The Comparative Analysis of SVC and STATCOM on Subsynchronous Oscillation Mitigation

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***Abstract*—The methods for subsynchronous oscillation mitigation based on SVC and STATCOM are analyzed in this paper. According to the IEEE first benchmark model, the electrical damping coefficients respectively provided by SVC and STATCOM connected at the generator terminal, as well as positive damping condition, are deduced by complex torque coefficient approach. Correlative factors which influence the two positive dampings are compared. The analysis results indicate that the positive damping provided by SVC is proportional to the size of system voltage. The positive damping provided by STATCOM is not affected by the size of system voltage, which is mostly proportional to the subsynchronous voltage produced itself. The controllers of SVC and STATCOM are designed and the positive dampings separately offered by SVC and STATCOM are optimized by phase compensation with test signal method. The time domain simulation reveals that STATCOM has stronger damping ability than SVC in the case of short circuit fault.**

Keywords-subsynchronous oscillation, SVC, STATCOM, damping, test signal method

I. INTRODUCTION

Fixed series capacitor compensation and HVDC are economical and effective measures to improve the transmission capability. However, both of them probably cause subsynchronous oscillation (SSO). In recent years, Flexible Ac Transmission Systems (FACTS) have been widely used to mitigate SSO [1,2]. Parallel FACTS are distinctly popular. The most common ones are static var compensator (SVC) and static synchronous compensator (STATCOM). In this paper, the basic principles of SVC and STATCOM on SSO mitigation are first introduced respectively. According to the IEEE first benchmark model, the electrical damping coefficients respectively provided by SVC and STATCOM connected at the generator terminal, as well as positive damping condition, are deduced. Correlative factors which influence the two positive dampings are compared. The controllers of SVC and STATCOM are designed and the positive dampings separately offered by SVC and STATCOM are optimized by phase compensation with the method of test signal. Time domain simulation method is used to compare the mitigation effects of SVC and STATCOM.

II. THE PRINCIPLES OF SVC AND STATCOM ON SSO MITIGATION

The Basic Principle of SVC on SSO Mitigation. The basic principle of SVC for SSO mitigation can be described as Eq. 1 [3].

$$i_{svc}=u_s B_1 = U_s\sin(\omega_0 t+\theta_s)[B_{10}+B_{1m}\cos(\omega_m t+\phi_m)]. \quad (1)$$

where u_s is the system voltage of access point of SVC, ω_0 and θ_s are the fundamental angular frequency and initial phase angle. B_1 is the equivalent admittance of SVC. B_{10} is fundamental admittance. B_{1m}, ω_m, φ_m are the amplitude, angular frequency and initial phase angle of subsynchronous admittance. The subsynchronous component is added to the reference value of fundamental admittance of SVC controller, which makes actual equivalent admittance containing a component with torsional frequency of the generator shaft. When the system voltage acts on the equivalent admittance, subsynchronous current is produced as shown in Eq. 2, which flows into the generator and the damping torque can be produced to mitigate SSO.

$$i'_{svc}=\frac{1}{2}U_s B_{1m}\sin((\omega_0-\omega_m)t+\theta_s-\phi_m). \quad (2)$$

The Basic Principle of STATCOM on SSO Mitigation. By designing STATCOM controller, a sinusoidal component at the complementary frequency with torsional frequency can be added to the fundamental modulating signal and the output voltage of STATCOM can be expressed as Eq. 3 where harmonic component is ignored.

$$u_i = m_a U_{dc}\sin(\omega_0 t+\theta_c)+m_{as}U_{dc}\sin((\omega_0-\omega_m)t+\gamma). \quad (3)$$

where m_a and m_{as} are the amplitude modulation rates at fundamental and complementary subsynchronous frequencies. If the system voltage of access point of STATCOM is still $u_s=U_s\sin(\omega_0 t+\theta_s)$, the current injected by STATCOM to the system can be expressed as Eq. 4, which flows into the generator and the damping torque can be produced to mitigate SSO.

$$i'_{statcom}=\frac{m_{as}U_{dc}}{(\omega_0-\omega_m)L_s}\cos((\omega_0-\omega_m)t+\gamma). \quad (4)$$

III. DAMPING CHARACTERISTICS ANALYSIS OF SVC AND STATCOM ON SSO MITIGATION

The linearizng equivalent circuit of the IEEE first benchmark model is shown in Fig. 1 where R and L are the resistance and inductance of the transformer and transmission line, and C is the capacitor of series compensation, and r_g and L_g are the equivalent resistance and inductance of the generator. SVC or STATCOM dedicated to mitigate SSO is connected in parallel to the generator terminal and either of them can be equivalent to a controlled current source. When the generator shaft vibrates at a subsynchronous frequency ω_m which is one of the torsional frequencies, the power angle deviation can be express as $\Delta\varphi = A\sin(\omega_m t)$ and the rotate speed deviation of the generator is $\Delta\omega = A\omega_m \cos(\omega_m t)$.

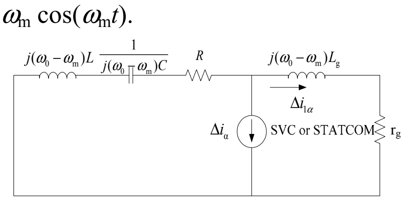


Fig. 1 Equivalent circuit of the IEEE first benchmark model

Damping Characteristic of SVC on SSO Mitigation. According to Eq. 2, the subsynchronous current of SVC under the αβ coordinate system can be expressed as Eq. 5.

$$\begin{bmatrix}\Delta i_{\alpha,\mathrm{svc}}\\ \Delta i_{\beta,\mathrm{svc}}\end{bmatrix}=\frac{1}{2}U_s B_{1m}\begin{bmatrix}\sin((\omega_0-\omega_m)t+\theta_s-\phi_m)\\ -\cos((\omega_0-\omega_m)t+\theta_s-\phi_m)\end{bmatrix}. \quad (5)$$

At the resonance frequency ω_0-ω_m, the subsynchronous current which is injected into the generator stator can be approximately expressed as Eq. 6. And according to the relationship between the electromagnetic torque deviation and the stator current deviation shown as Eq.7, the electrical damping coefficient provided by SVC can be approximately calculated as Eq. 8. It can be seen that if $\cos(\varphi_m-\pi/2)>0$, SVC can provide maximal positive damping.

$$\begin{bmatrix}\Delta i_{1\alpha,\mathrm{svc}}\\ \Delta i_{1\beta,\mathrm{svc}}\end{bmatrix}=-\frac{U_s B_{1m}R}{2(R+r_g)}\begin{bmatrix}\cos((\omega_0-\omega_m)t+\theta_s-\phi_m)\\ \sin((\omega_0-\omega_m)t+\theta_s-\phi_m)\end{bmatrix}. \quad (6)$$

$$\Delta T_e=\begin{pmatrix}-\psi_{q0} & \psi_{d0}\end{pmatrix}\left\{\begin{bmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{bmatrix}\begin{bmatrix}\Delta i_\alpha\\ \Delta i_\beta\end{bmatrix}+\begin{bmatrix}-\sin\theta_0 & \cos\theta_0\\ -\cos\theta_0 & -\sin\theta_0\end{bmatrix}\begin{bmatrix}i_{\alpha0}\\ i_{\beta0}\end{bmatrix}\Delta\theta\right\}. \quad (7)$$

$$D_e=\frac{B_{1m}U_s R\psi_0}{2A\omega_m(R+r_g)}\cos(\phi_m-\frac{\pi}{2}). \quad (8)$$

Damping Characteristics of STATCOM on SSO Mitigation. According to Eq. 4, the subsynchronous currents provided by STATCOM under the αβ coordinate system can be expressed as Eq. 9.

$$\begin{bmatrix}\Delta i_{\alpha,\mathrm{statcom}}\\ \Delta i_{\beta,\mathrm{statcom}}\end{bmatrix}=\frac{m_{as}U_{dc}}{(\omega_0-\omega_m)L_s}\begin{bmatrix}\cos((\omega_0-\omega_m)t+\gamma)\\ \sin((\omega_0-\omega_m)t+\gamma)\end{bmatrix}. \quad (9)$$

At the resonance frequency ω_0-ω_m, similar to SVC, the subsynchronous current which is injected into the generator stator can be approximately expressed as Eq. 10 and the electrical damping coefficient provided by STATCOM can be approximately calculated as Eq. 11. It can be seen that if $\cos(\theta_s-\gamma-\pi)>0$, STATCOM can provide maximal positive damping.

$$\begin{bmatrix}\Delta i_{1\alpha,\mathrm{statcom}}\\ \Delta i_{1\beta,\mathrm{statcom}}\end{bmatrix}=-\frac{m_{as}U_{dc}R}{(\omega_0-\omega_m)L_s(R+r_g)}\begin{bmatrix}\cos((\omega_0-\omega_m)t+\gamma)\\ \sin((\omega_0-\omega_m)t+\gamma)\end{bmatrix}. \quad (10)$$

$$D_e=\frac{m_{as}U_{dc}R\psi_0}{(\omega_0-\omega_m)\omega_m A L_s(R+r_g)}\cos(\theta_s-\gamma-\pi). \quad (11)$$

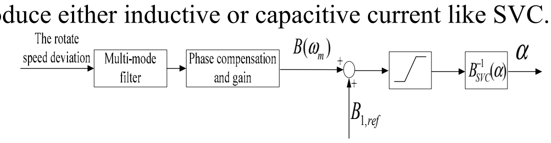
Comparative Analysis. It can be seen from Eq. 8 and Eq. 11 that the electrical dampings provided by SVC and STATCOM are affected primarily by factors as follows. A) As the resistance of the system increases, the subsynchronous current produced by SVC or STATCOM into the generator also increases and the corresponding damping torque will increase. B) The damping provided by SVC is only related to the torsional frequency, while the damping provided by STATCOM is not only related to the torsional frequency but also the resonance frequency of system. It is determined by the characteristics of the controllers. C) According to the Eq. 8, the positive damping provided by SVC is proportional to the size of system voltage. However, from Eq. 11 the positive damping provided by STATCOM is not affected by the size of system voltage, which is mostly proportional to the subsynchronous voltage $m_{as}U_{dc}$ produced itself. It is the essential difference between SVC and STATCOM.

IV. CONTROLLERS DESIGN OF SVC AND STATCOM ON SSO MITIGATION

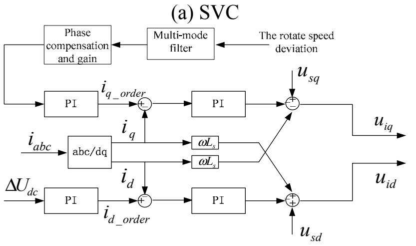
In order to compare SVC and STATCOM for SSO mitigation, both of the devices adopt damping control at the generator terminal and the rotate speed deviation of the generator is used as the inputs of the controllers.

Controller Design of SVC on SSO Mitigation. SVC is composed of TCR with delta connection which can prevent 3th harmonic from flowing into the system, and filters which are tuned to filter 5th and 7th harmonics. In steady state, the firing angle of TCR is chose based on the capacity of filters to keep reactive power of the whole SVC to be zero. The design can reduce the effect of SVC on system in steady state, and once SSO occurs, SVC can produce either inductive or capacitive current, which improve the mitigation effect of SVC [4]. The principle diagram of SVC controller is shown as Fig. 2(a). The multi-mode filter is used to get the modes from the rotate speed deviation. After passing phase compensation and gain, the modes are added to the admittance reference which is finally converted to the firing angle and the subsynchronous current can be produced.

Controller Design of STATCOM on SSO Mitigation. STATCOM adopts a topological structure of three-phase and two-level. The controller of STATCOM uses current decoupling control strategy in dq axis, shown as Fig. 2(b). The rotate speed deviation is used as the input of controller in q axis and the current reference in q axis i_{q_order} is formed after the link of phase compensation, gain and PI regulator. By the feedback control, the output subsynchronous voltage of STATCOM is regulated to make the actual subsynchronous current in q axis equal to i_{q_order}. And dc voltage deviation is used as the input signal of d axis and the current in d axis is controlled to maintain dc voltage. In steady state, STATCOM only needs to absorb a little active power to keep dc voltage constant. Once SSO occurs, it can produce either inductive or capacitive current like SVC.



(a) SVC



(b) STATCOM

Fig. 2 Principle diagram of SVC and STATCOM controllers

Test Signal Method for Phase Compensation. According to section 2, if related phase conditions are satisfied, SVC and STATCOM will provide the maximum electrical dampings [5]. However, Phase lags exist in the links of power system and control system. So phase compensation is needed. The test signal method is used in this paper to get angle of SVC and STATCOM to be compensated. In the controllers of SVC and STATCOM, the mode signal is replaced by a sinusoidal signal. And its frequency can be changed from 1Hz to power frequency, which will be injected into the generator by SVC or STATCOM and lead to the undamped oscillation of the shaft. Then the phase difference between the oscillating component of the electromagnetic torque and the sinusoidal signal is the angle to be compensated. The lead and lag component is used to compensate the phase lags.

V. SIMULATION ANALYSIS

The IEEE first benchmark model is adopted for time domain simulation shown in Fig. 3[6]. The mitigation device is connected to the generator terminal by the transformer. SVC is composed of 100Mvar TCR and -50Mvar filters. According to the section above, its operation capacity is ±50Mvar. STATCOM has a capacity of ±50Mvar.

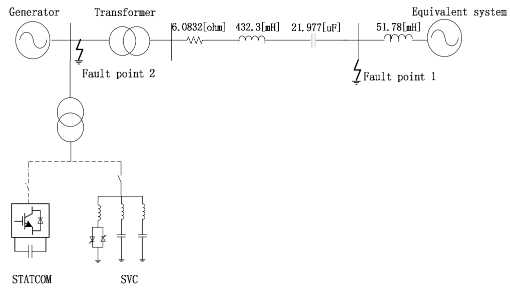
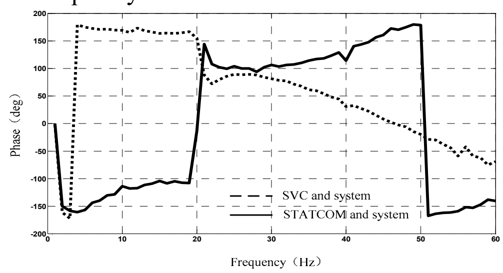
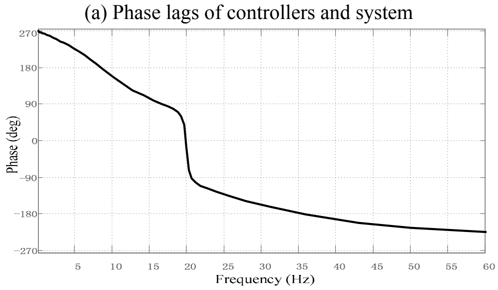


Fig. 3 System connection diagram of the IEEE first benchmark model with the mitigation device

According to the test signal method described above, the phase lags caused by the controller of the mitigation device and itself, and power system are scanned as shown in Fig. 4(a). Combined with the phase lag of the muti-mode filter shown in Fig. 4(b), the phase compensation angles needed respectively by SVC and STATCOM are 138° and -29° at torsional frequency 20Hz.



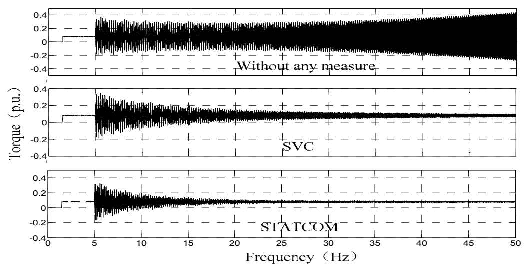
(a) Phase lags of controllers and system



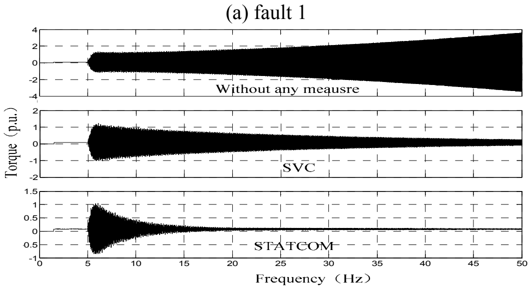
(b) Phase-frequency property of modal filter

Fig.4 Phase lags that need to be corrected

Three-phase-to-ground short circuit faults are set respectively at two fault points shown in Fig. 3. Under the two faults, the torques between low pressure cylinder and generator without any measure and with the two different measures are shown in Fig. 9. It can be seen that without any measure, the oscillation of torque tends to diverge, while the oscillation of torque finally converges with SVC or STATCOM. Compared with the fault 1, STATCOM has distinctly better mitigation effect than it under at fault 2. The closer the fault point is to SVC, the lower the voltage at the access point of SVC is, and the worse the mitigation effect of SVC is. However, the mitigation effect of STATCOM is not affected by the size of system voltage. So, STATCOM has stronger ability of SSO damping than SVC in the case of short circuit fault.



(a) fault 1



(b) fault 2

Fig. 9 The curves of torque between low pressure cylinder and generator in different faults

VI. SUMMARY

According to the IEEE first benchmark model, the electrical damping coefficients respectively provided by SVC and STATCOM connected at the generator terminal and their positive damping conditions are deduced by complex torque coefficient approach. Correlative factors which influence the two positive dampings are compared. The analysis results indicate that the positive damping provided by SVC is proportional to the size of system voltage. The positive damping provided by STATCOM is not affected by the size of system voltage, which is mostly proportional to the subsynchronous voltage produced itself. The controllers of SVC and STATCOM are designed and the positive dampings separately offered by SVC and STATCOM are optimized by phase compensation with test signal method. The time domain simulation reveals that STATCOM has stronger damping ability than SVC in the case of short circuit fault.

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