Statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

It is declared by the authors that this article is free of conflict of interest.

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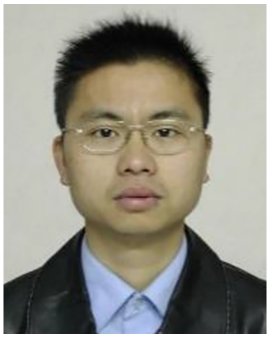
Appendix

Appendix A
List of Abbreviations for Papers

VSFR	Invested System Frequency Response
QOHS	Quasi Opposition Harmony Search
BOA	Butterfly Optimization Algorithm
OMPA	Based On Opposition
HHO	Harris Hawkes Optimization Algorithm
GWO-PSO	Grey Wolf Optimization And Particle Swarm Optimization
ORPD	Optimal Reactive Power Dispatch
VSC-HVDC	Voltage Source Converter based High Voltage Direct Current Transmission
VSC-HVC	Voltage Source Converter based High Voltage Current Transmission
SFR	System Frequency Response

Biographies



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