A Novel Control Strategy for Subsynchronous Resonance Mitigation Using SSSC

Massimo Bongiorno, *Student Member, IEEE*, Lennart Ängquist, *Member, IEEE*, and Jan Svensson, *Member, IEEE*

***Abstract*—In this paper, a novel control strategy for subsynchronous resonance (SSR) mitigation using a static synchronous series compensator will be presented. SSR mitigation is obtained by increasing the network damping only at those frequencies that are critical for the turbine-generator shaft. This is achieved by controlling the subsynchronous component of the grid current to zero. Using the IEEE First Benchmark Model, the effectiveness of the proposed control algorithm when mitigating SSR due to torsional interaction and torque amplification effect will be shown.**

***Index Terms*—Damping controller, series compensation, static synchronous series compensator (SSSC), subsynchronous resonance (SSR), torsional oscillation.**

I. INTRODUCTION

INTERCONNECTED transmission systems are complex and require careful planning, design, and operation. The continuous growth of the electrical power system (especially large loads such as industrial plants), resulting in growing electric power demand, has put greater emphasis on system operation and control. In this scenario, series compensation of long lines is extensively applied to enhance power transfer and improve system stability. However, the use of series compensation may lead to sustained oscillations in generator–turbine shaft systems in thermal power stations closely connected to the compensated line. This phenomenon is known under the name "subsynchronous resonance" (SSR) [1]. Two incidents of shaft failure occurred in December 1970 and October 1971. The SSR phenomenon was discovered during the extensive analysis work following these events. After these incidents, great effort was directed from the utilities to avoid the risk of SSR during system operation.

The problem of SSR is related to the interaction between a series-compensated transmission line and the mechanical system into the generator unit. SSR can be divided into two main groups [2]: steady-state SSR [induction generator effect (IGE), and torsional interaction (TI) and transient torques [also known under the name of torque amplification (TA)]. IGE is considered a theoretical condition that unlikely can occur in a series-compensated power system, whereas SSR due to TI and TA are dangerous conditions that must be avoided. Among the possible measures to minimize the risk for SSR, the use of the static synchronous series compensator (SSSC) is proposed in several publications [3]–[5]. The principle of operation of the SSSC is to replace (at least a portion of) the passive series capacitor with an injected voltage in series with the transmission line in order to modify the frequency of the electrical resonance in the network. Although effective, this control strategy presents the drawback that the SSSC must continuously inject reactive power into the system, regardless of the presence of SSR. Moreover, depending on the system parameters, a large amount of reactive power should be injected in the system in order to change the electrical impedance seen from the generator terminals.

This paper introduces a novel control strategy for an SSSC dedicated to SSR mitigation. The controller eliminates the frequency components of the line current corresponding to the natural resonance frequencies of the generator shaft. Reference [6] proposes a similar control strategy. However, in [6], the controller is developed under the nonrealistic assumption of accurate knowledge of the grid system parameters. Moreover, in [6], the SSSC is directly connected to the infinite bus, which allows a straightforward derivation of the control law, but is again not realistic.

In the following, the derivation of the control strategy will mitigate TI , and the TA effect will be presented. Simulation results will prove that with the proposed control system, the power rating of the SSSC can be drastically reduced, leading to a cost-effective solution for SSR mitigation.

II. INVESTIGATED SYSTEM

The system investigated for this paper is the well-known IEEE First Benchmark Model (FBM) [7], depicted in Fig. 1. The system consists of a 892.4-MVA turbine generator connected to an infinite bus through a radial series-compensated line. The rated voltage is 539 kV, while the rated frequency is 60 Hz. As shown in the figure, an SSSC has been connected downstream from the stepup transformer. The voltage at the machine terminals is denoted by $\underline{e}_s$, while the grid voltage at the point of common coupling (PCC) and the grid current are denoted by $\underline{e}_g$ and $\underline{i}$, respectively. The SSSC is modeled as a controlled ideal voltage source. The voltage injected by the SSSC is denoted by $\underline{u}$.

The rotor-shaft model of the system is typical of large turbine generators and it comprises six turbine sections modeled

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M. Bongiorno is with the Department of Energy and Environment, Division of Electric Power Engineering, Chalmers University of Technology, Göteborg 41296, Sweden (e-mail: massimo.bongiorno@chalmers.se).

L. Ängquist and J. Svensson are with ABB Power Technologies, Västerås SE 72178, Sweden (e-mail: lennart.angquist@se.abb.com; jan.r.svensson@se.abb.com).

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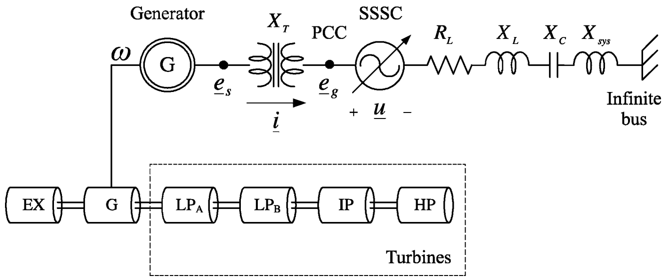

Fig. 1. Single-line diagram of the power plant with a generation unit and SSSC.

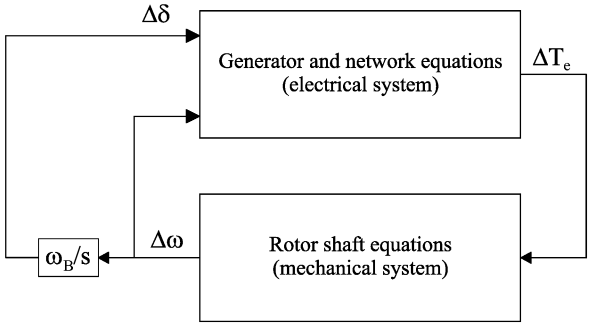

Fig. 2. Block scheme representing the interaction between an electrical and mechanical system.

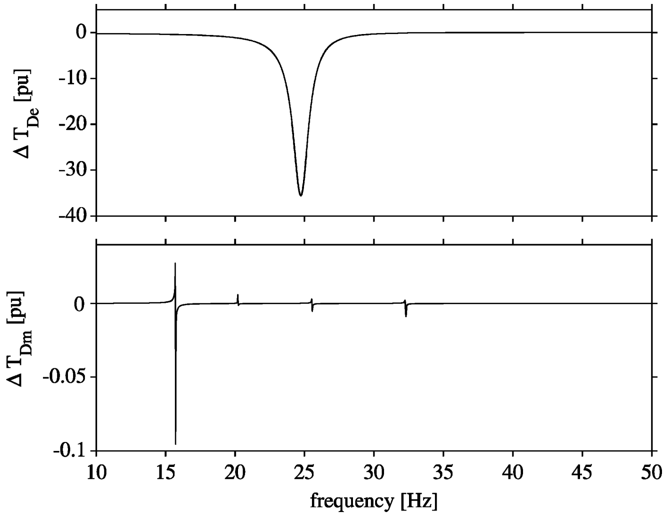

Fig. 3. Comparison between electrical damping torque (ΔT_{De}, upper plot) and mechanical damping torque (ΔT_{Dm}, bottom plot) for IEEE-FBM. $X_{\mathrm{c}} = 0.3$ p.u.

separately: a high-pressure stage (denoted by HP), an intermediate stage (IP), two low-pressure stages ($\mathrm{LP_A}$ and $\mathrm{LP_B}$), the generator, and the exciter (G and EX, respectively). All masses are mechanically connected to each other by elastic shafts. The complete electrical and mechanical data for the IEEE FBM are reported in the Appendix.

The risk for SSR due to the TI effect can be investigated using the feedback loop depicted in Fig. 2 [8], which describes the interaction between the electrical and the mechanical system in a rotating coordinate system which is synchronized with the generator rotor. The real part of the ratio between the electrical torque (ΔT_{e} in the figure) and the rotor speed ($\Delta\omega$) is called electrical damping torque (ΔT_{De})

$$\Delta T_{\mathrm{De}} = \mathrm{Re}\left(\frac{\Delta T_{\mathrm{e}}}{\Delta\omega}\right). \tag{1}$$

A similar definition holds for the mechanical damping torque ΔT_{Dm}. In a series-compensated network, the electrical damping torque can be considered to be equal to zero for all frequencies except at the resonance frequency of the electrical system [9], where ΔT_{De} becomes negative. SSR due to TI can occur in the power system if the electrical resonance of the system (described in the rotating coordinates) coincides with, or is electrically close to, one of the natural resonance frequencies of the generator-turbine shaft system. In fixed coordinates, this means that SSR may occur if the sum of the electrical resonance frequency and one of the natural resonance frequencies of the generator shaft system is close to the generator mechanical rotation frequency (i.e., the network frequency). The instability of a torsional mode of frequency ω_{m} is determined by

$$\Delta T_{\mathrm{D}}(\mathrm{j}\omega_{\mathrm{m}}) = \Delta T_{\mathrm{De}}(\mathrm{j}\omega_{\mathrm{m}}) + \Delta T_{\mathrm{Dm}}(\mathrm{j}\omega_{\mathrm{m}}) < 0. \tag{2}$$

A typical example that describes a situation with risk for SSR due to TI is depicted in Fig. 3, where the electrical and the mechanical damping torques for the IEEE FBM are shown. In this example, the series capacitor of the network is set equal to 0.3 p.u., corresponding to a series-compensation level of 60% of the 0.5-p.u. inductive reactance of the transmission line. Equations for the electrical and for the mechanical model are given in [9].

From Fig. 3, it can be observed that due the selected level of series compensation, the electrical resonance occurs at 24.7 Hz. From the eigenvalue analysis of the mechanical system, the natural frequencies of the generator shaft are 15.71, 20.21, 25.55, 32.28, and 47.46 Hz. Therefore, the electrical resonance is in the neighborhood of one of the natural frequencies of the generator shaft. This might lead to a resonance between the electrical and the mechanical systems. The instability of the system is confirmed by the eigenvalue analysis carried out on the combined electrical-mechanical system in Fig. 2 [2], [9]. Table I shows the eigenvalues of the combined mechanical-electrical system: as shown, due to the critical value of the series capacitor chosen for this example, there is an eigenvalue at 25.45 Hz with a positive real part.

TABLE I
CALCULATED EIGENVALUES FOR IEEE FBM

Real part [s^{-1}]	Imaginary part [Hz]
-4.695	±95.31
-3.553	±24.75
0.0	±47.46
-0.009	±32.29
0.445	±25.45
-0.049	±20.22
-0.021	±15.84
-1.433	±1.59

Next, the control strategy for the SSSC will be explained and the controller algorithm will be derived. The effectiveness of the proposed control system will be investigated both for the TI and TA effect.