Time-domain simulation analysis of combined suppression measures for subsynchronous oscillators

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Abstract. Subsynchronous oscillation (SSO) may occur in High Voltage Direct Current (HVDC) transmission systems during operation. It seriously affects the stability of the power system, and, if no reasonable control measures are taken, the shaft system of the unit can break. To study the AC side shafting of an HVDC system, the parameters of the first IEEE standard model of SSO were taken as the reference and combined with the CIGRE Benchmark two-terminal DC transmission model to build a complete set of HVDC systems for SSO research. The system SSO phenomenon was realized by setting the fault of a Supplementary Subsynchronous Damping Controller with wideband connection and a Supplementary Excitation Damping Controller with separate modes. They were designed at the network side to suppress the SSO of the system effectively, and the effectiveness of the suppression effect was verified by time-domain simulation.

1. Introduction
High-voltage direct current (HVDC) has many advantages in long-distance transmission, and it brings great convenience to people’s lives but also causes some inevitable problems, such as subsynchronous oscillation (SSO). SSO caused by an HVDC system usually results from the interaction between the rectifying side and the unit. When the inherent mechanical damping of the unit generated after the system is disturbed is not sufficient to offset the negative electrical damping generated by the system, the torsional vibration of the shafting intensifies, and this affects the unit life, at the very least resulting in a risk of shaft fracture and damage. Therefore, it is increasingly important to ensure the safe and stable operation of the power system.

The measures to restrain SSO include avoiding the resonance point, blocking the subsynchronous electric quantity, and increasing the electrical damping. In a previous study [1], taking the Yimin power plant as an example, the SSO problem of the system was effectively solved after the removal of the problematic unit. This is a less costly disincentive when it does not affect the overall operation of the system. In addition, a flexible alternating-current transmission system (FACTS) device can be connected in series to adjust the equivalent compensation capacitance to make the system deviate from the natural
torsional vibration frequency, to improve SSO, and to help the system avoid the resonance point. Common tandem FACTS devices include thyristor-controlled series capacitors [2], gate turn-off thyristor-controlled series capacitors [3], and static synchronous series compensators [4]. Because the SSO is caused by electromechanical coupling interaction, blocking the subsynchronous electric quantity is a good suppression method. Blocking and bypass filters can block the subsynchronous electric quantity well. In previous work [5], the method of blocking with a band-stop filter was used to increase the electrical damping near the modal frequency to suppress SSO. However, the use of a blocking filter has certain constraints. In multimodal SSO inhibition for different subsynchronous frequencies, when using a blocking filter to suppress SSO, it is necessary to adjust the parameters of each circuit in parallel resonance under the power frequency and line resistance in series resonance. Therefore, such parameters as the quality factor of the demand are higher. The design is somewhat difficult, and, because it is a side of the equipment, it is relatively expensive in terms of cost and maintenance.

If the unit cannot be removed, from an economic point of view, ascension electrical damping is a low-cost and effective measure to control the structure. This kind of method does not change the original system and has a relatively small scale of transformation. Efforts to improve the electrical damping are mostly applied to the secondary equipment of a power system, involving investment and economic loss. For the common methods used in practical engineering, from the viewpoint of system damping, the analysis of the complex torque coefficient shows that the total damping of the electrical and mechanical parts of the system is greater than 0. This can effectively relieve the divergent oscillation of the system shafting.

In this study, wideband-pass supplementary subsynchronous damping control (SSDC) and supplementary excitation damping control (SEDC) with separate modes were designed at the network side and the unit to suppress SSO. In a previous study [6], the multichannel separation mode method was used to design SSDC. In other research [7], an improved DC SSDC design method was proposed. The input signal of this method used the instantaneous voltage signal of a three-phase bus without transformation. This could omit the extraction of certain modes of the subsynchronous frequency component. In another study [8], the genetic algorithm was used to set SSDC parameters to make them robust. An SSDC design optimization algorithm based on a hybrid genetic algorithm and electromagnetic transient simulation was proposed [9]. The Electric Power Research Institute research project is based on the transfer function of the Byrd diagram design SSDC [10]. Hsu et al. [11] studied the problems of an AC–DC power system with series capacitor compensation, and they designed SSDC based on modal control theory. In another report [12], the suppression of SSO by SEDC was first mentioned, but the specific implementation was not mentioned. However, the necessity of an excitation system when SEDC is applied to the system was proposed [13], and analysis was performed to verify it. It has been pointed out [14] that the transient and steady-state characteristics of the system would not be affected if SEDC gain, limiting, and other parameters were reasonably set. In another study [15], the stator-side machine-end subsynchronous damping controller and SEDC were, respectively, applied to the stator and rotor sides of the unit to suppress SSO, and the suppression effect was verified by the eigenvalue method after the two suppression measures were applied to the rotor side of the unit. In other work [16-17], the operation of SEDC installed in a Shangdu power plant and Yimin power plant in China was examined in detail.

In this study, two kinds of controller for lifting system damping were designed for different degrees of system disturbance. The designed wideband-pass SSDC had a good inhibition effect on SSO generated by large disturbances in the system. An SEDC with separate modes was designed according to the deficiency of the SSO generated by small disturbances. It can suppress the SSO generated by small disturbances and supplement the deficiency of the SSDC inhibition ability. The parameters of the two controllers were adjusted by a signal test method and excitation method, respectively. Finally, the PSCAD/EMTDC simulation platform was used to verify that the two controllers designed in this study can cooperate with each other through time-domain simulation analysis, and the joint inhibition effect of the two controllers was verified by time-domain simulation.
2. Analysis of SSO in HVDC system

As shown in Figure 1, the DC line has a t-shaped structure, in which the rated voltage of the DC part is 500 kV and the rated transmission power is 1000 MW. The rectifying side and the inverter side of the converter station both use a single-pole 12-pulsation structure. The AC side generator outlet voltage is 26 kV, with a capacity of 892 MVA.

![Figure 1. HVDC system simulation model](image1)

In the AC system, because the CIGRE HVDC system power supply model cannot simulate the SSO phenomenon studied, generator replacement, including a communication system based on the IEEE subsynchronous resonance model, is used to make it easier to study the SSO caused by HVDC systems. In addition to the series compensation capacitor SSO, instead of the rated frequency of 50 Hz, the first standard of the series compensation capacitor, convenient for further study of SSO problems caused by HVDC systems. The parameters of six multimass block models refer to the first standard model. The AC system is shown in Figure 2.

![Figure 2. Alternating-current system](image2)

The HVDC system had a 1.5-s three-phase converter-side busbar voltage transient fault. For a simulation time set to 10 s, the duration of the fault was set to 0.075 s. Then, by time-domain simulation, observation system simulation was performed for 10 s. After the system was introduced, the SSO for the system occurred, when using the suppression measures of the unit shaft torque changes, as shown in Figure 3.
Figure 3. Shafting torque change

As Figure 3 shows, the SSO of the system at this time is serious, and the torque of the shafting of the unit shows a trend of divergent oscillation. If this is not suppressed, serious harm to the unit and even the whole power system can occur. The frequency spectrum of the generator speed was analyzed, as shown in Figure 4.

Figure 4. Frequency spectrum analysis of generator speed

The main oscillation frequencies of the system were 15.71, 25.55, and 32.33 Hz. Among them, the 15.71 Hz oscillation modes were the most serious.

3. Combined machine network suppression

3.1. SSDC and SEDC design

SSDC has a good inhibiting effect on a large disturbance of the system, but the inhibiting effect on SSO caused by a small disturbance is not very good; however, for SEDC, it is just the opposite. According to the advantages and disadvantages of SSDC and SEDC, the designed SSDC was added on the network side, and the designed SEDC was added on the machine end. The combined inhibiting scheme of the machine network was used to suppress the SSO of the system.

The SSDC design scheme was divided by channels — namely, single-mode suppression and multimode suppression — which were divided into two types: single-channel-mode wideband pass and multichannel-mode narrowband pass. In this study, a wideband pass-through SSDC was designed, which
used the three-phase instantaneous voltage of the bus as the input signal, as shown in Figure 5.

![SSDC structure design](image)

Figure 5. SSDC structure design

Here, $u_a$, $u_b$, $u_c$ is the three-phase voltage of the commutation bus system:

$$
\begin{bmatrix}
  u_a \\
  u_b \\
  u_c
\end{bmatrix} = U_{ml} \begin{bmatrix}
  \cos \theta \\
  \cos(\theta - \frac{2\pi}{3}) \\
  \cos(\theta + \frac{2\pi}{3})
\end{bmatrix}
$$

The transformation of rectangular coordinates is

$$
\begin{bmatrix}
  u_{\alpha} \\
  u_{\beta}
\end{bmatrix} = \begin{bmatrix}
  1 & -1/2 & 1/2 \\
  2 & 0 & \sqrt{3} \\
  \sqrt{3} & -2 & 0
\end{bmatrix} \begin{bmatrix}
  u_a \\
  u_b \\
  u_c
\end{bmatrix}
$$

The result of the above equation is $u_{\alpha} = U_{ml} \cos \theta$, $u_{\beta} = U_{ml} \sin \theta$, $\theta = \omega_0 t + \phi_0$, where $U_{ml}$ represents the amplitude of the fundamental frequency voltage, $\omega_0$ represents the fundamental angular frequency of the system, $\phi_0$ represents the initial phase angle of the bus voltage, $U_{\alpha}$ and $U_{\beta}$ are time period functions, and they are the voltage components of the three-phase voltage in the Cartesian coordinate system on the $\alpha\beta$ axis. If it is represented in terms of the rotational voltage phasor $\hat{V}$, there is:

$$
\hat{V} = u_{\alpha} + j u_{\beta} = U_{ml} \cos \theta + j U_{ml} \sin \theta = U_{ml} e^{j\theta}
$$

Then, the transformation of Equation (4) is as follows:

$$
\begin{bmatrix}
  u_d \\
  u_q
\end{bmatrix} = \begin{bmatrix}
  \cos \hat{\theta} & \sin \hat{\theta} \\
  -\sin \hat{\theta} & \cos \hat{\theta}
\end{bmatrix} \begin{bmatrix}
  u_{\alpha} \\
  u_{\beta}
\end{bmatrix}
$$

where $\hat{\theta}$ is the output of VOC in the voltage oscillation integral link, and $\hat{\theta} = \theta$ is in the steady state. If only considering the $q$ component,

$$
u_q = -u_{\alpha} \sin \hat{\theta} + u_{\beta} \cos \hat{\theta} = U_{ml} \sin(\theta - \hat{\theta}) = U_{ml} \sin \delta = e
$$

The output $u_q$ is the error quantity $e$, which generates the synchronous phase signal as the input of the loop filter. In Equation (5), if $\delta$ is small and $\sin \delta \approx 0$, then $e \approx U_{ml} \delta$ can be obtained.

Reasonable adjustment is made to the reasonable PI parameters of the loop filter, and output $\hat{\theta}$ can track the change of input $a$ phase voltage and phase $\theta$.

Assuming that the three-phase voltage contains harmonics, it can be expressed as:
After the transformation of $\alpha \beta$, 

\[
\begin{align*}
u_a &= \sum_{n=1}^{N} [U_{mn+} \cos \theta_{n+} + U_{mn-} \cos \theta_{n-}] \\
u_b &= \sum_{n=1}^{N} [U_{mn+} \cos(\theta_{n+} - \frac{2\pi}{3}) + U_{mn-} \cos(\theta_{n-} + \frac{2\pi}{3})] \\
u_c &= \sum_{n=1}^{N} [U_{mn+} \cos(\theta_{n+} + \frac{2\pi}{3}) + U_{mn-} \cos(\theta_{n-} - \frac{2\pi}{3})]
\end{align*}
\]

(6)

After the transformation of $dq$, the $q$ component is:

\[
\begin{align*}
u_q &= U_{m1} \sin \delta + \sum_{n=1}^{N} U_{mn+} \sin(\theta_{n+} - \hat{\theta}) - \sum_{n=1}^{N} U_{mn-} \sin(\theta_{n-} + \hat{\theta})
\end{align*}
\]

(8)

where $n$ is the harmonic number, $U_{mn+}$ is the amplitude of the positive sequence harmonic, $\theta_{n+} = n\omega t + \varphi_{n+}$ and $\varphi_{n+}$ are the initial phase angles of the positive sequence harmonic, $U_{mn-}$ is the amplitude of the negative sequence harmonic, and $\theta_{n-} = n\omega t + \varphi_{n-}$, $\varphi_{n-}$ is the initial phase angle of the negative sequence harmonic. The voltage component of positive sequence synchronization frequency is:

\[
\begin{align*}
u_{m+} &= U_{sm+} \cos(\omega_{t} + \varphi_{s+}) \\
u_{b+} &= U_{sm+} \cos(\omega_{t} + \varphi_{s+} - \frac{2\pi}{3}) \\
u_{c+} &= U_{sm+} \cos(\omega_{t} + \varphi_{s+} + \frac{2\pi}{3})
\end{align*}
\]

(9)

After the transformation of $\alpha \beta$ and $dq$, the required subsynchronous frequency signal is output:

\[
\begin{align*}
V_{s+}(t) &= u_q = U_{sm} \sin[(\omega_{t} + \varphi_{s+}) - (\varphi_{b} + \varphi_{0})] = -V_{sm+} \sin[(\omega_{b} - \omega_{t}) t - (\varphi_{s+} - \varphi_{b})] \\
&= -V_{sm+} \cos[(\omega_{b} - \omega_{t}) t - (\varphi_{s+} - \varphi_{b}) - \frac{\pi}{2}]
\end{align*}
\]

(10)

After the above transformation, the phase compensation link can be used to provide the unit with positive electrical damping to suppress SSO.

In this study, SEDC adopts the design idea of separate modes to suppress all SSO frequency modes, which makes up for the shortcoming that SSDC only inhibits the most-serious modes without suppressing other modes. The SEDC structure is shown in Figure 6.
The phase compensation \( a = \frac{T_2}{T_1} = \frac{1 - \sin \theta}{1 + \sin \theta} \), \( T_1 = \frac{1}{\omega \sqrt{a}} \), \( T_2 = aT_1 \) is adopted. The outputs of SSDC and SEDC are attached to the constant current controller and excitation regulator, respectively.

### 3.2. Combined inhibition effect analysis

The main reason for SSO in the system is that the inherent mechanical damping of the system is insufficient to offset the negative electrical damping that occurs because the absolute phase difference between the change in electromagnetic torque \( \Delta T_e \) and the change in rotational speed \( \Delta \omega \) is greater than 90°. The absolute values of the phase difference between the electromagnetic torque and the speed change after SSDC and SEDC are generated after the amplitude limiting output. The original electromagnetic torque change synthesized is positive when the absolute value of the phase difference between the new electromagnetic torque and the speed change is less than 90°. Previous research shows that the interaction between SSDC and SEDC is decoupled. The vector and relation of electromagnetic torque are shown in Figure 7. When SSDC and SEDC have no design problems, they can be well matched to suppress the SSO of the system.

The time-domain simulation of SSDC and SEDC acting on the system separately and starting together to suppress the SSO of the system is shown in Figures 8–11.
Figure 8. Hp-IP suppression effect

Figure 9. LPA-LPB suppression effect

Figure 10. LPB-GEN suppression effect
Figure 11. GEN-EXC suppression effect

It can be seen from the above inhibition effect diagram that both SSDC and SEDC can effectively inhibit SSO when acting on the system alone, and the inhibition effect is better when acting together than when acting separately. It is obvious from the time-domain simulation results that the joint inhibition scheme designed can effectively inhibit SSO. It also indirectly shows that the interaction between SSDC and SEDC is decoupled.

4. Conclusion
An attempt was made to improve the electrical damping to suppress the SSO of the system, realize the SSO phenomenon of the HVDC system by setting the fault, and obtain the frequency of each oscillation mode of SSO by analyzing the frequency spectrum of the generator speed. In view of the large disturbance of the system, the SSO was designed at the network side to suppress SSO. Because of the lack of SSDC suppression capability when the system is subjected to a small disturbance, SEDC with a separate mode was designed at the machine end to cooperate with the SSO of the SSDC joint suppression system. The parameters of the two were adjusted by means of phase compensation. With the two kinds of controller designed, the SSO of the frequency corresponding suppression can be seen from the time-domain simulation results. SSDC designed with a separate SEDC effect on the system can effectively restrain the SSO system. The joint inhibition effect of SSDC and SEDC was significantly better than the two actings separately, verifying the validity of the proposed design of joint suppression measures.

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