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

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Abstract

A TCSC (Thyristor Controlled Series Compensation) scheme for suppressing subsynchronous resonance is proposed for the IEEE First Benchmark Model for Subsynchronous Resonance. Using the PSCAD/EMTDC simulation software, simulation models for TCSC and its control system are established. Through simulation studies, a combined scheme of TCSC and fixed series compensation capable of suppressing subsynchronous resonance is obtained. The performance of TCSC in suppressing subsynchronous resonance is verified through simulation using an open-loop impedance control strategy.

Full Text

Preamble

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Title: 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 studies. Using PSCAD/EMTDC simulation software, a

TCSC and its control system model are established. Through simulation studies, a combined scheme of controllable series compensation and fixed series compensation capable of suppressing SSR is obtained. The performance of TCSC in mitigating SSR is verified 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 increasing the transmission capacity of long-distance power systems and improving transient stability, and has been widely applied in power systems. However, when series compensation is employed in transmission systems, the sending-end line connected to the receiving-end system through series compensation may experience line resonance phenomena caused by disturbances during normal operation. This resonance frequency is below the system' s power frequency and 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 resonance frequency, torsional amplification occurs, damaging the generator shaft system—this is known as subsynchronous resonance. In essence, subsynchronous resonance (SSR) is a transient stability issue in power systems. When SSR occurs, the multi-mass shaft system of a turbogenerator experiences torque at 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 the generator rotor' s angular displacement and angular velocity.

Reference [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 SSR suppression by TCSC results from its resistive and inductive properties, and that increasing the thyristor conduction angle during SSR can effectively suppress its continuation. Reference [3] analyzed the positive damping characteristics of TCSC in suppressing SSR.

This paper builds upon the IEEE First Benchmark Model for subsynchronous resonance [5] to construct a simulation model of TCSC for SSR suppression and employs open-loop impedance control for simulation and analysis of results. The primary advantage of this method is its simplicity, avoiding mutual interference between different control loops. Simulation results verify that TCSC can effectively suppress SSR and ensure safe operation of the power system.

2.1 Mechanism of Subsynchronous Resonance

Subsynchronous resonance is an abnormal operating condition of power systems, representing a state of energy exchange between the power system and turbogenerator at one or more frequencies below the system power frequency. Specific manifestations include three phenomena: induction generator effect, torsional interaction, and transient torque amplification [5].

2.2 Basic Principle of SSR Caused by Series Compensation

[Figure 1: see original paper] shows a series-compensated transmission system with line impedance elements represented by lumped parameters. The system' s natural electrical resonance frequency is:

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

where X'' is the generator' s 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 series compensation degree is generally less than 1, $X_C < X_L$, resulting in $fer < f_0$, where f_0 is the system power frequency [7].

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

3.1 Basic Principle 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 equivalently represented by a fixed capacitive reactance X_C in parallel with a variable inductive reactance $X_L(\alpha)$:

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

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

From this equation, 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. When $X_C - X_L(\alpha) = 0$, the TCSC equivalent reactance becomes infinite, effectively creating an open circuit for the external circuit—this condition must be avoided. The TCSC structure is shown in [Figure 2: see original paper].

3.2 Control Strategy for SSR Suppression

This paper employs open-loop impedance control. Based on SSR suppression requirements, a fixed capacitive reactance value is calculated and utilized to suppress SSR through TCSC' s positive damping capability. When SSR is severe, the reactance value can be adjusted according to the situation to improve suppression effectiveness. Since the entire process is open-loop, no error correction is applied to the reactance value for SSR suppression. The advantage of open-loop control is its simplicity and avoidance of mutual influence between different control loops; the disadvantage is that suppression effectiveness may be 不理想 under certain system conditions.

The specific implementation steps are as follows: using line current as the signal, the thyristor firing angle α is converted to the firing angle corresponding to the target impedance value. The generation of trigger pulses is shown in [Figure 4: see original paper], and the generation of real-time dynamic firing angles is shown in [Figure 5: see original paper].

[Figure 6: see original paper] shows the real-time dynamic impedance, whose electrical signals are the actual electrical quantities of the TCSC line. I_a is the actual line current and E_a is the voltage across the capacitor. The ratio of these two values gives the real-time dynamic impedance x_{effa}. This value is then compared with the reference impedance x_{ref}, and the difference passes through a proportional-integral controller and limiter to obtain the real-time line firing angle.

VA_1 is the voltage across the thyristor in phase A, serving as the synchronization signal for thyristor pulse triggering. Phase-shifted signals VB_1 and VC_1 can be obtained from it. The three-phase sinusoidal voltage signals are then converted to triangular wave signals through 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.

4.1 Generator Model

In subsynchronous resonance studies, the turbogenerator shaft system is equivalent to a six-mass model. The essence of SSR is that relative torsional vibrations occur between the various masses of the shaft system after a disturbance. If the grid system exhibits negative damping for this torsional vibration, the generator shaft torsional vibration may persist or even intensify, potentially leading to shaft breakage [11].

When analyzing the inherent mechanical characteristics of turbine shaft torsional vibrations, the shaft system is typically equivalent to several or even dozens of segments to achieve higher accuracy for the lumped mass model used in SSR studies. Therefore, in simulation studies, the turbogenerator shaft system model must also 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: see original paper] shows the generator shaft system model with six masses: High Pressure (HP), Intermediate Pressure (MP), Low Pressure A (LPA), Low Pressure B (LPB), Generator (GEN), and Exciter (EXC) [5,12]. A six-mass shaft system has five torsional modes.

4.2 System Simulation Model

The IEEE First Benchmark Model for subsynchronous resonance is adopted [11-13]. This model for SSR studies is based on an 892.3 MVA generator unit and 500 kV transmission system, comprising a standard power network and a turbogenerator unit. The system structure and partial parameters are shown in [Figure 8: see original paper]. The generator shaft system uses a six-mass model with five mechanical torsional frequencies at 15.71 Hz, 20.21 Hz, 25.55 Hz, 32.28 Hz, and 47.45 Hz. An 892.4 MVA generator is connected through a step-up transformer to an infinite bus system via 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 through .

TABLE:2 Generator Parameters
- Armature resistance R_a (pu)
- Leakage reactance X_σ (pu)
- d-axis parameters (pu)
- q-axis parameters (pu)

TABLE:3 Shaft System Parameters

- Inertia constant T_j (s)
- Spring constant K (pu)

TABLE:4 Transformer and Transmission Line Parameters
- r_T (pu), x_T (pu)
- r_L (pu), x_L (pu)

4.3 Time-Domain Simulation Results

The torsional torque variations on each segment of the generator shaft system following a major disturbance are compared for two cases: without TCSC and with TCSC. A three-phase short-circuit fault is applied to the series-compensated system at 1.5 seconds and cleared after 0.075 seconds. As shown in [Figure 9: see original paper], without TCSC, the torque values on each shaft segment diverge after the fault, indicating system instability.

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

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5 Conclusion

This paper presents the generation mechanism of subsynchronous resonance in power systems and provides the principles 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. The designed optimal control strategy is verified through time-domain simulations, which demonstrate that TCSC effectively suppresses subsynchronous resonance in power systems.

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