Research on Sub-synchronous Oscillation in Wind-HVDC-Thermal System

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Abstract. To comply with the characteristics of energy and source-load inverse distributed, the thermal-wind bundling system has been used in the grid of our country, such as Hami-Zhengzhou UHVDC channel and Jiuquan wind farm base power delivery channel. But it can induce some stability problem like sub-synchronous oscillation, especially in some limit operation state. This paper build a wind-thermal bundling system with HVDC in PSCAD/EMTDC simulation software, then by means of changing DC line parameter and manual putting 3-phase fault into inverter side PCC three aspects to explore the factor that entails SSO phenomenon. In conclusion, parameter mismatch and DC fault and so on factor can induce SSO phenomenon.

Keywords: Thermal-HVDC-wind farm system · SSO factor · Common coupled point

1 Introduction

Wind-Thermal bundling system operates with a method of bundling wind power and thermal power, and realizing power delivery through power transmission lines. This method can not only meet the needs of inter-regional power transmission and the construction of a strong grid, but also increase the use and development of renewable energy sources such as wind power. The wind-thermal bundling system can improve the power transmission capacity and reduce the cost of power supply, but it also brings some problems to the stable operation of the power grid. In the initial operation period of the wind and fire bundling energy base, the system is easy to run near the limit state, and the system stability cannot be guaranteed. At this time, it is particularly important to study the related technical issues such as the sub-synchronous oscillation caused by the transient stability and disturbance of the wind-fired AC/DC delivery system, and the coordination between the power supply and the line [1, 2].

Sub-synchronous oscillation (SSO) is an abnormal electromagnetic and mechanical oscillation phenomenon that occurs when the operating system's operating equilibrium point is disturbed or multiple natural oscillation frequencies for significant energy exchange [3]. The sub-synchronous oscillation belongs to the oscillation instability of

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the system. It is caused by a special electromechanical coupling effect in the power system. The biggest harm is that the serious electromechanical coupling effect may directly cause the serious damage to the shaft system of the large steam turbine generator set, which cause major accidents to endanger the safe operation of the power system. Wind-fired bundling via a DC transmission system is a new system structure that has emerged with the rapid development of wind power in recent years.

At present, most of the researches on sub-synchronous oscillation are focused on the single-synchronous generating unit, single wind-powered unit via DC transmission system and wind-fired bundling via series-supply delivery system, and the sub-synchronous oscillation of wind-fired bundling via DC-supply system Little research has been done [4]. With the increase of installed wind power capacity and the development of DC transmission projects, the possibility of the system structure increasing. In actual engineering, the problem of sub-synchronous oscillation does exist in the wind-fired bundled DC delivery system. On July 1st, 2015, the Hami region of Xinjiang, China, after the direct-drive wind farm was connected, a sub-synchronous oscillation accident occurred in the power system, which caused the torsional vibration protection of three thermal power units in the thermal power plant 300 km away from the wind farm to successively cause Power loss is 1280 MW. In July 2015, a thermal power plant accident caused by a synchronous synchronization occurred at a thermal power plant near the transmission terminal of the Harbin-Zhengzhou DC transmission was related to the large-scale wind power transmission at the transmission-side AC system. Therefore, it is of great significance to study the problem of sub-synchronous oscillation of wind and fire bundling via a DC output system.

2 Principe of Sub-synchronous Oscillation

Sub-synchronous oscillation (SSO) is a type of system stability problem that belongs to the dynamic process of electromechanics. Since the Mohave power station in the United States has experienced two times of generator shaft failure due to series compensation, this phenomenon has raised worldwide electrical workers. Note that the issue of sub-synchronous oscillation has also become a research hotspot in power system stability [5].

According to the different generation mechanisms, the mainstream problem of sub-synchronous oscillation is divided into two categories, namely: sub-synchronous resonance (SSR) problems and sub-synchronous control interaction (SSCI) problems. SSR problems can be divided into induction generator effect problems according to their causes and effects. SSR problems can be divided into three aspects according to their causes and effects: induction generator effect (IGE), sub-synchronous torsional interaction (SSTI), and sub-synchronous torque amplification (SSTA) [6].

IGE is because the rotor speed is higher than the sub-synchronous rotating magnetic field speed generated by the sub-synchronous current component on the stator side. From the perspective of the stator, the equivalent resistance of the rotor to the sub-synchronous stator current has a negative resistance characteristic. Effect, when this negative resistance is large enough, it can cause self-excited oscillation of the electrical system.

SSTI is a kind of electromechanical coupling self-excited oscillation phenomenon caused by the electrical system's electrical resonance frequency being complementary to the natural torsional vibration frequency of the generator shaft system. When the frequency generated on the generator rotor is equal to the natural torsional vibration frequency of the generator shaft system, it will A complementary secondary synchronization frequency voltage component is induced on the stator side. If the voltage component frequency is close to the electrical resonance frequency of the system at this time, the secondary synchronization torque generated by the rotor will be maintained. When the secondary synchronization torque is greater than or When it is equal to the mechanical damping torque of the generator, this trend will show increasing oscillation and form a continuous unstable process.

In the case of large disturbances such as faults, machine cuts, non-synchronous grid connection, and frequent operation of line switches, SSTA is due to the mutual increase of electromechanical oscillations, which causes mutual interactions on a certain natural frequency or frequencies on the shaft system and may cause severe damage in the first torsional vibration period [7].

3 Modeling of Wind-HVDC-Thermal System

3.1 Doubly-Fed Induction Generator (DFIG) Model

According to Aerodynamics, a wind turbine can transfer the wind power to the mechanical energy P_W as shown in Eq. 1. This Equation illustrates that the input mechanical power P_W is relevant to the air density ρ, blade radius R, wind speed V_W and power coefficient C_P [8].

$$P_W = \frac{1}{2} C_P \rho \pi R^2 V_W^3 \tag{1}$$

The power coefficient C_P as shown in the Eq. 2 could accurately demonstrates the power losses on the aspects of wind power utilization. And the variable value C_P is relative to one variation, the turbine angular velocity ω_W multiply by the blade radius R and divided by wind speed V_W, which we called tip speed ratio λ.

$$C_P = 0.22\left(116\left(\frac{1}{\lambda} - 0.035\right) - 5\right)e^{-12.5\left(\frac{1}{\lambda}-0.035\right)} \tag{2}$$

We can make a derivation of input mechanical torque T_W demonstrated in the Eq. 3 by combining Eq. 1 and 2.

$$T_W = \frac{P_W}{\omega_R} = \frac{1}{2}\frac{C_P \rho \pi R^3 V_W^2}{\lambda} \tag{3}$$

The drive mechanism in the turbine could be divided into 3 aspects: the hub, the transmission shaft and the gear box. On the static state, it could be illustrated by the Eq. 4 of the drive mechanism model. In Eq. 4, τ_W is the time constant of the entire mechanism.

$$\frac{\mathrm{d}T_M}{\mathrm{d}t} = \frac{1}{\tau_W}(T_W - T_M) \tag{4}$$

The turbine and the generator is connected by a speed-variable gear box, and there exist a N-times relationship of the angular velocity between the generator ω_G and turbine $\omega_{W,}$ which is shown in the Eq. 5.

$$\omega_G = N\omega_W \tag{5}$$

3.2 High Voltage Directive Current (HVDC) Model

At present, quasi steady state (QSS) models are used to model the dynamic problems caused by DC transmission. The converter uses a steady-state mathematical model and the related control system uses a dynamic model to describe transient process in the QSS model [9]. Figure 1 shows the converter part of the HVDC system. For this system, the AC system voltage E, the rectifier-side and inverter-side trigger angles α, β, and the commutation angle γ are known. U_{d0} is the converter-side equivalent voltage. X_T is the equivalent reactance of converter loss and transformer leakage reactance (Fig. 2). The steady-state model of the rectifier side and the inverter side and the dynamic model of the dc line are respectively shown in Eqs. (6)–(8).

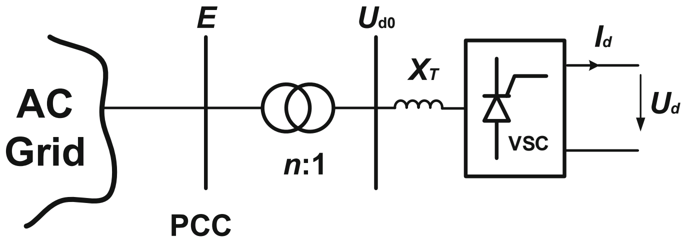


Fig. 1. HVDC converter model

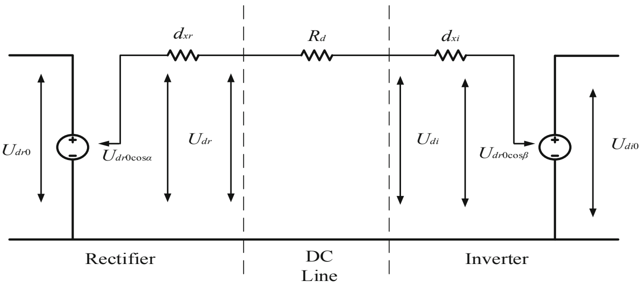


Fig. 2. QSS equivalent model

$$\begin{cases} U_{dr0} = \frac{3\sqrt{2}E_r}{n\pi} \\ \Delta U_{dr} = d_{xr}I_{dr} = \frac{1}{2}U_{dr0}(\cos\alpha - \cos(\alpha+\gamma)) \\ U_{dr} = U_{dr0}\cos\alpha - d_{xr}I_{dr} \end{cases} \tag{6}$$

$$\begin{cases} U_{di0} = \frac{3\sqrt{2}E_i}{n\pi} \\ d_{xi} = \frac{3X_T}{\pi} \\ U_{di} = U_{di0}\cos\beta + d_{xi}I_{di} \end{cases} \tag{7}$$

$$\begin{cases} C\frac{dU_{dr}}{dt} = I_{dr} - I_d \\ C\frac{dU_{di}}{dt} = I_{di} + I_d \\ L_d\frac{dI_d}{dt} = U_{dr} - U_{di} - R_d I_d \end{cases} \tag{8}$$

3.3 Thermal-HVDC-Wind Farm System

Figure 3 shows the schematic diagram of thermal-HVDC- wind farm system. The power frequency of the whole system is 60 Hz.The thermal power unit adopts the IEEE first standard model. The thermal power unit adopts the four-masses (LPA-LPB-GEN-EXT) block model, the rated voltage is 7.97 kV meanwhile the rated current is 3.136 kA, and the rated power is 892.4 MV.A, and is fed into the HVDC system through 13.8/62.5 kV boost transformer.

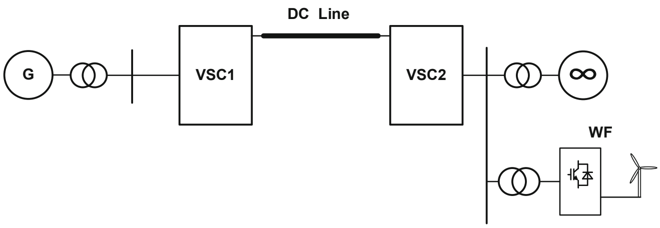
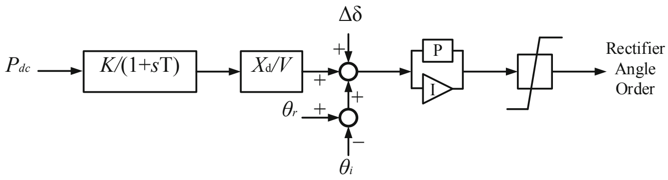


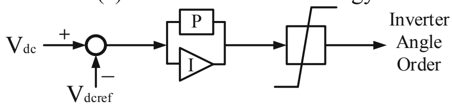
Fig. 3. Schematic graph of thermal-HVDC-wind farm system

The HVDC system transmits 115 kV DC voltage and 75 MW rated power, and the length of the DC line is 50 km. In order to ensure system voltage stability and stable power transmission, the rectifier side adopts the fixed active power control strategy shown in Fig. 4(a), and the inverter side adopts the fixed DC power control strategy shown in Fig. 4(b). The inverter is connected to a 110 kV power grid. The final equivalent of the power grid is an infinite system with a rated voltage of 110 kV and a rated power of 100 MV.A.

The wind farm is a N identical 2 MW DFIG wind turbines of the same model, with a rated voltage of 0.69 kV, which is connected to the inverter-side common coupling point (PCC) after 0.69/110 kV step-up transformer. The rotor side of the inverter adopts stator flux-oriented vector control, and decoupling control of active and reactive power is achieved through coordinate transformation. The stator side adopts the grid voltage-oriented vector control strategy to achieve stable output of the generator port voltage according to the grid current and provide a trigger angle for the rotor side flux control (Fig 5).

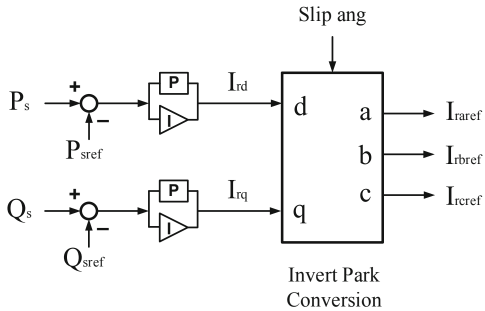


(a) Rectifier control strategy

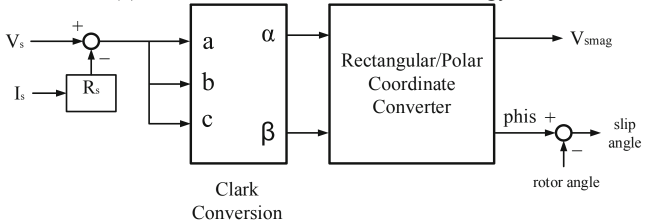


(b) Inverter control strategy

Fig. 4. HVDC system control strategy



(a) Rotor side convertor control strategy



(b) Stator side convertor control strategy

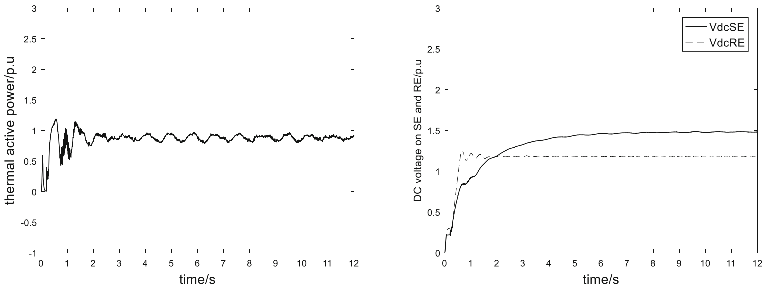
Fig. 5. Wind farm converter control strategy

4 Simulation

This paper uses PSCAD/EMTDC simulation software to build a model of wind-thermal bundle system with HVDC as shown in Fig. 3. By changing the related parameters of the DC transmission system, and the PCC fault on the inverter side, the factor and influence of SSO is explored in such wind-thermal system with HVDC.

4.1 Infects of the DC Line Parameters

To explore the effect of SSO by changing DC line parameter, the experience will change the length from 50 km to 200 km. It is shown that when the line span 50-km long, the system will operate at static state as demonstrated in Fig. 6.



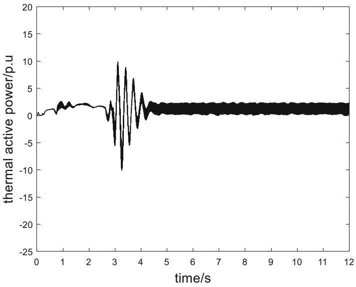
(a) Thermal active power output (b) DC line voltage

Fig. 6. Static state power and DC voltage characteristic

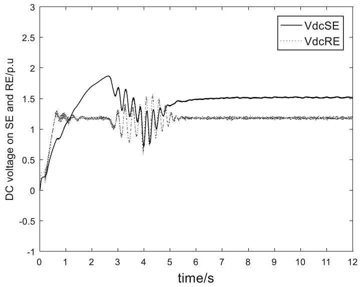
When the length become longer, the stability of the system may changed. At the length of 125 km, the active power of the thermal generator suffered a variation which was beginning at the time of 3 s and maintaining 1 s, then the power operated with small scale vibration as is shown in Fig. 7.(a). So did the DC voltage both on the rectifier side and on the inverter side in Fig. 7.(b), but after a 1 s period variation it finally operated in a new static state. So in reality, if the shaft is robust enough that can bear the first period torque amplification, the system could finally operates in a stable state.

However, there is a severe damage at the length of 150 km as is vividly demonstrated in Fig. 8(a)–(d). There is a variation at the time of 3 s and maintaining 1 s, rectifier side DC voltage V_{dcR} dropped to a very low level. About 3.5 s later, second variation occurs and it induced a severe unstable state: Torque LPA-LPB and Torque LPB-GEN amplified at times and maintaining till the end of the simulation.

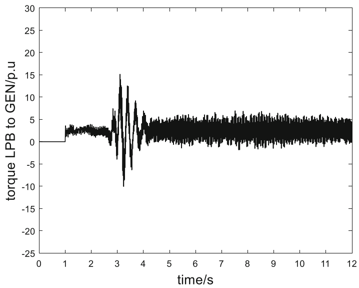
When the length span 200 km, a variation about 3–4 s occurs in the system. And the DC voltage finally emerged a trend to get close to a new stable state as shown in Fig. 9.(b). In the new state, DC line voltage dropped at the sending end.



(a) Thermal active power output



(b) DC line voltage



(c) LPB-GEN torque

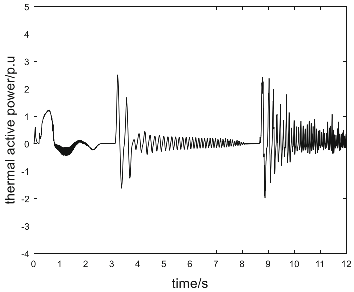
Fig. 7. Power, DC voltage and torque characteristic when L = 125 km

In conclusion, the mismatch of the DC line parameter may enduce SSO phenomenon in the system. A matched parameter is essential in the period of the system modeling and operating.

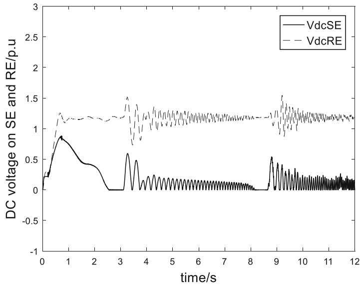
4.2 Infects of the Inverter Side PCC Fault

In this section, a single line short circuit, 3-phase fault will be manually put into at the 6 s, and the fault will sustain 1 s. When the single line to ground short circuit was putting into the PCC, it is shown that there is a small disturbance on generator output power and torque. There is a small transient voltage drop at inverter side DC line, while rectifier side shows no influence when the fault was put into operation (Fig. 10).

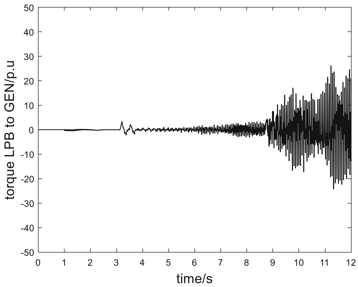
When the 3-phase short circuit was putting into the PCC, it could be seen that active power of thermal generator and torque amplified swiftly, meanwhile DC voltage at the inverter side dropped to a very low standard. But 2 s later, the fault was cleared and the system recovered to a new steady state. And if the fault time sustained longer, such transient process would be longer (Fig. 11).



(a) Thermal active power output

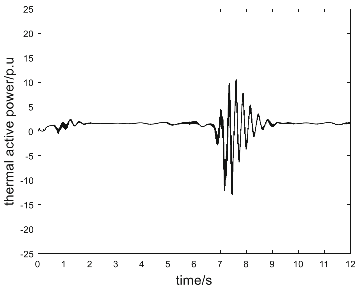


(b) DC line voltage

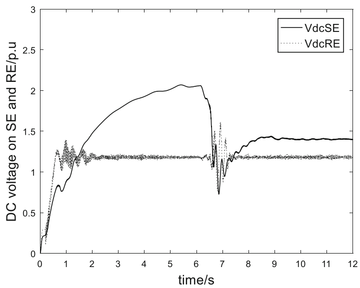


(c) LPB-GEN torque

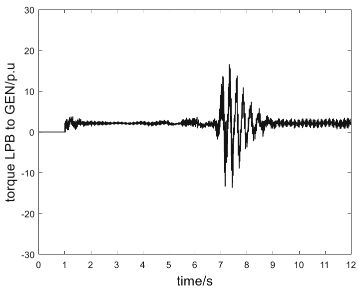
Fig. 8. Power, DC voltage and torque characteristic when L = 150 km



(a) Thermal active power output

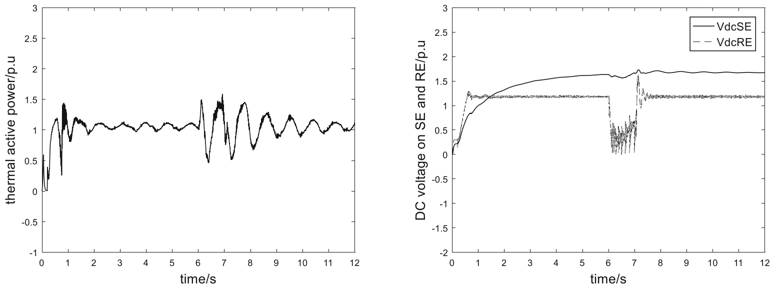


(b) DC line voltage



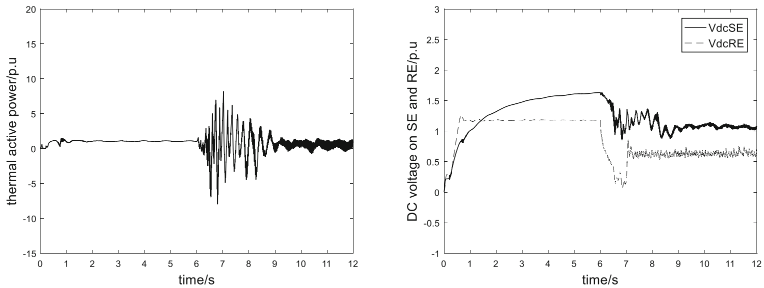
(c) LPB-GEN torque

Fig. 9. Power, DC voltage and torque characteristic when L = 200 km

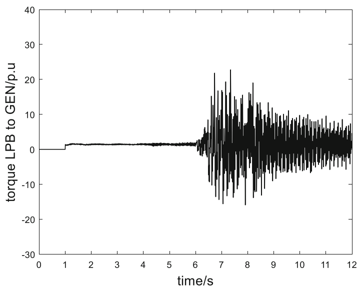


(a) Thermal active power output (b) DC line voltage

Fig. 10. Power and DC voltage graph when single line to ground short curcuit occurs



(a) Thermal active power output (b) DC line voltage



(c) LPB-GEN torque

Fig. 11. Power, DC voltage and torque characteristic when symmetric short circuit occurs in the system

5 Conclusion

(1) A mismatched DC line parameter may caused SSO in the thermal-HVDC-wind farm system. Such torsional interaction influence is stronger in the thermal system than in the DFIG wind farm. And the mainly factor of such SSO is power shortage, which entails DC line voltage unstable and thermal torque amplification. This SSO phenomenon should pay more attention on the first oscillaton period.

(2) Faults appears at inverter-side would induce a voltage drop at inverter DC line side, while the degree of the generator output power, torsional torque on the shaft and rectifier-side DC voltage will mostly depend on the fault type on inverter-side PCC and time scale of the fault.

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