Characteristics and Suppression Strategies of Subsynchronous Oscillation in AC Power Grid Containing Wind Power Base

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Abstract: *The use of renewable energy sources such as wind and solar energy to replace increasingly depleted fossil energy sources has become a key way to achieve sustainable development in human society. Wind energy is one of the fastest growing clean energy sources in the world and the third largest clean energy source behind hydropower and nuclear power. However, the wind turbine is connected to the power grid through power electronics and adopts the traditional vector control based on the locker ring. Its dynamic behavior is not as friendly as that of a synchronous generator, and its resistance to disturbances is even worse in a weak grid. As the proportion of wind power continues to increase, the strength of the power grid continues to decline, resulting in a series of safety and stability accidents. In recent years, there have been many related studies on the application of synchronous control in inverters, but very little research on the application of synchronous control in double-fed fans. In this context, this paper mainly studies the sub-synchronous oscillation of AC power grids with wind power bases. Characteristics and suppression strategies. In this paper, the time window is 6-10s, and the eigenvalue analysis method is used to identify the type of the model. It can be seen that the identification result of PRONY analysis is consistent with the eigenvalue analysis, which verifies the correctness of the model and eigenvalue analysis result.*

Keywords: *Subsynchronous Oscillation, Subsynchronous Voltage, Suppression Strategy, Wind Power Base, AC Grid*

1. Introduction

Energy is the foundation for maintaining human survival and sustainable development of society. Improvements and replacements of energy technologies have promoted the leap in social productivity and lifestyle. In the past and present energy consumption patterns, fossil energy has always accounted for most of the proportion. In 2013, the production of three fossil energy sources including oil, natural gas and coal accounted for 86.7% of the total primary energy production. The extraction and use of fossil energy has improved people's living conditions and caused serious impacts on the environment, and even disrupted the earth's ecological balance to a certain extent. And fossil energy is non-renewable energy and will eventually be exhausted. According to the current average world mining speed, all fossil energy will be fully exploited in about 113 years. And the continuous improvement of human material living standards, the continuous increase of population and the global industrialization and urbanization process require ever-increasing energy supply. And the greenhouse effect produced by burning fossil energy has attracted widespread attention from all walks of life. The battle for energy and the environmental issues brought about by fossil energy have become a smoke-free war between countries. How to solve the potential energy crisis and the existing environmental and climatic problems and realize the sustainable development of human society is a hot issue that is widely concerned by all countries and circles in the world. Therefore, vigorously developing renewable and clean energy and gradually replacing fossil energy, so as to solve the energy crisis, environmental pollution and climate change have become the consensus of countries around the world. Converting renewable and clean energy into low-carbon electricity is conducive to energy distribution, scheduling, and comprehensive utilization. Low-carbon power has become an important trend in the development of power systems in various countries.

It can be seen that the above characteristics of wind power restrict the ability of the grid to accept wind power. Therefore, to improve the grid's ability to accept wind power and reduce the rate of wind abandonment, we must start from two aspects: first, by improving the control of wind turbines or the control of auxiliary equipment of wind farms, to improve the friendliness of the grid; Reconstruction, strengthening the construction of UHV AC and AC transmission corridors, mobilizing resources everywhere to balance fluctuations in wind power, making the power grid stronger [1-2]. With the gradual development of onshore wind power resources, the use of flexible transmission systems to transport offshore wind power has also become the focus of new energy development in the future. In this context, it is very necessary to study the grid-connected characteristics of doubly-fed fans, including: the robustness and control performance of doubly-fed fans, sub-synchronous oscillation characteristics, fault ride-through performance, and systems connected to the flexible transmission grid Stability, and propose effective solutions to the problems found [3-4].

X. Xiao believes that with the increasing popularity of renewable energy, especially wind power, and the widespread use of high-power power electronics, renewable energy power systems are composed of complex multi-energy, multi-conversion AC systems. Therefore, the new sub-synchronous oscillation (SSO) problem is becoming increasingly prominent. The concept and connotation of SSO is gradually expanding. Various intricate issues, such as cause, form, impact, monitoring, and countermeasures, have once again attracted widespread attention from countries around the world [5]. *Wenjuan Du* established a closed-loop interconnection model of a high-voltage AC transmission line (VSC-HVDC) power system based on a voltage source converter (VSC). Loop subsystem for modeling. Based on the established model, a special condition of open-loop modal coupling when the complex pole of the VSC-HVDC line open-loop selection control subsystem is close to the sub-synchronous oscillation (SSO) mode of the open-loop power subsystem in the complex plane is studied. His theoretical analysis shows that when open-loop modal coupling occurs, sub-synchronous interactions (SSIs) between the VSC-HVDC line and the rest of the power system may be enhanced. Open-loop modal coupling is likely to reduce the system state stability of the power system. Therefore, from the perspective of open-loop modal coupling, the mechanism that VSC-HVDC lines cause SSOs in power systems is revealed [6]. *Y. Zhao* believes that the existing methods are difficult to effectively identify subsynchronous oscillations in power systems. Most methods are sensitive to noise and it is difficult to obtain vibration characteristics and development trends. He proposed a single input single output signal analysis method based on frequency slice wavelet transform (FSWT). FSWT can freely divide the time-frequency domain to achieve full-band time-frequency distribution analysis and fine analysis. He first uses FSWT to decompose the SSO signal to obtain the full frequency band of its time-frequency distribution. Then, due to its energy distribution, he can predict the occurrence of SSO and determine the number of modal components and frequency slices. By reconstructing the signals in the characteristic frequency slices, the SSO mode components are separated and extracted. Finally, he realized the high-precision detection of modal parameter recognition using Hilbert transform [7].

This paper proposes a sub-synchronous voltage modulation strategy based on a shunt voltage inverter specifically for suppressing sub-synchronous oscillations; the principle of damping SSO caused by series compensation is derived using the complex torque coefficient method. Because the dynamic model of the D-PMSG grid-side converter and the VSC-HVDC send-end converter is based on the bus voltage at different points as the reference and the rotating coordinate system is set, the D-PMSG is established outside the grid via VSC-HVDC. In the complete dynamic model, the interface between the D-PMSG and VSC-HVDC models needs to be further considered. This paper analyzes the transformation relationship between different d-q rotating coordinate systems in depth, and then derives the interface dynamic matrix and interface dynamic equation between the two models, thereby obtaining the complete dynamic model of the entire system. Because the interaction between D-PMSG and VSC-HVDC is intertwined, there is a strong damping coupling between the SSO / SupS modes induced by it. In order to minimize the damping coupling between the modes, the damping coupling problem is turned into a coordination optimization problem of the dominant controller parameters. Furthermore, with the leading controller parameters as the optimization target, the to-be-improved mode as the target mode, and the maximum damping ratio of the target mode as the optimization target, the machine-side and network-side controllers of D-PMSG and the sending end of VSC-HVDC, The parameter coordination optimization model of the receiving end controller validates the effectiveness of the proposed coordination optimization strategy with the results of LFO and SSO / SupSO. Eigenvalue calculation and time-domain simulation analysis of the comprehensive suppression system.

2. Proposed Method

2.1 Times Synchronous Oscillation

The sub-synchronous oscillation of the power system is a phenomenon of electromechanical coupling oscillation caused by the significant energy exchange between the electrical equipment in the system and the turbine shaft of the turbine-generator set after the power system is disturbed. A power system stability issue. At present, according to the causes of subsynchronous oscillation, it can be divided into subsynchronous resonance caused by series compensation capacitors and subsynchronous oscillation caused by electrical devices such as AC systems [8].

Subsynchronous Resonance (SSR) includes three types of induction generator effect, shafting torsional vibration interaction, and transient torque amplification, depending on the cause, all of which involve LC resonance in electrical systems. The induction generator effect (IGE) originates from the speed of the rotor of the generator is less than the speed of the sub-synchronous torque generated by the sub-synchronous current caused by the LC resonance of the power system in the stator winding, like the asynchronous induction motor, which makes the generator rotor circuit The sub-synchronous current exhibits a negative resistance characteristic, which in turn generates self-excited oscillations that cause the generator terminal voltage to increase continuously. The induction generator effect can be traced back to 1937. Shaft torsional interaction (TI) is an electromechanical interaction between the generator shaft and the series-compensated transmission line. When a natural torsional vibration mode of the generator shaft system oscillates, a current component complementary to the oscillation frequency will be induced in the stator circuit. When this current frequency is close to the resonance frequency in the system, the sub-synchronous torque and rotor speed change When in phase, the oscillation of the rotor shaft system at this frequency will be exacerbated. There have been two torsional vibration interaction accidents of the unit shaft system in the United States power plant, which caused the unit shaft system to be damaged [9-10].

Transient torque amplification (TA) is also an electromechanical interaction. When a torsional mode frequency of the generator shaft system is complementary to the grid resonance frequency, if the system has a large disturbance such as a fault or misoperation, the unit shaft system The electromechanical interaction with the AC system will generate a large impact torque on the shaft system of the unit, causing fatigue or damage to the shaft system. In the 1970s, the phenomenon of sub-synchronous oscillation caused by electrical devices such as AC systems was first discovered in a power plant in the United States. The torsional vibration phenomenon of the generator shaft system was confirmed by experiments to be closely related to the high-voltage AC transmission system. Subsequent research also found that electrical devices such as converter station controller systems, power system stabilizers, and reactive power compensation devices that can quickly adjust power or generator speed in the sub-synchronous frequency band may interact with the generator shafting. Initiate subsynchronous oscillation [11-12].

In recent years, with the large-scale construction of flexible AC transmission projects, new energy sources such as wind power and photovoltaics have grown rapidly and are connected to the power grid in large numbers, which has also made the generation factors and mechanisms of sub-synchronous oscillations in power systems more complex and changeable. For example, the rapid adjustment of power by various controllers in a high-voltage AC transmission system will change the electrical damping of the generator; the complex control characteristics between power electronic devices may also cause the occurrence of sub-synchronous control interactions; new energy power plants are concentrated via series compensation lines New engineering application scenarios such as long-distance delivery and back-to-back AC systems to realize asynchronous interconnection of the power grid will also further increase the possibility of sub-synchronous oscillation and the complexity of the mechanism.

2.2 Main Research Methods of Synchronous Oscillation

(1) Frequency sweep method

The frequency sweep method is mainly used to evaluate the effects of induction generators including series compensation systems. The system under study is expressed as a positive sequence network model, and the other units outside the unit under study are represented by sub-transient reactance. By injecting multiple frequency harmonic currents into the system at the unit under study, the calculation is performed from the unit under study to the power grid. The size of the real and imaginary parts of the equivalent impedance at each frequency. The zero crossing of the frequency curve of the imaginary part of the equivalent impedance can be used to observe the electrical resonance point of the system. If the real part of the equivalent impedance at a certain resonance point is negative, there is a risk of SSR at that point. The frequency sweep method has simple operation and clear results, but it has a narrow range of applications. It is impossible to analyze the changes in system operating modes and the influence of electrical equipment based on power electronic switching devices such as AC systems and flexible AC devices on SSO characteristics [13-14]. At the same time, for complex systems, it is difficult to find the situation where the equivalent impedance is negative, and the SSR risk can only be predicted based on the drop in impedance, and then combined with other methods for further analysis.

(2) Unit Coefficient Method

The unit interaction factor method, also known as the UIF (Unit Interaction Factor, UIF) method, is a preliminary screening method used to study SSO problems caused by high-voltage AC transmission systems. The unit-effect factor UIF of the generator is defined as

$$UIF = \frac{S_{HVDC}}{S_G}\left(1 - \frac{SC_G}{SC_{TOT}}\right)^2 \tag{1}$$

In formula (1), S_{HVDC} is the rated capacity (MW) of the AC transmission system, S_G is the rated capacity (MVA) of the generator, SC_{TOT} is the three-phase short-circuit capacity on the AC bus of the rectification side of the AC transmission system, and SC_G is not included. Study the three-phase short-circuit capacity of the rectifier-side AC bus of the AC transmission system including the generator. When UIF <0.1, this unit will not have SSO; when UIF> 0.1, it means that the coupling strength between the generator set and the AC transmission system is strong, and there is a risk of SSO, which needs further confirmation. The unit action coefficient method is simple to calculate and requires less data, but it is not accurate enough, and it needs to be further analyzed in combination with other methods [15-16]. The unit action coefficient method can only be used in the case where the natural torsional vibration modal frequencies of different generating units connected on the same bus are different. If they are the same, the equivalent value needs to be processed by one unit.

(3) Eigenvalue analysis method

The eigenvalue analysis method uses a set of differential state equations to describe the dynamic characteristics of the power system, and its state matrix can be obtained through linearization. By solving the state matrix of the system under study, the corresponding eigenvalues, eigenvectors, and influencing factors can be obtained. Further analysis can also obtain the oscillation and damping information at the natural torsional mode frequency of the unit shaft system, and then the sub-synchronous oscillation of the system characteristic. According to Lyapunov's law, when the real parts of the eigenvalues are all negative, the system is gradually stable with small disturbances. The eigenvalue analysis method has high calculation accuracy and can obtain a large amount of system information. Theoretically, any power system can be modeled and analyzed [17-18]. However, this method also faces the problem of "dimensional disaster" due to the sharp increase in the number of state variables in complex systems.

(4) Complex torque coefficient method

The complex torque coefficient method was first proposed in the 1980s. It is a method developed based on the eigenvalue analysis method to analyze the characteristics of subsynchronous oscillation in power systems. It is the most widely used method to analyze the problem of subsynchronous oscillation. One [19-20]. The complex torque coefficient method takes the generator shaft system as the main body, considers the influence of other parts of the system on the unit shaft system as a whole, and calculates the mechanical complex torque coefficient and electrical complex torque coefficient of the motor unit to be developed. The expression is

$$K_M(\omega) = K_m(\omega) + j\omega D_m(\omega) \tag{2}$$

$$K_\mathrm{E}(\omega) = K_e(\omega) + j\omega D_e(\omega) \tag{3}$$

In formula (2) and formula 3, $K_M(\omega)$ and $K_E(\omega)$ are the mechanical complex torque coefficient and electrical complex torque coefficient of the unit at w frequency, and $K_m(\omega)$ and $D_m(\omega)$ are the mechanical elastic coefficient and mechanical of the unit at w frequency Damping coefficient, $K_e(\omega)$ and $D_e(\omega)$ are the electrical elasticity coefficient and electrical damping coefficient of the unit at w frequency, respectively. According to the theory of complex torque coefficient, at a natural torsional vibration mode frequency w of the shafting system, when the total elastic coefficient of the system is zero, that is, $K_e(\omega)+K_e(\omega)\cong 0$, if the sum of the mechanical and electrical damping coefficients of the generator is less than zero, Sub-synchronous oscillation occurs, and its criterion expression is

$$D_m(\omega)+D_e(\omega)<0_{[K_m(\omega)+K_e(\omega)\cong 0]} \tag{4}$$

With the continuous application of the complex torque coefficient method, this method has also been continuously improved by researchers. Some people have proposed that the complex frequency domain admittance matrix of each device in the power system be established based on the principle of decentralized elimination. Calculation of the complex torque coefficient of the power network. However, this method also faces problems such as errors caused by system simplification and the lack of models for equipment that consider the dynamics of power electronic switching devices, which need to be further addressed. Some people have proposed a test signal method, that is, applying a series of small-value synchronization frequency disturbance signals to the torque of the unit to be studied in the steady state, and analyzing the relationship between the electromagnetic torque and the speed after entering the steady state again to obtain the electrical in the sub-synchronous frequency band. Complex torque coefficient. The test signal method simplifies the analysis process of the complex torque coefficient method by means of time-domain simulation. However, when analyzing complex systems, the choice of the injected signal will affect the results to a certain extent.

(5) Time domain simulation method

The time-domain simulation method is to establish the electromagnetic transient model of the generator, the unit shaft system, the power line and various electrical equipment in the system under study through electromagnetic transient simulation software, and describe the dynamic characteristics of the system through stepwise numerical integration. Simulate the effects of disturbances, faults and various non-linear factors in the power system, and obtain the variation curve of each variable with time. The time-domain simulation method is intuitive, clear, and easy to operate. It is suitable for the analysis of transient torque amplification. The disadvantage is that it is difficult to obtain the mechanism of sub-synchronous oscillation. At the same time, it also faces the problem of long simulation time in large-scale complex systems.

2.3 Power Control Strategies for Wind Turbines

The power control strategy of wind turbine in this paper includes maximum wind power tracking (MPPT) and pitch angle control. When the wind turbine is running below the rated wind speed, the pitch angle control does not work, only the maximum wind power is tracked: the wind turbine speed is continuously adjusted according to the wind speed, and the wind energy utilization coefficient Cp (λ, β) is always the maximum value; When the turbine is operating in a region above the rated wind speed, considering the limitations of the electrical and physical characteristics of the unit, the output pitch angle is used to reduce the wind energy utilization factor Cp (λ, β), thereby reducing the mechanical output of the wind turbine. This paper uses the power signal feedback method to achieve maximum wind power tracking. Based on the maximum wind power curve fitting polynomial of the wind turbine, the corresponding relationship between the wind turbine output mechanical power and the reference speed can be obtained at different wind speeds. In actual modeling, the active power of the stator of the permanent magnet synchronous generator is used instead of the output mechanical power of the wind turbine as the control input to reduce the influence of the real-time change of wind speed on the input signal. The specific realization process of maximum wind power tracking is: the current stator active power is used to estimate the reference value of the current speed at the current wind speed, and compared with the actual speed value, the reference value of the stator active power is re-assigned by controlling the speed deviation.

Pitch angle control is divided into two parts: main control and compensation control. When the wind speed is higher than the rated wind speed, the output pitch angle β1−β2 = 0 under the combined action of the main control and the compensation control; when the wind speed exceeds a certain limit, which causes the wind turbine output to exceed the limit, the output pitch angle β1 + β2. As the pitch angle increases, the wind energy utilization factor decreases rapidly, and the wind turbine output is effectively limited. In the sub-synchronous oscillation analysis in this paper, the situation of wind speed overspeed is not considered, and the pitch angle is considered to be equal to 0. Therefore, when establishing the mathematical model of the power control strategy of the wind turbine, only the maximum wind power tracking control is considered, and the pitch angle is not considered control.

3. Experiments

3.1 Experimental Design

Doubly-fed fans with synchronous control can be applied to weak grids or microgrids. The goal of synchronous control is to allow power electronics to simulate the external characteristics of a synchronous generator to provide frequency control, inertial response, and voltage regulation functions. It has been pointed out that the flexible AC transmission system adopts synchronous control with higher AC voltage stability margin than traditional vector control. This conclusion also applies to double-fed fans.

Due to the limited current overload capacity of doubly-fed fans, the power cannot be controlled according to the specified power reference value at low voltages, and usually only current control can be achieved. The grid standards generally assess the reactive current support in fault ride-through. Therefore, it is best to choose reactive current and active current as control objects during the grid fault period. When the FRT signal is 0, the external characteristics of the doubly-fed fan are normal operating modes of stator active power ~ frequency droop and stator reactive power-voltage droop. When the voltage drops below 0.9pu, the FRT signal will be set to 1 until the voltage recovers to above 0.9pu after the fault is cleared. When the FRT signal is 1, the system automatically switches to the fault ride-through modes of active current-frequency droop and reactive current-voltage droop. And during this period, the voltage base value attached to the current sag link is also switched from the rated value to the real-time voltage amplitude, and the compensation amount of the exciting current is switched from the PI output of the voltage error to 0. This not only avoids excessive external loops during the fault process It is saturated, and it can also provide reactive current that meets grid standards and additional active current. When the FRT signal is 0, the system returns to normal operation mode.

In the simulation example, the hardware protection settings of the doubly-fed fan model are as follows: When the AC bus voltage rating is 1050V, when the AC bus voltage exceeds 1.14pu, the chopper circuit turns on, and when it falls below 1.14pu, the chopper circuit turns off: the AC bus voltage exceeds 1.23 When pu, the crowbar circuit is triggered and the action duration is 20ms; when the instantaneous value of the rotor current exceeds 2.5 times the rated value, the IGBT is automatically blocked; when the AC bus voltage is lower than 0.3pu, the fan will automatically be disconnected from the network; the rotor current in the fault is short The overload does not exceed 1.8 times of the rated value.

3.2 Data Acquisition and Analysis

Analyze the transient response of doubly-fed fans using new fault ride-through control methods under symmetrical and asymmetrical grid faults, including the dynamic responses of stator and rotor currents, AC bus voltage, crowdbar and chopper circuits. The detailed switching actions of all the electromagnetic transients and converter IGBT circuits of the system must be considered. The simulation step size is microseconds, and the power grid needs to be simplified. In this paper, MATLAB / SIMULINK platform is used to perform detailed modeling and simulation of a case where the wind turbine is connected to the infinite power grid and isolated grid. In this model, various protection strategies of the doubly-fed wind turbine are simulated in detail, including the AC chopper circuit chopper. And rotor crowbar circuit crowbar protection logic, overcurrent protection, AC bus overvoltage and undervoltage protection, etc.

The influence of doubly-fed fans using a new fault ride-through control method on grid voltage is analyzed. The power grid needs to be modeled in detail and the simulation step size is milliseconds. Electromechanical transient simulation is an important tool for grid research institutions and third-party test institutions to evaluate the impact of wind farm access on the actual grid. Therefore, the DIGSILENT platform can be used to perform electromechanical transient modeling and simulation of wind turbine access to the actual grid.

4. Discussion

4.1 Small Interference Stability Analysis

(1) Eigenvalue calculation and participation factor analysis

As shown in Table 1 and Figure 1, the damping ratio of the LFO mode is 2.94%, which is less than the threshold of 5% required for its stabilization. In the sub / super-synchronous frequency band, the damping ratio of the SSO-1 and SSO-2 modes Less than 0; the damping ratios of SSO-3, SupSO and HFO modes are all smaller, but considering that the higher the oscillation frequency, the lower the damping ratio required for stabilization (96), while the damping ratios of SSO-3, SupSO and HFO are respectively It reached 0.0080, 0.0053, and 0.0307. Therefore, the most unstable oscillation modes are LFO, SSO-1, and SSO-2 modes.

Table 1: Eigenvalue calculation results

Oscillation mode	Eigenvalues	Frequency / Hz	Damping ratio
LFO	-0.4361+14.8313i	2.3605	0.0294
SSO-1	0.0200+19.4795i	3.1003	-0.0010
SSO-2	0.3352+94.5044i	15.0408	-0.0035
SSO-3	-1.7741+220.6611i	35.1193	0.0080
SupSO	-2.0629+392.3117i	62.4383	0.0053
HFO	-59.3885+1934.4217i	307.8728	0.0307

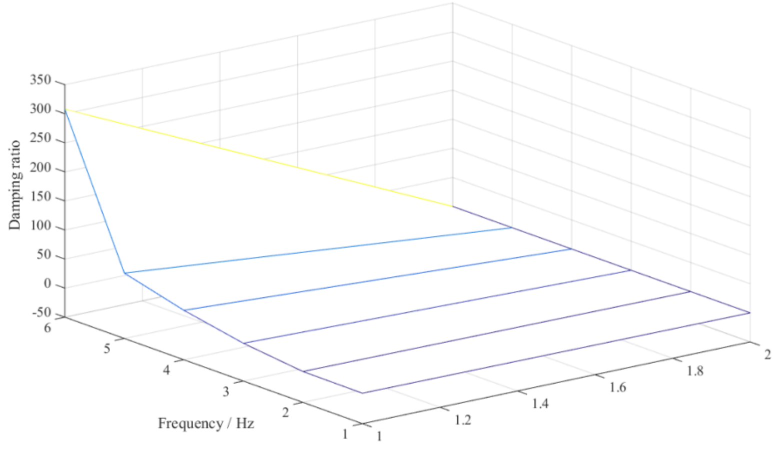

Figure 1: Eigenvalue calculation results

The transient response of the system when using classical coordinated control. After a fault occurs, the offshore wind farm receives an AC bus voltage signal with a delay of 150ms, reducing its active power to -0.2pu. Due to the delayed response, the AC bus voltage rose to a maximum of about 1.18 pu. According to the actual engineering protection data, the AC bus voltage exceeding 1.15 pu and the duration exceeding 10 ms will cause the over-voltage protection action of the flexible transmission system. After the fault is cleared, the active power of the converter at the sending end cannot fully recover to the level before the fault until 14s after the fluctuation. It can be seen that when the communication delay is large, this classic coordinated control strategy cannot achieve the system's fault ride-through function under severe receiving AC grid faults.

(2) Time domain simulation verification

Furthermore, a complete electromagnetic transient model is established in the PSCAD / EMTDC software, and the simulation system parameters are completely consistent with the small signal model parameters. Set the simulation time to 12s, and at t = 2s, set a single-phase short-circuit fault at the VSC-HVDC receiving bus, with a duration of 0.7s. Observe the output active power curve of the D-PMSG network side, as shown in Figure 2, it can be found that after the disturbance occurs, there is a continuous power oscillation in the active power output of the D-PMSG network side.

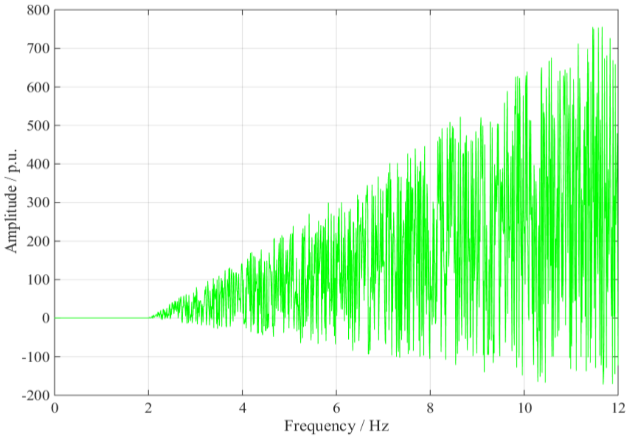

Figure 2: Grid-side output active power of D-PMSG

The PRONY analysis method is further used to analyze the frequency component of the D-PMSG output active power, and the time window is 6-10s. At the same time, the eigenvalue analysis method is used to identify the type of the mode. The identification result of PRONY analysis is consistent with the eigenvalue analysis, which verifies the correctness of the model and eigenvalue analysis result. Under the set small disturbance, the time window is 6-10s, the system has LFO, SSO-1 With SSO-2 mode.

Table 2: Identification results obtained by PRONY

Included modes	Frequency/Hz	Attenuation factor	Damping ratio
LFO	2.4	-0.44	0.0291
SSO-1	3.2	0.02	-0.0010
SSO-2	15.1	0.34	-0.0036

4.2 Eigenvalue Sensitivity Calculation and Determination of Leading Influencing Factors

(1) Eigenvalue sensitivity of grid-connected distance/impedance of wind power

Wind power grid-connected distance/impedance, that is, the distance/impedance of the AC line between the D-PMSG grid-side bus and the VSC-HVDC transmission-side bus is used as the influencing factor to calculate the eigenvalue sensitivity of each mode to the wind grid-connected distance / impedance the results are shown in Table 3.

Table 3: Characteristic sensitivity of wind power grid-connected distance / impedance

SSO-1	SSO-2	SSO-3	SupSO
0.1913 + 0.3033i	2.0500 - 0.5704i	0.0000 + 0.0000i	0.0000 - 0.0000i

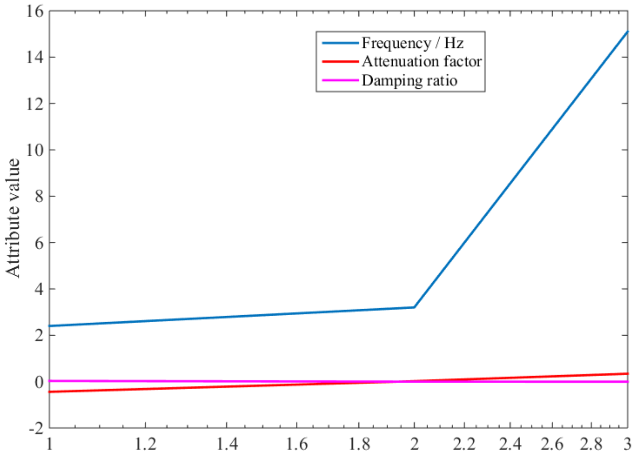

Figure 3: Identification results

As shown in Table 3 and Figure 3, it can be known that: 1) The real part sensitivity of the eigenvalues of all modes of wind power grid-connected distance / impedance is positive, indicating that as the wind grid-connected distance/impedance increases, the damping ratio of all modes Both decrease, the stability of the system's small interference decreases. 2) The sensitivity of the imaginary part of the eigenvalues of SSO-2 and SupSO modes is negative for wind power grid-connected distance / impedance, indicating that the frequency of SSO-2 and SupSO modes will decrease as the wind grid-connected distance/impedance increases; The sensitivity of the imaginary part of the eigenvalues of SSO-1 and SSO-3 modes is positive for wind power grid-connected distance/impedance, indicating that as the wind grid-connected distance/impedance increases, the frequencies of SSO-1 and SSO-3 modes will both improve. 3) The grid-connected distance / impedance of wind power mainly affect the characteristics of SSO-1 and SSO-2 modes.

4.3 Analysis of the Influence of the Short-Circuit Ratio of the Receiving Network

As shown in Figure 4, it can be known that: 1) with the increase of the short-circuit ratio of the receiving network, the damping ratio of the SupSO mode gradually increases, and its oscillation frequency gradually decreases. 2) The short circuit ratio of the receiving end has little effect on the SSO mode. 3) Therefore, from the perspective of dispatching operation, when the short-circuit ratio of the receiving network drops to a certain degree, the operating status of the receiving network should be monitored to prevent the short-circuit ratio of the receiving network from being too low and deteriorating. Oscillation mode.

The same controller parameter can affect multiple SSO / SupSO modes at the same time, and the same SSO/SupSO mode can be affected by multiple controller parameters at the same time, that is, there is a strong damping coupling between different SSO / SupSO modes. And the effect of this kind of damping coupling is very complicated, it may converge (adjust the controller parameter, the damping ratio of the two modes of coupling changes in the same direction), or it may reverse (adjust the controller parameter, the damping ratio of the two modes of coupling is reversed) It is also possible that coexistence and reversal coexist (adjust the controller parameter, the damping ratio of the two modes coupled in a certain parameter sub-region changes in the same direction, and the damping of the two modes coupled in other parameter sub-regions Than the reverse change).

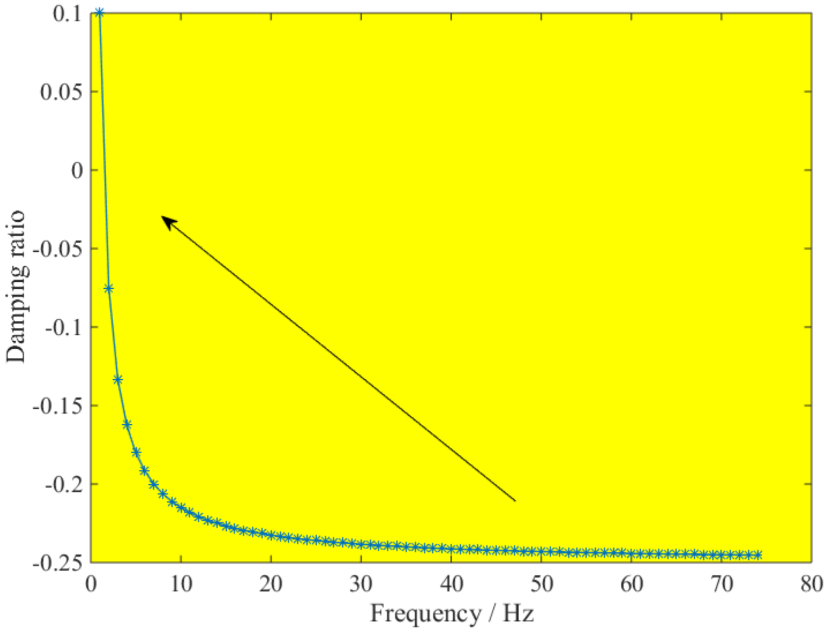

Figure 4: Frequency blocking characteristics of SSO / SupSO mode when the short-circuit ratio of the receiving network changes.

5. Conclusions

In this paper, the complex torque coefficient method and time-domain simulation method are used to study the sub-synchronous oscillation problem of the parallel hybrid AC transmission end system and the adjacent thermal power plant shaft system. A small-signal model of each system unit in the parallel hybrid AC send-end system is established, and the influence of the controller bandwidth on the electrical damping characteristics of the synchronous unit when the conventional AC and flexible AC units are operated separately is analyzed. Influence of grid strength and AC transmission power on electrical damping characteristics of synchronous units. A sub-synchronous oscillation suppression strategy based on the additional damping control branch of the flexible AC transmission control system is proposed, and the proposed method is used to deal with the risk of sub-synchronous oscillation in the case of different power grid line faults in a back-to-back parallel hybrid AC project in a province in China. Control measures and verify the effectiveness of the control measures.

In this paper, a small-signal model of the synchronous machine is established, and the transfer relationship between the unit speed and electromagnetic torque of the external impedance equivalent network information of the synchronous machine port, which can be used for the analysis of the complex torque coefficient method, is established. The power network, LCC- Equivalent output impedance model of HVDC send-end system and VSC-HVDC send-end system. The modeling method adopted in this paper is more convenient and clear for analyzing the electrical damping characteristics of synchronous machines. The models established can be used to analyze the sub-synchronous oscillation problem individually or jointly.

This paper analyzes and finds that the q-axis grid voltage feed-forward control parameters in the AC current controller of the flexible AC system have a large influence on the electrical damping of the synchronous machine, and proposes a sub-synchronous oscillation suppression measure based on the additional q-axis grid voltage damping control branch. The time-domain simulation method was used to screen the risk of sub-synchronous oscillation of the unit shaft system under different fault operation modes of a provincial back-to-back parallel hybrid AC engineering AC system. The suppression measures proposed in this paper were used and the suppression effect was verified.

References

[1] L. Liu, H. Li, K. Luo. Flexible Atom Filtering for Subsynchronous Oscillations Mode Extraction [J]. Transactions of China Electrotechnical Society, 2017, 32(6):98-105.

[2] G. Chen, M. Li, T. Xu. Study on technical bottleneck of new energy development [J]. Proceedings of the Csee, 2017, 37(1):20-26.

[3] J. Lü, X. Cai. Frequency-domain Analysis and Design of Stabilization Controllers for Wind Farm Integration through VSC-HVDC System [J]. Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering, 2018, 38(14):4074-4085.

[4] W.-J. Zhang, H.-M. Ma, R. Gao. Speed sensorless control of doubly-fed induction generator based on flux differential feedback [J]. Dianji yu Kongzhi Xuebao/Electric Machines and Control, 2017, 21(10):77-84.

[5] X. Xiao, C. Luo, K. Liao. Review of the Research on Subsynchronous Oscillation Issues in Electric Power System with Renewable Energy Sources [J]. Transactions of China Electrotechnical Society, 2017, 32(6):85-97.

[6] Wenjuan Du, Qiang Fu, Haifeng Wang. Subsynchronous Oscillations Caused by Open-Loop Modal Coupling between VSC-Based HVDC Line and Power System [J]. IEEE Transactions on Power Systems, 2018, 33(4):3664-3677.

[7] Y. Zhao, W. Li, Y. Nie. A Method for Subsynchronous Oscillation Detection Using Frequency Slice Wavelet Transform [J]. Transactions of China Electrotechnical Society, 2017, 32(6):106-114.

[8] X. Bian, L. Shi, X. Zong. Analysis and Mitigation of Wind Turbine Converters in Sub-Synchronous Interaction under Multi-operating Conditions [J]. Transactions of China Electrotechnical Society, 2017, 32(11):38-47.

[9] Elena R. Magro‐Malosso, Gabriele Saccone, Mariarosaria Di Tommaso. Exercise during pregnancy and risk of gestational hypertensive disorders: a systematic review and meta‐analysis[J]. Acta Obstetricia Et Gynecologica Scandinavica, 2017, 96(8):921-931.

[10] V. Knop, D. Hoppe, T. Welzel. Regression of fibrosis and portal hypertension in HCV ssociated cirrhosis and sustained virologic response after interferon‐free antiviral therapy[J]. Journal of Viral Hepatitis, 2016, 23(12):994-1002.

[11] Francesca Marini, Valentina Squeri, Pietro Morasso. Robot-aided developmental assessment of wrist proprioception in children [J]. Journal of Neuroengineering & Rehabilitation, 2017, (2017) 14:3(1).

[12] Mulualem T. Yeshalem, Baseem Khan. Design of an off-grid hybrid PV/wind power system for remote mobile base station: A case study [J]. Aims Energy, 2017, 5(1):96-112.

[13] TOMOKI ISHIKAWA, TAKAAKI KOJIMA, TORU NAMERIKAWA. Shortmilerm Wind Power Prediction for Wind Turbine via Kalman Filter Based on JIT Modeling [J]. Electrical Engineering in Japan, 2017, 198(3):86-96.

[14] Young Joon Ko, Dong Yeong Kim, Sung Sik Won. Flexible Pb (Zr0.52Ti0.48) O3 Films for a Hybrid Piezoelectric-Pyroelectric Nanogenerator under Harsh Environments [J]. Acs Appl Mater Interfaces, 2016, 8(10):6504-6511.

[15] Yu Chen, Qiang Hu, Jakobus A. le Roux. Analysis of Small-scale Magnetic Flux Ropes Covering the Whole Ulysses Mission [J]. The Astrophysical Journal, 2019, 881(1):58.

[16] Yu Zhang, Wei Wang. Convection: a neglected pathway for downward transfer of wind energy in the oceanic mixed layer [J]. Journal of Oceanology and Limnology, 2018, 36(4):1189-1197.

[17] P. Mu, D. Zhao, J. Wang. Influence Mechanism Analysis of Large-scale Wind Power Integration on Power System Angle Stability [J]. Proceedings of the Csee, 2017, 37(5):1324-1332.

[18] Kang Li, Aoife Foley, Daren Yu. Optimal Generation Scheduling of Interconnected Wind-Coal Intensive Power Systems [J]. Iet Generation Transmission & Distribution, 2016, 10(13):3276-3287.

[19] Baseem Khan, Pawan Singh. Selecting a Meta-heuristic Technique for Smart Micro-grid Optimization Problem: A Comprehensive Analysis [J]. IEEE Access, 2017, 5(99):13951-13977.

[20] MENG Zhongju, DANG Xiaohong, GAO Yong. Interactive effects of wind speed, vegetation coverage and soil moisture in controlling wind erosion in a temperate desert steppe, Inner Mongolia of China [J]. Journal of Arid Land, 2018, 10(4):1-14.