Design and Implementation of Subsynchronous Damping Controller for HVDC

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Abstract: The interaction between High Voltage Direct Current (HVDC) transmission lines and turbogenerator units will cause the damage of the generator shafting and the electrical system by exchanging energy at one or more lower synchronous frequencies, resulting in the damage or even breakage of the generator shafting, seriously affecting the safe operation of the power system. To solve this problem, the Supplementary Subsynchronous Damping Controller (SSDC) is an effective method to suppress the secondary synchronous oscillation of turbogenerator units connected to rectifier side caused by HVDC. This paper combines the first standard model parameters of IEEE subsynchronous oscillation with CIGRE HVDC transmission system, and builds a HVDC transmission test system for Subsynchronous Oscillations (SSO) research in PSCAD. Based on signal test method, a narrow band SSDC is designed, and the damping in each synchronization frequency band is greatly increased. When the proportional coefficient is appropriate, the electrical damping is positive. The effectiveness of the designed SSDC is also verified by time domain simulation.

1. Introduction

High Voltage Direct Current (HVDC) has many advantages in transmission technology and economy, and plays an important role in transmission system. HVDC technology brings convenience to the power system in many aspects, but also brings new problems to the safe operation of the system, such as Subsynchronous Oscillations (SSO) of the power system\cite{1}. The problem of SSO caused by HVDC is mainly due to the interaction between HVDC (usually rectifier side) control system and turbogenerator shafting. Under certain conditions, it will strengthen the torsional vibration of some modes of the shafting system, that is, to provide negative damping. When the inherent mechanical damping of the shafting is insufficient to overcome the negative damping, the torsional vibration of the shafting system will cause the continuous increase of the amplitude. It will affect the life of the shafting system of the unit and even damage the unit in serious cases\cite{2}. How to take effective measures to suppress SSO is an important research content in the power system. Therefore, it is increasingly important to ensure the safe and stable operation of the power system. It is of great practical significance to study the measures to suppress SSO caused by DC control.

The traditional way to overcome SSO caused by DC is to suppress SSO by additional devices (such as SVC, TCSC, etc.) \cite{3}, However, this method requires additional equipment, or additional Generator Pole damper resistance, excitation damper and so on. These measures need to be changed to the generator, which is difficult to implement for the generator already in operation. Literature [4-5]
suppresses SSO based on SVC, controls the trigger angle of SVC by collecting subsynchronous frequency signals, generates complementary subsynchronous frequency currents and injects them into generators to form subsynchronous electromagnetic torque to suppress subsynchronous oscillation of generating units. Literature [6] adopts the Static Synchronous Compensator (STATCOM) to generate subsynchronous electromagnetic torque damping and control the subsynchronous current of the injection system to suppress SSO. Literature [7] extracts the eigenvalues of the torsional vibration of the system, and uses the neural network method to analyze the eigenvalues in real time. The method can be used to monitor SSO online. Literature [8] introduced the theory of modal control into the field of SSO inhibition, and designed an auxiliary control link by using the eigenvalue method. Literature [9] proposed a parameter setting method of additional damping controller based on classical control theory. In reference [10], genetic algorithm is introduced into the parameter tuning of the additional damper controller to provide sufficient positive damp for the generator and improve the suppression effect.

In summary, the existing research mainly focuses on the on-line monitoring of SSO and the additional damping control method. In the additional damping control, HVDC additional subsynchronous damping controller is a more economical method. Aiming at the SSO problem caused by HVDC current regulator, this paper will deeply analyze the principle of restraining SSO based on the mechanism of SSO triggered by HVDC. According to the working characteristics of HVDC, an Supplementary Subsynchronous Damping Controller (SSDC) design method based on the phase compensation principle of test signal method is proposed. The following first introduces the principle of HVDC SSO, and then analyzes the HVDC SSO for time domain analysis. Finally, according to the suppression mechanism of HVDC SSO, additional subsynchronous damping controller is designed to suppress the SSO. Finally, PSCAD/EMTDC software is used to verify the inhibition effect on the basis of IEEE first standard model.

2. Mechanism Analysis of Subsynchronous Oscillation Caused by HVDC System

In the research of SSO caused by HVDC, the power system can be divided into mechanical and electrical parts. The SSO of HVDC system is related to the operating conditions of HVDC system, control mode, transmission the power and the coupling degree between generator and HVDC power. Figure 1 below is a simplified model of DC transmission system.

![Simplified model of HVDC transmission system.](image)

Figure 1. Simplified model of HVDC transmission system.

When the shafting of generator changes slightly in power angle \( \Delta \theta = A \sin(\omega_\theta t) \), the principle of torsional vibration of generator shaft caused by HVDC is shown in Figure 2.

![Mechanisms of subsynchronous oscillation induced by HVDC.](image)

Figure 2. Mechanisms of subsynchronous oscillation induced by HVDC.

Assuming that the generator shafting oscillates at a natural torsional frequency \( \omega_m \), the power angle deviation can be expressed as:
\[ \Delta \delta = A \sin(\omega_d t) \] (1)

By calculating the time partial derivative, the generator speed deviation can be obtained as follows:
\[ \Delta \omega = p \Delta \delta = A \omega_d \cos(\omega_d t) \] (2)

According to the complex torque coefficient method, the electromagnetic torque increment of generator can be expressed as the sum of synchronous torque and damped torque, as follows:
\[ \Delta T_e = K_e \Delta \delta + D_e \Delta \omega \] (3)

In the formula, \( \Delta \delta \) and \( \Delta \omega \) are the power angle increment and angular velocity increment of the generator (relative to the synchronous rotating coordinate system), \( K_e \) and \( D_e \) are the synchronous torque coefficient and the damping torque coefficient, \( K_e \Delta \delta \) is the synchronous torque, \( D_e \Delta \omega \) is the damping torque. The ratio of electromagnetic torque increment to generator angular velocity increment is further obtained:
\[
\frac{\Delta T_e}{\Delta \omega} = D_e(\omega) - j \frac{1}{\omega} K_e(\omega) = \begin{vmatrix} \Delta T_e \\ \Delta \omega \end{vmatrix} \begin{vmatrix} \Delta \omega \\ \Delta \omega \end{vmatrix} \cos \varphi + j \begin{vmatrix} \Delta T_e \\ \Delta \omega \end{vmatrix} \begin{vmatrix} \Delta \omega \\ \Delta \omega \end{vmatrix} \sin \varphi
\] (4)

\( \varphi \) is the phase between electromagnetic torque increment \( \Delta T_e \) and generator speed increment \( \Delta \omega \).

If the phase difference \( \varphi \) between the electromagnetic torque perturbation \( \Delta T_e \) caused by the mechanical disturbance of the generator rotor and the increment \( \Delta \omega \) of the generator speed is within the range of \([-90^\circ, 90^\circ]\), the electric damping coefficient is positive and the system converges after oscillation, but if \( \varphi \) exceeds the range of \([-90^\circ, 90^\circ]\), the damping torque coefficient in the above formula will be less than 0, that is, there will be negative electric damping[11]. At this time, if the inherent mechanical damping of the generator itself cannot offset the negative electrical damping caused by the disturbance, the total system damping will be negative, which will make the unit torsional vibration unstable, and the SSO will diverge.

3. Working principle and phase compensation of SSDC
Supplementary Subsynchronous Oscillation Damping Controller (SSDC) adds an additional control link to the system in order to suppress SSO. By using the controllable and fast response characteristics of converter, it can provide positive electrical damping for generating units that may occur SSO phenomenon, as shown in Figure 3.

For generators, mechanical power is the input power of generators. Mechanical power can be changed by the intake of steam turbines. Electromagnetic power is the electromagnetic induction power or armature reaction power of generator stator windings. Its magnitude depends on the magnitude and nature of induction potential and stator current[12]. Electromagnetic power minus
stator winding loss is the output power of generator. Mechanical power drives the generator to rotate, and electromagnetic power prevents the generator from rotating. Both of them reach a balance at a certain speed (e.g. rated speed). When the load increases, the electromagnetic power increases. At this time, if the mechanical power is not increased, the rotational speed will decrease (the frequency will decrease). On the contrary, the mechanical power is limited, so the electromagnetic power, or the output power of the generator is limited[13,14]. Under the fast response characteristics of HVDC converter, the SSDC control strategy can enhance the subsynchronous oscillation damping characteristics of generating units and achieve the purpose of restraining the subsynchronous oscillation.

The existing SSDC structures are mainly divided into two categories: narrow bandpass SSDC and broad bandpass SSDC.

Broadband SSDC provides positive damping for severe torsional vibration modes of some units, but it does not provide much relative to narrowband SSDC. The principle of narrowband SSDC is based on the idea of sub modal, and the desired modal signal is extracted from the input signal by bandpass filter. It can extract and suppress each mode separately. This paper uses narrow bandpass SSDC to suppress SSO.

Signal test method is used to measure the phase, the specific steps are as follows: first of all, based on the simulation system is shown in figure 5, the dc current regulator of applying a series of small signal current reference point in $\Delta I_0$ oscillating current (containing different frequency components, the frequency range for 5-45 HZ), the system simulation to the steady state, on the electromagnetic torque of the generator to get the appropriate output response $\Delta T_e$; And then you take the Fourier decomposition of $\Delta I_0$ and $\Delta T_e$ in the common period, The phase difference between the electromagnetic torque and the test signal at different frequencies can be calculated.

The following formulas are used to determine the time constant of the compensation link with the lead and lag link such as $\frac{1+sT_1}{1+sT_2}$: $a = \frac{T_2}{T_1} = \frac{1-\sin \theta}{1+\sin \theta}$, $T_1 = \frac{1}{\omega_o \sqrt{a}}$, $T_2 = a T_1$

In the formula, $\omega_o$ is the frequency of the selected phase compensation and $\theta$ is the leading phase angle of $\omega_o$ which needs to be compensated. $T_1$ and $T_2$ are the time constants of the compensation link. SSDC consists of a straightening link, an amplifying link, a phase compensation link and a limiting link.

4. Testing System and Simulation Verification
For the study of the SSO of HVDC transmission system, the simulation system model is shown in Fig. 4. In this paper, PSCAD/EMTDC software is used to simulate and test the SSO in time domain. The simulation time is 10 seconds, the instantaneous three-phase short circuit of AC bus in converter station causes SSO, and the short circuit time is 0.075 seconds. Mechanical damping is set to 0, considering the worst condition of mechanical damping. The shafting system consists of six lumped mass blocks: HP, IP, LPA, LPB, GEN and EXC. The shafting system consists of five torsional vibration modes. The parameters of the shafting system are the same as the first standard test system model of IEEE. After the fault lasts 0.075 seconds, the shafting mass torque of the generator will undergo SSO.
The parameters of the generator and shafting models of the system are all based on the first resonance model of IEEE, and the standard CIGRE HVDC model is used in the DC part.

The amplitude of each frequency component of the generator speed deviation is obtained by Spectrum analysis. As it can be seen from Fig. 5.

The control structure of SSDC includes phase compensation and PI control, Among them $K_p = 1.0989, \ k_i = 1.57$. Three-phase instantaneous grounding fault occurs in the converter bus system at 1.5s. The duration is 0.075s and the total guideline time is 10s. Time domain simulation is carried out for the system without SSDC and the system with SSDC link. The response of the system with or without SSDC is observed, and the active power, reactive power and the variation of the torsion on the shafting of the generator are examined respectively.

When SSO occurs in the system, the variation of the torque on the shafting of each section of the system is shown in figs. 6 and 7. The first set of curves in figs. 6 and 7 represent the output torque of the generator; the second group of curves represents the change of torque between LPA and LPB; the third group of curves represents the change of torque between GEN and EXC. At 1.5 seconds, the system malfunction results in the change of generator torque. Torque propagates from HP to EXC, resulting in different modes of torsional vibration. Torque of high pressure cylinder to medium pressure cylinder, medium pressure cylinder to low pressure cylinder has obvious increasing oscillation trend.
SSO occurs when large disturbance occurs and SSDC is not added. The shafting of the generator is in divergent state, and the speed of the generator is in divergent state. If not controlled, it will destroy the stable operation of generator and transmission system.

The phase difference of SSDC and the time constants of compensation link $T_1 = 0.0027$, $T_2 = 0.0378$ are obtained from the above signal test method, and the gain coefficient is 1.

The simulation of narrow bandpass SSDC is shown in Figure 8.

![Figure 6. Torque of HP to LPB shafting.](image)

![Figure 7. LPB to EXC and rotational speed.](image)

**Figure 6. Torque of HP to LPB shafting.**

**Figure 7. LPB to EXC and rotational speed.**

**Figure 8. Narrow bandpass SSDC simulation**
When the SSDC control is not added, the torsional vibration occurs in each section of the generator shafting after the system failure, and the torque of each section of the generator shafting is divergent, indicating that SSO is unstable. Adding SSDC, as shown in figs. 9 and 10 above, the torque of each section of the generator shafting decreases rapidly after the fault, which shows that SSDC effectively damps the torsional vibration of the shafting and verifies the effectiveness of the SSDC controller.

5. Conclusion
SSDC can improve the SSO problem of dc power system. When SSDC is designed for a certain torsional vibration mode, the optimal compensation phase exists on the premise of a certain amplitude-frequency response of the controller. The phase lag characteristic of the system can be obtained through the test signal method and the compensation phase can be approximated by analyzing the frequency response of the system. The larger the gain of the additional controller, the better the damping control effect. When multiple SSDC circuits are adopted, multiple modes can be damped at the same time, and SSDC channel parameters can be reasonably and accurately adjusted. The simulation results of PSCAD/EMTDC electromagnetic transient time domain show that the damping of the system under various torsional modes can be significantly improved by reasonably configuring various parameters of the multi-channel variable parameter SSDC, so as to suppress the SSO, avoid the risk of SSO divergence, and effectively guarantee the safe and stable operation of the unit and the power grid.

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