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Comparative Study On Damping Of SSR Using SSSC With & Without Incorporation Of Subsynchronous Current Suppressor

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Abstract

Series capacitive compensation is the most economical way to increase transmission capacity and improve transient stability of transmission grids. However, one of the impeding factors for the widespread use of series capacitive compensation is the potential risk of Subsynchronous Resonance (SSR). Subsynchronous Resonance is a phenomenon in which electrical power is exchanged with the generator shaft system in an increasing manner which may result in damage to the turbine generator shaft system.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 sub-synchronous current suppressor and effectively mitigates SSR.Using the IEEE First Benchmark Model, the effectiveness of the proposed controller when mitigating SSR due to torsional interaction and torque amplification effect will be shown. Linear analysis is performed on D-Q model of the system with SSSC and the results are tested by executing transient simulation based on detailed nonlinear three-phase model.

***Keywords*–**SSCS,SSSC, Subsynchronous resonance (SSR), Flexible AC transmission system (FACTS),Torsional oscillation.

1. 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 with andwithout SSCS are compared in [8] and 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 and without SSSC based on SSCS 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 SSSC with and without SSCS is compared to same system individually.

2. SUBSYNCHRONOUSRESONACNE IN POWER SYSTEMS

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.

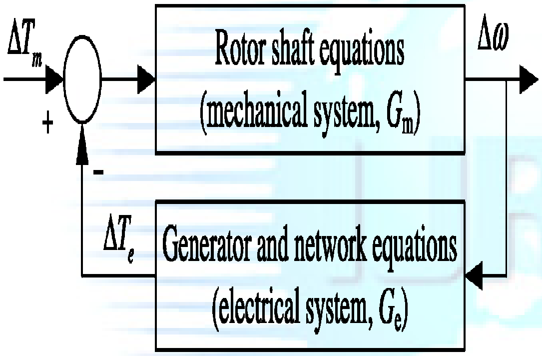


Fig.1. Block scheme representing interaction between electrical and mechanical system.

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

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

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}.

3. 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].

3.1 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."

3.2Torsional 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."

3.3 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 analyzedusing linear models, suggesting that Transient simulation analysis is appropriatefor the study of these problems.

4. SYSTEM MODELLING

We shall now demonstrate the damping effects of SSSC based SSCS 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].

4.1. Combined Generator and Shaft System Model

The linearized state equations are given by:

$$\Delta x_G = [\ A_G\ ]\ \Delta x_G + [\ B_{G1}\ ]\ \Delta u_g + [\ B_{G2}\ ]\ E_{fd} \quad (3)$$

$$\Delta y_G = [\ C_G\ ]\ \Delta x \qquad (4)$$

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

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

$$[\Delta x_e]^t = [\Delta\Psi_e \ \ \Delta\Psi_q \ \ \Delta E_{d'} \ \ \Delta E_{q'}] \qquad (6)$$

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

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

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

4.2. 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):

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

4.3. 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. 2shows the schematic representation of SSSC.

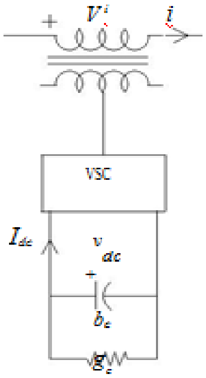


Fig. 2SSSC Model

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 .

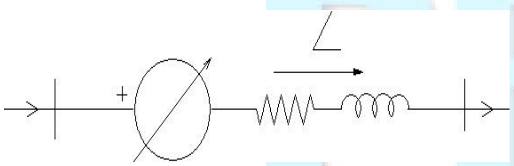


Fig. 3SSSC Equivalent Circuit

In Fig. 3, 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:

$$V^i = \sqrt{V_D^{i2} + V_Q^{i2}} \qquad (10)$$

$$V_D^i = k_m V_{dc} \sin(\emptyset + \gamma) \qquad (11)$$

$$V_Q^i = k_m V_{dc} \cos(\emptyset + \gamma) \qquad (12)$$

where ,

$k_m = k \cos \beta_{se}$; $k = \frac{2\sqrt{6}}{\pi}$ 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.

$$V_{R(se)} = V_D^i \cos \emptyset - V_Q^i \sin \emptyset \qquad (13)$$

$$V_{P(se)} = V_D^i \sin \emptyset + V_Q^i \cos \emptyset \qquad (14)$$

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.

5.DESIGN OF SSCS

Damping of SSR can be obtained by designing a subsynchronous damping controller (SSDC) which provides positive damping in the range of critical torsional mode of frequencies. Damping of SSR using SSSC is achieved by SSDC which takes Thevenin voltage signal using locally available SSSC bus voltage and is used to modulate the reactive reference current to improve the damping of unstable torsional modes. The present work pro- poses the improvement of damping of critical torsional modes by extracting subsynchronous components of line current and injecting a proportional voltage to suppress the subsynchronous frequency currents. This is a simple method which reduces the magnitude of subsynchronous currents flowing through the generator and is termed as subsynchronous current suppressor(SSCS).

The extraction of subsynchronous frequency current com- ponent is achieved by band-pass filters operate in rotating D-Q coordinates. Accordingly the tuning of filters depends on the multimass turbine-generator shaft torsional frequencies. Hence it is adequate to design filter based on the knowledge of torsional mode frequencies to extract the subsynchronous frequency components to damp SSR.

In this paper, the IEEE FBM with six mass mechanical system is considered, which has five natural torsional mode frequencies. The torsional mode frequency is taken as the center frequency and the pass band of filter is chosen from the Eigen value analysis in which torsional mode is unstable for the band of subsynchronous network mode frequencies closer to that of critical torsional frequency. The frequency response of band-pass filters for all critical torsional modes. This method of filter design is also valid for any transmission network topologies as only the complement of network resonance frequencies $(\omega_0 - \omega_{er})$ matches with torsional frequencies (ω_m) cause SSR.

The block diagram of subsynchronous current suppressor to extract subsynchronous frequency components from the line current. Two band-pass filters (in D-Q frame) are used to extract each torsional frequency component I_{Dsub} and I_{Qsub} from the line current I_D and I_Q. Each filter set is effective only for their corresponding torsional mode frequency and improve the damping of respective torsional modes by reducing the negative damping.

Subsynchronous current suppressor extracts subsynchronous frequency currents corresponding to modes 1, 2, 3, and 4 passed through appropriate gains k_1 to k_8 for obtaining V_{Dsub} and V_{Qsub} and sum up the signal to obtain V_{Ds} and V_{Dq} as mentioned in the following.

$$V_{Ds} = \sum_m V_{Dsub} \qquad (15)$$

$$V_{Ds} = \sum_m V_{Dsub} \qquad (16)$$

where m is the torsional mode (1, 2, 3, and 4)

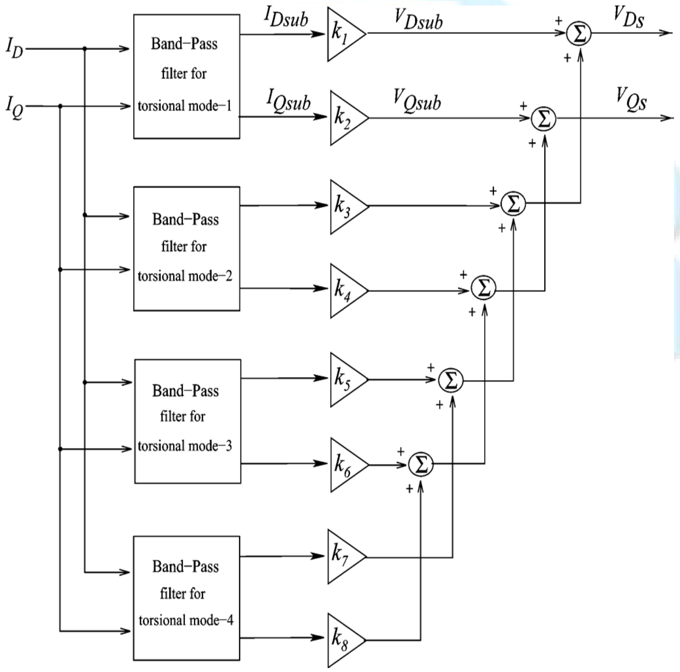


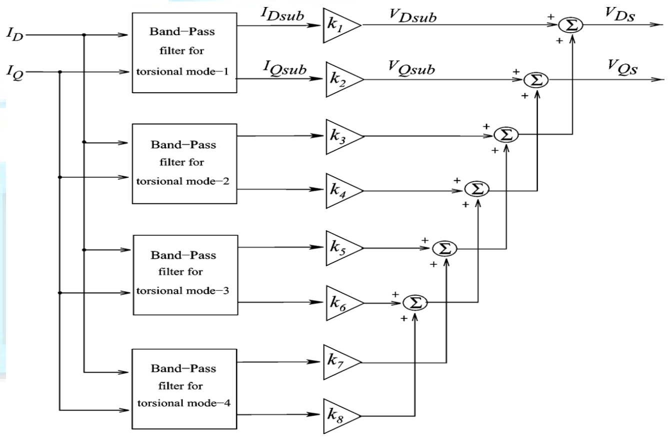
Fig 4. Block diagram of Subsynchronous Current Suppressor

Since modal inertia of torsional mode 5 is very high, mode 5 is never excited and filter to extract mode 5 frequency component is not desired. The extracted subsynchronous voltage orders V_{Ds} and V_{Dq} (in D-Q frame of reference) are transformed to inphase and quadrature components $V_{P(sub)}$ and $V_{Q(sub)}$ respectively, and are used to modulate the in phase and quadrature voltage orders $V_{P(ord)}$ and $V_{Q(ord)}$ of SSSC.

The subsynchronous frequency components of various modes extracted from line current are passed through a suitable gains k_1 to k_8 and the damping of critical torsional modes are improved by properly tuning k_1 to k_8 using GA making use of damping torque analysis. Genetic algorithm has been used to optimize the parameters of control system that are complex and difficult to solve by conventional optimization methods.

6. 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 SSSC based SSCS to analyse the controller path of damping controller, step-up transformer to step up the supply, and the grid side is connected to a 500 MW load.



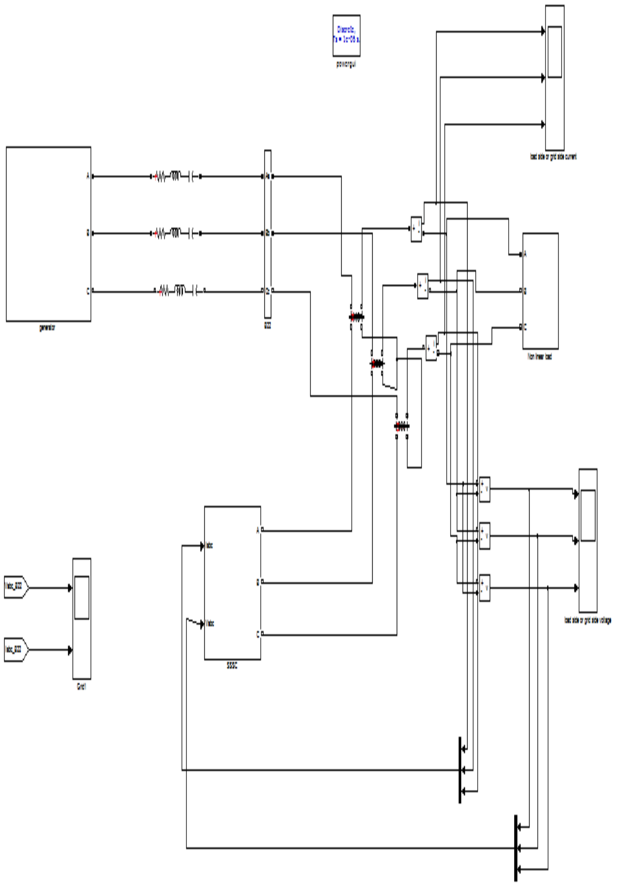


Fig 5 Simulation Diagram of Damping of SSR Without SSCS

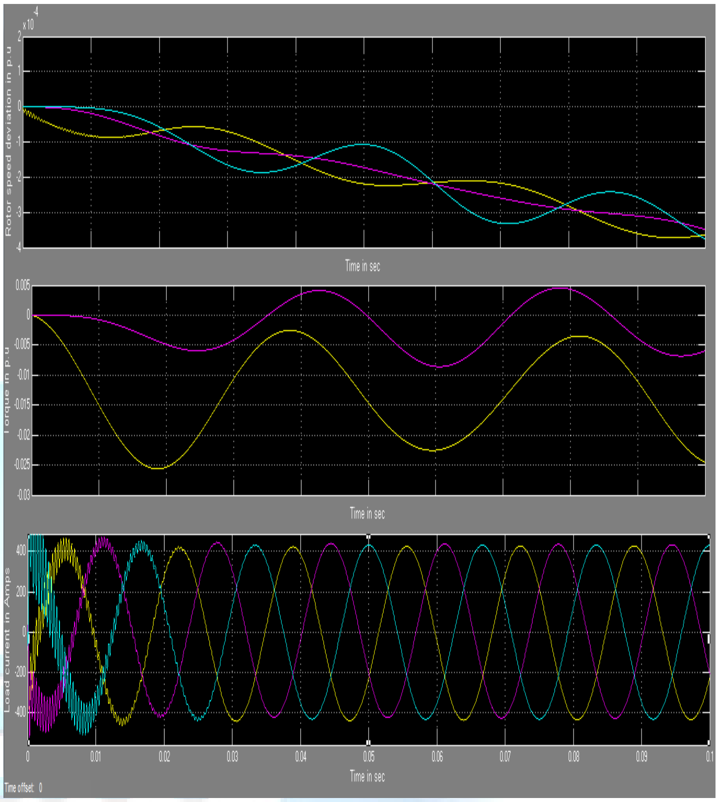


Fig 6 Rotor speed deviation, Torque, Load current waveforms of simulated system without SSCS.

In general, 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.esubsynchronous oscillations (SSR) would be very high which is shown in the Fig 4.2.

Variation of damping torque is shown in Fig. 8 for case 1 and 2. It is to be noted that without SSCS (case-1), damping torque goes maximum negative at a frequency and matches with torsional mode-1 frequency and severe torsional interactions are expected. In case-2 with the inclusion of SSCS, the peak negative damping is significantly reduced and shifts the network mode frequency (subsynchronous) and hence undamping of torsional mode-1 is also reduced.

The shifted subsynchronous electrical frequency matches with mode-2 torsional frequency and the corresponding torsional mode becomes unstable. Again, the active power exchanged with the line has to be maintained at zero hence, in steady state operation, SSSC is a functional equivalent of an infinitely variable series connected capacitor. The SSSC offers fast control and it is inherently neutral to sub synchronous resonance.

In Subsynchronous current suppressor both magnitude (modulation index) and phase angle of converter output voltage are controlled. The dc side capacitor voltage is maintained at a constant voltage by controlling real voltage. The real voltage reference is obtained as the output of dc voltage controller. The reactive voltage reference may be kept constant or obtained from a power scheduling controller. However, for the SSR analysis constant reactive voltage control is considered.

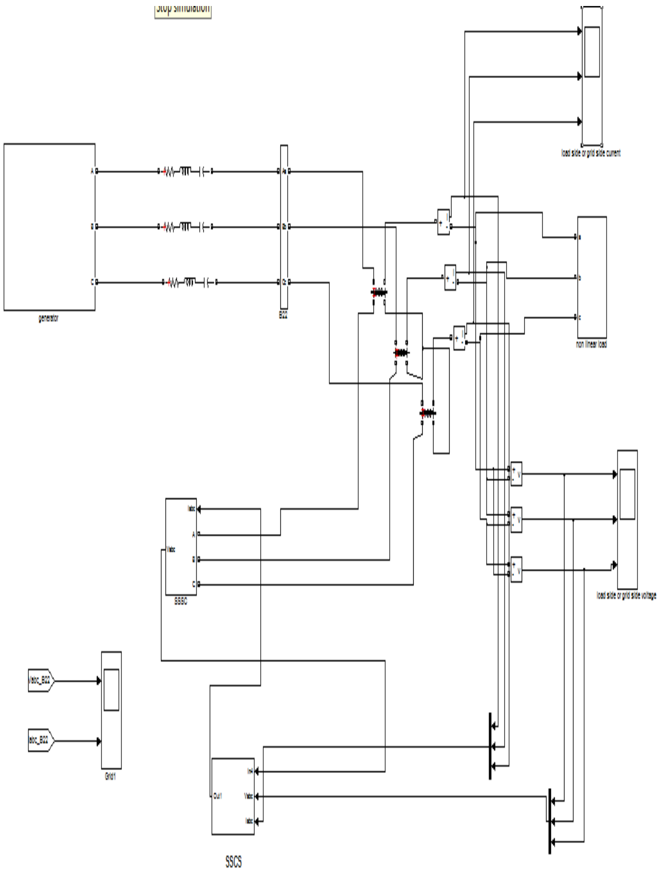


Fig 7 Simulation Diagram of Damping of SSR With SSCS

Where as in SSSC combined with SSCS, high pressure turbine (during transmission) peak torque was limited to a much lesser value compared to general system and even in low pressure turbine the peak torque could be maintained well within 1 N-m. Hence in the system connected with SSSC based SSCS the grid side current oscillations i.,esubsynchronous oscillations was mitigated to a much lower value as shown in the Fig 4.4 and Fig 4.5.

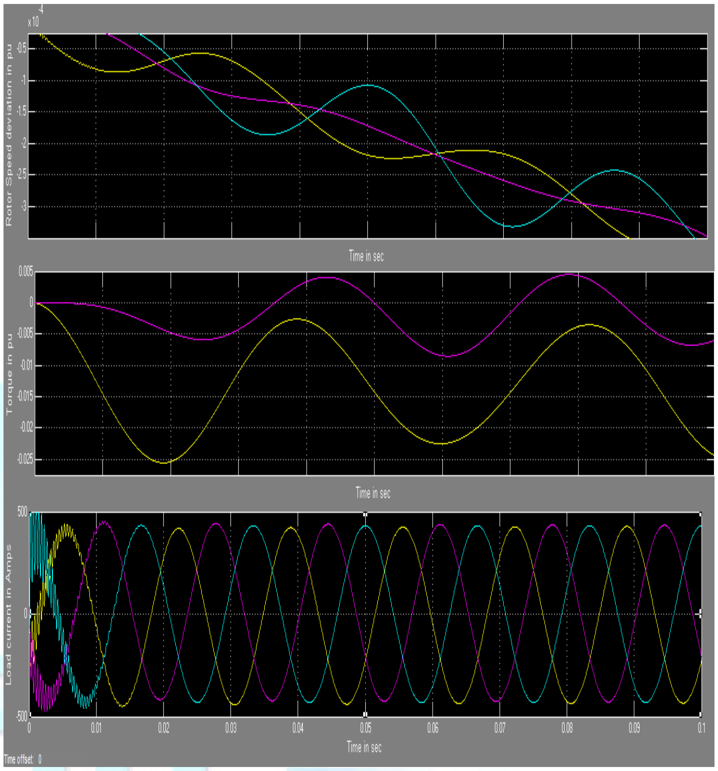


Fig 8 Simulation Output of Damping of SSR With SSCS

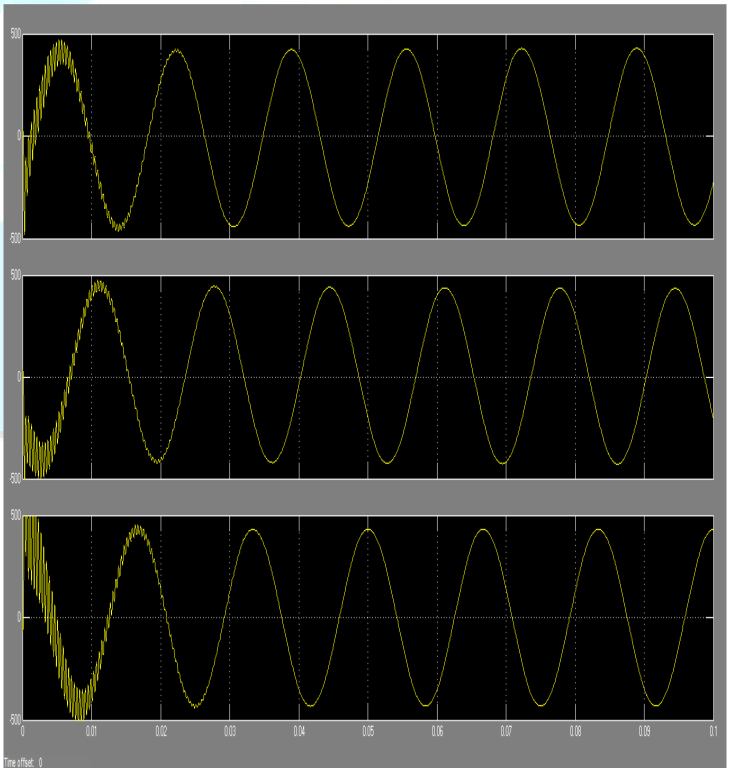


Fig 9 Simulation Diagram of Damping of SSR With SSCS

The turbine generator has a natural mechanical resonant frequency that is in the order of 18-25 Hz. The most likely candidates for this are long shafts with multiple masses a high-pressure turbine, low-pressure turbine, generator, exciter, etc. The combinations of masses lead to a natural resonant frequency, and in most cases, a single shaft may have multiple resonance 'modes' or frequencies.

The SSR problems under various operating conditions can be predicted by using damping torque analysis. The correlation of damping torque analysis and eigen value results in predicting torsional mode stability is discussed in detail in which demonstrates the importance of damping torque analysis to determine the torsional mode stability.

7. CONCLUSION

In this project, we have analyzed the characteristics of a transmission line compensated by series capacitor with SSSC. The converters are modeled using switching functions. Neglecting harmonics in the switching functions enables the derivation of time invariant models based on D-Q variables. The Subsynchronous Current Suppressor parameters are tuned based on damping torque to get optimum performance to improve the damping of all torsional frequencies. The performance of Subsynchronous Current Suppressor is satisfactory in the entire range compensation level and found to be robust. SSSC reduces the peak negative damping, properly designed Subsynchronous Current Suppressor improves the damping of all the critical torsional modes at all compensation level. Simulation results reveal that SSR is mitigated with the placement of SSSC.

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