Design of Additional Damping Controllers with Subsynchronous Oscillation

Damping Effectiveness

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Abstract

When we research the suppression problem of subsynchronous oscillation based on time domain simulation method, we find the appropriate parameters for phase compensation and amplitude gaining links are important to the damping effect of the additional damping controllers, supplementary excitation damping controller(SEDC) and subsynchronous supplementary damping controller(SSDC). Some scholars attempt to optimize parameters by various optimization algorithms. But when they are applied in the complex system, there might have some practical problems. A novel method—simulation test method, which is simple but practical, is introduced in this paper. We can effectively identify the compensation phase and gain coefficient by this way, combined with test signal method. The specific design of SEDC and SSDC is realized in this paper. With these parameters obtained, SEDC and SSDC have a good inhibitory effectiveness. So the feasibility of this new method is validated. It is of great significance for engineering research.

Keyword

subsynchronous oscillation(SSO); supplementary excitation damping controller(SEDC); subsynchronous supplementary damping controller (SSDC); time domain simulation method

1. INTRODUCTION

Subsynchronous oscillation(SSO)[LIU Daixiang et al, 2012] first appeared in AC transmission system with series compensation capacitor, then was also found in high-voltage direct current transmission system, because of improper control parameters. Along with the implementation of China's "West to East" project, the DC transmission line will be widely used. SSO caused by HVDC gradually becomes a remarkable problem. Therefore, the research of inhibition measures of SSO is of great significance.

Supplementary excitation damping controller (SEDC) based on excitation voltage regulator and subsynchronous supplementary damping controller (SSDC) based on constant current controller of HVDC system are the two typical additional suppression controllers. The domestic and foreign scholars have done a lot of research work in supplementary damping controllers[2-7]. In the design process, the parameter design of phase compensation and gaining links is the key whether the controllers have the inhibitory effect. Some scholars tried to optimize the parameters design by all kinds of optimization algorithms[8-12], such as genetic algorithm, fuzzy immune algorithm, so on, and they achieved some good results. But when the power system structure and subsynchronous oscillation excitation factors are becoming more and more complicated, there may be some practical problems such as signal not converging, modeling difficulty, and so on. How to get the best parameters of damping controller is the key about the suppressing problem of SSO.

In this paper, a practical simulation model is established based on the actual AC/DC hybrid system of Southern network. The compensation phase and gain parameters of the controller are obtained simply and efficiently by a novel method—simulation test method, combined with test signal method. The design of SEDC and SSDC is implemented efficiently in this paper, so the feasibility of the method is verified. It is of great significance for the engineering application and simulation study about SSO problem.
The remainder of this paper is organized as follows: Section 2 reviews inhibition mechanism of additional suppression controllers. Section 3 presents a novel method—simulation test method and reveals test signal method. Section 4 reveals the proposed model. The design of SEDC and SSDC is implemented efficiently in section 5 and section 6. Final conclusions are given in Section 7.

2. THE INHIBITION MECHANISM

According to the complex torque coefficient method, the electrical damping coefficient of the system can be represented by the formula (1).

$$D_e = \text{Re}(\frac{\Delta T_e}{\Delta \omega})$$  \hspace{1cm} (1)

![Diagram of electromagnetic torque](image)

Where, $\Delta T_e$ and $\Delta \omega$ are respectively referred to as generator electromagnetic torque variable quantity and speed offset. And the phase difference between $\Delta T_e$ and $\Delta \omega$ determines the nature of electrical damping system. If its absolute value is less than $90^\circ$, electrical damping coefficient of the system is positive, so there is no SSO problem. If its absolute value is more than $90^\circ$, electrical damping coefficient is negative, so there may occur the phenomenon of SSO. The phase relationship is shown in Figure 1. When the phase lags $90^\circ ~ 270^\circ$ between $\Delta T_e$ and $\Delta \omega$, namely $\Delta T_e$ is located at third (or fourth) quadrant, the electromagnetic torque $\Delta T_e$ is negative, and there exists the possibility of SSO. If the additional electromagnetic torque $\Delta T_e^\prime$ located in the first quadrant is provided, the phasor sum of $\Delta T_e$ and $\Delta T_e^\prime$ is $\Delta T_e^\prime$, which is located in the first quadrant, and the electrical damping coefficient $D_e$ is positive. So SSO can be inhibited[13-15].

Based on the above ideas, some scholars put forward that additional electromagnetic torque is provided by SEDC and SSDC to solve the SSO problem in AC/DC system. The principle of SEDC and SSDC is similar. They put the generator speed deviation, or the system frequency deviation as the input signal, through appropriate proportion gain and phase compensation, and the output signal of SEDC enters into excitation control circuit and the output signal of SSDC enters into constant current control loop. They all provide $\Delta T_{SEDC}$ and $\Delta T_{SSDC}$ by system responses.

3. INTRODUCTION OF METHODS

3.1 Test signal method

By analysis[JIANG Ping, 2011], the compensated phase is lag phase from signal input end of additional damping controllers, namely excitation voltage reference links of excitation controller for SEDC and current reference links of constant current controller for SSDC, to generator electromagnetic torque. The lag phase is very difficult to calculate by the mathematical analytical method, but can be easily obtained by test signal method. The specific steps are as follows: firstly, in the power system, a series of small signal($\Delta i_0$) is applied to an additional damping controller input end (including different frequencies components in the frequency range of 5~45Hz); until the system simulated to the steady state, obtain the corresponding output response ($\Delta T_e$) of the electromagnetic torque; then do Fourier decomposition analysis for $\Delta i_0$ and $\Delta T_e$ in the common period. So we can calculate the lag phase difference between electromagnetic torque and test signal in different frequency.

3.2 Simulation test method

The phase compensation links of SEDC and SSDC all use the same design principle. They are formed in series by four same shape lead lag links as $(1+sT_a)/(1+sT_b)$.

The time constants of phase compensation link can be calculated from (2).

$$\begin{align*}
\alpha &= \frac{T_a}{T_b} = \frac{1 - \sin \phi}{1 + \sin \phi} \\
\phi &= \left(\omega_c \sqrt{a}\right)^{-1} \\
T_a &= aT_d \\
T_b &= aT_d
\end{align*}$$

Where, $\omega_c$ is referred to as the chosen frequency. $\phi$ is referred to as the corresponding compensation phase angle. $T_a$, $T_b$ are referred to as the time constants of the compensation links.

Considering characteristic of sine function, the
same four compensation links should be set up, and compensation angle of each link does not exceed 90°. According to the above formula (2), the time parameters of compensation links can be calculated, when the total Tab. 1 The corresponding time parameter of compensation links when compensation angle is changed from 10° to 350°

<table>
<thead>
<tr>
<th>T phase</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T_a )</td>
<td>( T_b )</td>
<td>( T_a )</td>
</tr>
<tr>
<td>350</td>
<td>0.5337</td>
<td>0.00025412</td>
<td>0.2917</td>
</tr>
<tr>
<td>340</td>
<td>0.2667</td>
<td>0.00050848</td>
<td>0.1458</td>
</tr>
<tr>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>20</td>
<td>0.0127</td>
<td>0.0107</td>
<td>0.0069</td>
</tr>
<tr>
<td>10</td>
<td>0.0122</td>
<td>0.0111</td>
<td>0.0066</td>
</tr>
</tbody>
</table>

If the compensation degrees are negative, just put the time parameter \( T_a \) and \( T_b \) of corresponding degree swap.

The principle of simulation test method to determine the compensation phase is simple. It is in order to obtain the inhibitory effect as the final purpose. In the simulation platform, when doing the time domain simulation analysis, the total compensation degree is gradually changed from -350° to 350°, then observe, record and analyze the change rule of the simulation model shaft system oscillation. We can identify the effective compensation phase range, according to the change rule. Within this range, the appropriate compensation degree can be found out by continuous debugging.

Generally the larger is gain coefficient, the stronger is damping inhibitory effect of damping controller. But if the gain coefficient is too large, it will cause the system to oscillate intensively, even it may make the system breakdown. The principle of simulation test method to determine the gain coefficient is expressed as follows: after the appropriate compensation phase is found, through continuous debugging, correct gain coefficient by increasing or decreasing gain coefficient. The correcting principles are when in serious failure cases, the saturated time of output signal is limited within a certain range (such as 6s), and the closed-loop damping for each torsional vibration mode is increased. In the end, we can identify the appropriate gain coefficient according to the change rule of the shaft system oscillation.

4. THE PROPOSED MODEL

Based on the actual data of AC/DC hybrid system of the guizhou power grid, AC/DC hybrid system model, with a power plant in the stand-alone operation model, is built by the electromagnetic transient simulation software PSCAD/EMTDC. The model structure diagram is shown in Figure 2.

Fig. 2 The schematic diagram of the model structure

\( G_1 \) is referred to as a certain power plant unit studied, and HP, LP-A, LP-B, GEN are referred to as four shafting quality blocks of turbo-generator set, respectively the high pressure cylinder, low pressure cylinder A, low pressure cylinder B. generator. The shaft system model parameters of generator unit are shown in Table 2.

Tab. 2 The shaft model parameters table of a power plant
<table>
<thead>
<tr>
<th>Lumped mass block</th>
<th>rotational inertia $M_i$, kg $m^2$, $K_i$</th>
<th>elastic coefficient $K_i$, KNm rad$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pressure cylinder rotor, HP</td>
<td>2936</td>
<td>86790</td>
</tr>
<tr>
<td>Low pressure cylinder rotor, LP-A</td>
<td>22404</td>
<td>115950</td>
</tr>
<tr>
<td>Low pressure cylinder rotor, LP-B</td>
<td>21634</td>
<td>148330</td>
</tr>
<tr>
<td>generator rotor, GEN</td>
<td>9654</td>
<td></td>
</tr>
</tbody>
</table>

The natural modal frequencies are solved by the eigenvalue analysis of the more mass model of shaft system. And the three modal frequencies respectively are 13.666Hz、25.002Hz、29.343Hz.

5. DESIGN OF SEDC AND ITS INHIBITION EFFECT VALIDATION

5.1 The structure design of SEDC

5.2 The determination of compensation phase and the gain in the design process of SEDC

The initial setting parameter of gain link should not be too large. If the setting is too large, it may make the system oscillation aggravate. Generally the initial gain parameter is about 1 to 10.

In order to avoid a wide range of simulation debugging, the lagging phases range is firstly obtained by test signal method, as shown in Table 3.

Tab. 3 The measured lag phase by test signal method

<table>
<thead>
<tr>
<th>Lagging phase (°)</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>162.5</td>
<td>293.4</td>
<td>124.8</td>
</tr>
</tbody>
</table>

Keep gain coefficient invariable at the beginning.

The total compensation degree of four compensation links add and subtract 90° relative to the lagging phase measured by test signal method. Do the simulation debugging by simulation test method, and observe and record the modal component change situation of speed difference.

After finding the best compensation degree, through constantly adjusting the gain coefficient, we realize that the system oscillation attenuation is the fastest and SEDC has the most obvious inhibitory effect. After many experiments, a group of appropriate parameters is obtained, as shown in Tab. 4.

Tab. 4 The compensation phase and gain coefficient parameter table of SEDC

<table>
<thead>
<tr>
<th>Mode</th>
<th>The total compensation phase (°)</th>
<th>Ta</th>
<th>Tb</th>
<th>Gain coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>0.0281</td>
<td>0.0048</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>320</td>
<td>0.0728</td>
<td>0.00055693</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>0.0110</td>
<td>0.0027</td>
<td>10</td>
</tr>
</tbody>
</table>

5.3 The effect validation of SEDC

According to a set of optimal parameter as the above, SEDC is designed well. Based on the proposed simulation system, the oscillations of the shafting modal speed difference are compared when SEDC not applied and applied in the system, as shown in Figure4.
broadband controller structure. And it will make the damping effect for all the units strengthened. Also this structure is simple, and easy to implement in engineering. Therefore, a single-channel design idea is used in this paper. The structure diagram of SSDC is shown in Figure 5.

![Diagram of single-channel broadband SSDC]

The bus voltage is measured from the bus near the converter by measuring link, then it get through the phase lock loop (PLL) link to get the frequency deviation signal. The information for the sub-synchronous oscillation modes is retained by the band-pass filter, and finally through phase compensation and amplitude adjustment link, the current compensation amount is obtained. And it’s added to the reference current, and works together with the original HVDC control system to achieve the purpose of inhibiting SSO [YANG Tingzhi et al, 2008].

6.2 The determination of compensation phase and the gain in the design process of SSDC

We can similarly obtain lagging phase range by test signal method. The result measured is about 21.5°.

When doing the simulation test, according to the measured lagging phase by test signal method, the total compensation degree, is gradually changed from -90° to 110°. The amplitude frequency characteristics of transfer function of compensation link have the different gain characteristics when the compensation degrees are different. There may make the controller output is too large, so when we adjust compensation degree, we must adjust the gain coefficient to ensure the amplitude size of the output signal of SSDC varies between 0 to 0.3 at the same time.

In the effective compensation degree range, through continuous simulating and debugging, finally we can get a set of relatively effective parameters, as
shown in Table 5.

Tab. 5  The effective parameter table of SSDC

<table>
<thead>
<tr>
<th>parameters of SSDC</th>
<th>The total compensation phase (°)</th>
<th>the time constant of each link</th>
<th>gain coefficient</th>
<th>Limiting link</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>0.0122</td>
<td>0.0111</td>
<td>0.01</td>
</tr>
</tbody>
</table>

6.3 The effect validation of SSDC

According to a set of optimal parameter as the above, SSDC is designed well. Based on the simulation system, the shafting modal speed differences are compared when SSDC not applied and applied in the system, as shown in Figure 6.

![Graph](image1)

(a) The shaft rotation speed difference graphics for mode 1

![Graph](image2)

(b) The shaft rotation speed difference graphics for mode 2

![Graph](image3)

(c) The shaft rotation speed difference graphics for mode 3

Fig. 6  The comparison of speed difference for three modes when SSDC not applied and applied

From Figure 6, it shows that when SSDC is not applied in the system, the speed difference is slow convergence. When applied, the unit speed difference achieves fast convergence. According to the convergence speed, we can obviously see that the SSDC designed has a good inhibition effect.

In summary, the increasing convergence rate shows that SSDC can effectively inhibit SSO. The accuracy and reliability of parameter design are validated, and at the same time the feasibility of this method is verified.

7. CONCLUSION

Through the design process of two additional damping controllers, SSDC and SEDC, and their inhibiting effect validation, we can reach a conclusion that this new idea is reliable. Based on time domain simulation method, firstly, the scope of compensation phase is obtained by test signal method. Then, a set of optimal parameters of phase compensation links and gain link is simply and effectively identified by simulation test method according to the phase scope obtained before. This method is simple and easy, and the efficiency is high. It does not need to consider a series of factors, such as the complexity of system model, the convergence of signal, and so on. So it has a wide applicability. It is of great significance to the actual engineering research and the simulation research on subsynchronous oscillation problem.

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