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An EMTP Study of SSR Mitigation Using the Thyristor Controlled Series Capacitor

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Abstract This paper presents an EMTP (Electro-Magnetic Transient Program) simulation study of the SSR mitigation effect of Thyristor Controlled Series Compensation (TCSC) operated in the vernier mode, based on a simplified model of the North-Western American Power System (NWAPS). The study shows that TCSC vernier operation provides significant mitigation of SSR in some cases. An analysis of the equivalent TCSC impedance with respect to different frequencies is used to supplement these studies.

1. Introduction

It is known that series capacitor compensation benefits power systems in more than one way, such as enhancing transient stability limits, increasing power transfer capability, etc.[1]. It is also known that fixed series compensation may cause Subsynchronous Resonance (SSR) in power systems, which can lead to severe problems, such as damage to the machine shaft[1]. However, it has been noted that the newly developed Thyristor Controlled Series Compensation (TCSC) operated in vernier mode benefits the mitigation of SSR[2,3]. This is among several TCSC benefits to power systems, which include enhancing transient stability limits to higher values than using fixed series compensation, making load flows more flexible, and controlling loop flows[2, 3]. A detailed simulation study of the SSR mitigation effect of TCSC vernier operation, compared with fixed series compensation case is necessary for each application. Also, it is desirable to base the simulation on realistic power system models and to use standard power system simulation programs, such as EMTP. Moreover, analytic techniques to integrate and explain the underlying characteristics are needed. Assuming slow dynamics of SSR, one approximate method of analyzing the mitigation effect is to view TCSC as an electrical element in the power system and study the frequency domain characteristics of the equivalent TCSC impedance for a typical level of excitation. In this paper, we present our studies as mentioned. The studies focus on the SSR mitigation effect of TCSC vernier operation compared with fixed series compensation. This phenomenon has been observed repeatedly in our simulation studies, and is supported by previous studies[2]. The study of the modal damping provided by TCSC vernier operation is currently underway. A field test of the TCSC device installed[3] is currently being planned by Bonneville Power Administration (BPA) with a view to assessing TCSC performance.

2. Model Considerations

The simulation studies discussed are based on a model representing the 500kV-level network of the North-Western American Power System (NWAPS) and using the standard EMTP.

A diagram of the power system model used is shown in Fig.1 . The TCSC is installed between SLATT and BUCKLEY. It has been noted that when the generator at BOARDMAN, shown in Fig.1, is radialized to BUCKLEY and beyond, the generator is most vulnerable to the excitation of SSR at one or more of its shaft modes through the effect of the SLATT series compensation and the fixed series compensation beyond GRIZZLY in the NWAPS. Thus, in the model used, the BOARDMAN generator is modelled in detail by a system of differential equations while the remaining 21 generators are modelled by voltage sources. The BOARDMAN generator is radialized to BUCKLEY and beyond by operating the breakers at SLATT and GRIZZLY. Both transient and subtransient electrical sub-system dynamics of the BOARDMAN generator are represented. Five masses, namely, mass #1 through mass #5, are mounted on the shaft of the generator. The mass #1 through mass #5 represents high-pressure turbine, low-pressure-1 turbine, lower-pressure-2 turbine, generator, and exciter, respectively. The mechanical damping values used represent nominal values. The BOARDMAN generator field tests are needed to establish actual damping constants. In addition to a 2.2 Hz local *swing mode*, the BOARDMAN generator has the following 4 shaft modes:

mode 1 - 12.5 Hz; *mode 2* - 25.0 Hz;
mode 3 - 29.0 Hz; *mode 4* - 50.0 Hz

The transmission lines are described by distributed parameters, while the fixed series compensation installations in the system are modelled accordingly. The load flow of the system is regulated such that it represents the heavy load condition of the NWAPS. The real and imaginary power output of the BOARDMAN generator is 540MW and -62MVar, respectively.

A simplified TCSC model used in this simulation study is simulated using the "MODELS" feature of EMTP. An earlier version of the model is described in[4, 5]. As shown in Fig.2, the TCSC model used in this study is represented by an 8 ohms internal capacitor equivalently (The SLATT TCSC consists of six segments of 1.33 ohms each), in parallel with a path including thyristor switches and commutation inductor. The TCSC also has a bypass breaker, as shown in Fig.2. The TCSC can be operated at three basic modes. In the

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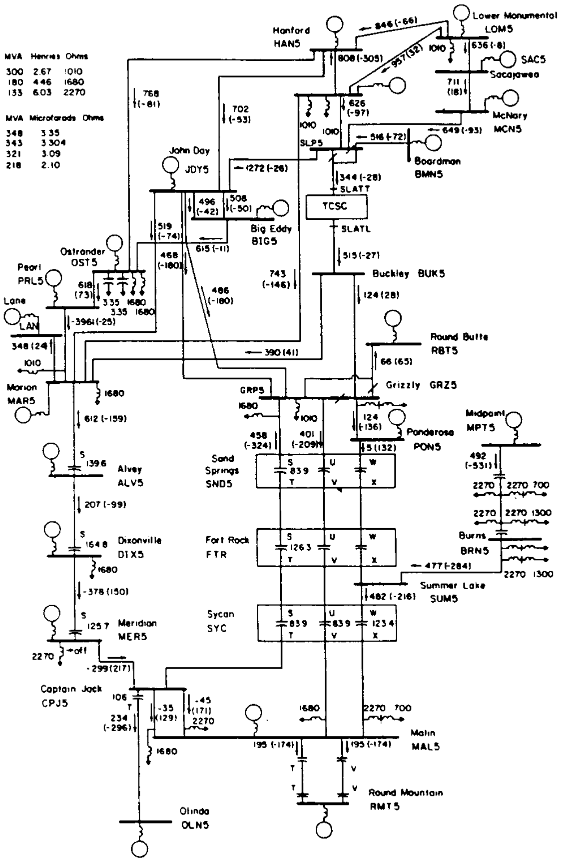

Fig.1 NWAPS model used in the SSR simulation study

bypassed mode, the thyristor path is conducting continuously. In the blocked mode, the thyristor path is blocked continuously, which is equivalent to the fixed series compensation at the capacitor reactance, i.e., 8 ohms in this study. Finally, in the vernier mode, the thyristor path is partially conducting to achieve a specified ohms order. When the TCSC is operated in the vernier mode, thyristor firing results in a loop current flowing through the inductor in the opposite direction of the internal capacitor current[6, 7], as shown in Fig.2. This loop current results in an increase of the equivalent TCSC impedance over the internal capacitor reactance with respect to synchronous frequency. The term "ohms order", or "Xorder" is used to describe the series compensation capability of the TCSC[6, 8]. In this paper it is defined as the ratio of the 60 Hz equivalent TCSC impedance to the internal capacitor reactance, i.e., 8 ohms in this study, under steady-state operating conditions. The larger the Xorder, the higher the series compensation level with respect to synchronous frequency in the steady state. Ohms order is limited by a number of practical considerations[6]. In this study, the values of Xorder is limited between 1.0 p.u. and 3.0 p.u., with a base value equal to the internal capacitor reactance, i.e., 8 ohms.

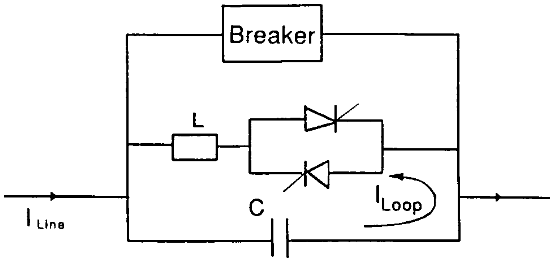

Fig.2 TCSC model

3. Simulation Results

In this section, the results of the simulation cases for two different disturbances with different Xorders of the TCSC vernier operation are presented. Comparison is made of the post-disturbance responses with the TCSC in vernier mode to the response with the fixed series compensation.

Case I

A disturbance is applied by switching in the series compensation initially. The operation scenario is as follows:

In the case of the TCSC,

At t = 0-,	TCSC is bypassed;
At t = 0+,	TCSC is switched into vernier mode,

and in the case of the fixed series compensation,

At t = 0-,	TCSC is bypassed;
At t = 0+,	TCSC is blocked.

Figs.3 through 6 show the speed responses of the BOARDMAN generator shaft elements after the disturbance. Fig.3 shows the responses of the system with 8 ohms fixed compensation after the disturbance. It can be seen that the SSR at shaft mode 4 of 50.0 Hz is dominantly excited after the disturbance, as shown in the mass #4 and #5 speed responses. Also, oscillation at shaft mode 1 of 12.5 Hz can be observed in the mass #1 and mass #2 speed responses, and oscillation at shaft mode 2 of 25.0 Hz can be observed in the mass #3 speed response. Figs.4 through 6 shows the speed responses of the system with the TCSC at Xorder = 1.5 p.u., Xorder = 2.0 p.u., and Xorder = 3.0 p.u., respectively, after the disturbance. It is shown that with the TCSC vernier operation at the studied Xorder values, the amplitude of the dominant shaft mode 4 oscillation becomes significantly smaller compared with the case of the fixed compensation. This results from the TCSC vernier operation changing the network characteristics affecting the SSR. Figs.4 through 6 also show that the shaft mode 1 and shaft mode 2 oscillations are better mitigated with increasing Xorder, as seen by comparing the mass #1 through mass #4 speed responses in the figures.

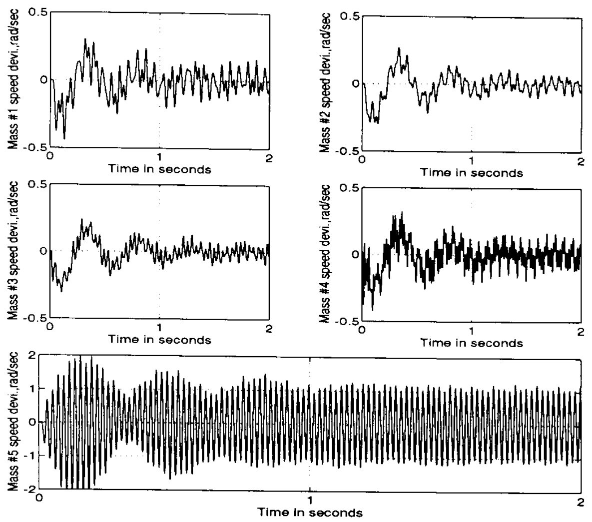

Fig.3 Post-disturbance system responses, 8 ohms fixed compensation

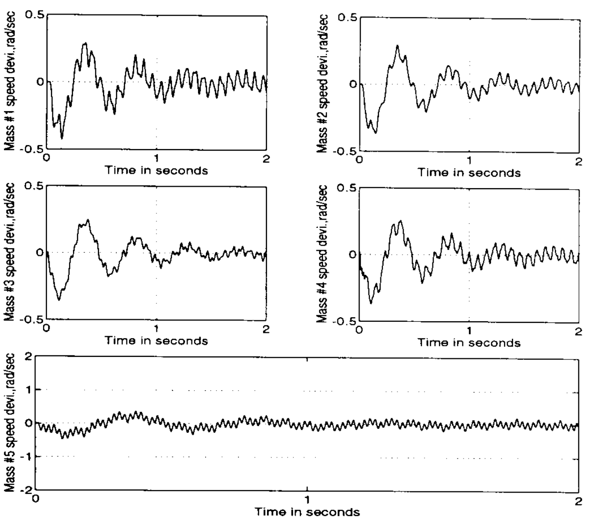

Fig.4 Post-disturbance system responses, Xorder = 1.5 p.u.

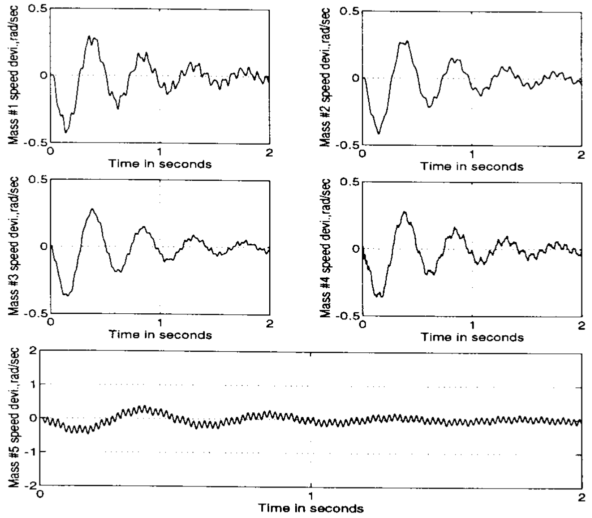

Fig.5 Post-disturbance system responses, Xorder = 2.0 p.u.

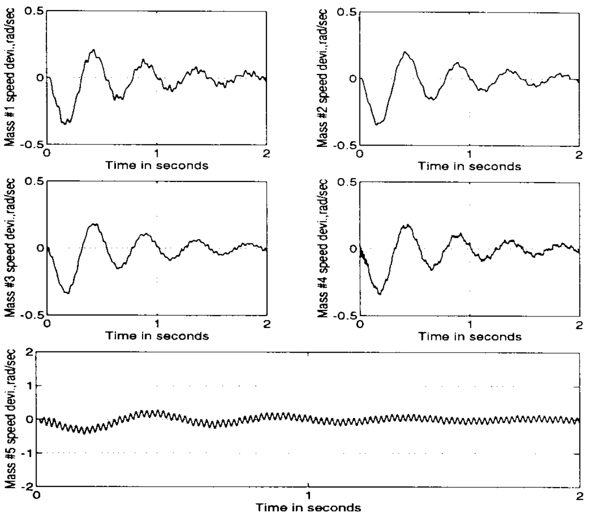

Fig.6 Post-disturbance system responses, Xorder = 3.0 p.u.

Figs.7 through 9 show the electrical responses of the system after the disturbance. Fig.7 shows the blocked TCSC (which is equivalent to 8 ohms fixed compensation) voltage of the system, after the disturbance. The electrical oscillation due to the interaction between the electrical and mechanical subsystems after the disturbance can be seen clearly from the response during the first 0.5 second simulation time. Fig.8(a), Fig.8(b), and Fig.8(c) shows the TCSC voltage of the system with the Xorder of 1.5 p.u., 2.0 p.u., and 3.0 p.u., respectively. The increase of the TCSC voltage reflects the increase of Xorder. It is shown that the electrical oscillation is well mitigated in the cases of the TCSC vernier operation, in contrast to the case of the fixed series compensation. Fig.9 shows the thyristor currents when TCSC is in vernier mode at the studied Xorder values.

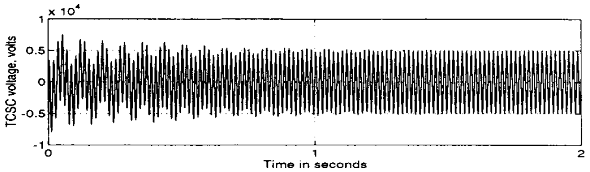

Fig.7 Post-disturbance response of the system, 8 ohms fixed compensation

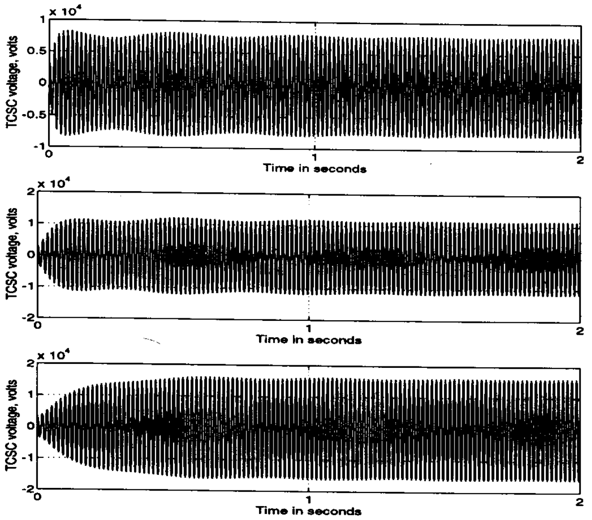

Fig.8 Post-disturbance responses of the system
(a) Xorder = 1.5 (upper plot), (b) Xorder = 2.0 p.u. (middle plot)
(c) Xorder = 3.0 p.u. (lower plot)

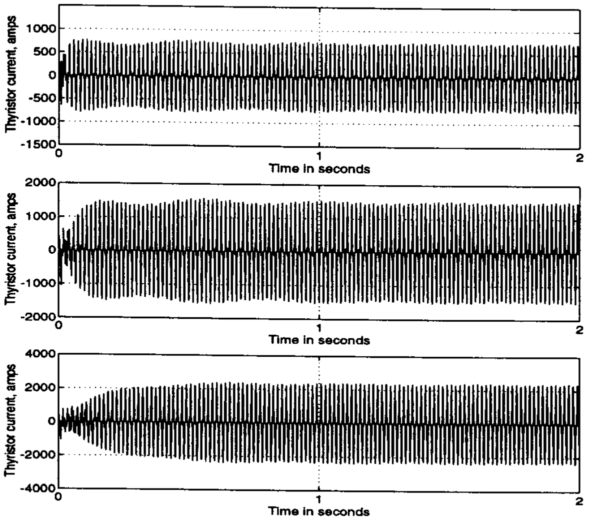

Fig.9 Post-disturbance responses of the system
(a) Xorder = 1.5 p.u. (upper plot), (b) Xorder = 2.0 p.u. (middle plot)
(c) Xorder = 3.0 p.u. (lower plot)

Case II

In this simulation case, the *Case I* disturbance is enlarged by switching out a small shunt impedance branch at SLATT initially. The operation scenario is as follows:

At t = 0-,	TCSC is bypassed & the shunt branch at SLATT is in the system;
At t = 0+,	TCSC is either blocked (in the case of fixed compensation), or switched into vernier mode; & the shunt branch is switched out of the system

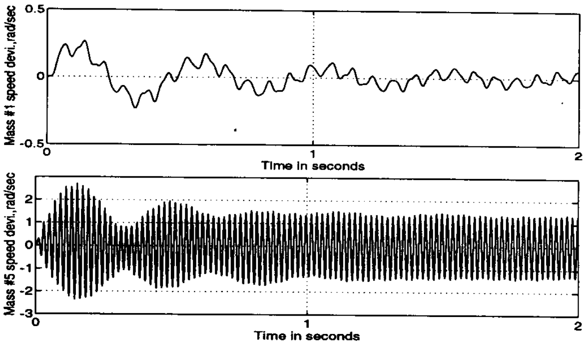

Fig.10 Post-disturbance system responses, 8 ohms fixed compensation

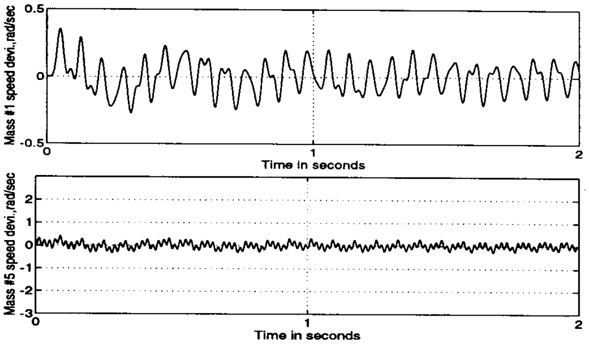

Fig.11 Post-disturbance system responses, Xorder = 1.5 p.u.

In this case, shaft mode 4 is dominantly excited, as in the *Case I*, which can be seen from the mass #5 speed response in Fig.10. Oscillation at shaft mode 1 can also be observed, as shown in the mass #1 speed response in Fig.10. Fig.11 shows the system responses with a TCSC Xorder of 1.5 p.u.. It can be seen that compared with the fixed series compensation, the TCSC vernier operating provides significant mitigation of the shaft mode 4 oscillation. However, although the magnitudes of the shaft mode 1 oscillation are small in both the case of the fixed compensation and the case of the TCSC vernier operation, the oscillation is notably more active in the latter case, as seen by comparing the mass #1 speed responses shown in Figs.10 and 11. An investigation of the cause of this phenomenon is currently underway. But it may be that this mode is excited more by initiating the disturbance with the TCSC vernier operation.

4. Frequency Domain Study of the Equivalent Impedance of TCSC

An analysis of the equivalent TCSC impedance can offer an explanation for the effectiveness of the TCSC at different oscillation frequencies. In the following, we present the frequency domain characteristics of the equivalent TCSC impedance using a 1.33 ohms internal capacitor reactance (one segment at SLATT).

A network including the TCSC in series with the network impedance and the voltage sources at both synchronous frequency and subsynchronous frequency is simulated in EMTP. The relationship between the voltage across the TCSC and the current through the TCSC at synchronous frequency and at different subsynchronous frequencies has been studied to determine the equivalent impedance of the TCSC with respect to different frequencies. The network for the simulation is shown in Fig.12 . The magnitudes of the subsynchronous voltage sources are chosen to be much smaller than the magnitude of the synchronous voltage source.

As an example, voltage sources at frequencies of 60 Hz and 10 Hz are considered with a thyristor conducting time of 70 electrical degree within half cycle. The simulated TCSC voltage is shown in Fig.13 . The square root of the Power Density Spectrum (PDS) of the TCSC voltage is shown in Fig.14. It can be seen that the two main frequency components of the response are at 60 Hz and 10 Hz. Similarly, the TCSC current, that is, line current, has the two main frequency components at 60 Hz and 10 Hz. The filtered 60 Hz and 10 Hz components are shown in Fig.15, where a Chebychev second-order filter was used. This analysis can be done conveniently using design packages, such as MATLAB[9]. From the magnitude and phase angle relationship between the voltage and current at a given frequency, we can obtain the equivalent TCSC impedance at these frequencies for the excitation level used. In this case, the equivalent TCSC impedances at 60 Hz and 10 Hz are $1.65\angle{-90.0°}$ ohms and $3.40\angle{-8.5°}$ ohms, respectively. The Xorder is 1.2 (=1.65/1.33) p.u., with a base value equal to the internal capacitor reactance, i.e., 1.33 ohms, in this case.

Based on the simulation studies and the analysis procedure illustrated, we obtain values of the equivalent TCSC impedance for different frequencies and Xorder values. Fig.16 shows the resulting real and imaginary parts of the equivalent TCSC impedance. It can be seen that for the studied values of Xorder, the equivalent TCSC impedance has negative(capacitive) imaginary part and positive (resistive) real part, with respect to subsynchronous and synchronous frequencies. Thus, if we view the TCSC as an electrical element, it can be represented as a resistor in series with a capacitor as follows:

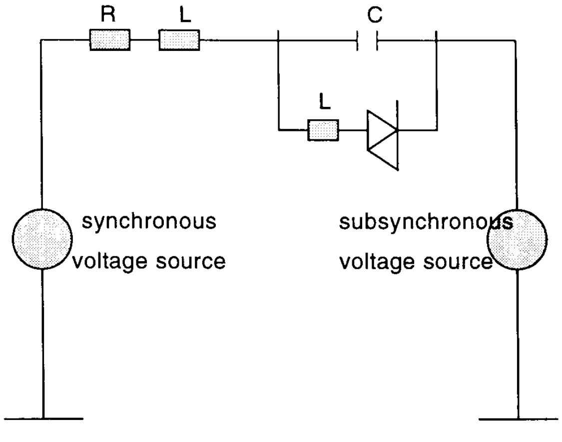

Fig.12 Network for the simulation study of the TCSC equivalent impedance

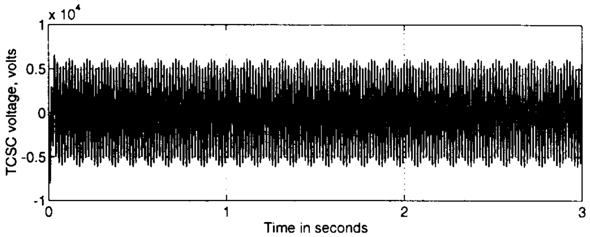

Fig.13 The simulated TCSC voltage

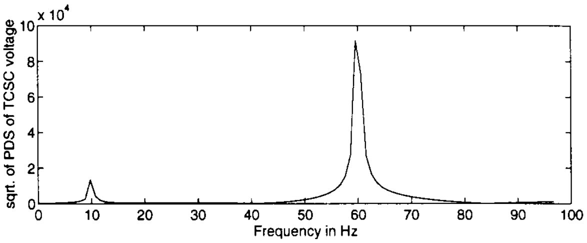

Fig.14 The square root(sqrt.) of the Power Density Spectrum (PDS) of the simulated TCSC voltage

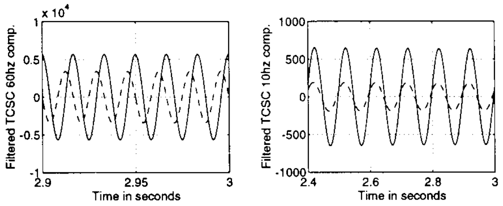

Fig.15 Filtered frequency components of the system responses
__ voltage in volts, --- current in amps

$$Z_e(\omega) = R_e(\omega) + jX_e(\omega),$$

where the subscript "e" stands for "equivalent", and $R_e \geq 0$, $X_e < 0$, the frequency domain characteristics of which are described in Fig.16. Because the TCSC operation involves nonlinearity, these characteristics may also depend on excitation level.

Fig.16(a) shows that $R_e(\omega)$ tends towards zero at synchronous frequency for any studied Xorder. Fig.16(b) shows that the equivalent TCSC reactance at synchronous frequency is enlarged over the internal capacitor reactance, which reflects the increased series compensation capability. Thus, it can be reasoned that with respect to synchronous frequency, the TCSC in vernier mode behaves as a lossy capacitor in an average sense.

Fig.16(a) shows that $R_e(\omega)$ is nonzero and positive with respect to subsynchronous frequencies for any studied Xorder. It can be reasoned that the TCSC provides resistive damping to SSR. Fig.16(b) shows that for any studied Xorder, the frequency domain characteristic of $X_e(\omega)$

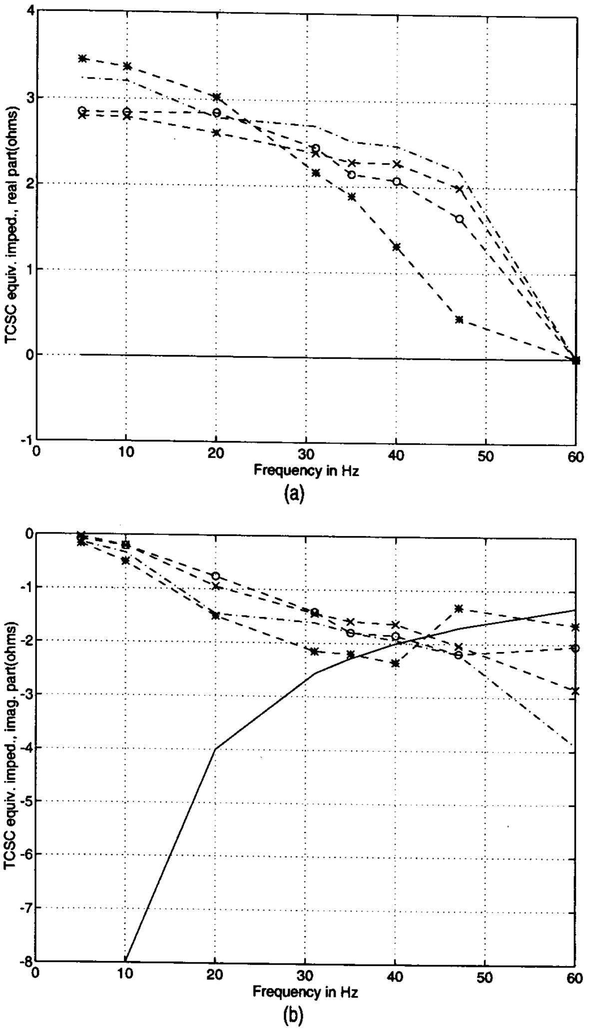

Fig.16 Frequency domain characteristics of the real part & imaginary part of the TCSC equivalent impedance

___	TCSC internal capacitor
--*--	Xorder = 1.2
--o--	Xorder = 1.5
--x--	Xorder = 2.1
-.-.-.-.	Xorder = 2.9

deviates from that of the TCSC internal capacitor reactance with respect to subsynchronous frequencies, as well as with respect to synchronous frequency. Thus, it can be reasoned that the TCSC operated in vernier mode avoids a resonant condition by changing the capacitive reactance at SSR frequencies and by introducing equivalent resistive damping.

Fig.16(a) shows that the value of $R_e(\omega)$ is somewhat larger at lower network frequencies for a given Xorder. Fig.16(b) shows that the deviation of $X_e(\omega)$ from the internal capacitor reactance is somewhat more significant at lower network frequencies for a given Xorder. Since the electrical frequencies of SSR are the complementary frequencies of the shaft modes[1, 10], it can be reasoned that the SSR mitigation effect of the TCSC vernier operation may be more significant with respect to higher frequency shaft modes, e.g., shaft mode 4 of 50.0 Hz in the studied system. We note further that for network frequencies between 28 and 60 Hz, the value of $R_e(\omega)$ increases as Xorder is increased, as shown in Fig.16(a). This may indicate that higher Xorder introduces a larger effective resistance at relatively low shaft mode frequencies (high network frequencies), e.g., at shaft mode 1 of 12.5 Hz.

5. Conclusions

A simulation study of the SSR mitigation effect of TCSC vernier operation has been performed using a model of the NWAPS and the standard EMTP simulation program. The frequency domain characteristics of the equivalent TCSC impedance has been used to give an explanation of the issues involved. The study serves as an exploration of the SSR mitigation effect provided by TCSC vernier operation in a realistic power system model. It is shown that the TCSC vernier operation provides significant mitigation of 50 Hz shaft mode that was dominantly excited with the fixed compensation.

The equivalent TCSC impedance study shows that the TCSC in vernier mode no longer behaves as only a capacitor in an average sense with respect to subsynchronous frequencies for the studied Xorders. The TCSC vernier operation may benefit the mitigation of SSR in two aspects. One is that the TCSC vernier operating provides equivalent resistive damping to subsynchronous oscillations, and the other is that the equivalent reactance of the TCSC in vernier mode deviates from the internal capacitor reactance with respect to subsynchronous frequencies, as well as at synchronous frequency. These effects lead to a change of the system characteristics and suppression of SSR.

The frequency domain analysis also shows that the SSR mitigation effect of the TCSC vernier operation may change with the dominant SSR frequencies. Both the simulation study *Case I* and the equivalent TCSC impedance study suggest that with respect to SSR at shaft modes of relatively low frequencies, e.g., shaft mode 1 of 12.5 Hz in the studied system, the SSR mitigation effect of the TCSC vernier operation increases with increasing Xorder. Small Xorders can provide good mitigation of SSR at shaft modes of relatively high frequencies, e.g., shaft mode 4 of 50.0 Hz in the studied system.

As in any dynamical system studies, the results of the simulation studies presented can be influenced by a number of factors, such as, system configurations, system parameters, TCSC operation conditions, etc. Thus, the conclusions presented are related to the specified problems studied. Additional study is needed to account for the larger mode 1 amplitude with TCSC control (Fig.11), and to verify the relationships suggested. Also, the study of the modal damping provided by TCSC vernier operation is currently underway.

6. References

[1] IEEE Committee Report, "Reader's Guide to SSR," IEEE Transactions on Power Systems, Vol.7, No.2, 150-157, February 1992

[2] E.V. Larsen, C.E.J. Bowler, B.L. Damsky, S.L. Nilsson, "Benefits of Thyristor-Controlled Series Compensation," CIGRE Paper 14/37/38-04, Paris, 1992

[3] J. Urbanek, R.J. Piwko, E.V. Larsen, B.L. Damsky, B.C. Furumasu, W.A. Mittelstadt, J.D. Eden, "Thyristor Controlled Series Compensation Prototype Installation at the Slatt 500 kV Substation," IEEE PES Paper 92-SM-467-1PWRD, Seattle, July 1992

[4] R. Spee, W.Zhu, "Flexible AC Transmission Systems - Simulation and Control", Proc. Africon, Swaziland, 1992

[5] Advanced Concepts Studies Related to FACTS: Operation and Nonlinear Control - Phase II, OSU ECE Technical Report FACTS 9201, February, 1992, EPRI Contract No. RP 4000-06, BPA Contract No. DE B179-90BP08423

[6] E.V. Larsen, K. Clark, S.A. Miske, Jr., J.Urbanek, "Characteristics and Rating Considerations of Thyristor Controlled Series Compensation," IEEE PES Paper 93-SM-433-3PWRD, Vancouver, B.C., Canada, July, 1993

[7] Scott G. Helbing, G.G. Karady, "Investigation of an Advanced Form of Series Compensation," IEEE PES Paper 93-SM-431-7PWRD, Vancouver, B.C., Canada, July, 1993

[8] S. Nyati C.A. Wegner, R.W. Delmerico, R.J. Piwko, D.H. Baker, A. Edris, "Effectiveness of Thyristor Controlled Series Capacitor in Enhancing Power System Dynamics: an Analog Simulator Study," IEEE PES Paper 93-SM-432-5PWRD, Vancouver, B.C., Canada, July, 1993

[9] MATLAB, The Mathwork, Inc., 24 Prime Park Way, Natick, MA 01760

[10] IEEE Power System Engineering Committee Report, "Terms, Definitions and Symbols for Subsynchronous Oscillations," IEEE Transactions on PAS, Vol. PAS-104, No.6, 1326-1334, June 1985

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