Modal Control Design of Damping Controllers for Thyristor-Controlled Series Capacitor to Stabilize Common-Mode Torsional Oscillations of a Series-Capacitor Compensated Power System

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Abstract—This paper proposes a unified approach based on modal control theory to design damping controllers of a thyristor-controlled series capacitor (TCSC) for stabilizing the inherent common-mode torsional interactions occurred in a series-capacitor compensated power system. The studied power system includes two nonidentical turbine-generator sets connected to an infinite bus through a common series-capacitor compensated transmission line. The employed TCSC is properly connected in parallel with a part of the series-capacitor bank of the compensated transmission line. The damping controllers of the TCSC employ the speed deviations of both turbine-generator sets as input signals to stabilize unstable torsional modes of the studied system by increasing the damping of these modes. Both frequency-domain approach based on eigenvalue analysis and time-domain scheme based on nonlinear-model simulations under different disturbance conditions are systematically performed. It can be concluded from the simulated results that the employed TCSC joined with the damping controllers designed by using modal control theory can effectively stabilize the common-mode torsional oscillations of the studied series-capacitor compensated system.

Index Terms—Common-mode torsional oscillations, damping controller, modal control theory, stability, subsynchronous resonance (SSR), thyristor-controlled series capacitor (TCSC).

NOMENCLATURE

General
TG Turbine-generator set.
HP, LP High-pressure and low-pressure turbines.
GEN, EX Generator and exciter.

Subscripts
C, E, SYS per-phase capacitance of TCSC.
R Resistance and reactance of TCSC.
L Resistance and reactance of infinite bus.

Superscripts
D, Q Quantities of D- and Q-axis based on common coordination transformation.

1, 2 Quantities of TG1 and TG2.

I. INTRODUCTION

Since the first two shaft failures due to subsynchronous resonance (SSR) occurred at Mohave Station, USA, in 1970 and 1971, extensive studies on suppression of torsional oscillations and/or SSR occurring in power systems containing series-capacitor compensated lines have been performed for approximately 50 years [1]. The first and second benchmark models for the computer simulations of SSR phenomena were proposed by IEEE SSR Working Group in 1977 [2] and 1985 [3], respectively. Numerous contributions, conference/journal papers, books, etc., for damping SSR of the three different benchmark models have been proposed and published. A thyristor-controlled series capacitor (TCSC) joined with the damping controllers designed by using modal control theory is employed to effectively stabilize the unstable common-mode torsional oscillations of the IEEE second benchmark model, system-2 in this paper.

It is well known that the proposed TCSC can benefit the connected power systems in several ways, such as improvement of...
transient stability and enlargement of power transfer capability [4], [5]. A typical TCSC consists of a series capacitor and a parallel path with a thyristor valve and an inductor. Such TCSC configuration is similar to one of a metal-oxide varistor for conventional over-voltage protection of series-capacitor banks. A complete series-capacitor compensation system may consist of several TCSC sections connected in series. The series-capacitor compensation system may include a fixed series-capacitor bank that becomes a part of the overall compensation.

According to the past studies on damping SSR, the key problem of SSR was due to the fixed series-capacitor banks in series with the transmission lines; however, such SSR problems were able to be mitigated by the utilization of a TCSC [6]–[9]. The N. G. Hingorani (NGH) scheme is also one of the alternative countermeasures for damping SSR [10]–[12]. The configuration of the NGH scheme is very similar to the one of a TCSC but the inductor in series with the thyristor valves in the TCSC is replaced by a resistor or a conductance [13]. Although the performance of damping SSR using both NGH scheme and TCSC were compared, the principals of operations of both methods are fundamentally different [8].

The utilization of the TCSC scheme between Slatt and Buckley in a realistic power system model using a northwestern American power system and an electro-magnetic transients program served as an exploration of SSR mitigation effect provided by TCSC vernier operation [4], [9], [14]. Both TCSC vernier operation and fixed series-capacitor banks were practically employed as compensation schemes. The analytical model of a TCSC for SSR studies [15] and the damping effects of the employment of the TCSC on the IEEE first benchmark model [16] were also performed by previous investigators. The SSR mitigation effect provided by the TCSC vernier operation was shown in [4], [9], and [14] while the TCSC scheme was also used for damping SSR in different systems [15], [16]. This paper proposes the design of damping controller for the TCSC using modal control theory and applies the TCSC to the IEEE second benchmark model, system-2 to demonstrate the effectiveness of suppressing common-mode torsional oscillations. Other countermeasures were also proposed by the authors to damp out torsional oscillations of IEEE benchmark models [17]–[26].

Recent SSR problems have focused on the wind farms based on induction or doubly fed induction generator (DFIG) connected to power systems through series-capacitor compensated transmission lines. Theoretical work and practical observations for the newly emerging SSR caused by the interaction of DFIGs with series compensation were performed in [27]. A more accurate method based on aggregated resistor-inductor-capacitor (RLC) circuit model was proposed in [28] to explain and evaluate a new SSR or subsynchronous control interaction that was recently observed in DFIGs interfaced with series-compensated power networks. The modeling and explanations of the impedance-based SSR and high-frequency resonance phenomena between DFIG systems and weak networks were achieved in [29]. An impedance network model based on the SSR stability analysis method was proposed in [30] to analyze the impedance frequency characteristics, while the new development stability standard was used to quantify the stability of the SSR. Practical SSR with resonant frequency of about 6–8 Hz was observed in the DFIG-based wind farms connected to series-compensated transmission lines in North China [31]. Modal analysis and time-domain simulations were used in [32] to study SSR of a DFIG-based series compensated wind farm, while the results showed that a fixed-series compensated DFIG was highly unstable due to SSR mode.

Regarding the application of TCSC on damping SSR in recent years, the application and control of gate-controlled series capacitor (GCSC) for series compensation and SSR mitigation in fixed-speed wind turbine generator systems were demonstrated in [33] to evaluate and compare the characteristics of SSR time-varying frequency of GCSC and TCSC on the IEEE first benchmark model [2]. A framework for selecting the line compensation device, the optimal configuration of TCSC, and the conventional fixed series capacitor, to reduce the risk of SSR was proposed in [34], while the risk of SSR was able to be successfully managed in the series-compensation line under low TCSC participation. The impedance model-based frequency domain analysis to detect SSR in type-3 wind farms with TCSC was proposed in [35], while the derivation of dynamic phasor-based TCSC impedance model and the application of the impedance model in type-3 wind energy systems for SSR analysis were also achieved.

The novel part of this paper is divided into two parts. The first part is to design the damping controller for the TCSC using modal control theory in order to effectively move unstable common torsional modes that have nearly identical torsional frequencies to the desired stable locations on the complex plane. The second part is to apply the TCSC joined with the designed damping controllers to damp out SSR of the studied IEEE second benchmark model, system-2. The paper is organized as follows. Section II introduces the IEEE second benchmark model, system-2, and the mathematical model of the proposed TCSC. Section III depicts the fundamental procedure to design damping controllers for the TCSC using modal control theory. Sections IV and V describe frequency-domain approach based on eigenvalue analysis and time-domain approach based on nonlinear model simulations to demonstrate the effectiveness of the proposed scheme, respectively. Specific important conclusions of this paper are drawn in Section VI.

II. SYSTEM MODEL

The one-line diagram of the studied IEEE second benchmark model, system-2 [3] is shown in Fig. 1. This system consists of two nonidentical turbine-generator sets (TG1 and TG2) connected to an infinite bus through two individual step-up transformers and a common series-capacitor compensated transmission line. The mechanical equivalent mass-spring-damper models for the TG1 and the TG2 have four masses and three masses, respectively. These masses are mechanically coupled on the individual shafts. The TG1 comprises high-pressure turbine 1 (HP1), low-pressure turbine 1 (LP1), generator 1 (GEN1), and exciter 1 (EX1). The TG2 comprises high-pressure turbine 2 (HP2), low-pressure turbine 2 (LP2), and generator 2 (GEN2). The electrical network includes the stator windings of GEN1 and GEN2, the primary windings and the secondary windings of the two step-up transformers with the equivalent
inductive reactance of $X_{T1}$ and $X_{T2}$, the series-compensated transmission line, and an infinite bus. The total series capacitive reactance ($X_C$) of the transmission line is divided into two parts, i.e., the adjustable series capacitor’s capacitive reactance ($X_{CE1}$) and the TCSC’s capacitive reactance ($X_{CE2} = \omega C_2$), where $X_{CE1} = 55\%$ of $X_C$ and $X_{CE2} = 45\%$ of $X_C$.

From the mechanical structure of the equivalent mass-spring-damper models of both TG1 and TG2 shown in Fig. 1, it is well known that TG1 contains three torsional modes (modes 1–3) and an electromechanical mode (mode 0), while TG2 has two torsional modes (modes 1 and 2) and an electromechanical mode (mode 0). For detailed simulations, the IEEE type 1 exciter model and the IEEE type 1S exciter model are proposed, respectively [36]. Since Fig. 1 has two synchronous generators, the common $D$-axis components of the current flowing across $X_{CE2}$, respectively; $I_{LF_D}$ and $I_{LF_Q}$ are the common $D$- and $Q$-axis components of the current flowing through $L_D$, respectively, and $I_{LF_D}$ and $I_{LF_Q}$ are the common $D$- and $Q$-axis components of the current flowing through the transmission line, respectively. In this paper, the base values of the studied system are properly selected as 600 MVA, 22/500 kV. The nominal operating condition of the studied system is as follows: GEN1 has the output active power of $P_{G1} = 0.9$ p.u. and the output power factor of PF1 = 0.9488 lagging, GEN2 has the output active power of $P_{G2} = 0.9$ p.u. and the output power factor of PF2 = 0.9718 lagging, the infinite bus voltage magnitude is $V_\infty = 1.0$ p.u., the series compensation ratio is $X_C/X_L = 50\%$, the steady-state value of $\alpha$ is $60^\circ$, and $L_0$ is selected as 0.001 p.u.

The eigenvalues of the SSR modes of both TG1 and TG2, and other modes of the studied system operated under the nominal operating condition without the proposed TCSC in service are listed in the second column of Table I. It can be clearly observed from Table I that the torsional mode 1 of TG1 and the torsional mode 1 of TG2 have nearly the same torsional frequencies at about 156 rad/s and these two modes are called the common torsional modes.

On the other hand, both torsional mode 2 of TG1 and torsional mode 1 of TG2 have positive real parts that exhibit unstable characteristics. These two modes must be effectively stabilized or suppressed, or the studied system will become unstable even if the studied system is subject to a very small disturbance. Severe damage on the mechanical shafts of TG1 and/or TG2...
could happen when the studied system is without proper control or strategy to suppress the unstable characteristics.

Fig. 3 shows the real parts of the SSR modes as a function of \( \frac{X_C}{X_L} \) of the studied system with the proposed TCSC but without damping controller. It is found from Fig. 3 that the torsional mode 1 of TG1 has much larger unstable range of \( \frac{X_C}{X_L} \) than the torsional mode 2 of TG1. It can be clearly observed from Table I and Fig. 3 that a designed damping controller must be included in the TCSC to effectively damp out unstable SSR modes.

III. DESIGN OF DAMPING CONTROLLERS FOR THE PROPOSED TCSC USING MODAL CONTROL THEORY

This section presents a unified approach based on modal control theory [17]–[26] to design damping controllers for the TCSC to achieve damping enhancement of the unstable SSR modes of the studied system. Fig. 4 shows the control block diagram of the firing angle control of the TCSC with the designed damping controllers. The shaft speed deviations of GEN1 and GEN2, i.e., \( \Delta \omega_1 \) and \( \Delta \omega_2 \), are fed to the input terminals of the top and the down TCSC damping controllers, respectively, where \( \Delta \omega_1 = \omega_1 - \omega_{REF1} \) and \( \Delta \omega_2 = \omega_2 - \omega_{REF2} \). The firing angle of the TCSC, \( \alpha \), is properly modulated by the outputs of the two damping controllers in order to produce effective damping characteristics to stabilize unstable torsional modes listed in Table I.

The first step to design the TCSC damping controllers using modal control theory is to linearize the nonlinear system equations derived in the previous section around a nominal operation point. A set of linearized system state equations can be written in matrix form as follows:

\[
p\dot{X}(t) = AX(t) + BU(t) \tag{3}
\]

\[
Y(t) = CX(t) \tag{4}
\]

where \( X(t) \) is the state vector containing several selected state variables, \( U(t) \) is the input vector, \( Y(t) \) the output vector, and \( A, B, \) and \( C \) are the constant matrices of appropriate dimensions.

The output vector in (4) can be referred to Fig. 4 and it can be expressed by

\[
Y(t) = [\Delta \omega_1, \Delta \omega_2]^T. \tag{5}
\]

Taking the Laplace transformation of (3) and (4), the system state equations in \( s \) domain can be described by

\[
sX(s) = AX(s) + BU(s) \tag{6}
\]

\[
Y(s) = CX(s). \tag{7}
\]

The signal \( \Delta \alpha \) shown in Fig. 4 can be written by

\[
\Delta \alpha(s) = \frac{K_R}{1 + sT_R} [\Delta \omega_1(s) + \Delta \omega_2(s)] = H(s)Y(s) \tag{8}
\]

where \( H(s) = [H_1(s), H_2(s)], Y(s) = [\Delta \omega_1(s), \Delta \omega_2(s)]^T, \) and

\[
H_1(s) = \left( \frac{sT_W}{1 + sT_W} \right) \frac{K_1(1 + sT_2)}{(1 + sT_1)}. \tag{9}
\]

\[
H_2(s) = \left( \frac{sT_W}{1 + sT_W} \right) \frac{K_2(1 + sT_4)}{(1 + sT_3)}. \tag{10}
\]

The first terms with identical parameter of \( T_W \) on the right-hand side of (9) and (10) are called washout terms to eliminate the steady-state offset of the input signals. The second terms on the right-hand side of (9) and (10) represent the lead–lag compensators with constant gains, \( K_1 \) and \( K_2 \), and time constants, \( T_1, T_2, T_3, \) and \( T_4 \). The washout-term time constants for both \( H_1(s) \) and \( H_2(s) \) are the same and they can be prespecified. The most vulnerable modes of the studied system are the common modes, i.e., mode 1 of TG1 and TG2, which must be shifted.
to the desired stable locations on the complex plane by simultaneously determining the parameters of the TCSC’s damping controllers.

On the other hand, both mode 0 of TG1 and TG2 can be severely affected by various loading conditions and different values of $X_C/X_L$. These two modes must also be effectively controlled. Although mode 2 of TG1 exhibits negative damping under small ranges of $X_C/X_L$, its effect on system damping is much smaller than the one on mode 1 and mode 0 of both TG1 and TG2. Hence, both mode 1 and mode 0 of TG1 and TG2 should be effectively controlled to stabilize the studied system.

To design the damping controllers of the TCSC, the closed-loop system characteristic equation is obtained by substituting (7) into (8) and combining with (6). The resultant characteristic equation of the closed-loop system is expressed by

$$\det \left[ \lambda I - A - B \frac{K_R}{1 + sT_R} H(s)C \right] = 0 \quad (11)$$

where $I$ is an identify matrix, $\lambda$ is one of the eigenvalues of the closed-loop system, and $\det(\cdot)$ is the determinant operation of $\cdot$. When the prespecified eigenvalues corresponding to mode 0 and mode 1 of both TG1 and TG2 are substituted into (11), four complex-number algebraic equations with eight parameters of the damping controllers can be obtained. By separating the real parts and the imaginary parts of the four complex-number algebraic equations, the unknowns of the damping controllers of the TCSC can be solved by the resultant equations with real number. The calculated results for the parameters of the designed damping controllers of the TCSC are given by:

- $K_1 = 3.5$, $T_1 = 0.3$ s, $T_2 = 0.96$ s, $K_2 = 5.0$, $T_3 = 0.225$ s, $T_4 = 0.88$ s, $K_R = 50$, $T_{R1} = 0.8$ s, and $T_{W} = 0.02$ s.

The eigenvalues of the closed-loop system containing the designed damping controllers of the TCSC are listed in the third column of Table I. It is found from Table I that all SSR modes have been located on the left half of the complex plane. The constraints for designing the damping controllers of the TCSC are described as follows. The gains $K_1$ and $K_2$ should be as small as possible, while the time constants of the lead–lag compensators and washout terms must be positive.

1) The eigenvalues of the closed-loop system including the designed damping controllers of the TCSC must be completely positioned on the left-hand side of the complex plane.

It can be observed from the eigenvalue results listed in the third column of Table I and the parameters of the damping controllers of the TCSC shown above that both constraints mentioned above are simultaneously met. Fig. 5 shows the real parts of SSR modes as a function of $X_C/X_L$ of the studied system with the designed damping controllers of the TCSC. (a) SSR modes of TG1. (b) SSR modes of TG2.

**IV. EIGENVALUE ANALYSIS**

To examine the effectiveness of the designed damping controllers of the TCSC on damping SSR modes of the studied system, a frequency-domain approach based on a linearized closed-loop system model using eigenvalue analysis is performed. The analyzed results are depicted as follows.

**A. Effects of Different Operating Conditions**

Tables II and III list the SSR modes of both TG1 and TG2 of the studied system with the TCSC and the designed damping controllers under various values of terminal voltage ($V_t$) and output active power ($P_G$) of both GEN1 and GEN2, respectively. The terminal voltages of both generators are varied from 1.0 to 1.15 p.u., while the output active powers of both generators are changed from 0.8 to 0.95 p.u. The operating points of the studied system are solved by using a set of conventional Newton–Raphson power-flow equations.

From the SSR modes of TG1 and TG2 listed in Tables II and III, it is clearly found that all SSR modes of both TG1
TABLE II
SSR MODES OF BOTH TG1 AND TG2 OF THE STUDIED CLOSED-LOOP SYSTEM WITH THE PROPOSED TCSC AND THE DESIGNED DAMPING CONTROLLERS UNDER VARIOUS VALUES OF $V_{t1}$ (P.U.) AND $V_{t2}$ (P.U.)

<table>
<thead>
<tr>
<th>$P_{G1}$</th>
<th>1.00</th>
<th>1.05</th>
<th>1.10</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG1 Mode 0</td>
<td>-2.75 ± j1.15</td>
<td>-2.03 ± j1.21</td>
<td>-2.28 ± j1.27</td>
<td>-2.50 ± j1.33</td>
</tr>
<tr>
<td>Mode 1</td>
<td>-0.39 ± j1.56</td>
<td>-0.39 ± j1.57</td>
<td>-0.39 ± j1.57</td>
<td>-0.39 ± j1.57</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-0.09 ± j2.04</td>
<td>-0.09 ± j2.04</td>
<td>-0.09 ± j2.04</td>
<td>-0.08 ± j2.04</td>
</tr>
<tr>
<td>Mode 3</td>
<td>-0.01 ± j3.21</td>
<td>-0.01 ± j3.21</td>
<td>-0.01 ± j3.21</td>
<td>-0.01 ± j3.21</td>
</tr>
<tr>
<td>TG2 Mode 0</td>
<td>-0.64 ± j6.72</td>
<td>-0.76 ± j6.92</td>
<td>-0.87 ± j7.12</td>
<td>-0.97 ± j7.33</td>
</tr>
<tr>
<td>Mode 1</td>
<td>-0.21 ± j156</td>
<td>-0.21 ± j156</td>
<td>-0.21 ± j156</td>
<td>-0.21 ± j156</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-0.01 ± j283</td>
<td>-0.01 ± j283</td>
<td>-0.01 ± j283</td>
<td>-0.01 ± j283</td>
</tr>
</tbody>
</table>

TABLE III
SSR MODES OF BOTH TG1 AND TG2 OF THE STUDIED SYSTEM WITH THE PROPOSED TCSC AND THE DESIGNED DAMPING CONTROLLERS UNDER DIFFERENT VALUES OF $P_{G1}$ (P.U.) AND $P_{G2}$ (P.U.)

<table>
<thead>
<tr>
<th>$P_{G1}$</th>
<th>0.80</th>
<th>0.85</th>
<th>0.90</th>
<th>0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG1 Mode 0</td>
<td>-2.57 ± j12.6</td>
<td>-2.43 ± j12.7</td>
<td>-2.29 ± j12.7</td>
<td>-2.15 ± j12.9</td>
</tr>
<tr>
<td>Mode 1</td>
<td>-0.36 ± j157</td>
<td>-0.38 ± j157</td>
<td>-0.40 ± j157</td>
<td>-0.42 ± j157</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-0.07 ± j204</td>
<td>-0.07 ± j204</td>
<td>-0.08 ± j204</td>
<td>-0.08 ± j204</td>
</tr>
<tr>
<td>Mode 3</td>
<td>-0.01 ± j321</td>
<td>-0.01 ± j321</td>
<td>-0.01 ± j321</td>
<td>-0.01 ± j321</td>
</tr>
<tr>
<td>TG2 Mode 0</td>
<td>-0.97 ± j7.11</td>
<td>-0.95 ± j7.11</td>
<td>-0.94 ± j7.10</td>
<td>-0.92 ± j7.09</td>
</tr>
<tr>
<td>Mode 1</td>
<td>-0.21 ± j156</td>
<td>-0.21 ± j156</td>
<td>-0.22 ± j156</td>
<td>-0.22 ± j156</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-0.01 ± j283</td>
<td>-0.01 ± j283</td>
<td>-0.01 ± j283</td>
<td>-0.01 ± j283</td>
</tr>
</tbody>
</table>

and TG2 of the closed-loop system with the TCSC joined with the designed damping controllers are insensitive to the large changes on different terminal voltage and output active power of both GEN1 and GEN2. The closed-loop system under the wide operating conditions can guarantee stable operation provided that the TCSC joined with the designed damping controllers is in service.

B. Analysis of Stable Regions

Fig. 6(a) and (b) draws the stable regions of the studied system without TCSC and with the TCSC joined with the designed damping controllers, respectively. The stable regions are obtained by calculating all system eigenvalues that are completely located on the left half of the complex plane under different combinations of $R_E$ and $X_C$. where $R_E$ and $X_C$ are the equivalent resistance and the equivalent capacitive reactance as seen between the bus at the high-voltage side of the two step-up transformers and the infinite bus, respectively. It is clearly observed that the TCSC joined with the designed damping controllers can provide more stable regions than the open-loop system without TCSC. In other words, the TCSC joined with the designed damping controllers can extend the effective stable operation conditions or regions for the studied system.

V. NONLINEAR MODEL SIMULATIONS

To further explore the effectiveness of the TCSC joined with the designed damping controllers on stabilizing SSR modes of the studied system, time-domain simulations based on a nonlinear-system model of the studied system under disturbance conditions are performed in this section. For simulating system nonlinearities in detail, the exciter output ceilings, the speed voltage of both GEN1 and GEN2, the upper and lower limits of the firing angle of the TCSC, the control signal’s output limiters, etc., of the studied system are all included. The simultaneous nonlinear first-order differential equations of the studied system are solved by using the fourth-order Runge–Kutta algorithm on a personal computer.

Figs. 7 and 8 show the dynamic responses of the open-loop system and the closed-loop system with the TCSC and the designed damping controllers subject to a torque disturbance of...
10% (0.1 p.u.), starting at \( t = 0.5 \) s and lasting for six cycles of 60 Hz base, on the shaft of GEN1, respectively. It can be found from the dynamic responses shown in Fig. 7 that the open-loop system without TCSC is unstable, which is as expected since two pairs of SSR modes listed in Table I were located on the right half of the complex plane. On the other hand, the dynamic responses shown in Fig. 8 exhibit well-damped oscillations and the unstable common-mode torsional oscillations in Fig. 7 have been effectively stabilized when the TCSC joined with the designed damping controllers is in service.
Fig. 9. Transient responses of the open-loop system subject to a three-phase short-circuit fault at the infinite bus. (a) Torsional torque of LP1-GEN1. (b) Torsional torque of LP2-GEN2. (c) Speed deviation of GEN1. (d) Speed deviation of GEN2.

Fig. 10. Transient responses of the closed-loop system subject to a three-phase short-circuit fault at the infinite bus. (a) Torsional torque of LP1-GEN1. (b) Torsional torque of LP2-GEN2. (c) Speed deviation of GEN1. (d) Speed deviation of GEN2.

Figs. 9 and 10 illustrate the transient responses of the open-loop system and the closed-loop system with the TCSC joined with the designed damping controllers subject to a three-phase short-circuit fault, starting at $t = 0.5$ s and lasting for six cycles of 60 Hz base, at the infinite bus, respectively. It can be observed from the transient responses shown in Fig. 9 that the open-loop system without TCSC is unstable since Table I has two pairs of SSR modes located on the right half of the complex plane. On the other hand, the transient responses shown in Fig. 10 demonstrate good damping characteristics and the unstable common-mode
torsional oscillations in Fig. 9 have been effectively stabilized when the closed-loop system is with the TCSC joined with the designed damping controllers.

It can be concluded from the dynamic and transient simulation results in this section that the unstable common-mode torsional oscillations of the studied system can be effectively stabilized or suppressed by the TCSC joined with the designed TCSC damping controllers under the selected torque disturbance on the shaft of GEN1 and the selected three-phase short-circuit fault applied to the infinite bus.

VI. CONCLUSION

A unified approach based on modal control theory to design damping controllers of the TCSC to effectively stabilize common-mode torsional oscillations occurring in the IEEE second benchmark model, system-2 has been presented. Both frequency-domain approach and time-domain method have been systematically employed to examine the effectiveness of the TCSC joined with the designed damping controllers on suppression of unstable common-mode torsional oscillations in the studied system. Some specific important conclusions are drawn as follows.

1) The employment of modal control theory for the design of damping controllers of the TCSC can effectively locate the specified SSR modes on the desired positions on the complex plane. The parameters of the damping controllers can also be simultaneously determined.

2) According to the eigenvalue analysis, SSR-mode eigenvalues are insensitive to the wide changes of the operating conditions of the two synchronous generators of the studied system. The closed-loop system exhibits more stable operating regions than the open-loop system provided that the designed damping controllers are included in the control loop of the TCSC.

3) Dynamic simulations and transient responses of the closed-loop system subject to a torque disturbance on one synchronous generator’s shaft and a three-phase fault applied to the infinite bus, respectively, have clearly shown that the effectiveness of the TCSC joined with the designed damping controllers on suppression of unstable common-mode torsional oscillations in the studied system.

REFERENCES


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