SSR study for the Thyristor Controlled Series Compensation application on the Kanpur-Ballabgarh 400kV line in India

Sujatha Subhash, A K Tripathy, K R Padiyar, Satish Nayyar, Manoj Kumar, P J Thakkar & K K Arya

Abstract—This paper presents the results of a detailed SSR study carried out to support the task of designing the first commercial TCSC application in the Indian Power sector, on the 400kV Kanpur-Ballabgarh line(395km long). The study is based on two methods – damping coefficient analysis and EMTP time domain solutions. The study shows negative damping coefficient in some network conditions at Unchahar bus implying less damping to SSR oscillations. EMTP simulations show that with the operation of TCSC, the oscillations are damped. The paper presents the details of network representation including HVDC line from Rihand-Dadri, SVC at Kanpur and TCSC.

Keywords: SSR oscillations, TCSC, EMTP, FACTS, torsional interaction

I. Introduction

The use of fixed series compensation for increase power transfer levels has long been in vogue. But the potential risk of Sub Synchronous Resonance (SSR), leading to damages to turbine-generator shaft failure and electrical instability at oscillation frequencies lower than the normal system frequency, has deterred utility engineers in applying series compensation. But the newly developed TCSC Thyristor controlled series compensation [1] operated in vernier mode provides mitigation of SSR consequences. A study on SSR consequences is important for any series compensation project.

The first FACTS project- in Indian power sector was awarded by M/s POWERGRID on M/s BHEL in the year 2000. The FACTS system was to be installed on the 400kV, 395km long , Kanpur- Ballabgarh line. Kanpur-Ballabgarh and Kanpur-Agra 400kV lines in Northern grid of UP carry about 800MW power from Singrauli and Rihand belt to western UP and Rajasthan as shown in Fig 1. The Ballabgarh- Agra line serves as a tie between Kanpur-Ballabgarh-Jaipur area and the Kanpur-Agra-Jaipur area. A "Thyristor controlled series compensator TCSC " is planned for better utilization of this corridor. Several studies have been carried out to assess the system performance with the application of TCSC, but this paper focus only on the performance of TCSC in sub-synchronous frequency range.

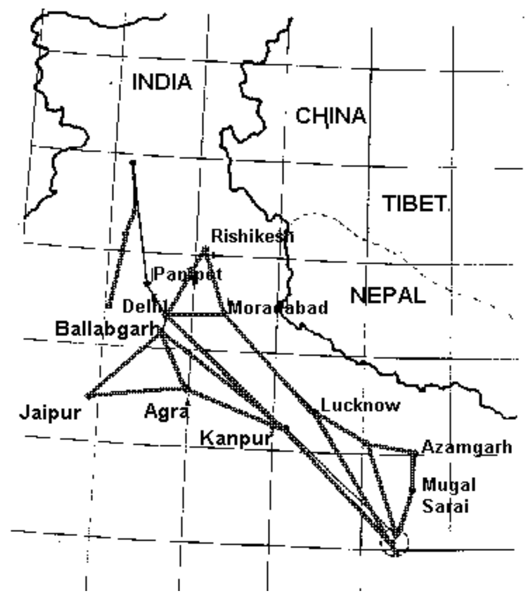

Fig 1 Northern region system of Indian power system

The network around the TCSC is quite complex with two FACTS devices in its vicinity namely, a HVDC line from Rihand to Dadri and the SVC installed at Kanpur.

A simplified analysis based on damping torque concept is adopted to get an insight to the behaviour of the network at sub- and super- synchronous frequencies on damping torque coefficient of different machines. The results are validated through detailed time domain solutions. ATP, a standard power system simulation program [3], is used to represent the system in detail including mass dynamics of the synchronous machines, firing circuits of TCSC and dynamics of HVDC line. The system dynamics following a fault are captured to study the occurrence of SSR oscillations and the results obtained from the two methods are compared.

The study demonstrated the advantages of applying TCSC in providing desired level of series compensation without adversely affecting the SSR oscillations.

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II. TCSC AND SITE CHARACTERISTICS

The "Thyristor controlled series compensator planned at Ballabgarh is a vernier type of TCSC, comprising 27% fixed compensation in series with 8% compensation made variable with a boost factor of 2. The network around the TCSC is shown in Fig 2.

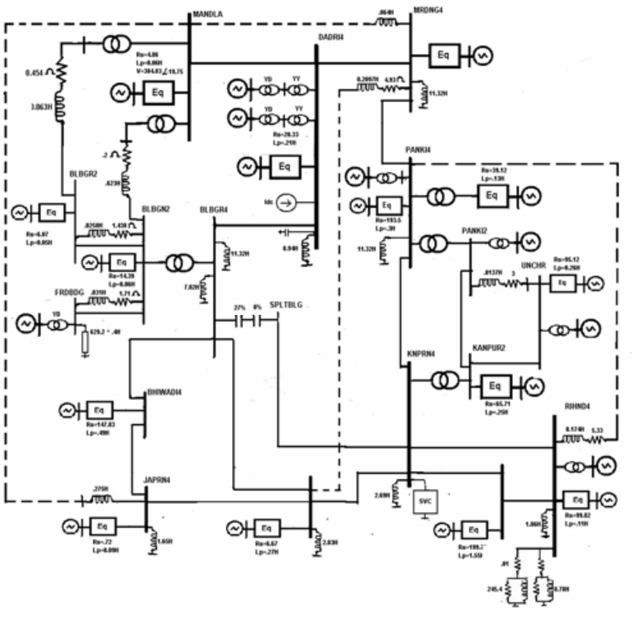


Fig 2 Single line diagram of reduced network around Kanpur-Ballabgarh line

There are five generator buses in the vicinity of TCSC, namely Panki, Dadri, Unchahar, Dadri_G, Faridabad and Rihand. The generator ratings are given in Appendix A. The computed torsional mode frequencies and modal inertia for the 210MW, 247 MVA machine are given in Table I. It is observed that the torsional mode 1 (24.746 Hz) has low modal inertia

TABLE I
Torsional mode frequencies of 210MW, 247MVA machine

no	Mode frequency Hz	Modal inertia
Mode 1	24.746	1.55
Mode 2	56.46	615
Mode 3	96.818	66435.87
Mode 0	0.0	3.3

III. ANALYSIS BY DAMPING COEFFICIENT METHOD

In SSR phenomenon, the torsional interaction is more important than the induction generator effect. Thus it is convenient to ignore the flux decay, damper circuits and transient saliency in the analysis. For the purpose of computation of damping torque coefficient T_D, the synchronous machine is represented as a positive sequence voltage source behind a transient reactance. This voltage is given by,

$$e_{pos} = \varpi E' \sin(\omega_o t + \delta) \tag{1}$$

where, E' – induced voltage proportional to the flux linkage, and $\tilde{\varpi}$ pu speed. It is to be noted that E' is constant as we have assumed negligible flux decay, and

$$\varpi = \varpi_o + A\sin(\omega_m t)\,, \tag{2}$$

since we have assumed that the generator rotor oscillates about a constant speed sinusoidally. We can show that the induced emf in the stator $e_{pos}(t)$ consists of three sinusoidal components, viz., one of frequency ω_o and other two components of frequencies $\omega_o \pm \omega_m$., for small amplitude (A) of oscillations . The expression for $e_{pos}(t)$ is given by [2],

$$e_{pos}(t) = \varpi_o E' \sin(\omega_o t + \delta_o) - \frac{AE'}{2\omega_m}(\omega_o - \omega_m)\cos[(\omega_o - \omega_m)t + \delta_o]$$
$$-\frac{AE'}{2\omega_m}(\omega_o + \omega_m)\cos[(\omega_o + \omega_m)t + \delta_o] \tag{3}$$

We can write the expression [2] for the damping coefficient torque T_D as

$$T_D = -\frac{(E')^2}{2\omega_m}\left[\frac{(\omega_o - \omega_m)}{Z_{sub}}\cos\phi_{sub} - \frac{(\omega_o + \omega_m)}{Z_{sup}}\cos\phi_{spb}\right] \tag{4}$$

where Z_{sub} and Z_{sup} are the positive sequence impedance of the electrical network at sub- synchronous and super synchronous frequencies and are determined from the knowledge of the network configuration. The computation of T_D over the subsynchronous frequency range gives an idea about the damping effect of the electric network.

The generator is represented one at a time as a positive sequence voltage source behind a transient reactance and the network is represented as a Thevenin impedance at its terminal. The damping torque coefficient T_D is calculated for different modulating frequencies ω_m varying from 0 – 300 rad/sec. At each modulating frequency the positive sequence impedance as seen from the generator bus, Zsub and Zsup at subsynchronous frequency and super-synchronous frequencies resp. are calculated to compute T_D using (4).

Fig 3. shows the variation of T_D as seen at the Unchahar machine bus. The damping coefficient is observed to be more negative at lower frequencies (closer to zero) and also at frequencies closer to 50Hz. This implies that the network offers less damping to oscillatory shaft torques to Unchahar machine. Fig 4 shows the variation of T_D at Dadri machine bus. It is observed that the damping coefficient is almost zero over the subsynchronous frequency range, implying that there is no possibility of SSR. Similar results are seen at other generator buses .

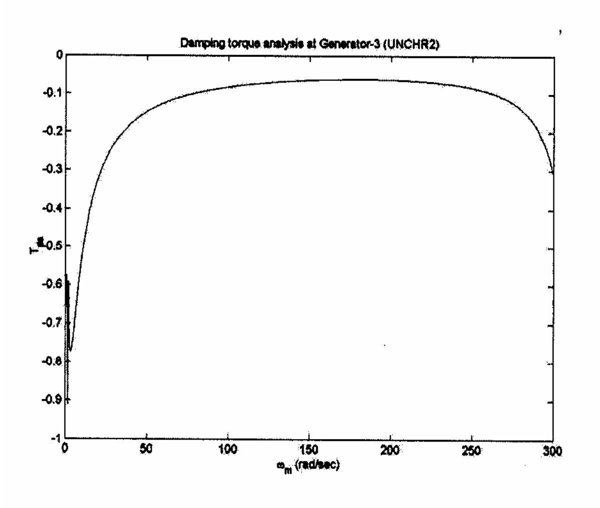


Fig 3. Variation of T_D with mechanical frequency of rotor oscillation at Unchahar generator bus

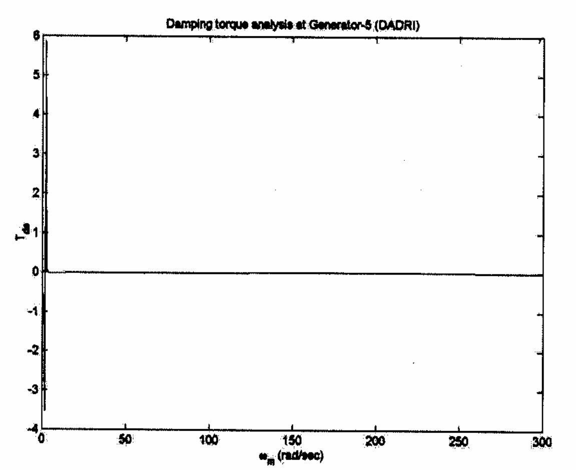


Fig . 4 Variation of T_D with mechanical frequency of rotor oscillation at Dadri generator bus

IV. Analysis by Time domain simulations

The reduced network around Kanpur- Ballabgarh line as shown in Fig 2 is considered for time domain analysis by ATP. The network behind the far off buses is represented by equivalents (Fig2.)

The synchronous machines at the buses Dadri, Faridabad, Panki, and Unchahar are represented by Type 59 source model in EMTP. Two generators (210MW) one at Dadri and other at Unchahar are represented as four mass spring system :- high pressure turbine (HP), intermediate pressure turbine (IP), low pressure turbine (LP) and the generator (GEN-EXC) coupled on a single shaft. The mechanical damping for Unchahar machine is assumed to be 0.58pu. The damping is spread over the masses in the ratio of their inertias. The mass with maximum inertia has maximum damping.

It is reported in literature that HVDC system do not cause adverse torsional oscillations particularly on the inverter side [4]. Hence a detailed modeling of the valves in HVDC line is not considered. Instead at the rectifier end of the HVDC line from Rihand to Dadri, is represented as a load at Rihand. On other hand at the inverter end, it is represented as a constant current type load, because the HVDC line maintains constant dc current through rectifier current control at the Dadri bus. In time domain simulation, the constant current type load is modeled as a TACS controlled current source, as shown in Fig 5.

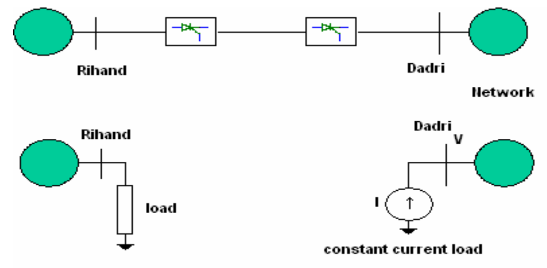
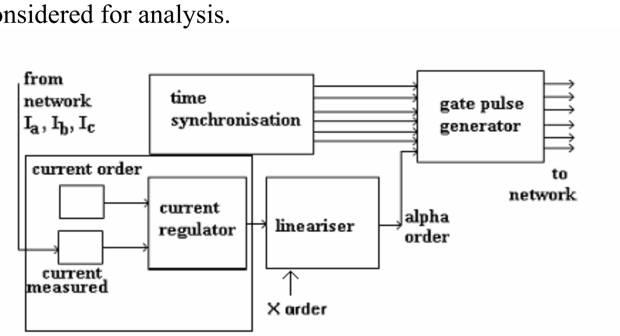


Fig 5 . Modelling of Rihand-Dadri HVDC line in ATP for SSR study

The current injected into the Dadri bus maintains a constant magnitude, I and constant phase angle difference ϕ with the bus voltage. The magnitude and phase angle difference (I & ϕ) are determined by the initial steady state load flow conditions . TACS cards are used to compute the phase angle of the bus voltage by computing its d,q components, as shown in (5) and corresponding instantaneous values of three phase current. Type 60 source model of EMTP is used for the current injection.

$$\theta = \tan^{-1}\left(\frac{Vd}{Vq}\right) \quad \text{and} \quad \begin{aligned} Id &= I\sin(\theta + \varphi) \\ Iq &= I\cos(\theta + \phi) \end{aligned} \qquad (5)$$

A simple control structure for TCSC as shown in Fig 6 below, with a given impedance order Xorder, is considered for analysis.



Lineariser block :

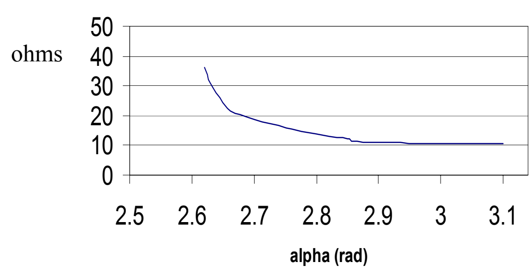


Fig 6. TCSC control structure

The SVC at Kanpur is represented by its capacitance.

V. Case Studies

Three phase to ground faults cleared after 5cycles, are created in the network to excite transient torques on the shaft and analysed for subsynchronous resonance conditions. The TCSC is operated at constant impedance mode for the SSR study. Three phase ground fault is applied at Panki bus and cleared after 5 cycles. The simulation is carried out for the following vernier steady state operating conditions, viz.,

1. Valves are in blocked condition
2. Xorder = 1.12pu, 1.2pu boost factors

The computed transient shaft torques at Unchahar and Dadri machines are shown in Fig.7 & Fig 8 resp. The torques damp out slowly for Unchahar machine, whereas the shaft torques for Dadri machine are smaller in magnitude and damp out rapidly.

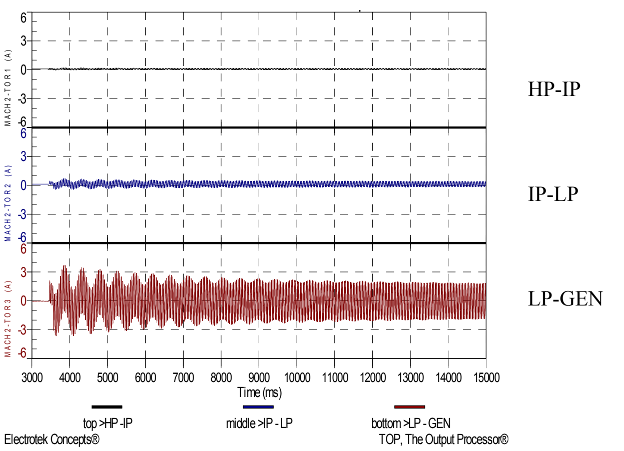


Fig 7. Computed shaft torques in MNm for Unchahar machine for 3phg fault at Panki at 3.4s, 5cycles clearing time, TCSC in blocked mode

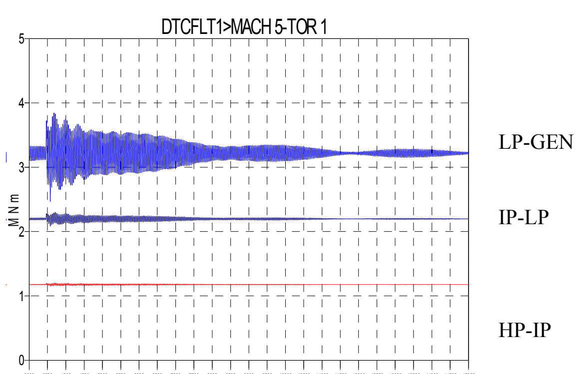


Fig 8. Computed shaft torques in MNm for Dadri machine for 3phg fault at Panki at 3.4s, 5cycles clearing time, TCSC in blocked mode

The FFT is carried out after 4s to see the frequency spectrum of the torques on the three shafts. Fig 9 shows the frequency spectrum of the shaft torques of Unchahar machine. It is observed out of the three torsional modes, only the torsional mode 1 (subsynchronous frequency component 24.56hz), having least modal inertia is excited for the LP-GEN shaft torque and not for other shaft torques.

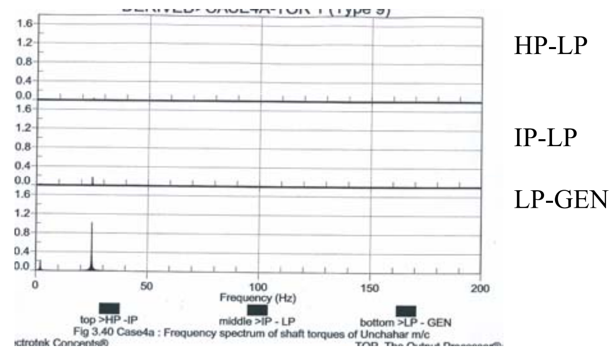


Fig 9. Frequency spectrum of shaft torques for Unchahar machine for 3phg fault at Panki at 3.4s, 5cycles clearing timeng, TCSC in blocked mode

With the operation of TCSC, the magnitudes of the transient shaft torques are considerably reduced and damped in time. Fig 10 shows the comparison of LP-GEN

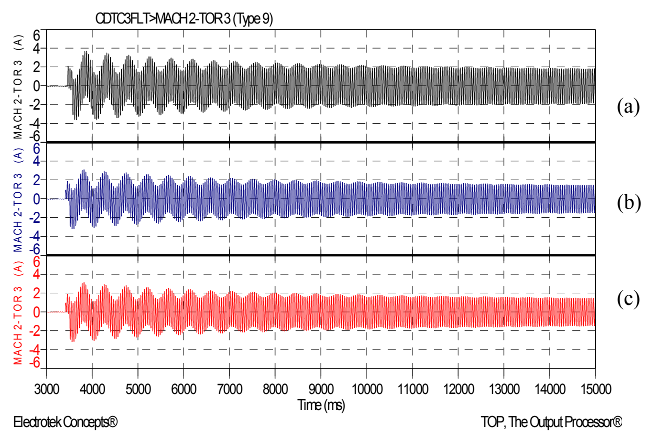


Fig 10. Comparison of LP-GEN shaft torques in MNm for Unchahar machine for 3phg fault at Panki at 3.4s, 5cycles clearing time TCSC in (a) blocked (b) 1.12 boost factor (c) 1.2 boost factor

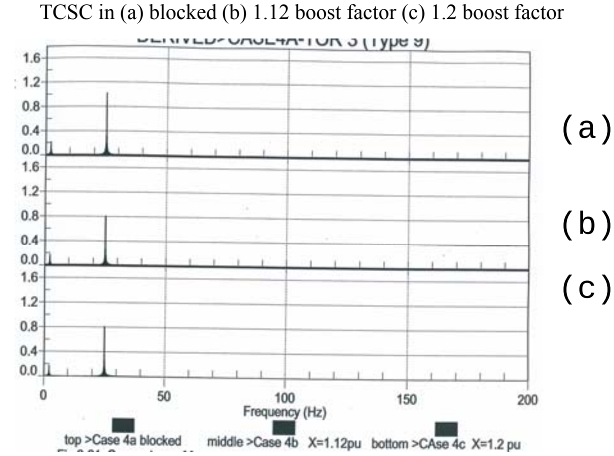


Fig 11. Frequency spectrum of LP-GEN shaft torques for Unchahar machine for 3phg fault at Panki at 3.4s, 5cycles clearing time TCSC in (a) blocked (b) 1.12 boost factor (c) 1.2 boost factor

shaft torque of Unchahar machine with TCSC operating at different boost factors and the corresponding frequency spectrum is shown in Fig11. Excitation of torsional mode frequencies of 24.56 Hz (sub synchronous mode frequency) is observed in LP-GEN shaft torque for all the cases. But with the operation of TCSC, the subsynchronous frequency component is damped considerably. This clearly shows that TCSC has positive damping effect and there is no risk of SSR phenomenon.

The FACTS scheme at Ballabgarh was operated as fixed compensation of 35% (27% + 8%) for about 18 months , after which the 8% was converted into variable compensation. The complete scheme has been commissioned in the year 2004 and is operating satisfactorily.

VI. CONCLUSIONS

The SSR study carried out for the TCSC installation on 400kV line at Ballabgarh show that the application of TCSC has positive effect in mitigating SSR consequences. It is seen that the damping torque concept is a useful tool to get an insight into the effects of the network characteristics on torsional interactions. This study shows that the network under some contingencies offer negative damping torque coefficient to Unchahar bus, whereas it is positive at other generator buses.

This is further confirmed with detailed simulations on ATP. In some contingencies closer to Unchahar, like fault at Panki bus, the transient shaft torques of Unchahar machine are oscillatory and damp out slowly, whereas for contingencies far from Unchahar bus there is negligible shaft torques on generator buses. But with the operation of TCSC the subsynchronous frequency component in transient torques are reduced considerably. Hence it is concluded that there is no risk of SSR resonance and the tools used for analysis are found to complement one another.

VII. APPENDIX

TABLE II
Generator ratings

Bus	No of units	MVA rating
Dadri	4	247
	5	154
	1	172
Faridabad	3	104
	1	175
Panki	2	129
Rihand	4	588
Unchahar	4	247

VIII. ACKNOWLEDGEMENT

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K R Padiyar is presently an Emeritius Professor of Electrical Engineering at Indian Institute of Science, Bangalore, India. He obtained his BE degree in Electrical Engineering from Poona University in 1962, ME degree from IISc in 1964 and PhD degree from University of Waterloo, Canada in 1972. He was with IIT Kanpur from 1976-1987 prior to joining IISc. His research interests are in the area of HVDC and FACTS, system dynamics and control. He has authored three books and over 200 papers. He is a Fellow of National Academy of Engineering (India).