A Control Strategy for Damping Subsynchronous Oscillation Based on Voltage Source Converter Excitation System

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Abstract. As the traditional thyristor static excitation system is widely applied in the power system, the electrical damping of the system is weakening, and that makes the system facing the risk of subsynchronous oscillation (SSO). Although some research on Flexible AC Transmission Systems (FACTS) for damping SSO has been proposed, the applying of the FACTS is not economic enough. The Voltage Source Converter (VSC) Excitation system is a kind of excitation system using full-controlled power switches. There is no research on damping SSO based on the VSC excitation system. By analyzing the characteristics of the VSC excitation systems, a control strategy for damping SSO based on phase compensation method is proposed.

1. Introduction

With the improvement of domestic grid of China, a kind of multi-set coupled generator group weaknesses construction is gradually formed as the deepening regional connection and construction of long-distance heavy-load transmission lines in large scale. These conditions cause the system facing risk of subsynchronous oscillation (SSO), which affects the transmission capacity of long-distance heavy-load transmission lines and security of power system operation[1].

In order to enhance the transmission capability of long-distance lines, using series compensation devices for AC transmission systems can effectively improve the transmission capacity of the lines, and it makes the power system facing SSO risk as well. The use of Supplementary Excitation Damping Controller (SEDC)[2] and the installation of Flexible AC Transmission Systems (FACTS) on the primary side of the system are two effective SSO suppression methods. SEDC has the advantage of low costs, but its ability for damping is limited when the transient torque amplification caused by the series compensation system occurs big disturbance. Although FACTS has the advantage of flexible control, its high costs limits the widely industrial application[3].

The Voltage Source Converter (VSC) Excitation system is a kind of device that combines the functions of excitation and FACTS. Considering the features of the VSC excitation system, it could be treated as a combination of a STATOM which is connected to the generator terminal and a regular static excitation system[4]. Thus, the VSC excitation system could supply additional active electrical damping for the power system by adjusting the reactive power on the AC side of the VSC. Compared with the static excitation systems with thyristor, the responding speed of the VSC excitation system is improved, for the reason that the switching frequency of VSC is higher than the converter with thyristor[5].
At present, there is no research on applying the VSC excitation system to solve SSO problem. In this paper, a control strategy for damping SSO based on VSC excitation system is proposed. The complex torque coefficient approach and its time domain simulation realization are introduced in Section 2. The equivalent mathematical model of VSC Excitation System is given in Section 3. The control strategy for damping SSO based on VSC excitation system is proposed in Section 4. The conclusions are present in Section 5.

2. Complex torque coefficient approach and simulation

2.1. Principle of complex torque coefficient approach

As described in the linearized state equation of a single-machine infinite system[6], it can be found that the mechanical system and the electrical system is connected by the generator electromagnetic torque increment $\Delta T_e$ and angular velocity increment $\Delta \omega$ relative to a synchronous rotating coordinate system, the relationship between $\Delta T_e$ and $\Delta \omega$ is shown in Figure 1.

![Figure 1. Diagram of system generator-net torsional oscillation](image)

$\Delta T_m = 0$ + Steam turbine and Shafting system $G_m(s)$ \hspace{1cm} $\Delta \omega$

$\Delta T_e$ + Generator and grid system $G_e(s)$ \hspace{1cm} $\Delta \delta$

Figure 1. Diagram of system generator-net torsional oscillation

$\Delta T_m$ is mechanical torque increment on the generator rotor, usually $\Delta T_m = 0$; $G_m(s)$ is transfer function for mechanical system; $G_e(s)$ is transfer function for electrical system.

The basic idea for obtaining complex torque coefficient proposed by I.M.Canay is described as follows[7]: through linearized state equation for electrical part and mechanical part of the system, the electrical and mechanical features of the system could be found. $\Delta T_e$ and $\Delta \delta$ should be kept during the calculating process, while the other unrelated variables should be ignored.

For a single-machine fixed-frequency infinite power system, when the system encounters a small disturbance, the electromagnetic torque increment of the generator could be expressed as[8]:

$$\Delta T_e = K_e(s)\Delta \delta + D_e(s)\Delta \omega$$

(1)

where $K_e(s)\Delta \delta$ is synchronous torque, $D_e(s)\Delta \omega$ is damping torque, $K_e(s)$ and $D_e(s)$ are synchronous torque coefficient and damping torque coefficient separately. And there is

$$\Delta \omega = \frac{1}{\omega_0} \frac{d\Delta \delta}{dt}$$

(2)

where $\omega_0$ is synchronous speed.

Applying a steady-state small oscillation disturbance that $\Delta \dot{\delta} = \Delta \delta_m e^{jh}$, with an angular frequency that $h = \lambda \omega_0$ (where $0 < \lambda < 1$, $\omega_0$ is fundamental wave frequency) on generator rotor, for equation (2), there is

$$\Delta \dot{\omega} = \frac{1}{\omega_0}(jh)\Delta \dot{\delta}$$

(3)

From equation (1), it can be deduced that

$$\Delta \dot{T}_e = K_e(h)\Delta \dot{\delta} + D_e(h)\Delta \dot{\omega}$$

(4)

Combined with equation (3), it could be found that
\[ K_e(j\omega) = \frac{\Delta \dot{T}_e}{\Delta \delta} = K_e(h) + jhD_e(h) \]  
\[ \frac{\Delta \dot{T}_e}{\Delta \dot{\omega}} = D_e(h) - j \frac{1}{h} K_e(h) \]  

Thus, the electrical damping torque coefficient \( D_e \) could be got by equation (6) directly.

### 2.2. Time domain simulation realization for complex torque coefficient approach

In time domain simulation, the electrical part of the complex torque coefficient can be obtained by test-signal method. The generator shafting is treated as a single rigid body model, the other electrical part of the generator adopts detailed electrical model. The electromagnetic network adopts electromagnetic transient model.

The electrical damping torque coefficient of the system is given by equation (6), that is

\[ D_e(h) = \text{Re} \left( \frac{\Delta \dot{T}_e}{\Delta \dot{\omega}} \right) \]  

The steps of the test-signal method are as follows[8]:

1. First, detailed model of units in power system should be built in time domain simulation software environment, containing generator model, power network electromagnetic transient model, FACTS switch model and so on.

2. A small value oscillation torque within an angular frequency that is \( h = \lambda \omega_b \) \((0 < \lambda < 1)\), is applied to the generator rotor to be studied, when the system is running in a certain steady state.

3. After applying the pulsating torque, the simulation is performed until the system enters the steady state again, and the generator electromagnetic torque \( \dot{T}_e \) and the generator angular frequency \( \omega \) of the pulsating torque for a common period are intercepted.

4. Perform Fourier decomposition on \( \dot{T}_e \) and \( \omega \), for getting the electrical damping \( D_e(h) \) at the frequency \( h \) by equation (7).

5. Repeat the above four steps until electrical damping coefficients for all required subsynchronous frequency ranges are obtained.

### 3. Mathematical Model of VSC Excitation System

On the study of the SSO problem, since it is not necessary to consider the switching process of the power electronic device of the VSC excitation system, the full-controlled converter can be equivalent to a controlled source.

#### 3.1. VSC equivalent model

Figure 2 shows the topology of VSC. The AC side power of VSC is supplied by a three-phase excitation transformer. The three-phase full-controlled bridge is connected through a boost filter inductor, and the DC side capacitor is connected to the input of the H bridge chopper to provide excitation power indirectly.
The AC side active power is
\[ P_{S,AC} = u_{sa}i_a + u_{sb}i_b + u_{sc}i_c \]  
(8)

The DC side active power is
\[ P_{S,DC} = u_{dc}i_{dc} \]  
(9)

Ignoring the power loss of VSC, the relationship between the AC side power and that of DC side is
\[ P_{S,AC} = P_{S,DC} \]  
(10)

The DC side current \( i_{dc} \) is deduced as
\[ i_{dc} = \frac{u_{sa}i_a + u_{sb}i_b + u_{sc}i_c}{u_{dc}} \]  
(11)

The DC side reference voltage is set as \( V_{dc,ref} \). In PWM modulation mode, the voltage utilization rate is \( \mu \) (0 < \( \mu \) ≤ 1), modulation ratio is \( M \) (0 ≤ \( M \) ≤ 1), phase shift angle is \( \delta \), the output voltage on AC side of VSC is given by
\[ \hat{U}_C = \frac{\mu M}{\sqrt{2}} V_{dc,ref} \angle (\delta_s - \delta) \]  
(12)

As for equation (11), it is indicated that the DC side of VSC can be equivalent to a current controlled current source (CCCS). And for equation (12), it is indicated that the AC side of VSC can be equivalent to a three-phase voltage controlled voltage source (VCVS). As a result, the equivalent circuit of VSC is shown as Figure 3[9].

### 3.2. Excitation equivalent model

The excitation voltage of the generator is provided by the H-bridge connected to the VSC DC-side capacitor. The functions are essentially the same as those of traditional static excitation system. Here, IEEE ST1A[10] type excitation standard model is used for being equivalent to the excitation part of the VSC excitation system. Figure 4 shows the structure of the model.
4. Control strategy for damping SSO

4.1. Basic principle of the controller design

Usually, the value of the mechanical damping of the generator is much smaller than that of the electrical damping. Thus, the effect caused by the mechanical damping to the system is always neglected. When the electrical damping of the system is negative, the system is under risk of SSO. While the electrical damping of the system is positive, the system is stable. The vector relationship of $e_T\Delta$ and $\omega\Delta$ is depicted in Figure 5. When the phase of $e_T\Delta$ lags that of $\omega\Delta$, and the lag phase is in range between $90^\circ$ and $270^\circ$, the electrical damping torque $D_T\Delta$ is negative, and $D_e$ is negative, resulting in system instability.

For guaranteeing the system has positive electrical damping, an affixation electromagnetic torque $e_T'\Delta$ could be applied in the first quadrant. Make sure the phase of $e_T'\Delta$ is same as that of $\omega\Delta$. So, $e_T'\Delta$ and the electromagnetic torque $T_e\Delta$ of the generator will be combined into vector $T_{etotal}\Delta$ in the first quadrant. Thus, the original unstable system has the conditions for SSO stability.

4.2. Mathematical model of the controller

Based on phase compensation theory, an SSO damping controller (QSSDC) is proposed for the VSC excitation system. The structure of QSSDC is shown in Figure 6. The generator speed deviation $\Delta\omega$ is input signal. First, the straight-through link ensures the steady-state output of the stabilizer is zero. Then, after amplification, phase compensation and limiting, the control signal is output as the reference value of the reactive current $I_{q,ref}$, and $I_q$ is the reactive current that is converted by rotation transformation.
While the QSSDC is applied in the VSC excitation system, the generator speed and electromagnetic torque transfer function block diagram is shown in Figure 7.

Figure 6. Structure diagram of QSSDC

Figure 7. Relationship between speed deviation and torque increment

\( E(s) \) is transfer function that without QSSDC, \( G(s) \) is transfer function that from the reactive current of the VSC to the generator affixation electromagnetic torque \( \Delta T_e' \), \( C(s) \) is transfer function for QSSDC. Thus, the transfer function for the entire system is given by

\[
\frac{\Delta T_{\text{total}}}{\Delta \omega} = \frac{\Delta T_e + \Delta T_e'}{\Delta \omega} = E(s) + C(s)G(s) \tag{13}
\]

The parameters of the lead-lag link is adjusting with respect of the phase characteristics of \( G(s) \), make sure the phase difference between \( \Delta T_e' \) and \( \Delta \omega \) being in the range of \(-90^\circ\) and \(90^\circ\) as possible, that is \( \arg(\frac{\Delta T_e'}{\Delta \omega}) = \arg[C(s)G(s)] \).

4.3. Design of QSSDC

Before designing the phase compensation link of QSSDC, the phase-frequency characteristics of the transfer function should be known first. It is achieved by using test signal method. The basic steps of test signal method are as follows:

1. For the determined operating point, after the system runs in steady state, a series of small-value pulsation test signals are applied to the VSC reactive reference current \( I_q \) with an integral multiple of the frequency \( \omega_0 \) of interest, and the \( \Delta I_q \) is given by

\[
\Delta I_q = \sum_{\lambda} I_A \cos(\lambda \omega_0 t + \phi_\lambda) \tag{14}
\]

where \( \lambda < 1 \); \( I_A \) and \( \phi_\lambda \) are amplitude and phase of pulsating torque with frequency \( \lambda \omega_0 \). The value of \( I_A \) should be as minimum as possible, so that the value of \( \Delta I_q \) does not destroy the assumption that the system can be linearized.

2. After the disturbance is applied, it is simulated until the system enters the steady state again, intercepting the generator electromagnetic torque increment \( \Delta T_e \) and the disturbance test signal \( \Delta I_q \) in a common period of the disturbance test signal.

3. Make Fourier decomposition for \( \Delta T_e \) and \( \Delta I_q \), getting \( \Delta T'_e \) and \( \Delta I'_q \) at different frequencies.
(4) Calculate and plot the frequency characteristic curve of \( \frac{\Delta T}{\Delta \lambda_{q,\text{ref}}} \), obtaining phase frequency characteristic for transfer function \( G(s) \).

Based on the phase frequency characteristics for \( G(s) \) obtained, the frequency point at which phase compensation is required can be determined. Only the phase near the SSO point should be compensated for. The time constants of the compensation link are given by:

\[
a = \frac{1 - \sin \phi}{1 + \sin \phi} \tag{15}
\]

\[
T_a = \frac{1}{(2\pi f_s \sqrt{a})} \tag{16}
\]

\[
T_b = a T_a \tag{17}
\]

where \( f_s \) is the frequency point where the phase needs to be compensated, \( \phi \) is the lag phase angle needs to be compensated corresponded to \( f_s \). \( T_a \) and \( T_b \) are the time constant for lead-lag link.

As for the washout link \( \frac{sT_w}{1+sT_w} \), the value of time constant \( T_w \) is usually set as 5. The gain factor of the amplification link can be adjusted according to the specific effect of QSSDC for damping SSO. In addition, a limiter is needed to restrict the output of QSSDC, which reflects the reactive power capacity of the VSC.

5. Conclusions
The basic principle of complex torque coefficient approach is introduced, and the time domain simulation realization is given. By analyzing the characteristics of the VSC, it can be equivalent to a CCCS and a VCVS for SSO research. Based on phase compensation theory, a controller QSSDC for SSO damping is proposed. The proposed strategy provides a new way for solving SSO.

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References
[1] Zhou, X.X., Guo, J.B., Lin, J.M. (2009) Power System Controllable Series Capacitor Compensation. Science Press, Beijing.

[2] Ooi, E.T., M.M. Sartawi. (1978) Concepts on Field Excitation Control of Subsynchronous Resonance in Synchronous Machines. IEEE Transactions on Power Apparatus and Systems., PAS-97(5): 1637-1645.

[3] Xie, X.R., Wang, L., Guo, X.J. et al. (2014) Development and Field Experiments of a Generator Terminal Subsynchronous Damper. IEEE Transactions on Power Electronics., 29(4): 1693-1701.

[4] Yang, J.W., Chen, Z., Mao, C.X. et al. (2014) Analysis and assessment of VSC excitation system for power system stability enhancement. INTERNATIONAL JOURNAL OF ELECTRICAL POWER & ENERGY SYSTEMS., 57: 350-357.

[5] Chen, Z., Mao, C.X., Wang, D. et al. (2016) Design and Implementation of Voltage Source Converter Excitation System to Improve Power System Stability. IEEE Transactions on Industry Applications., 52(4): 2778-2788.

[6] Ni, Y.X., Chen, S.S., Zhang, B.L. (2002) Theory and analysis of dynamic power systems. Tsinghua University Press, Beijing.

[7] Canay, I.M. (1982) A Novel Approach to the Torsional Interaction and Electrical Damping of the Synchronous Machine. Part I: Theory. Power Engineering Review., PER-2(10): 24-24.
[8] Xu, Z. (2000) The Complex Torque Coefficient Approach's Applicability Analysis and Its Realization by Time Domain Simulation. Proceedings of the CSEE., 20(6): 1-4.

[9] Teng, S. (2013) Development and Research on Modeling of VSC-HVDC Based on PSD Program. North China Electric Power University.

[10] IEEE Std 421.5-2005 (Revision of IEEE Std 421.5-1992). (2005) IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. IEEE.