

Postprint of Research on TCSC Application for Subsynchronous Resonance Mitigation in Power Systems

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Date: 2019-03-05T00:00:00+00:00

Abstract

A thyristor-controlled series compensation (TCSC) scheme is proposed to mitigate subsynchronous resonance in the IEEE First Benchmark Model for Subsynchronous Resonance. The PSCAD/EMTDC simulation software is utilized to establish a simulation model of the TCSC and its control system, through which a combined scheme of thyristor-controlled series compensation and fixed series compensation capable of suppressing subsynchronous resonance is derived. An open-loop impedance control strategy is employed to verify via simulation the performance of TCSC in subsynchronous resonance suppression.

Full Text

Research on Suppression of Subsynchronous Resonance in Power Systems Using TCSC

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Abstract

This paper proposes a thyristor-controlled series compensation (TCSC) scheme to suppress subsynchronous resonance (SSR) based on the IEEE First Benchmark Model for SSR. Using PSCAD/EMTDC simulation software, a TCSC and its control simulation model are established. Through simulation studies, a combined scheme of controllable and fixed series compensation capable of suppressing SSR is obtained. The performance of TCSC in suppressing SSR is verified through simulation using an open-loop impedance control strategy.

Keywords: Thyristor controlled series compensation, subsynchronous resonance, series compensation

1 Introduction

Series compensation technology is one of the most economical methods for improving the transmission capacity of long-distance power systems and enhancing transient stability, and has been widely applied in China's power systems. However, when series compensation is employed in transmission systems, with the sending-end line connected to the receiving-end system through series compensation, resonance phenomena in transmission lines may be caused by disturbances under normal operating conditions.

2 Mechanism of Subsynchronous Resonance

2.1 Fundamental Principles of SSR

Subsynchronous resonance is an abnormal operating condition in power systems, referring to a state where energy is exchanged between the power system and the turbine-generator network at one or more frequencies below the system power frequency. SSR manifests in three specific phenomena: induction generator effect, torsional interaction, and transient torque amplification [5].

2.2 Basic Principle of SSR Caused by Series Compensation

Figure 1 [Figure 1: see original paper] shows a series-compensated transmission system where line impedance elements are represented by lumped parameters. When resonance occurs in the transmission line, its resonant frequency is lower than the system power frequency, which is referred to as power system resonance [1]. Under this resonant condition, a subsynchronous rotating magnetic field is generated in the generator. If a certain mechanical torsional vibration frequency of the generator complements the electrical resonant frequency, torsional vibration amplification occurs, damaging the generator shaft system—this is subsynchronous resonance (SSR). In essence, SSR is a transient stability issue in power systems. When SSR occurs, the multi-mass shaft system of a turbine-generator unit experiences torque at one or more frequencies below the rated frequency, exchanging energy with the power network. The power system influences the turbine shaft system through electromagnetic torque, while the shaft system affects the power system through changes in generator rotor angular displacement and velocity.

Previous research [1] investigated the generation mechanism of SSR and the electrical parameter design of TCSC for SSR suppression. Reference [2] analyzed the subsynchronous frequency impedance characteristics of TCSC, demonstrating that TCSC suppresses SSR through its resistive and inductive properties, and that increasing the thyristor conduction angle during SSR can significantly

inhibit its continuation. Reference [3] analyzed the positive damping characteristics of TCSC during SSR suppression.

The natural electrical resonant frequency of the entire system is given by:

$$f_{er} = f_0 \sqrt{\frac{X_C}{X'' + X_T + X_L}}$$

where X'' is the generator subtransient reactance, X_T is the transformer leakage reactance, and X_L and X_C are the line inductive reactance and series compensation capacitive reactance, respectively.

Since the line series compensation degree is generally less than 1, we have $X_C < X_L$, and thus $f_{er} < f_0$, where f_0 is the system power frequency [7].

The condition for SSR occurrence is: when a disturbance occurs in the power grid, a current component at frequency f_{er} is generated between the transmission line and the generator armature. This subsynchronous current component in the armature induces an electrical torque at frequency $f_0 - f_{er}$ on the rotor. If the rotor's mechanical torsional vibration frequency f_m complements the electromagnetic oscillation frequency f_{er} in the armature circuit, such that $f_0 \approx f_{er} + f_m$, mechanical resonance occurs in the rotor. The rotor then induces an oscillation component at frequency f_m , which in turn induces a subsynchronous current at frequency $f_0 - f_m$ in the armature windings, forming an electrical-mechanical resonance. If the resonant energy is greater than or equal to the energy losses in the mechanical and electromagnetic oscillations—that is, if the system exhibits negative damping for this resonance—the oscillations can persist or even diverge, leading to subsynchronous resonance [8].

This paper uses the IEEE First Benchmark Model for SSR [5] as the foundation to build a simulation model of TCSC for SSR suppression and employs open-loop impedance control for simulation and analysis of results. This method's primary advantage is its simplicity, avoiding mutual influence between different controls. Simulation results verify that TCSC can suppress SSR and effectively ensure safe operation of the power system.

3 TCSC Fundamentals and Control Strategy

3.1 Basic Principles of TCSC

The reactance value $X_L(\alpha)$ in TCSC varies continuously with the firing angle α . Therefore, the TCSC reactance X_{TCSC} can be equivalent to a parallel combination of fixed capacitive reactance X_C and variable inductive reactance $X_L(\alpha)$, with a value of:

$$X_{TCSC} = \frac{X_C \cdot X_L(\alpha)}{X_C + X_L(\alpha)}$$

Thus, by changing the thyristor firing angle α , the value of $X_L(\alpha)$ can be varied, thereby changing the equivalent reactance X_{TCSC} of TCSC [10].

According to Equation (2), when $X_C - X_L(\alpha) > 0$, TCSC presents a variable inductive reactance to the external circuit; when $X_C - X_L(\alpha) < 0$, TCSC presents a variable capacitive reactance; and when $X_C - X_L(\alpha) = 0$, the equivalent reactance of TCSC becomes infinite, effectively creating an open circuit for the external circuit, which should be avoided. The TCSC structure is shown in Figure 2 [Figure 2: see original paper].

3.2 Control Strategy for SSR Suppression

This paper employs open-loop impedance control. Based on the requirements for SSR suppression effectiveness, a fixed capacitive reactance value is calculated to utilize the positive damping capability of TCSC for SSR suppression. When SSR is severe, the reactance value can also be adjusted according to conditions to enhance suppression effectiveness. Since the entire process is open-loop, no error correction is performed on the reactance value for SSR suppression. The advantage of open-loop control is its simplicity, which helps avoid mutual influence between different controls; the disadvantage is that suppression effectiveness may be unsatisfactory under certain system conditions.

The specific implementation steps are: using line current as the signal, the thyristor fires after a fixed delay, corresponding to a fixed thyristor firing angle. This firing pulse is calculated based on the fixed TCSC fundamental target impedance value, combined with the normal operating impedance value, normal operating conduction angle, and the firing angle corresponding to the target impedance value.

- (1) **Normal system operation.** The internal simulation of the TCSC model is shown in Figure 3 [Figure 3: see original paper]. As seen in Figure 3, the line voltage V_{TCSC} and active power P_{TCSC} at the TCSC terminal are measured and compared with their respective setpoints. The difference constitutes the system error signal, which after phase compensation is summed with the impedance setpoint X_{set} , then passed through limiting and phase compensation stages to obtain the TCSC impedance reference value X_{ref} . By comparing with Table 1, the thyristor firing angle can be determined. Based on $X_{eff} = X_{TCSC}/X_C$, the value of X_{TCSC} corresponding to X_C can be obtained, which represents the initial setpoint for constant impedance control of the system.
- (2) **Trigger pulse generation.** The thyristor trigger pulses are generated based on the fundamental thyristor firing angle. A PLL (Phase-Locked Loop) is used to generate a signal synchronized with line electrical quantities, which is transmitted to the pulse generator. This pulse corresponds to the firing angle calculated from the impedance value. To ensure system stability after disturbances, local variables are introduced in the open-loop control to transform the normal operating firing angle α into the firing angle corresponding to the target impedance value. The generation of trigger pulses is shown in Figure 4 [Figure 4: see original paper], and the genera-

tion of real-time dynamic firing angles is shown in Figure 5 [Figure 5: see original paper].

Figure 6 [Figure 6: see original paper] shows the real-time dynamic impedance, whose electrical signals represent the actual electrical quantities of the TCSC line. I_a is the actual line current, and E_a is the voltage across the capacitive reactance. The ratio of these two values yields the real-time dynamic impedance value x_{effa} . This is then compared with the reference impedance value x_{ref} , and the resulting difference passes through a proportional-integral control stage and a limiting stage to obtain the real-time line firing angle α . V_{A1} is the voltage across the thyristor of phase A, serving as the synchronization signal for thyristor pulse triggering. Through phase shifting, signals V_{B1} and V_{C1} can be obtained. The three-phase sinusoidal voltage signals are then converted to triangular wave signals via a phase-locked loop (PLL). The H-input of the differential point trigger pulse generator receives the line synchronization signal, while the L-input receives the thyristor trigger pulse. The H and L signals are compared: if H is greater than L, a pulse is issued; otherwise, no pulse is issued.

4 Simulation Model and Results

4.1 Generator Model

In subsynchronous resonance analysis, the turbine-generator shaft system is equivalent to a six-mass model. The essence of SSR is that after a disturbance, relative torsional vibrations occur between the various masses of the shaft system. If the power grid system presents negative damping relative to this torsional vibration, the shaft torsional vibration may persist and even intensify, potentially leading to shaft breakage [11]. When analyzing the inherent mechanical characteristics of turbine shaft torsional vibrations, to achieve higher accuracy, the shaft system is typically equivalent to several or even dozens of segments for the lumped-mass model used in SSR studies. Therefore, in simulation, the turbine-generator shaft system model also needs to be equivalent to a six-mass model. In the IEEE First Benchmark Model in PSCAD, the generator shaft system is divided into six sections. Figure 7 [Figure 7: see original paper] shows the generator shaft system model with six masses, which are the high-pressure cylinder (HP), intermediate-pressure cylinder (MP), low-pressure cylinder A (LPA), low-pressure cylinder B (LPB), generator (GEN), and exciter (EXC) [5,12]. With a six-mass shaft system, there are five torsional vibration modes.

4.2 System Simulation Model

The IEEE First Benchmark Model for subsynchronous resonance is adopted [11-13]. The model for SSR studies is based on an 892.3 MVA generator unit and a 500 kV transmission system, comprising a standard power network and a turbine-generator unit. The system structure and partial parameters under study are shown in Figure 8 [Figure 8: see original paper]. The generator shaft

system uses a six-mass model with five mechanical torsional vibration frequencies of 15.71 Hz, 20.21 Hz, 25.55 Hz, 32.28 Hz, and 47.45 Hz, respectively. An 892.4 MVA generator is connected to an infinite bus system through a step-up transformer and a transmission line with series capacitor compensation. The line series compensation degree is 57%, corresponding to a conventional series compensation of 88 Ω . Generator, shaft system, transformer, and line parameters are provided in Tables 2 through 4 .

4.3 Time-Domain Simulation Results

The torque variations on each segment of the generator shaft system after a large disturbance are compared for two cases: without TCSC and with TCSC. The fault is set to occur 1.5 seconds after the start of operation. In the system simulation model shown in Figure 8, a three-phase short-circuit fault is applied at the series compensation capacitor and cleared after 0.075 seconds. As seen in Figure 9 [Figure 9: see original paper], when TCSC is not installed, the torque values of each shaft segment diverge after the short-circuit fault, indicating system instability.

When TCSC is installed, Figure 10 [Figure 10: see original paper] shows that after fault disturbance, the torque amplitudes on each generator shaft segment are significantly reduced, demonstrating that TCSC effectively damps the torsional vibrations between shaft sections. This verifies that TCSC can suppress the persistence of SSR in power systems by adjusting the thyristor firing angle, thereby maintaining power system stability.

5 Conclusion

This paper presents the generation mechanism of subsynchronous resonance in power systems and provides the principle of TCSC for SSR suppression along with the corresponding controller design methodology. TCSC is incorporated into the IEEE First Benchmark Model for SSR, and its simulation model is established in PSCAD/EMTDC. Time-domain simulation verification of the designed optimal control strategy demonstrates that TCSC effectively suppresses subsynchronous resonance in power systems.

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