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Performance Evaluation of Mitigation of SSR Using TCSC and SSSC

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***Abstract---*A long transmission line needs controllable series as well as shunt compensation for power flow control and voltage regulation. This can be achieved by suitable combination of passive elements and active FACTS controllers.The advent of series FACTS controllers,Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC) has made it possible not only for the fast control of power flow in a transmission line, but also for the mitigation of SubSynchronous Resonance (SSR) in the presence of Fixed series capacitors. While the technology of TCSC using thyristor valves is well established, SSSC based on Voltage Source Converter (VSC) with GTO valves is anPWM Hysteresis controller and has several advantages compared to TCSC. The MATLAB/Simulink was used to successfully accomplish the comparative analysis and simulation studies.**

***Index Terms*–TCSC,SSSC, Subsynchronous resonance (SSR), Flexible AC transmission system (FACTS),Torsional oscillation.**

I. INTRODUCTION

Growth of electric power transmission facilities is restricted despite the fact that bulk power transfers and use of transmission systems by third parties are increasing. Transmission bottlenecks, non-uniform utilization of facilities and unwanted parallel path or loop flows are not uncommon. Transmission system expansion is needed, but not easily accomplished. Factors that contribute to this situation include a variety of environmental, land-use and regulatory requirements.

As a result, the utility industry is facing the challenge of the efficient utilization of the existing AC transmission lines. Flexible AC Transmission Systems (FACTS) technology is an important tool for permitting existing transmission facilities to be loaded, at least under contingency situations, up to their thermal limits without degrading system security . The most striking feature is the ability to directly control transmission line flows by structurally changing parameters of the grid and to implement high-gain type controllers, based on fast switching.

A problem of interest in the power industry in which FACTS controllers could play a major role is the mitigation of Subsynchronous Resonance (SSR) oscillations. SSR is a dynamic phenomenon in the power system which has certain special characteristics.

The onset of series connected FACTS controllers, like thyristor controlled series capacitor (TCSC) and static Synchronous series compensator (SSSC), has made it possible not only to regulate power flow in critical lines and also to counter the problem of SSR. SSSC has several advantages over TCSC.SSSC is a voltage source converter (VSC) based FACTS controller, and has one degree of freedom (i.e., reactive voltage control) injects controllable reactive voltage in quadrature with the line current. The risk of SSR can be minimized by a suitable combination of hybrid series compensation consisting of passive components and VSC based FACTS controllers such as STATCOM or SSSC. The advantage of SSSC compensation is reported in [13] and shown that reactive voltage control mode of SSSC reduces the potential risk of SSR by detuning the network resonance.

The SSR characteristics of TCSC and SSSC are compared in [8] and studies indicate that vernier operation of TCSC is often adequate to damp SSR whereas a subsynchronous damping controller (SSDC) with SSSC is desired for damping critical torsional modes when the line resistance is low. A method for online estimation of subsynchronous voltage components in power systems is described in and used for the mitigation of SSR . The damping of SSR using single phase VSC based SSSC is reported in [5].

In this paper, the analysis and simulation of a hybrid series compensated system with TCSC and then SSSC based on PWM controller is presented. The major objective is to investigate SSR characteristics of the hybrid series compensated power system in detail using both linear analysis, nonlinear transient simulation and propose a simple method for the extraction of subsynchronous component of line current using filter. The extracted subsynchronous frequency component of line current is used to inject a proportional subsynchronous voltage in series with the transmission line which suppresses subsynchronous current in the transmission network. This novel technique is termed as subsynchronous current suppressor and effectively mitigates SSR. Then finally the mitigation of SSR using TCSC is compared with the SSSC connected to a same system individually.

II. SUBSYNCHRONOUS RESONACNE IN POWER SYSTEMS

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In this section, conditions leading to SSR will be described. It is of importance to mention that while SSR due to TI effect can be analyzed analytically by using linear models, the analysis of SSR due TA is fairly complicated and can be approached only byusingasimulationprogram.TheconditionsthatleadtoSSRdueTIeffectwillbeanalyzed.

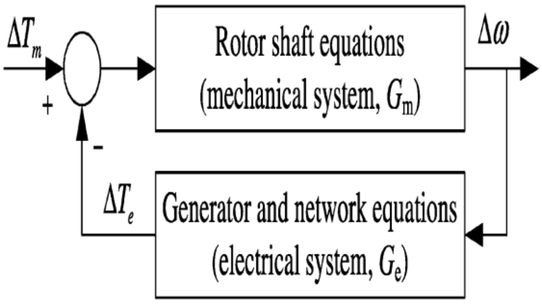

Fig.1. Block scheme representing interaction between electrical and mechanical system.

SSR due to TI effect can be investigated using the feedback loop depicted in Fig. 1, [15]. The mechanical system is typically constituted by several masses representing different turbine stages (low-pressure, intermediate-pressure, high-pressure) interconnected by elastic shafts. When a torsional mode is ex- cited, the masses perform small amplitude twisting movements relative to each other. The phase angle of the generator mass becomes modulated, causing a variation in the stator flux $(\underline{\psi}_s)$. Depending on the series-compensated network, substantial modulation of the stator current $(\underline{i})$ will results. In particular, if the frequency of this oscillating current is electrically close to the resonance frequency of the series compensated network, undamped currents will result. The flux in the generator and the stator current will create an electrical torque T_e that will act on the generator mass. As a result, the feedback loop depicted in the figure is established. Call G_e the transfer function from the rotor speed $\Delta\omega$ to the electrical torque ΔT_e

$$G_e(s) = \frac{\Delta T_e}{\Delta\omega}(s) \qquad (1)$$

To investigate the response of the electrical system at different frequencies, the Laplace variable can be simply substituted with $j\omega_k$, where is the frequency of interest (for example, one of the natural frequencies of the generator-shaft system). At each frequency, the transfer function G_e can be split up into its real and imaginary part, as

$$G_e(j\omega_k) = Re[G_e(j\omega_k)] + j\mathrm{Im}[G_e(j\omega_k)] = \Delta T_{De}(j\omega_k) - j\frac{\omega_B}{\omega_k}\Delta T_{De}(j\omega_k) \qquad (2)$$

with the base frequency. The terms ΔT_{De} and ΔT_{Se} are named electrical damping and synchronizing torque, respectively. Similar definition holds for the mechanical damping and synchronizing torques, ΔT_{Dm} and ΔT_{Sm}.In a series-compensated network, the electrical damping can be considered equal to zero for all frequencies except at the resonance of the electrical system, where ΔT_{De} becomes negative. Assuming that the synchronizing torque is negligible, SSR due to TI occurs in the power system if ΔT_{De} equals or is lower than the mechanical damping torque ΔT_{Dm}.

III. TYPES OF SSR

There are many ways in which the system and the generator may interact with sub synchronous effects. A few of thoseinteractions are basic in concept and have been given special names. We mention three of those that are of particularinterest: Induction Generator Effect, Torsional Interaction Effect, and Transient Torque Effect [5].

A. *Induction Generator Effect*

Induction generator effect is caused by self excitation of the electrical system. The resistance of the rotor to sub synchronous current, viewed from the armature terminals, is a negative resistance. The network also presents a resistance to these same currents that is positive. However, if the negative resistance of the generator is greater in magnitude than the positive resistance of the network at the system natural frequencies, there will be sustained sub synchronous currents. This is the condition known as the "induction generator effect."

B. *Torsional interaction*

Torsional interaction occurs when the induced sub synchronous torque in the generator is close to one of the torsional natural modes of the turbine generator shaft. When this happens, generator rotor oscillations will build up and this

motion will induce armature voltage components at both sub synchronous and super synchronous frequencies. Moreover, the induced sub synchronous frequency voltage is phased to sustain the sub synchronous torque. If this torque equals or exceeds the inherent mechanical damping of the rotating system, the system will become self excited. This phenomenon is called "torsional interaction."

C. *Transient Torques*

Transient torques is those that result from system disturbances. System disturbances cause sudden changes in the network, resulting in sudden changes in currents that will tend to oscillate at the natural frequencies of the network. In a transmission system without series capacitors, these transients are always dc transients, which decay to zero with a time constant that depends on the ratio of inductance to resistance. For networks that contain series capacitors, the transient currents will be of a form similar to above equation, and will contain one or more oscillatory frequencies that depend on the network capacitance as well as the inductance and resistance. In a simple radial R-L-C system, there will be only one such natural frequency, which is exactly the situation described in above equation , but in a network with many series capacitors there will be many such Sub synchronous frequencies. If any of these sub synchronous network frequencies coincide with one of the natural modes of a turbine-generator shaft, there can be peak torques that are quite large since these torques are directly proportional to the magnitude of the oscillating current. Currents due to short circuits, therefore, can produce very large shaft torques both when the fault is applied and also when it is cleared. In a real power system there may be many different sub synchronous frequencies involved and the analysis is quite complex.Of the three different types of interactions described above, the first two may be considered as small disturbanceconditions, at least initially. The third type is definitely not a small disturbance and nonlinearities of the system alsoenter into the analysis. From the view point of system analysis, it is important to note that the induction generator andtorsional interaction effects may be analyzed using linear models, suggesting that Transient simulation analysis is appropriatefor the study of these problems.

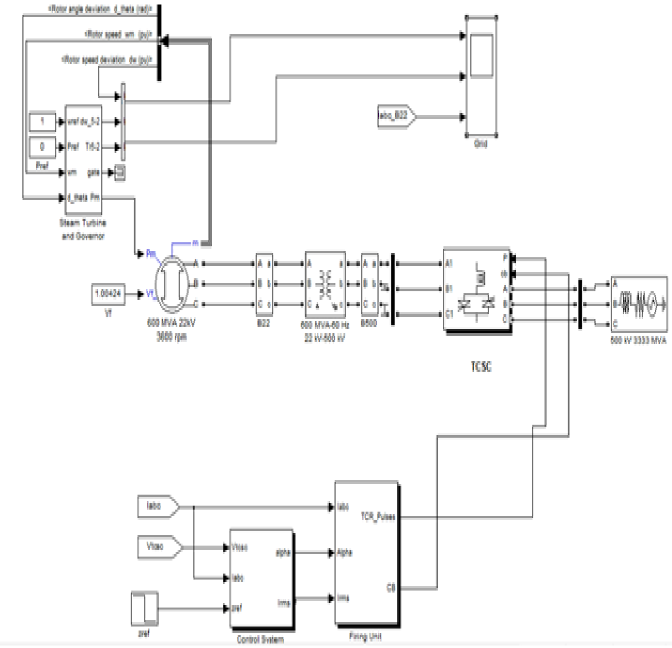

Fig. 2 Simulation of TCSC connected system

IV. SYSTEM MODELLING

We shall now demonstrate the damping effects of TCSC and SSSC through eigenvalue analysis. To do this, we have to develop a linear model of the overall system. The linearized models for the generator and shaft system for IEEE first benchmark model are well documented. Here, we use theapproach given in [14].

A. Combined Generator and Shaft System Model

The linearized state equations are given by:

$$\Delta x_G \square \ \square\square A_G \square \Delta x_G \square \ \square\square B_{G1} \square \Delta u_g$$

$$\square \ \square\square B_{G2} \square E_{fd} \quad (3)$$

$$\Delta y_G \square \ \square\square C_G \square \Delta x \qquad (4)$$

Where the state vector Δx_G, input vector Δu_g and outputvector Δy_G are given by

$$[\Delta x_G]^t = [\Delta x_e \quad \Delta x_m] \qquad (5)$$

$$[\Delta x_e]^t = [\Delta\Psi_e \quad \Delta\Psi_q \quad \Delta E_d' \quad \Delta E_q'] \qquad (6)$$

$$[\Delta x_m]^t = [\ \delta_{GEN} S_{EXC} T_{GE} S_{GEN} T_{LBG} S_{LPB}$$

$$T_{LAB} S_{LPA} T_{ILA} S_{IP} T_{HI} S_{HP}\ ] \quad (7)$$

$$[\Delta y_G]^t = [\Delta i_d \quad \Delta i_q] \qquad (8)$$

B. Modelling the Transmission Line

The differential equations for the circuit elements, after applying Park's transformation, can be expressed in the d-q reference frame as following

The voltage across the capacitor (12):

$$\begin{bmatrix}\Delta Vcd\\ \Delta Vcq\end{bmatrix} = \begin{bmatrix}0 & -\omega\\ \omega & 0\end{bmatrix}\begin{bmatrix}Vcd\\ Vcq\end{bmatrix} + \begin{bmatrix}\omega Xc & 0\\ 0 & \omega Xc\end{bmatrix}\begin{bmatrix}id\\ iq\end{bmatrix} \quad (9)$$

C. TCSC Modelling

A typical TCSC module consists of a fixed series capacitor (FC) in parallel with a thyristor controlled reactor (TCR). The TCR is formed by a reactor in series with a bi-directional thyristor valve that is fired with a phase angle α ranging between 90° and 180° with respect to the capacitor voltage.

Typically, the principal steady state function of a TCSC is power flow control, which is usually accomplished either automatically with a "slow" PI controller or manually through direct operator intervention. Additional functions for stability improvement, such as damping controls, may be included in the external control.

The TCSC is modelled in detail taking into consideration of the switching action of thyristors for transient simulation. The eigenvalue analysis is based on the dynamic phasor model of TCSC given in reference [8], where the TCSC is modelled as a variable capacitor.

The equations of TCSC in D-Q frame of reference can be given as

$$\frac{dV_{\tau CD}}{dt} = (I_D - b_{Ceff} V_{\tau CQ})\frac{\omega_B}{b_{c\tau c}} \qquad (10)$$

$$\frac{dV_{\tau CQ}}{dt} = (I_Q - b_{Ceff} V_{\tau CD})\frac{\omega_B}{b_{c\tau c}} \qquad (11)$$

Where,

$$b_{Ceff}(p.u.) = C_{\tau c}(p.u.) = \frac{1}{X_{\tau c}}(p.u.)$$

$$b_{Ceff}(p.u.) = C_{\tau c}(p.u.)$$

$$L_d(p.u.) = X_d(p.u.)$$

$$C_{eff(\sigma)} = \left[\frac{1}{C_{tC}} - \frac{4}{\pi}\left\{\frac{1}{2C_{tC}}\frac{1}{1-k_t^{-2}}\left(\frac{\sigma}{2} + \frac{\sin(\sigma)}{2}\right) + \frac{\omega_r L_{tL} S_{kt}}{k_t^2 - 1} cos^2\left(\frac{\sigma}{2}\right)\left(\tan\left(\frac{\sigma}{2}\right) - k_t \tan\left(\frac{k_t\sigma}{2}\right)\right)\right\}\right] \quad (12)$$

Where,

$$\omega_r = \sqrt{\frac{1}{C_{tC} L_{tL}}}$$

$$S = \frac{1}{1 - k_t^{-2}}$$

$$k_t = \sqrt{\frac{X_{tC}}{X_{tL}}}$$

The prevailing conduction angle σ can be approximated as

$$\sigma = \sigma^* + 2\emptyset$$
$$= \sigma^* + 2\arg[-jIV_{tc}]$$
$$= \sigma^* + 2\arg[(I_D V_{tcQ} \text{-} I_Q V_{tcQ}) - j(I_Q V_{tcQ} + I_D V_{tcD})] \quad (13)$$

To simplify the analysis, only constant ring angle control is considered. In steady state, this is equivalent to the constant reactance control.

D. SSSC Modelling

Static Synchronous Series Compensator (SSSC) is one of the important series FACTS devices. SSSC is a solid-state voltage source inverter, injects an almost sinusoidal voltage, of variable magnitude in series with the transmission line. The injected voltage is almost in quadrature with the line current. A small part of the injected voltage, which is in phase with the line current, provides the losses in the inverter.

Most of the injected voltage, which is in quadrature with the line current, emulates an inductive or a capacitive reactance in series with the transmission line. This emulated variable reactance, inserted by the injected voltage source, influences the electric power flow through the transmission line.

A SSSC operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted active power.

The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behaviour of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall resistive voltage drop across the line.

The Fig. 3 shows the schematic representation of SSSC.

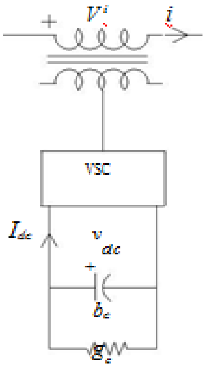

Fig. 3SSSC Model

Here, the SSSC is realized by a combination of 12 pulseand three level configuration [5]. The three level converter topology greatly reduces the harmonic distortion on the ac side . The detailed three phase model of SSSC is developed by modelling the converter operation by switching functions [5, 13].

When switching functions are approximated by their fundamental frequency components, neglecting harmonics, SSSC can be modelled by transforming the three phase voltages and currents to D-Q variables using Kron'stransformation .

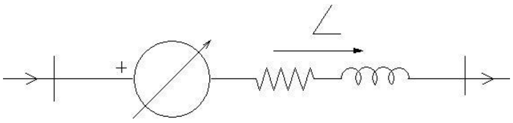

Fig. 4SSSC Equivalent Circuit

In Fig. 4, R_{st} and X_{st} are the resistance and reactance of the interfacing transformer of VSC. The magnitude control of converter output voltage V^i is achieved by modulating the conduction period affected by dead angle of converter while dc voltage is maintained constant.

The converter output voltage can be represented in D-Q frame of reference as:

$$V^i = \sqrt{V_D^{i2} + V_Q^{i2}} \quad (14)$$

$$V_D^i = k_m V_{dc} \sin(\emptyset + \gamma) \quad (15)$$

$$V_Q^i = k_m V_{dc} \cos(\emptyset + \gamma) \quad (16)$$

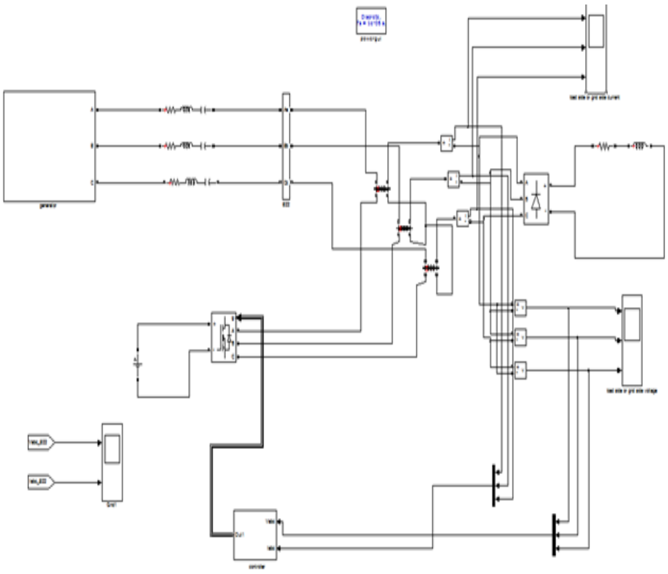

Fig. 5Simulation of SSSC Model

where ,

$k_m = k\cos\beta_{se}$; $k = \frac{\sqrt[2]{6}}{\pi}$ for a 12 pulse converter.

From control point of view it is convenient to define the active voltage ($V_{P(se)}$) and reactive ($V_{R(se)}$) voltage injected bySSSC
in terms of variables in D-Q frame (V_D^i and V_Q^i) as follows.

$$V_{R(se)} = V_D^i \cos\emptyset - V_Q^i \sin\emptyset \qquad (17)$$

$$V_{P(se)} = V_D^i \sin\emptyset + V_Q^i \cos\emptyset \qquad (18)$$

Here, positive $V_{R(se)}$,implies that SSSC injects inductive voltage and positive $V_{P(se)}$,implies that it draws real power to meet losses.

V. Comparison of the SSSC and TCSC

The SSSC offers inherent functional characteristics and compensation features, steaming from the unique attributes of a voltage source converter for series line compensation not achievable by thyristor-controlled series capacitors schemes. These characteristics and features can be summarized as follows:

1. It is capable of internally generating a controllable compensating voltage over an identical capacitive and inductive range independently of the magnitude of the line current.
2. With the ability to interface with an external dc power supply it can provide compensation for the line resistance, as well as for the line reactance , for the purpose of keeping the effective X_{Leff}/R ratio high, independently of the degree of series compensation.
3. With an energy storage (or sink), highly effective damping of power oscillation is possible by modulating by series reactive compensation to increase and decrease transmitted power, and by concurrently injecting an alternating virtual positive and negative real impedance is sympathy with the prevalent machine swings.
4. It has a substantially voltage source type impedance versus frequency characteristics which excludes classical series resonance with the reactive line impedance.

VI. Simulation

In the system considered, in generator side we have low pressure and high pressure turbine, the transmission line with parameters like resistance inductance and capacitance to install the TCSC or SSSC to analyse the controller path of PWM hysteresis controller, step-up transformer to step up the supply, and the grid side is connected to a 500 MW load.

The analysis is carried out in MATLAB/Simulink on the following initial operating condition and assumptions.
1. The generator delivers 0.9 p.u. power to the transmission system.
2. The input mechanical power to the turbine is assumed constant.
3. The total series compensation level is set at 0.6 p.u.(60% of the transmission line reactance).

The following cases are considered for the analysis.
Case-1: Without TCSC/SSSC (compensation only by fixed capacitor, Xc = 0:60)
Case-2: With TCSC (Xc=0.40, XT CSC = 0:20 with vernier ratio=XT CSC =X tc =1.25)
Case-3: Without TCSC/SSSC,Xc = 0:40
Case-4: With SSSC (Xc=0.40,XSSSC = 0:20 with constant reactive voltage control).

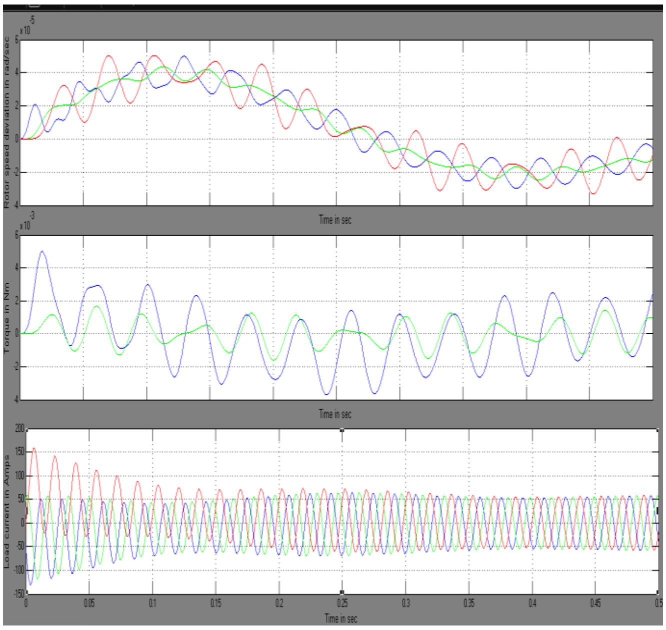

Fig. 6Rotor deviation, Torque, load current waveforms of simulated system with TCSC connected.

In TCSC, high pressure turbine (during transmission) peak torque exceeds 4 N-m and in low pressure turbine the peak torque exceeds 1.5 N-m. Due to this above variations the grid side current oscillations i.,e subsynchronous oscillations would be very high which is shown in the Fig 6.

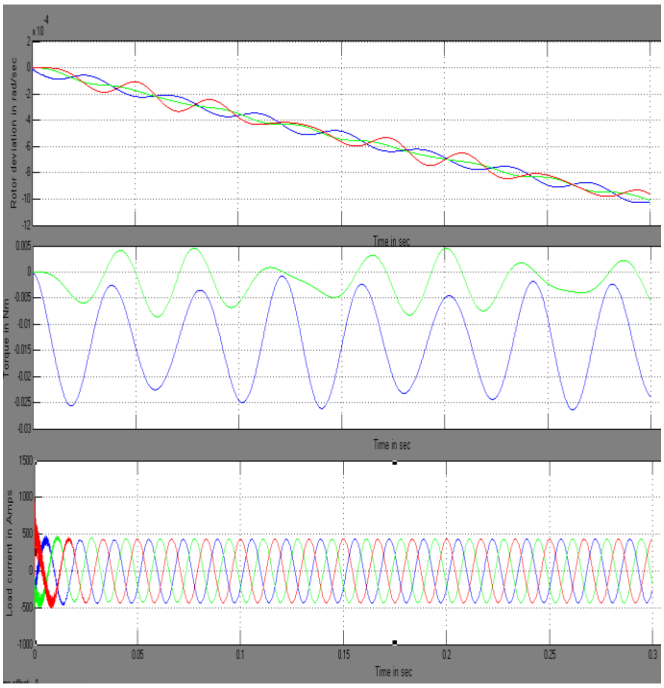

Fig. 7Rotor deviation, torque, load current waveforms of simulated system with SSSC connected.

Where as in SSSC, high pressure turbine (during transmission) peak torque was limited to a much lesser value compared to TCSC and even in low pressure turbine the peak torque could be maintained well within 1 N-m. Hence in the system connected with SSSC the grid side current oscillations i.,e subsynchronous oscillations was mitigated to a much lower value as shown in the Fig 7&8.

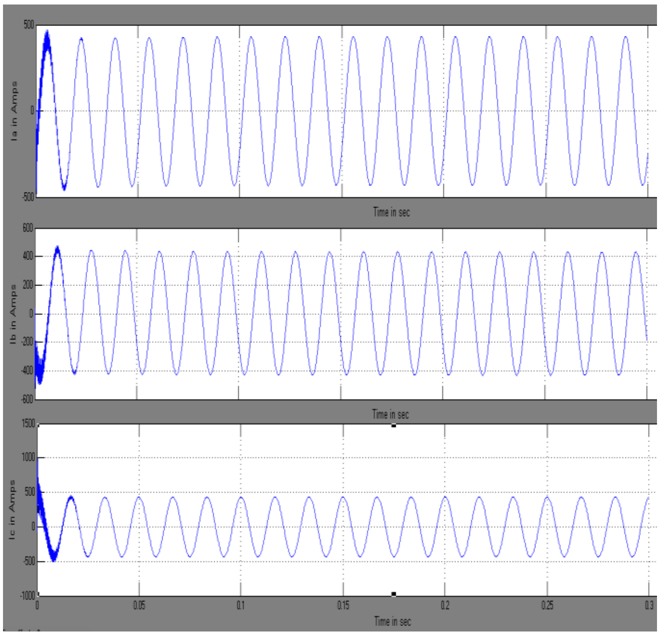

Fig. 8Load current (I_a, I_b, I_c) waveforms of simulated system with SSSC connected.

VII. CONCLUSION

In this paper, we have analyzed the SSR characteristics of a series compensated transmission line with TCSC and SSSC. While in the case of TCSC, a properly designedPI was used for damping the critical torsional mode oscillations. In SSSC, a PWM based controller was used which shows a better damping of both torsional oscillation on the generator side and grid current oscillations.

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