



Research on SSO Influence with Consideration of Topology Structure Based on CTC Analysis Method

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Abstract. In order to study the phenomenon of sub-synchronous oscillation (SSO) in thermal power plants considering different topologies, based on the IEEE first standard model, this paper uses the PSCAD simulation platform to build models of different topological structures of thermal power plants. The complex torque coefficient (CTC) analysis method is used to obtain the electrical damping (D_e) in each topology. The analysis shows that the topology will affect the sub-synchronous oscillation, if the system topology is more complex, the system's ability to withstand the sub-synchronous oscillation will be stronger, and it is verified by time-domain simulation..

Keywords: Sub-synchronous oscillation · Complex torque coefficient · Topology · Electrical damping

1 Introduction

Sub-synchronous oscillation is an abnormal operating state in the power system. When sub-synchronous oscillation occurs in the system, it will produce continuous or even increased oscillations in the related variables of the mechanical system's shafting and electrical system. In severe cases, it can even cause The shaft system is damaged or even broken, becoming a major threat to the stable operation of the power system [1]. Since 1970 and 1971, sub-synchronous oscillation accidents occurred in the Mohave power plant in the United States, resulting in damage to the shaft system. The issue of sub-synchronous oscillation began to receive widespread attention [2, 3]. Because the sub-synchronous oscillation is very harmful, the analysis and research of the sub-synchronous oscillation phenomenon is of great significance to the stability of the system.

Commonly used sub-synchronous oscillation analysis methods are: frequency scanning method, complex torque coefficient analysis method, eigenvalue analysis method and time domain simulation method [4]. The frequency scanning method can screen out system operating conditions with potential sub-synchronous oscillation threats, but the frequency scanning method results are not accurate and can only be used as a preliminary screening method to identify units that may have SSO problems. The eigenvalue analysis method needs to solve the eigenvalues of the system coefficient matrix. As the

complexity of the system increases, the matrix dimension becomes larger and larger, and it has the problem of dimensional disaster. The complex torque coefficient analysis method can get the full picture of the electrical damping coefficient changing with frequency, and can also take into account the effects of dynamic processes and operating conditions of various control systems on sub-synchronous oscillation [5, 6].

The topology of the power grid will have a direct impact on the stability of the power system. A reasonable grid structure can improve its reliability. Therefore, it is particularly important to analyze and study the influence of network topology on sub-synchronous oscillation of power systems [7].

In this paper, simulation models of different topologies are built on the PSCAD electromagnetic simulation platform. The complex torque coefficient analysis method is used to analyze the electrical damping under different topologies. The influence of the topology on sub-synchronous oscillation is analyzed, and verify with time domain simulation.

2 Complex Torque Coefficient Analysis Method

2.1 Principle of Complex Torque Coefficient Analysis Method

The complex torque coefficient analysis method is to divide the system into two parts, namely the electrical part and the mechanical part. Consider the two subsystems separately and add small disturbances, then we can obtain the electric complex torque coefficient $K_E(j\zeta)$ and the mechanical complex torque coefficient $K_M(j\zeta)$, and write them in plural, when the sum of the real parts is equal to zero, and the sum of the imaginary parts is less than zero, the system will oscillate sub-synchronously.

The specific method of the complex torque coefficient method is: apply a forced small amplitude oscillation with a frequency f to the relative angle of the rotor of a generator set in the system, that is,

$$\Delta\delta = \Delta\delta_m e^{j\zeta t} \quad (1)$$

Where $\zeta = 2\pi f$, $\Delta\delta_m$ is the amplitude of the oscillation. The electrical complex torque increment ΔT_e and the mechanical complex torque increment ΔT_M in the generator electrical system and mechanical system response caused by this small amplitude oscillation $\Delta\delta$ can be obtained through calculation, respectively, and define the equivalent electrical complex torque coefficient $K_E(j\zeta) = \Delta T_e / \Delta\delta$, the equivalent effective mechanical complex torque coefficient $K_M(j\zeta) = \Delta T_M / \Delta\delta$. Usually $K_E(j\zeta)$ and $K_M(j\zeta)$ are plural.

$$K_E(j\zeta) = K_e(\zeta) + j\zeta D_e(\zeta) \quad (2)$$

$$K_M(j\zeta) = K_m(\zeta) + j\zeta D_m(\zeta) \quad (3)$$

Where K_e, D_e are called electrical elastic coefficient and damping coefficient respectively; K_m, D_m are called mechanical elastic coefficient and damping coefficient, respectively, they are functions of frequency ζ , D_e and D_m indicate the damping characteristics of the system at different frequencies. By comparing these coefficients, we can analyze the oscillation characteristics of the system at frequency $f = \zeta/2\pi$. The discriminant formula for unstable sub-synchronous oscillation is as follows:

$$[D_m(\zeta) + D_e(\zeta)]_{K_m(\zeta)+K_e(\zeta)=0} < 0 \quad (4)$$

When the frequency f changes from 0 to 60 Hz, the characteristic curves of the system's coefficients $K_m(\zeta)$, $D_m(\zeta)$, $K_e(\zeta)$, $D_e(\zeta)$ as a function of frequency can be obtained. In fact, it is usually only necessary to scan the coefficients within a narrow frequency range near the natural torsional oscillation frequency of the shaft system to determine whether the system will have unstable sub-synchronous oscillations.

3 Model Establishment

3.1 Establishment of Shafting Model

In this paper, a six-mass block model is adopted. The generator shaft system is a six-mass block model. The high-pressure cylinder HP, the medium-pressure cylinder, the two low-pressure cylinders LPA, LPB, the generator GEN and the exciter EXC are connected in sequence through a massless spring. Figure 1 is the schematic diagram of the model.

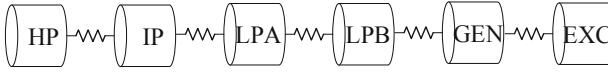


Fig. 1. Shaft structure diagram

The equation of the shafting system is Eq. (4) and Eq. (5)

$$\frac{d\delta_i}{dt} = \omega_i - \omega_0, \quad i = 1, 2, \dots, 6 \quad (5)$$

Where δ_i is the electrical angular displacement of the i -th mass with respect to the synchronous rotation reference cycle, and ω_i is the electrical angular velocity of the i -th mass.

T_{ji} Is the inertia time constant of the i -th mass, T_{mi} is the original torque on the i -th mass, D_{ii} is the self-damping of the i -th mass, and $D_{i,i+1}$ is between the i -th and $i + 1$ -th masses Mutual damping.

$$\begin{cases} T_{J1} \frac{d\omega_1}{dt} = T_{m1} - D_{11}\omega_1 - D_{12}(\omega_1 - \omega_2) - K_{12}(\delta_1 - \delta_2) \\ T_{J2} \frac{d\omega_2}{dt} = T_{m2} - D_{22}\omega_2 - D_{12}(\omega_2 - \omega_1) - D_{23}(\omega_2 - \omega_3) \\ \quad - K_{12}(\delta_2 - \delta_1) - K_{23}(\delta_2 - \delta_3) \\ T_{J3} \frac{d\omega_3}{dt} = T_{m3} - D_{33}\omega_3 - D_{23}(\omega_3 - \omega_2) - D_{34}(\omega_3 - \omega_4) \\ \quad - K_{23}(\delta_3 - \delta_2) - K_{34}(\delta_3 - \delta_4) \\ T_{J4} \frac{d\omega_4}{dt} = T_{m4} - D_{44}\omega_4 - D_{34}(\omega_4 - \omega_3) - D_{45}(\omega_4 - \omega_5) \\ \quad - K_{34}(\delta_4 - \delta_3) - K_{45}(\delta_4 - \delta_5) \\ T_{J5} \frac{d\omega_5}{dt} = T_{m5} - D_{55}\omega_5 - D_{45}(\omega_5 - \omega_4) - D_{56}(\omega_5 - \omega_6) \\ \quad - K_{45}(\delta_5 - \delta_4) - K_{56}(\delta_5 - \delta_6) \\ T_{J6} \frac{d\omega_6}{dt} = -T_{m6} - D_{66}\omega_6 - D_{56}(\omega_6 - \omega_5) - K_{56}(\delta_6 - \delta_5) \end{cases} \quad (6)$$

Linearize Eqs. (5) and (6) at the operating point to obtain Eq. (7).

$$\begin{cases} T_{Ji} P \Delta\omega_i = \Delta T_i - D_{ii} \Delta\omega_i - D_{i-1,i} (\Delta\omega_i - \Delta\omega_{i-1}) - D_{i,i+1} (\Delta\omega_i - \Delta\omega_{i+1}) \\ \quad - K_{i-1,i} (\Delta\delta_i - \Delta\delta_{i-1}) - K_{i,i+1} (\Delta\delta_i - \Delta\delta_{i+1}) \\ P \Delta\delta_i = \omega_b \Delta\omega_i \end{cases} \quad (7)$$

$$i = 1, 2, \dots, 6$$

3.2 Establishment of Disturbance Model

The addition of disturbances should not destroy the linearity of the system, so the amplitude of the disturbances is chosen as 0.01 pu. Due to the complexity of the system, adding only one disturbance per simulation will cause too low efficiency, but it will add disturbances of multiple frequencies at the same time. The superimposed perturbation signal will have spikes, and the amplitude is large enough to destroy the linearization of the system, so a nonlinear lag phase is added to the perturbation of each frequency [9]. In summary, the disturbance model established is as follows:

$$N = \sum_{k=5}^{60} T_k \cos(2\pi k f_0 + (k f_0)^5) \quad (8)$$

Since the sub-synchronous oscillation frequency range is 5–60 Hz, the disturbance frequency f_0 is taken as 5–60 Hz. Set up the disturbance model in PSCAD/EMTDC as shown below (Fig. 2).

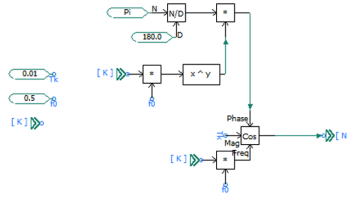


Fig. 2. Disturbance model

4 Simulation Analysis

In the PSCAD/EMTDC simulation platform, this paper combines the IEEE standard model and a 39-node system to build a simulation model to study the influence of the topology on the sub-synchronous oscillation of the system with series compensation. Because mechanical damping D_m is generally a small positive value, electrical damping D_e is the main factor affecting sub-synchronous oscillation. Therefore, electrical damping coefficients are often used to judge the factors that affect the system's sub-synchronous oscillation [10].

4.1 Topology 1: 39 Asynchronous System Connected to the Generator's Far End

The 39-node system is connected to the side of the series compensation capacitor, that is the end away from the steam turbine. Its topology is shown in Fig. 3.

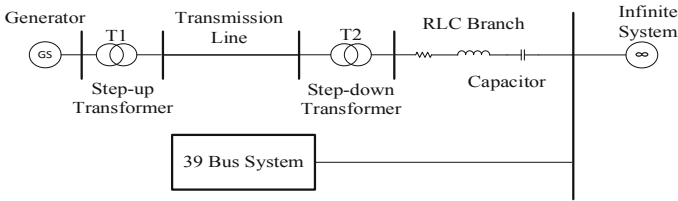


Fig. 3. Schematic of topology 1

The complex torque coefficient analysis method can be used to obtain the D_e value in this topology as shown in Fig. 4. The electrical damping coefficient has a large negative value around 10 Hz, which is about $-8000pu$. This shows that the system has a higher risk of sub-synchronous oscillation.

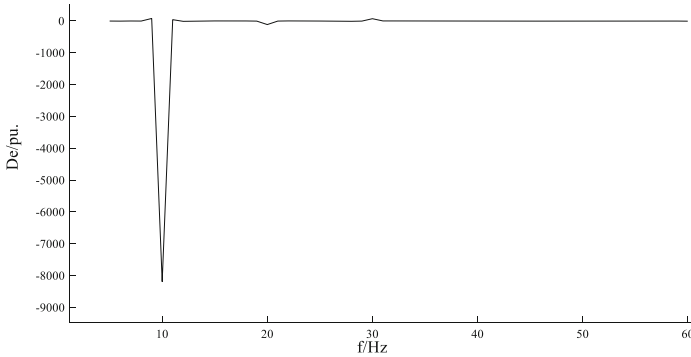


Fig. 4. De for topology 1

4.2 Topology 2: 39 Asynchronous System Connected to the Generator’s Near End

The 39-node system is connected to the primary bus of the step-down transformer. Compared with the topology, a 39-node system is closer to the turbine. Its topology is shown in Fig. 5.

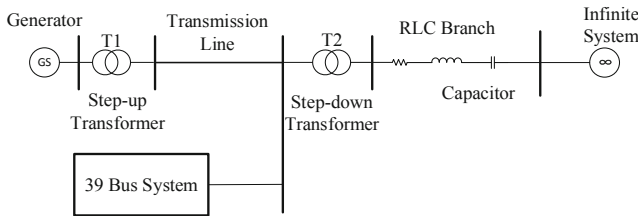


Fig. 5. Schematic of topology 2

The complex torque coefficient analysis method can be used to obtain the De value in this topology as shown in Fig. 6. The electrical damping coefficient has a large negative value of about -70pu around 24 Hz. It shows that the system has the risk of sub-synchronous oscillation.

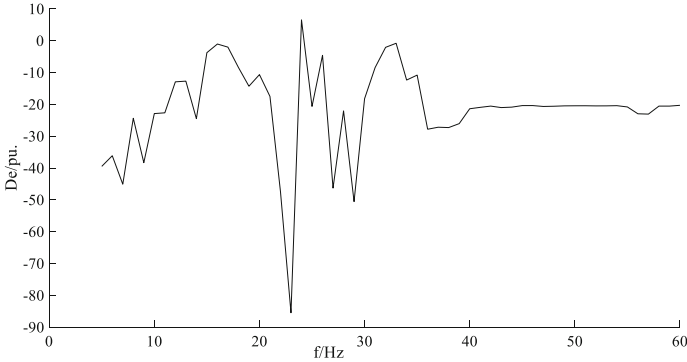


Fig. 6. De for topology 2

4.3 Topology 3: 39-Node System in Parallel with Step-Down Transformer and Inductor at Both Ends

The 39-node system is connected to the IEEE first standard model as shown in Fig. 7. It can be found that the topology of this model is more complicated than the above two models.

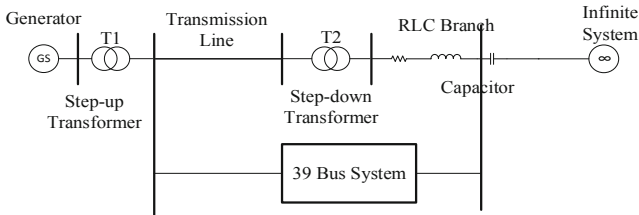


Fig. 7. Schematic of topology 3

Using the complex torque coefficient analysis method, the value of De in this topology can be obtained as shown in Fig. 8. The electrical damping coefficient has a large negative value around 10 Hz, which is about -1500 pu. This indicates that the system is at risk of sub-synchronous oscillation. The frequency at which the De value peaks is similar to that of Topology 1 at about 10 Hz, but its negative value is much smaller than that of Topology 1, and larger than the DE value of Topology 2.

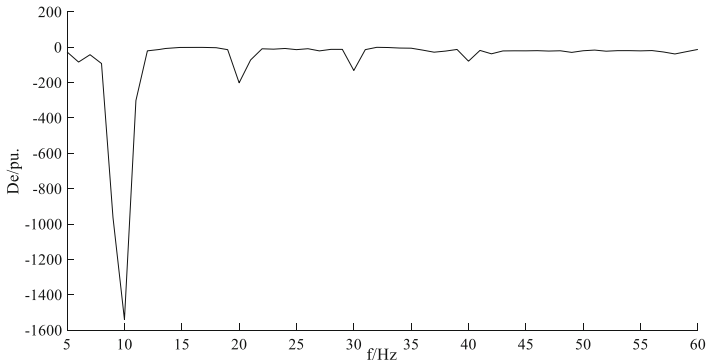


Fig. 8. De for topology 3

4.4 Time Domain Simulation to Verify

In the PSCAD/EMTDC electromagnetic simulation software, the time domain simulation is performed on the models of the above three topologies, and a three-phase short-circuit fault is added in 1.5 s, and the fault lasts for 0.075 s. Figure 9, 10 and 11 shows the torque between the two low-pressure cylinders LPA and PLB in each model.

It can be found that the three topologies have sub-synchronous oscillations, which are consistent with the results obtained by the complex torque coefficient method in the previous chapter. Among them, topology 1 oscillates most intensely, topology 2 has a tendency to converge, and topology 3 has For small amplitude equal amplitude oscillations. It can be seen that the complex torque coefficient method can effectively analyze the risk of sub-synchronous oscillations in the system, but the magnitude of De and the severity of the oscillations are not directly related. The topology structure will affect the sub-synchronous oscillation. The structure of topology 3 is more complicated, but the system is relatively more stable.

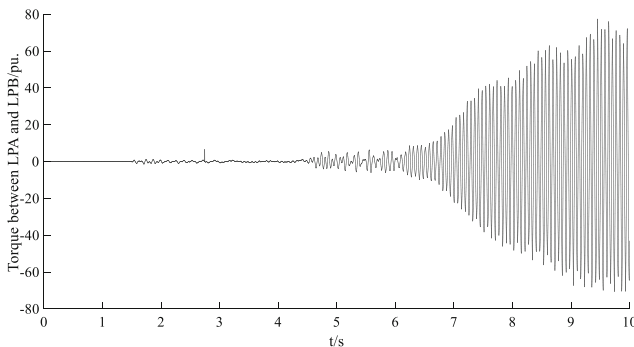


Fig. 9. Torque between LPA and LPB for topology 1

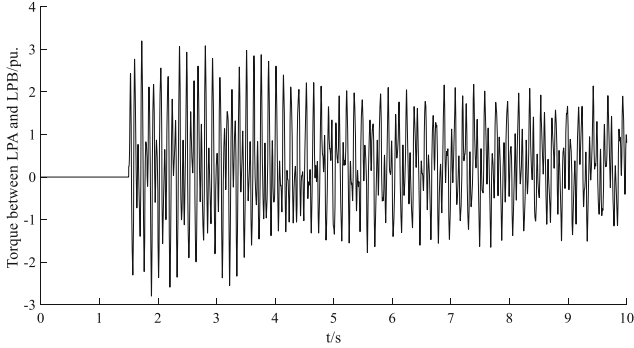


Fig. 10. Torque between LPA and LPB for topology 2

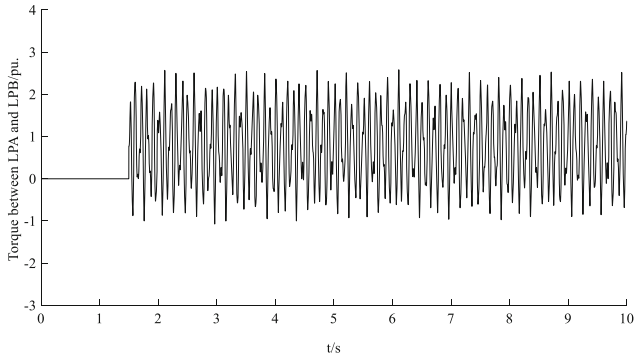


Fig. 11. Torque between LPA and LPB for topology 3

5 Conclusion

Based on the IEEE first standard model, this paper uses the PSCAD/EMTDC simulation platform to build models of different topologies. The complex torque coefficient analysis method is used to obtain the electrical damping of each system, and the risk of sub-synchronous oscillation in each system is evaluated. And verified by time domain simulation, the following conclusions are obtained:

- (1) The complex torque coefficient analysis method can effectively analyze the risk of sub-synchronous oscillation of the system, and can obtain the curve of the electrical damping coefficient change in the full frequency domain.
- (2) The electrical damping obtained by the complex torque coefficient analysis method can explain the possibility of subsynchronous oscillation of the system.
- (3) Different topological structures will affect the risk of sub-synchronous oscillations. The more complex the topology, the stronger the ability to resist sub-synchronous oscillations. The topological structure of the system should be reasonably designed to avoid the occurrence of sub-synchronous oscillations.

Acknowledgment. This work was supported by the National Science Foundation of China under Grant (51677057), Local University Support plan for R & D, Cultivation and Transformation of Scientific and Technological Achievements by Heilongjiang Educational Commission (TSTAU-R2018005) and Key Laboratory of Modern Power System Simulation and Control & Renewable Energy Technology, Ministry of Education (MPSS2019-05)

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