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Damping of Sub synchronous Resonance Using SSSC Based PWM Hysteresis Controller

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Abstract—Electricity systems are very complex systems and are composed of numerous transmission lines, generators and loads. The generating stations are generally far away from load centers and that may cause transmission line congestion and overloading. Series capacitive compensation is the most economical way to increase transmission capacity and improve transient stability of transmission grids. However, one of the impending factors for the widespread use of series capacitive compensation is the potential risk of Subsynchronous Resonance (SSR). In this paper a brief analysis of SSR using series connected FACTS devices for subsynchronous resonance (SSR) and power swing damping was accomplished and effectiveness of SSSC based three phase hysteresis current controller. The MATLAB/Simulink was used to successfully accomplish the analysis and simulation studies.

Index Terms—SSSC, SSR, FACTS devices, Torsional oscillation, Hysteresis current controller.

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 Sub synchronous 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 hybrid compensation is reported 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 sub synchronous damping controller (SSDC) with SSSC is desired for damping critical torsional modes when the line resistance is low. A method for online estimation of sub synchronous voltage components in power systems is described and used for the mitigation of SSR [13]. The damping of SSR using single phase VSC based SSSC is reported. 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 sub synchronous component of line current using filter. The extracted sub synchronous frequency component of line current is used to inject a proportional sub synchronous voltage in series with the transmission line which suppresses sub synchronous current in the transmission network. This novel technique is termed as sub synchronous current suppressor and effectively mitigates SSR. Then finally the mitigation of SSR using SSSC based hysteresis current controller.



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II. ANALYSIS OF SUBSYNCHRONOUS RESONANCE

Sub synchronous Resonance (SSR) is a condition that can exist on a power system where the network has natural frequencies that fall below the fundamental frequency of the generated voltages and produce sub synchronous oscillation of the steam turbine and generator shaft. The oscillations are caused by the electrical resonance of the synchronous generator and the capacitor compensated transmission lines. Turbine-generators are increasingly subject to electrical environments that react with turbine-generator shafts to produce resonance (torsional vibrations) at shaft natural frequencies. These torsional vibration cause cumulative fatigue damage when they exceed material fatigue limits and result in reduced component life of parts such as shafts, buckets (blades), retaining rings, and rotors. In some severe cases, these adverse interaction have led to growing oscillations and shaft damage, including twisted couplings and broken shafts. There are several ways in which the system and the generator may interact with sub synchronous effects. A few of these interactions are basic in concept and have been given special names.

A. INDUCTION GENERATOR EFFECT

This phenomenon is caused by self-excitation of the electrical network. The resistance of the generator to sub synchronous current, viewed looking into the generator at the armature terminals is a negative resistance over much of the sub synchronous frequency range. If the negative resistance of the generator is greater in magnitude than the positive resistance of the network at one of the network natural frequencies, growing sub synchronous currents can be expected.

B. TORSIONAL INTERACTION

When a torsional oscillation occurs to the turbines and generator rotating system at a sub synchronous frequency, while the generator field winding itself on the rotor is rotating at an average speed corresponding to the system frequency, there will be voltages and currents induced in the generator armature three phase winding at frequency of subtract of them. If this frequency coincide or be very close to an electrical resonance frequency of the generator and transmission system, the torsional oscillation and the electrical resonance will be mutually excited or reinforced resulting in SSR.

C. TRANSIENT TORQUES

Transient torques are torques that results from large system disturbance, such as faults. System disturbances cause sudden changes in the network, resulting in sudden changes in currents with components that oscillate at the natural frequencies of the network for networks that contain series capacitors, the transient currents will contain one or more oscillatory frequencies that depend on the network capacitors.

III. NATURAL FREQUENCY

The Natural Radian Frequency is

$$\omega_n = \frac{1}{\sqrt{LC}} = \left(\frac{\omega_s}{X_L} \omega_s X_C \right)^{\frac{1}{2}} = \omega_s \sqrt{S} \quad (1)$$

Where

$$L = \frac{X_L}{\omega_s} \text{ And } C = \frac{1}{\omega_s X_C}$$

In terms of system frequency

$$\frac{f_n}{f_s} = \frac{\omega_n}{\omega_s} = \sqrt{S} \quad (2)$$

Where s is degree of series compensation “ S ” varies between 0 and 1 i.e. ($0 < S < 1$) If $S = 0$, there is no series compensation. If $s=1$, we have 100% series compensation, the line has no reactance and only resistance predominates. Then power transfer, as with direct current, only by difference of voltage magnitudes, not by phase difference, and system is unstable. For $s > 1$, the net circuit reactance is capacitive, and power curve is inverted. If $0 < s < 1$, then also $0 < \sqrt{S} < 1$ and $f_n < f_n$ There exit a risk of SSR. Where ω_n is the natural frequency associated with a particular line LC product, ω_n is the system base frequency, and X_L and X_C are the inductive and capacitive reactance’s respectively. These frequencies appear to the generator rotor modulations of the base frequency, giving both sub synchronous and super synchronous rotor frequencies. It is the sub synchronous frequency that may interact with one of the natural torsional modes of the turbine-generator shaft, there by setting up the conditions for an exchange of energy at a sub synchronous frequency, with possible torsional fatigue damage to the turbine-generator shaft. The torsional modes (frequencies) of shaft oscillation are usually known, or may be



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obtained from the turbine-generator manufacturer. The network frequencies depend on many factors, such as the amount of series capacitance in service and the network switching arrangement at a particular time.

IV. IMMUNITY TO RESONANCE

A series capacitor is also used to provide series compensation in power systems so far. However, the impedance of the series capacitor is a function of frequency and thus it may cause resonances at various frequencies with other reactive impedances present in the network. The resonance of greatest concern is that occurring with the series reactive impedance of the system at a frequency below the fundamental. At this frequency the electrical system may reinforce one of the mechanical resonances of certain turbine generators, causing the well-understood phenomenon of Sub-Synchronous Resonance (SSR), which may result in serious damage to the generator. In contrast to a series capacitor or to the combination of a series capacitor and a Thyristor Controlled Reactor (TCR), the static synchronous series compensator is essentially an ac voltage source which, with fixed control inputs, would operate only at the selected (fundamental) output frequency, and its output impedance at other frequencies would theoretically be zero. In practice, the SSSC does have relatively small inductive output impedance provided by the leakage inductance of the series insertion transformer. The voltage drop across this impedance is automatically compensated at the fundamental frequency when the SSSC provides capacitive line compensation. Thus, the effective output impedance versus frequency characteristic of the SSSC remains that of a small inductor at all but its fundamental operating frequency. Consequently, the SSSC is unable to form a classical series resonant circuit with the inductive line impedance to initiate sub synchronous system oscillations. On the other hand, the SSSC has a very fast (almost instantaneous) response and can be very effective in the damping of sub synchronous oscillations (which may be present due to existing series capacitors) if the electronic control is structured to provide this function. (In discussing dynamic interactions, it is of course that the SSSC, like all actively controlled equipment, could under abnormal conditions exhibit instability or oscillatory interaction with the ac system if, for example, its closed-loop gains, providing automatic power flow control or other regulative functions, are improperly set, or if the electronic control itself malfunctions. However, these considerations are generic to all actively controlled systems and involve other subjects like control robustness, control redundancy, and protection, which are out of scope of this paper.)

V. INTERNAL CONTROLS

From the standpoint of output voltage control, converters may be categorized as “directly” and “indirectly” controlled. For directly controlled converters both the angular position and the magnitude of the output voltage are controllable by appropriate valve (on and off) gating. For indirectly controlled converters only the angular position of the output voltage is controllable by valve gating; the magnitude remains proportional to the dc terminal voltage. The control method of maintaining a quadrature relationship between the instantaneous converter voltage and line current vectors, to provide reactive series compensation and handle SSR, can be implemented with an indirectly controlled converter.

The method of maintaining a single frequency synchronous (i.e. fundamental) output independent of dc terminal voltage variation requires a directly controlled converter. Although high power directly controlled converters are more difficult and costly to implement than indirectly controlled converters (because their greater control flexibility is usually associated with some penalty in terms of increased losses, greater circuit complexity, and/or increased harmonic content in the output), nevertheless they can be realized to meet practical utility requirements.

VI. CLASSICAL HYSTERESIS CURRENT CONTROLLER

In this work, the current control of converter is a hysteresis current controller. It is used due to simple, fast dynamic response and insensitive to load parameters. Figure.1 (a) and 1(b) represents the hysteresis current controller. In this method each phase consists of comparator and hysteresis band. The switching signals are generated due to error in the current. The error comes from comparing between the reference current and actual current. The main task of this method of control is to force the input current to follow the reference current in each phase. The deviation of these currents (error current) represents the current distortion which can be calculated as

$$distortion = \frac{100}{I_{rms}} \sqrt{\frac{1}{T} \int (i_{act} - i_{ref})^2 dt} \% \quad (3)$$

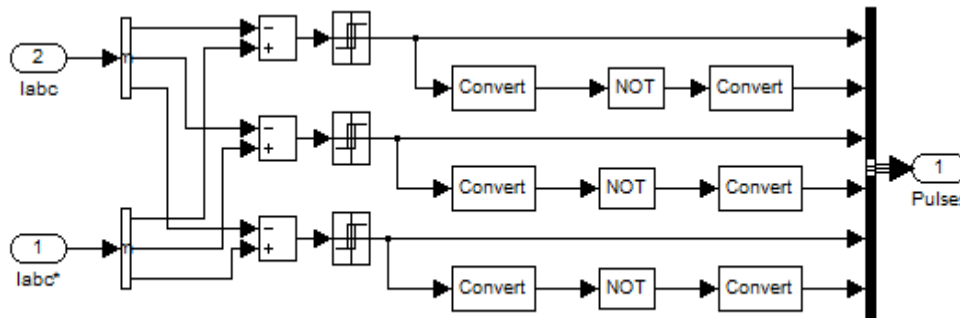


Fig.1 (a) Basic structure of Hysteresis Current Controller

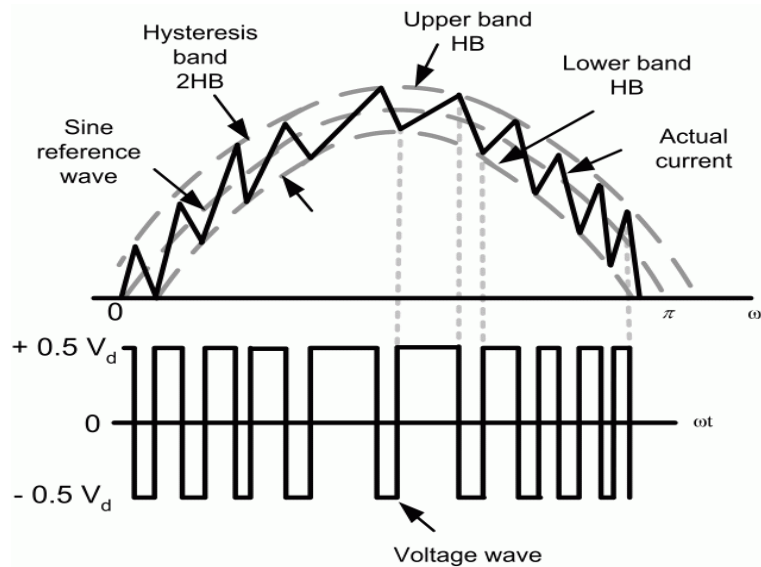


Fig. 1(b) Waveform of Hysteresis Current Controller

In this method of control, the deviation of the current between the upper and lower in the hysteresis band is limited. In any phase, if the actual current becomes more than the upper limit of hysteresis band ($i_{ref} + HB$) the upper switch of the inverter arm is turned off, the lower switch is turned on and the current starts to decay. In contrast if the actual current reaches lower limit or less than of hysteresis band ($i_{ref} - HB$) the lower switch of the inverter arm is turned off, the upper switch is turned on and the current comes back into the hysteresis band. The band width calculates the switching frequency and current ripple. The band width is directly to current ripple and inversely proportional to switching frequency so the selection of the band width means performance of inverter. This is because the increasing in the band width will increase the current ripple in contrast; a decrease in the band width will increase the switching losses.

VII. MODELLING OF SSSC

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 behavior 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. 2 shows the schematic representation of SSSC.

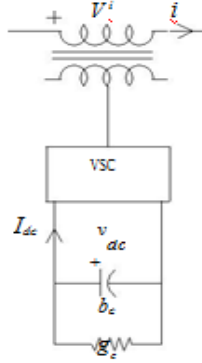


Fig. 2 SSSC Model

Here, the SSSC is realized by a combination of 12 pulse and three level configurations [4]. The three level converter topology greatly reduces the harmonic distortion on the aside [5, 6, 7, 8, 9]. The detailed three phase model of SSSC is developed by modeling the converter operation by switching functions [4, 10]. When switching functions are approximated by their fundamental frequency components, neglecting harmonics, SSSC can be modeled by transforming the three phase voltages and currents to D-Q variables using transformation. The SSSC can be represented functionally as shown in Fig. 3.

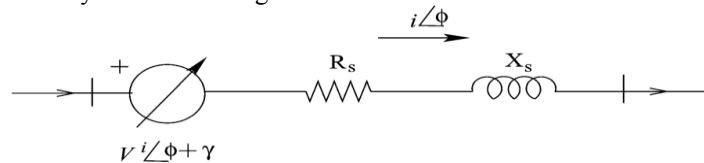


Fig. 3 Equivalent Circuit of SSSC

In Fig.3, R_{sr} and X_{sr} are the resistance and reactance of the interfacing transformer of VSC. The magnitude control of converter output voltage 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:

$$V^i = \sqrt{V_D^{i2} + V_Q^{i2}} \quad (4)$$

$$V_D^i = k_m V_{dc} \sin(\theta + \gamma) \quad (5)$$

$$V_Q^i = k_m V_{dc} \cos(\theta + \gamma) \quad (6)$$

where $k_m = k \cos \beta_{ss}$; $k = \frac{\sqrt{6}}{\pi}$ 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 by SSSC in terms of variables in D-Q frame (V_D^i and V_Q^i) as follows.

$$V_{R(se)} = V_D^i \cos \theta - V_Q^i \sin \theta \quad (7)$$

$$V_{P(se)} = V_D^i \sin \theta + V_Q^i \cos \theta \quad (8)$$

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.

VIII. SIMULATION RESULTS AND DISCUSSION

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 analyses 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).

A. WITHOUT SSSC

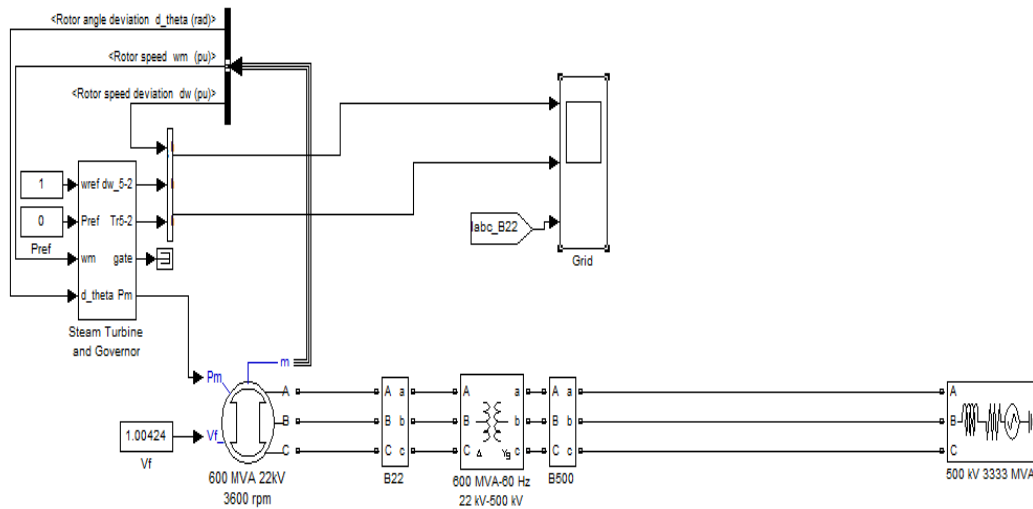


Fig. 4 Simulation Diagram of Without SSSC

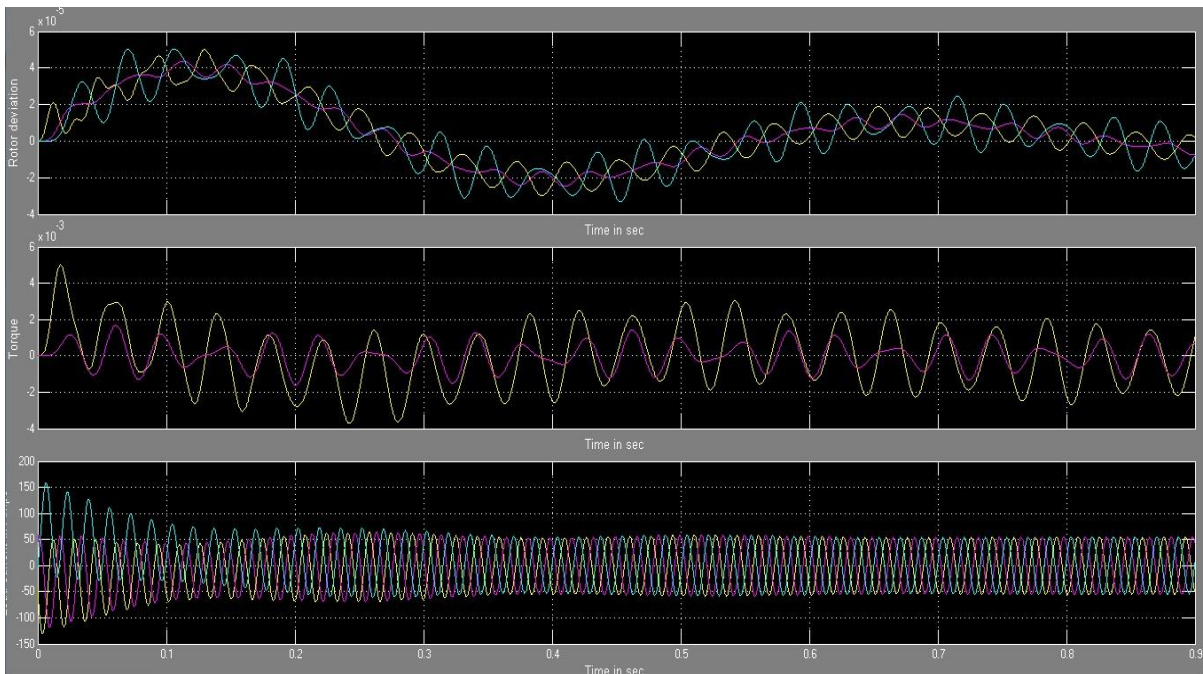


Fig. 5 Rotor deviation, Torque, Load current waveforms of simulated system without SSSC

B. WITH SSSC

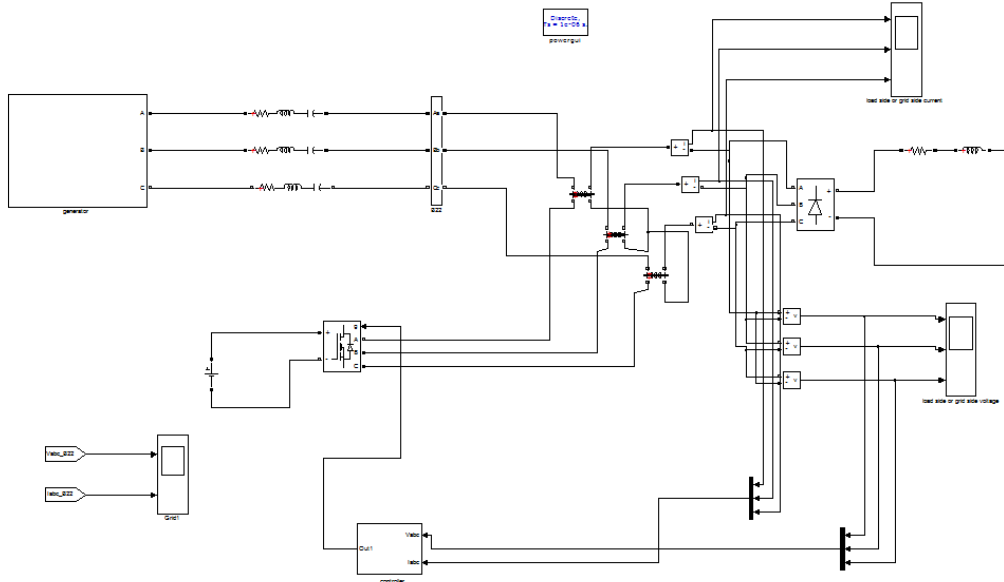


Fig. 6 Simulation Diagram of With SSSC

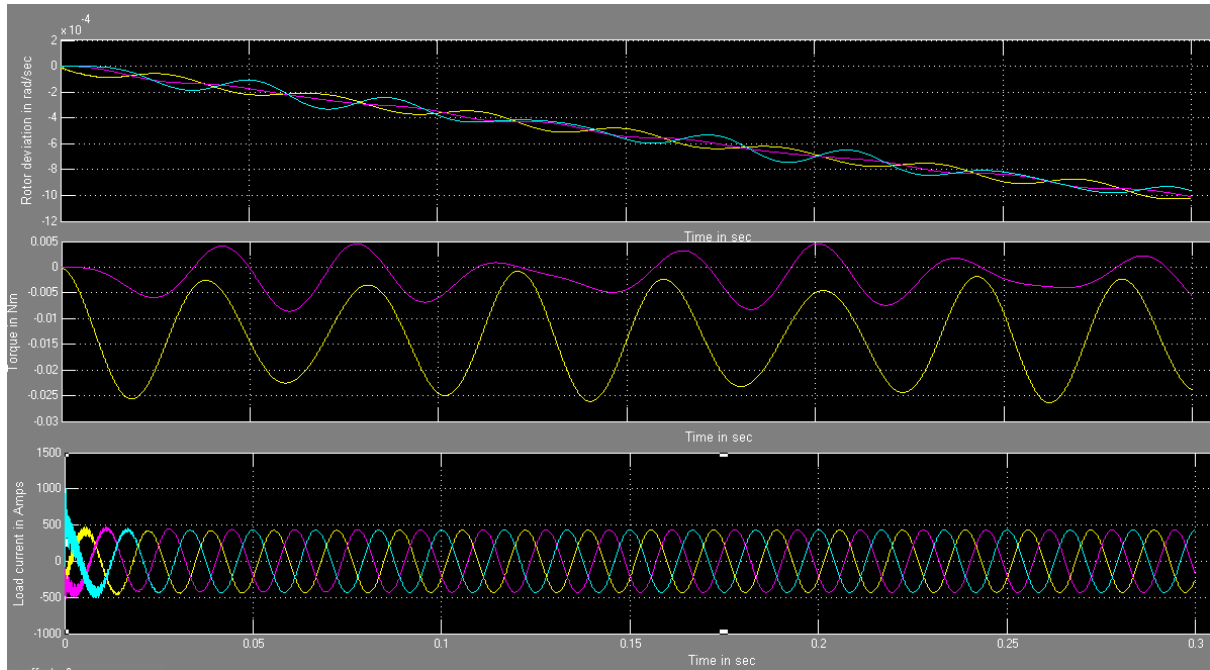


Fig. 7 Rotor deviation, Torque, Load current waveforms of simulated system with SSSC.

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.e. subsynchronous oscillations would be very high which is shown in the Fig 5



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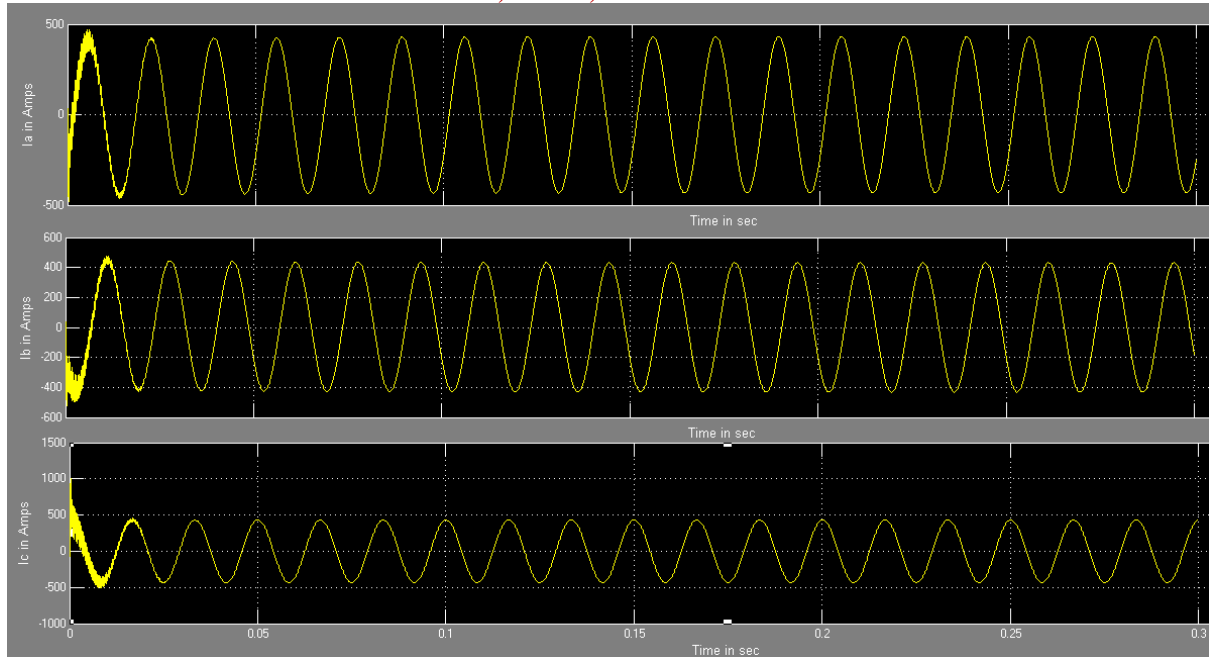


Fig. 8 Load current (I_a , I_b , I_c) waveforms of simulated system with SSSC connected.

Where as in SSSC, high pressure turbine (during transmission) peak torque was limited to a much lesser value compared to 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 the grid side current oscillations i.e sub synchronous oscillations was mitigated to a much lower value as shown in the Fig 7 and Fig 8 .

IX. CONCLUSION

In this paper, 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 predictions about the torsional mode stability using the various methods of analysis show good agreement. The following points emerge based on the results of the case study. 1) The inclusion of SSSC reduces the risk of SSR by detuning the network resonant frequency. 2) Although the SSSC reduces the peak negative damping, properly designed Hysteresis controller also reduces the harmonics transients and unwanted ripple quantities. 3) A simple and novel technique for the extraction of Sub synchronous frequency components using filters is proposed. The Hysteresis controller parameters are tuned based on damping torque to get optimum performance to improve the damping of all torsional frequencies. The performance of Hysteresis controller is satisfactory in the entire range compensation level and found to be robust.

REFERENCES

- [1] N. G. Hingorani and L. Gyugyi, Understanding FACTS. New York: IEEE Press, 2000.
- [2] Lie, X., Jaing, D., Yang, Y.T., 'Analyzing Sub synchronous Resonance Using a Simulation Program', IEEE Transaction on Power Apparatus and Systems, 2000.
- [3] Hossiani, S.H., Mirshekar, O., 'Optimal Control of SVC for Sub synchronous Resonance Stability in Typical Power System', IEEE Transaction on Power Apparatus and Systems, 2001.
- [4] K. R. Padiyar, Power System Dynamics—Stability and Control, 2nd ed. Hyderabad, India: B.S. Publications, 2002.
- [5] K. R. Padiyar and N. Prabhu, "Analysis of sub synchronous resonance with three level twelve-pulse VSC based SSSC," in Proc. IEEE TENCON-2003, Oct. 14–17, 2003.
- [6] K. R. Padiyar and V. SwayamPrakash, "Tuning and performance evaluation of damping controller for a STATCOM," Int. J. Elect. Power Energy Syst., vol. 25, pp. 155–166, 2003.



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International Journal of Engineering Science and Innovative Technology (IJESIT)

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- [7] [7] N.Prabhu, “Analysis of Sub Synchronous Resonance with Voltage Source Converter based FACTS and HVDC Controllers,” Ph.D.dissertation, IISc Bangalore, 2004.
- [8] K. R. Padiyar and N. Prabhu, “A comparative study of SSR characteristics of TCSC and SSSC,” in Proc. PSCC Conf. 2005, Liege, Belgium,
- [9] K. R. Padiyar and N. Prabhu, “Design and performance evaluation of sub synchronous damping controller with STATCOM,” IEEE Trans.Power Del., vol. 21, no. 3, pp. 1398–1405, Jul. 2006.
- [10] X. P. Zhang, Flexible AC Transmission Systems: Modeling and Control, Berlin: Springer, 2006.
- [11] K. R. Padiyar, FACTS Controllers in Power Transmission and Distribution. New Delhi, India: New Age International, 2007.
- [12] M. Bongiorno, J. Svensson, and L. Angquist, “Online estimation of subsynchronous voltage components in power systems,” IEEE Trans.Power Del., vol. 23, no. 1, pp. 410–418, Jan. 2008.
- [13] M. Bongiorno, J. Svensson, and L. Angquist, “On control of static synchronous series compensator for SSR mitigation,” IEEE Trans. Power Electron., vol. 23, no. 2, pp. 735–743, Mar. 2008.
- [14] M. Bongiorno, J. Svensson, and L. Angquist, “Single-phase VSC based SSSC for sub synchronous resonance damping,” IEEE Trans. Power Del., vol. 23, no. 3, pp. 1544–1552, Jul. 2008.
- [15] N. Prabhu and K. R. Padiyar, “Investigation of sub synchronous resonance with VSC based HVDC transmission systems,” IEEE Trans.Power Del., vol. 24, no. 1, pp. 433–440, Jan. 2009.