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Mitigation of SSR using Sub-Synchronous Current Control Technique – Analysis and Simulation using Matlab/Simulink

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Abstract: In this paper, the mitigation of sub–synchronous resonance using three single phase VSC based bridges (SSSC) will be presented. The sub-synchronous current will be separated using estimation algorithm as well as resonant filter and made zero by Injecting sub-synchronous voltage using novel control strategy as it is responsible for Sub-Synchronous resonance. The results obtained in both the cases are same. IEEE first benchmark model has been taken to analyse the effectiveness of the proposed control algorithm when mitigating SSR due to torsional interaction. The simulation has been done using MATLAB/SIMLINK software and results have been shown. As using three single phase bridges the cost of transformer is reduced so that overall cost decreases. As the voltage is being injected at sub-synchronous frequency generally the sub-synchronous voltage magnitude is very less the rating of SSSC is reduced.

Index terms: Estimation algorithm, Resonant filter, sub-synchronous resonance, sub-synchronous current control, voltage source converter.

INTRODUCTION

Series capacitors are used in transmission lines to improve power transfer capability. It was generally believed until a few decades ago that series compensation up to 70% can be used in any transmission line without too many concerns. However in 1971 it was discovered that using series capacitors can generate a significant adverse effect on thermal turbine- generator units connected to a series compensated power system. This phenomenon is referred to as sub-synchronous resonance SSR[1]. SSR is a resonant condition having frequency below the fundamental frequency. The problem of SSR is related to the interaction between a series compensated transmission line and the mechanical system of the generation unit. If the resonant frequent frequency either equal or nearer to the one of the natural frequencies of the turbine-generator shaft system, sustained or worst case growing oscillations in the generator shaft can be experienced [2].To avoid problem of SSR in power systems, a large effort has been addressed concerning the use of flexible ac transmission system devices, such as the static compensator(STASTCOM) [5], the static synchronous series compensator(SSSC) [6],the thyristor controlled series capacitor [7]. However, regardless of the solution adopted, a critical issue is a fast and accurate estimation of sub-synchronous components from the measured voltages and currents. The detection of sub-synchronous voltages and currents in the power system is important for proper monitoring and for a timely operation of the protection system in order to avoid damage in the generator shaft. Previous work has addressed the fast Fourier transform (FFT) as a means for the estimation of frequency components from the measured signals. However, due to its computational complexity, the FFT is usually not adequate for real-time estimation. Here Estimation algorithm [4] has been adopted to separate sub-synchronous frequency component in voltage and current.

CONTROL OF SSSC FOR SSR MITIGATION

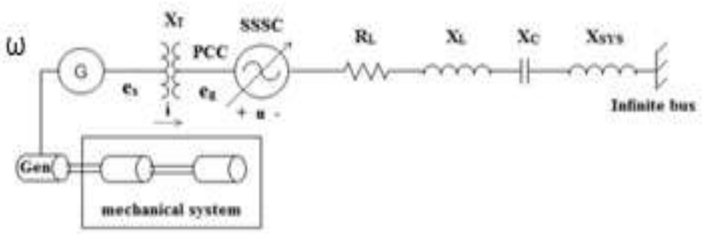

Fig.1. Single-line diagram of power plant with generation unit and SSSC.

Fig. 1 shows the single-line diagram of a series-compensated transmission line with an SSSC installed downstream the step-up transformer located at the output of the power station. The voltage at the machine terminals is denoted by e_s, while the grid voltage at the Point of Common Coupling (PCC) and the grid current are denoted by e_g and i respectively. The SSSC is modelled as a controlled ideal voltage source. The injected voltage is denoted by u .

The principle of the SSR mitigation using the classical control is to replace the fundamental frequency voltage created by(at least a portion of) the inserted fixed capacitor banks by injecting a similar voltage that has been created by the SSSC.As the capacitive reactance from the capacitor bank is eliminated (or reduced), the electrical resonance of the system becomes shifted, thus avoiding the risk of SSR. The effectiveness of this control strategy has been described in several publications and has been proved both analytically and through real-time simulations.

SUB-SYNCHRONOUS VOLTAGE

The derivation of the sub-synchronous component of the voltage at the generator terminals, the generic case of a synchronous generator connected to a transmission line can beconsidered . The per-unit voltage at the generator terminals can be shown in the αβ-plane as[3].

$$e_s^{(\alpha\beta)}(t) = e_{s,\alpha}(t) + je_{s,\beta}(t) = \overline{\omega}(t)E_s e^{j(\omega_o t+\delta(t))} \tag{1}$$

Terminals at rated speed, δ is phase displacement ω(t) is per-unit rotor-speed. ω_0 is the fundamental frequency expressed in radian per seconds. The generator rotor oscillates around its fundamental frequency, that is represented as (2)

$$\overline{\omega}(t) = \overline{\omega_o}(t) + A\sin(\omega_m t) \tag{2}$$

Where A is the amplitude of the oscillation and ω_m is the frequency of oscillation of the rotor. Substituting (2) in(1), the α Component of the output voltage can be represented as

$$\begin{aligned} e_{s,\alpha}(t) &= [\overline{\omega_o}(t) + A\sin(\omega_m t)]E_s\cos(\omega_o t + \delta(t)] \\ &= \overline{\omega_o}E_s\cos(\omega_o t + \delta(t)) + \frac{AE_s}{2}\{-\sin[(\omega_o - \omega_m)t + \delta(t)] + \sin[(\omega_o + \omega_m)t + \delta(t)]\} \end{aligned} \tag{3}$$

The derivative of the rotor angle is given by

$$\frac{d}{d^{\delta_o}}\delta(t) = [\overline{\omega}(t) - \overline{\omega_o}(t)]\omega_B = A\sin(\omega_m t)\omega_B \tag{4}$$

Where ω_B as the base frequency in radian per s$_{\delta_o}$ond. Therefore by integrating both sides of (4) and calling the rotor angle in steady- state condition. The rotor angle can be written as

$$\delta(t) = \delta_o - A\frac{\omega_B}{\omega_m}\cos(\omega_m t) \tag{5}$$

$$e_{s,\alpha}(t) = \omega_o E_s\cos(\omega_o t + \delta_o) + \frac{AE_s}{2\omega_m}\{(\omega_o - \omega_m)\sin((\omega_o - \omega_m)t + \delta_o)$$

The α and β components of the output voltage are obtained by Substituting equation (5) in (3). The α component is obtained as

$$+(\omega_o + \omega_m)\sin((\omega_o + \omega_m)t + \delta_o)\} \tag{6}$$

The β component is obtained as

$$\begin{aligned} e_{s,\beta}(t) &= \omega_o E_s\sin(\omega_o t + \delta_o) + \frac{AE_s}{2\omega_m}\{-(\omega_o - \omega_m)\cos((\omega_o - \omega_m)t + \delta_o) \\ &\quad -(\omega_o + \omega_m)\cos((\omega_o + \omega_m)t + \delta_o)\} \end{aligned} \tag{7}$$

From the above two equations, when a small oscillation is applied to the generator rotor .The voltage will be constituted by the sum of three terms. They are fundamental frequency component and sub-synchronous component of frequency (ω_o-ω_m), super-synchronous component of frequency (ω_o+ω_m). The component of super-synchronous frequency is higher than sub-synchronous frequency component. However, the network shows a small positive damping at super-synchronous frequ-ency, thus the super-synchronous voltage does not represents a risk for a power plant. Therefore super-synchronous component of the voltage is not taken in the following. The grid voltage vector can be transformed in the synchronous reference plane as

$$e_s^{(dq)}(t) = e_s^{(\alpha\beta)}(t)e^{-j\omega_o t} = e_{s,f}^{(dq)}(t) + e_{s,sub}^{(dq)}(t) \quad (8)$$

Where $e_{s,f}^{(dq)}$ is the dq voltage vector at the fundamental frequency and the sub-synchronous frequency component is written as

$$e_{s,sub}^{(dq)}(t) = -\frac{AE_s}{2\omega_m}(\omega_o - \omega_m)e^{-j[(\omega_m t+\delta(t)+\frac{\pi}{2}]} \quad (9)$$

SUB-SYNCHRONOUS COMPONENT ESTIMATION ALGORITHM

When the generator rotor oscillates around its rated speed, the voltage at the terminals can be expressed in the synchronous dq co-ordinate system as (10)

$$e_s^{dq}(t) = e_{s,f}^{dq}(t) + e_{s,sub}^{dq}(t) + e_{s,\sup}^{dq}(t) \quad (10)$$

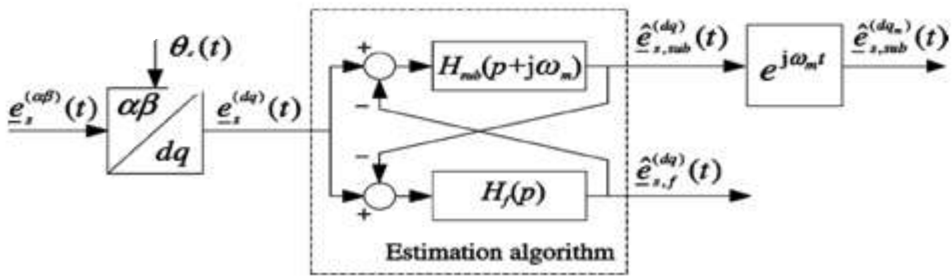

Fig.2: Block diagram of sub-synchronous component estimation algorithm.

When the subscripts "f " "sub" and "sup" denote the fundamental, the sub-synchronous and the super-synchronous component of the measured grid voltage respectively. As explained in [3]the network presents a small positive damping for frequencies above the fundamental. Therefore, the super-synchronous component is not taken in this paper. The sub-synchronous voltage rotates clockwise in the synchronous reference frame. Consider that the generator rotor oscillates with angular frequency ω_m. The dq_m plane denotes a new set of co-ordinate systems that rotates synchronously with the synchronous voltage vector ,(10) can be rewritten as

$$e_s^{dq}(t) = e_{s,f}^{dq}(t) + e_{s,sub}^{dq}(t)e^{-j\omega_m t} \quad (11)$$

In order to extract the sub-synchronous component from the measured signal, (11) can be rearranged so that $e_{s,f}^{(dq)}$ and $e_{s,sub}^{(dq)}$become isolated and then applying low-pass filtering on the resulting expression, the estimation algorithm (EA) can be expressed as follows,

$$\hat{e}_{s,f}^{(dq)}(t) = H_f(p)[e_s^{dq}(t) - \hat{e}_{s,sub}^{(dq)}(t)e^{-j\omega_m t}] \quad (12)$$

$$\hat{e}_{s,sub}^{(dq_m)}(t) = H_{sub}(p)[e_s^{dq}(t)e^{j\omega_m t} - \hat{e}_{s,f}^{(dq)}(t)e^{j\omega_m t}] \quad (13)$$

Where, ^ indicates estimated values and p is shown as(d/dt), $H_f(p)$ and $H_{sub}(p)$ represents the transfer function of a low-pass filter for the fundamental and for the sub-synchronous component respectively, equation (13) can be written in the synchronous dq- frame , yielding

$$\hat{e}^{(dq)}_{s,sub}(t) = H_{sub}(p + j\omega_m)[e_s^{dq}(t) - \hat{e}^{(dq)}_{s,f}(t)] \tag{14}$$

Equations (12) and (14) can thus, be combined together in-order to extract the fundamental and sub-synchronous components as shown in Fig 2 where the block diagram of the described EA is depicted. The oscillation frequency is assumed to be equal to 32Hz(200.96rad/sec). The cut of frequency of the filters has been set to 1Hz both for Hsub(p) and Hf(p). The EA has the same behaviour as a resonant filter with centre frequency at ωm.

IV. ALTERNATE METHOD (RESONANT FILTER)

$$G_s(s) = k_p + \frac{2k_i\omega_{cut}s}{s\wedge 2 + 2\omega_{cut}s + \omega_o\wedge 2} \tag{15}$$

Where k_p and k_i are the gain constants, ω_0 and ω_{cut} are the grid frequency and cut off frequency. From (15) it can be observed that There are three parameters in resonant filter k_p, k_i and ω_{cut}. For simplicity we can take k_p=0, it can be observed that the effect of changes in k_i and ω_{cut}.

(1) The change of k_i has no effect on bandwidth but effects gain of the controller.
(2) The change of the ω_{cut} effects the magnitude and phase of the resonant filter. The magnitude and phase increases with increase of Cut off frequency.

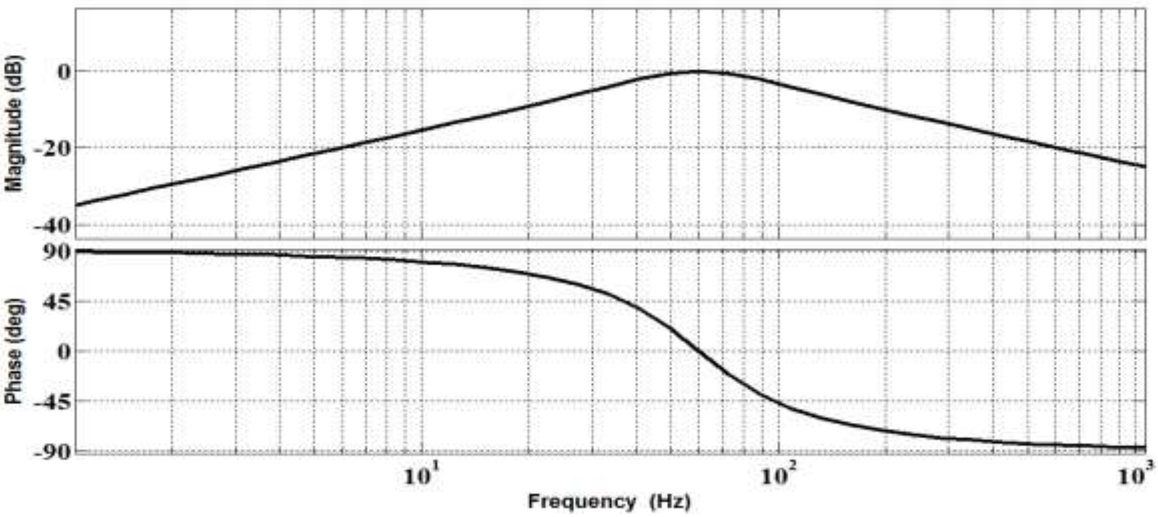

Fig.3: Frequency response of EA and resonant filter at 32Hz.

V. SUB-SYNCHRONOUS CURRENT CONTROLLER

Consider the generator is modelled as an ideal voltage source behind the sub-transient inductance of the generator .To be able to control the sub-synchronous current to zero, the objective of the control system is to rebuild the sub-synchronous component of the internal bus voltage. Assume that the voltage downstream the SSSC is equal to zero, i.e., the voltage drop over the impedance downstream the compensator is treated as a disturbance . With the signal references given in Fig. 1, the law gove rning the sub-synchronous current controller (SSCC) can be written in the Laplace domain as

$$u_{sub}^{(dq_m)}(s) = e_{g,sub}^{(dq_m)}(s) + [R + j(\omega - \omega_m)(L_T + L")]i_{sub}^{(dq)}(s) + (K_p + \frac{K_i}{s})(i_{sub}^{(dq_m)}(s) - i_{sub}^{(dq_m)*}(s)) \tag{16}$$

where R, L_T, and L" are the resistance of the system upstream the SSSC (i.e., the sum of the stator resistance of the generator and the series resistance of the transformer), the leakage inductance of the transformer and the sub-transient inductance of the generator, respectively. Where k_p and k_i are the proportional a- nd integral gains of the PI controller.

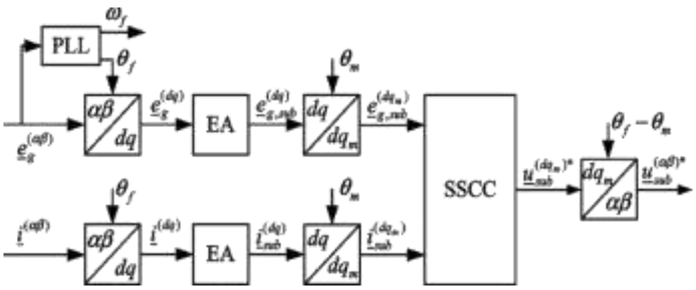

Fig.4. Block diagram of proposed control system.

From Fig: 4 the operation of the controller can be described as the measured three-phase quantities are transformed to the fixed -αβ-plane(not shown for clarity of the Figure) and then to the synchronous reference frame by using the grid voltage angle, obtained from the PLL. The estimated sub-synchronous components of voltage and current are transformed from the dq to the dq_m reference frame using transformation angle θ_m obtained from the integration of ω_m. The obtained quantities are sent to the SSCC as shown in the Fig:4. The result of SSCC is again converted into αβ and then abc. These are given to the PWM generator. From PWM generator gate pulses are obtained .These pulses are given to the three single phase VSC based bridges.

VI. SYSTEM PARAMETERS

In this paper, the system investigated is the well-known IEEE- First benchmark model. The system consists of a 600MVA, turbine-generator connected to an infinite bus through radial series compensated line. The voltage and frequency are 500KV and 60Hz respectively. Program has been written to Figure out turbine natural frequencies. Here three mass system has been taken to study, the obtained natural frequencies are 1.8686Hz,24.843Hz, 32.423Hz. 55% series compensation has been used the obtained resonant frequency is 28.14Hz, the complementary frequency is nearer to the mode2 frequency. The turbine-generator mode shapes are shown below.

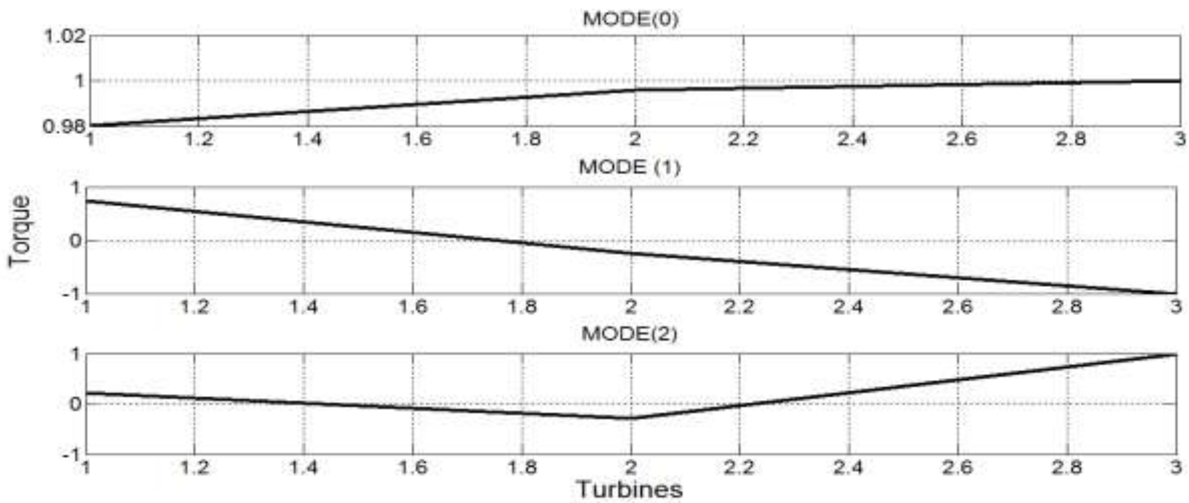

Fig.5. Position of shaft torque between HP (mode2), HP-LP (mode1), LP-GEN(mode0).

Table-1 Ieee Fbm Model Parameters

Parameter	Symbol	Value
Network resistance	R_L	0.0074Ω
Transformer reactance	X_T	0.12pu
Transformation ratio	K	22kv/500kv
Transmission line reactance	X_L	0.08pu

VIII. DESIGN OF SSSC.

In this paper three single phase VSC based bridges are used as SSSC. As the sub-synchronous frequency component of voltage and current is low, The rating of SSSC is low(0.1%). The voltage rating is 8KV (either DC source or capacitor). The power rating is 12MVA.The results are obtained for active power 0.1pu.The results are shown when SSSC is in idle mode and SSSC is in active mode.

IX. PERFORMANCE RESULTS

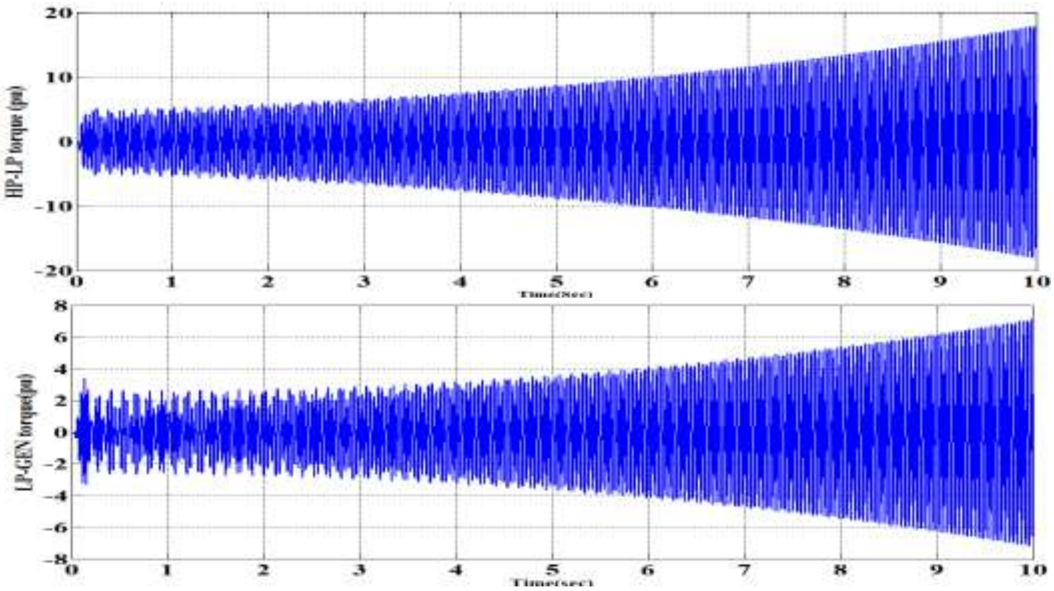

Fig.6 Simulated generated shaft torques for IEEE first benchmark model without SSSC. HP-LP turbine shaft torque, LP-GEN turbine shaft torque.

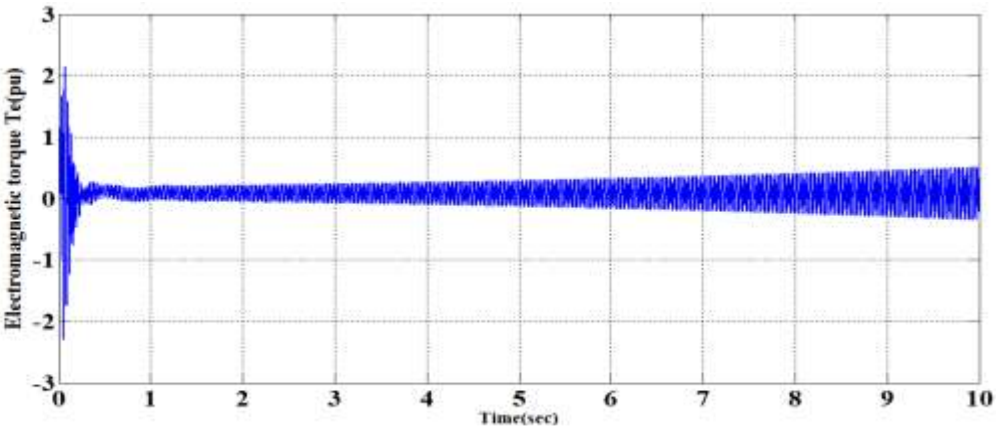

Fig.7 Electro-magnetic torque of the generator without SSSC.

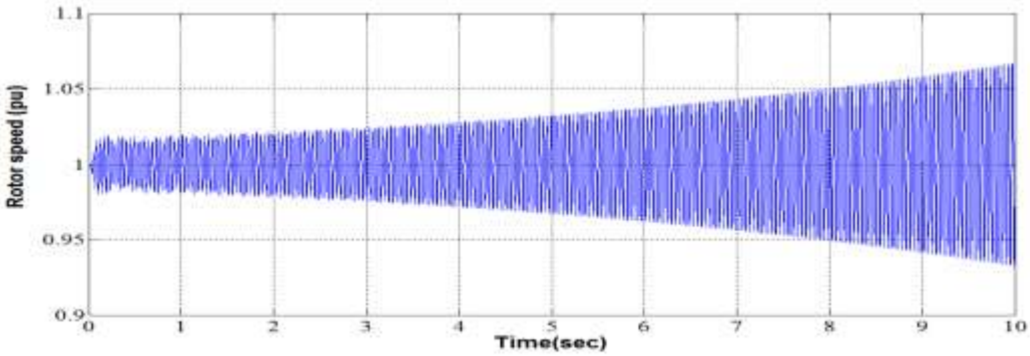

Fig.8 Represents rotor speed in pu without SSSC.

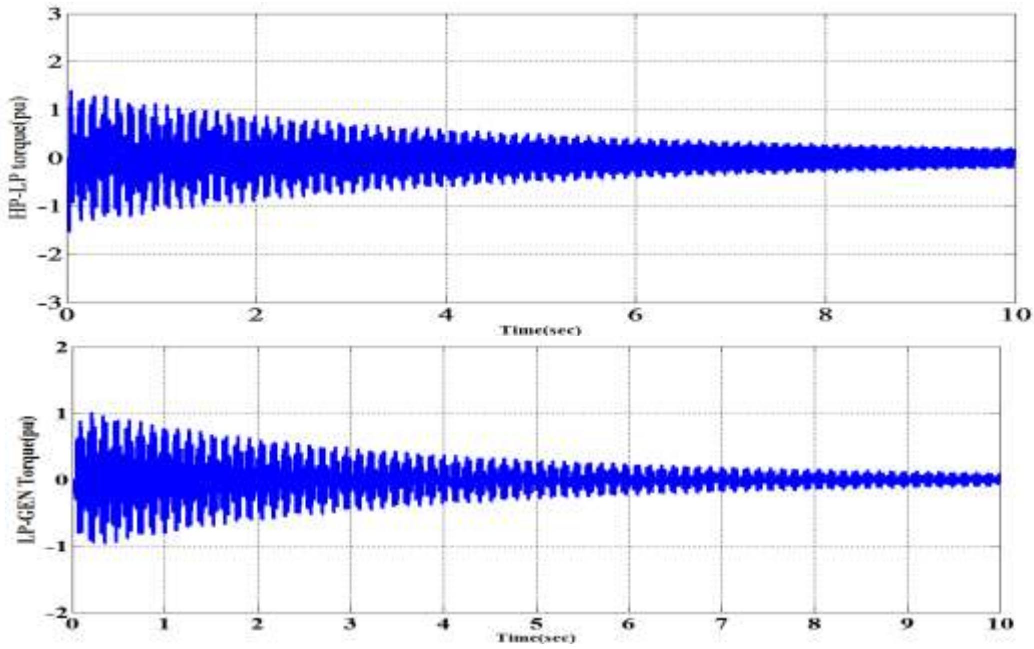

Fig.9 Simulated generator shaft torques when SSSC is in active mode. HP-LP torque, LP-GEN torque.

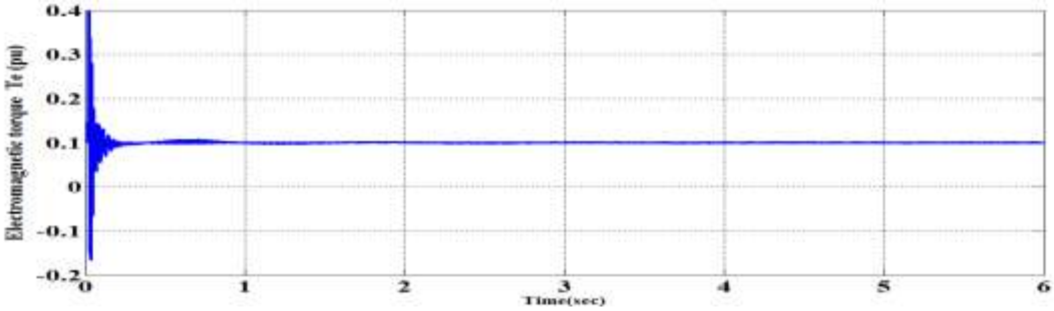

Fig.10 Electro-magnetic torque of the generator when SSSC is in active mode.

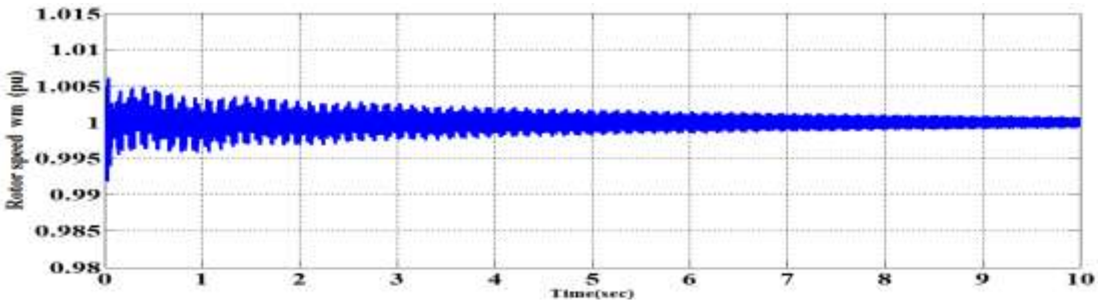

Fig.11 Rotor speed when SSSC is in active mode.

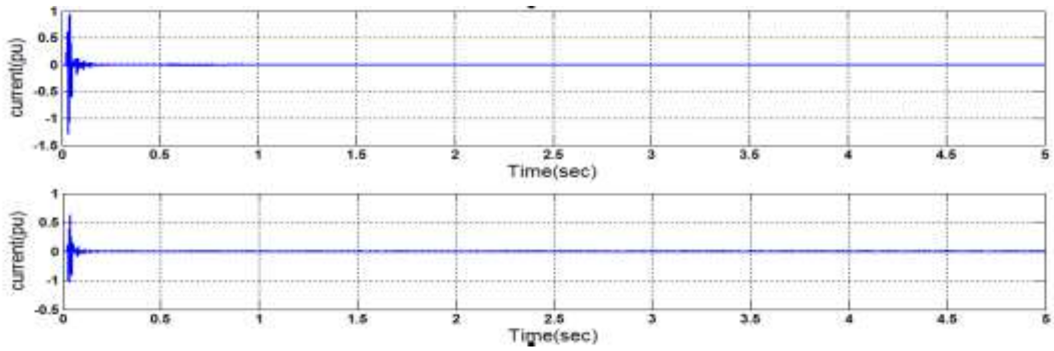

Fig.12 d-q_m axes sub-synchronous current.

CONCLUSION

In this paper, a control algorithm for SSR mitigation using SSSC has been presented. The SSSC is constituted by three single-phase VSCs connected in series with the power line. Based on a current controller implemented in the sub-synchronous reference frame, SSR mitigation is obtained by increasing the system damping at those frequencies that are critical for the gene rotor shaft. Sub-Synchronous frequencies are filtered by using Resonant filter also and same results have been obtained. The results are presented using Matlab/simulink.

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