

## MITIGATION OF TORSIONAL OSCILLATIONS IN TURBINE GENERATOR SET USING GATE CONTROLLED SERIES CAPACITOR

ANKAMMA RAO J<sup>1</sup>, SRINIVAS S. T. P<sup>2</sup> & B. VENKATA PRASANTH<sup>3</sup>

<sup>1</sup>Assistant Professor, Samara University, Samara, Afar Region, Ethiopia

<sup>2</sup>Assistant Professor, QIS College of Engineering and Technology, Ongole, Andhra Pradesh, India

<sup>3</sup>Professor & Head, Department of Electrical & Electronics Engineering, QIS College of Engineering and Technology,  
Ongole, Andhra Pradesh, India

### ABSTRACT

The sub synchronous resonance (SSR) phenomenon may occur when a steam turbine-generator is connected to a long transmission line with series compensation. The main purpose of this work is to verify the capability of the gate-controlled series capacitor (GCSC) to mitigate SSR. For this study the GCSC was tested in conjunction with the IEEE First Benchmark Model. The actual possibility of controlling SSR was verified by digital simulation using the Alternative Transients Program/Electromagnetic Transients Program. As a result it was shown that GCSC can damp SSR even without a specific control. It was also shown that, using a simple controller, SSR as well as electromechanical oscillation can be damped.

**KEYWORDS:** Capacitor Compensated Transmission Lines, Power Generation, Mechanical Factors, Power System Dynamic Stability, Power System Modeling, Sub Synchronous Resonance, Thyristor Applications, Turbo-Generators

### INTRODUCTION

Series capacitive compensation is a useful and economical technique to improve the power transfer capability of transmission lines. However, when this technique is applied together with a steam turbine-generator, it may lead to sub synchronous resonance (SSR) phenomenon. SSR problems result from the interaction between an electrical mode of the series compensated network and a mechanical shaft mode of a turbine-generator group that this may generate oscillating torsional torques.

In general, if series flexible ac transmission system (FACTS) devices be used, it would be possible to say that the advantages of the series compensation can be guaranteed without risks of SSR phenomenon. The gate-controlled series capacitor (GCSC) is a new series FACTS device proposed initially for series compensation of transmission line to control power flow [1], [2]. In [3], it was shown that the GCSC, when compared to the TCSC, presents a series of advantages. Naturally, when it is compared to the more sophisticated and expensive SSSC, the GCSC has less flexibility. On the other hand, it has the key advantage of being a much simpler device[4]. Turn-off angle control of the GCSC for the SSR damping was given in [4]-[6]. In these references, it was shown that if a proper controller be designed for the GCSC, this device can effectively mitigate the SSR and can properly stabilize the system.

The oscillation cover a wide frequency range approximately from 0.001 Hz to 50 MHz. Due to transient disturbance, generator speeds up causing rotor angle to increase resulting in the development of varying torque.

This varying torque develops the varying stresses on the T-G shaft, which leads to damage of the shaft and may reduce life of T-G set. Some techniques to mitigate SSR with FACTS devices can be found in the literature. These techniques can provide controllable series compensation and reduce or even eliminate the effects of the SSR [5].

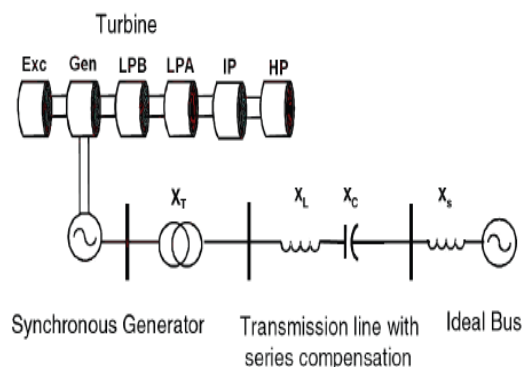
There has been considerable interest in predicting the effects of electrical system disturbances on the shaft stresses of large turbine-generator sets. As a result of the large electrical disturbances and switching incidents, the shafts of T-G sets are subjected to severe transient torsional stresses. Fatigue phenomenon is a cumulative process and in each cycle of torsional stress shaft loses some of its lifetime.

The level of induced fatigue depends upon the amplitude of the imposed mechanical stress and its time. When these stresses exceed the endurance limits i. e.  $45 \times 10^7$  N/m<sup>2</sup> [12], [13], the shaft may get damaged due to over stresses at the couplings. Hingorani [6] proposed a very effective device for SSR mitigation called NGH-SSR. This device is basically a thyristor-controlled discharge resistor that is operated synchronously with the power system frequency. This resistor is inserted in the circuit close to the end of each half cycle on the series capacitor voltage. The NGH-SSR was installed at Southern California Edison's Lugo substation to mitigate SSR phenomenon in 1993.

On the other hand the thyristor-controlled series capacitor (TCSC) is one FACTS device that has been most analyzed to mitigate SSR [7]. Kakimoto and Phongphananee have also demonstrated that TCSC can damp SSR if its firing angle is modulated with the rotor angle variation [8]. Jowder and Ooi have shown that the static synchronous series capacitor (SSSC) can also damp SSR [9]. The SSSC is more flexible device than the TCSC and GCSC.

However, its cost and complexity is much higher. Another FACTS device that can mitigate SSR is the unified power flow controller (UPFC) [10]. However, it has a series and shunt converter, it is more expensive and complex than the SSSC. It will be shown that this controller can be improved to damp electromechanical oscillation. Several time-domain simulations were evaluated to investigate the performance of the GCSC.

## SYSTEM MODELING



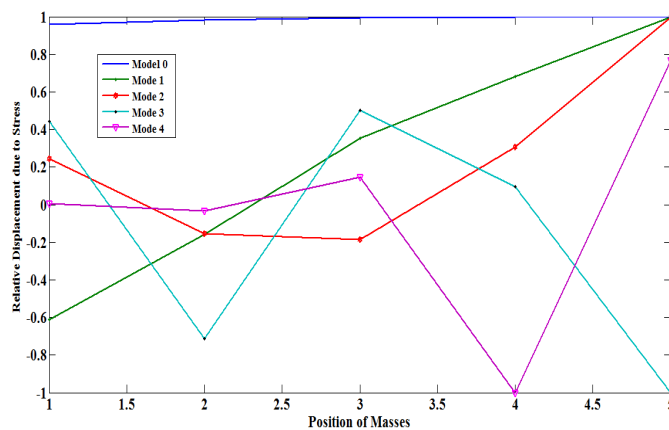
**Figure 1: IEEE First Benchmark Model for SSR Damping Studies**

Figure 1 shows the "IEEE System First Benchmark" [7] used in the analysis of the sub synchronous resonance (SSR) phenomenon. The circuit is composed of a synchronous generator connected to an infinite bus via a compensated 500 kV transmission line. This transmission line is represented by a resistance, an inductance ( $X_L=0.9$  p.u.) and a series compensation capacitor,  $X_C$  (its value will depend on the compensation level). Table 1 shows the torsional modes of oscillations of this system with the corresponding frequencies and shows also the value of the series capacitive reactance

that, if used, would excite the SSR. The mechanical system consists of four-stage steam turbine, the generator and a rotating exciter. The transformer was considered without magnetic saturation.

**Table 1: Oscillation Modes and Capacitive Reactance that Excite SSR**

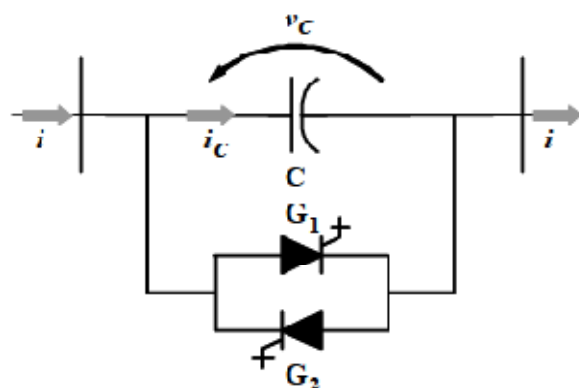
Mode	Frequency (HZ)	$X_c$ (p.u)
Torsional mode 4	32.285	0.164
Torsional mode 3	25.545	0.285
Torsional mode 2	20.214	0.378
Torsional mode 1	15.746	0.472
Self-excitation	9.733	0.609



**Figure 2: SSR Mode Shapes of First Benchmark Model for 60% Compensation**

## GATE CONTROLLED SERIES CAPACITOR

The GCSC is composed of two anti-parallel gate-controlled switches and a capacitor bank in series with the transmission line as shown by the single line diagram in Figure 5. The principle of operation of the GCSC [1]-[3] is based on the variation of the turn-off angle ( $\gamma$ ) of the gate-controlled switches. By controlling the turn-off angle ( $\gamma$ ), the voltage on the capacitor is controlled; as a result, the series compensation level of transmission line can be controlled.



**Figure 3: Basic Configuration of the GCSC**

Figure 3 shows typical current and voltage waveforms for the GCSC of Figure 5, for a given turn-off angle ( $\gamma$ ). The turn-off angle ( $\gamma$ ) is measured from the zero crossing of the line current and the compensation level of the GCSC is determined by the fundamental component of the voltage  $C v$  on the GCSC. The relationship between equivalent capacitive reactance and turn-off angle ( $\gamma$ ) is given by [6]:

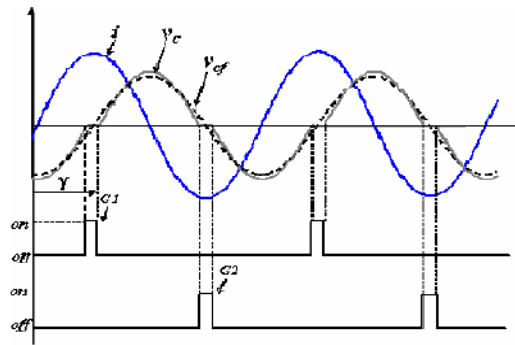


Figure 4: GCSC Voltage, Current and Switch Control

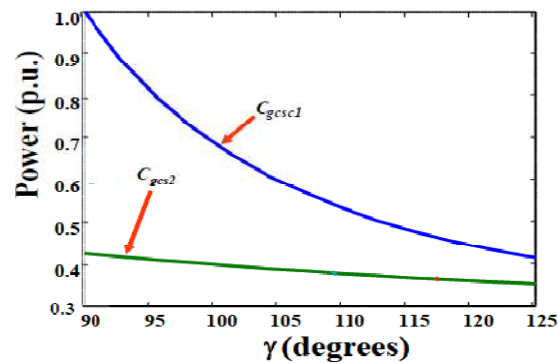


Figure 5: Equivalent Reactance of GCSC as a Function of Turn off Angle

$$X(\gamma) = \frac{X_c}{\pi} (2\gamma - 2\pi - \sin(2\gamma)) \quad (1)$$

where  $XC$  is the reactance of the GCSC capacitor, in Figure 5. Figure 7 shows the nonlinear relationship between the equivalent capacitive reactance( $X(\gamma)$ ) and turn-off angle ( $\gamma$ ). At the fundamental frequency, the GCSC is equivalent to a continuously variable series capacitor, where its reactance varies from its maximum value (1p.u) for  $\gamma = 90\text{deg}$  to minimum value (0 p.u) for  $\gamma = 180\text{ deg}$ . This continuous reactance control of GCSC is one of the advantages of this device over the TCSC [3].

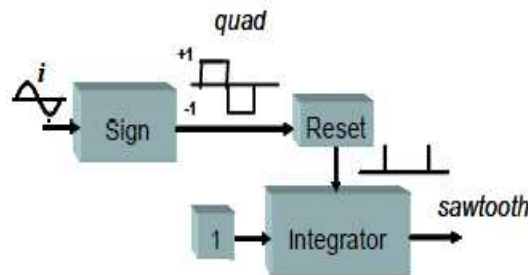
## SERIES COMPENSATION WITH GCSC

As explained before, the GCSC was originally proposed for power flow control. In this case, its reactance has to be chosen in such a way as to guarantee a wide compensation range. Figure 5 shows two examples of compensations. In this figure it is shown the power flowing in the transmission line as a function of the turn-off angle  $\gamma$  for two values for the GCSC capacitors:  $C_{gscs1} = 17.4 \mu\text{F}$  and  $C_{gscs2} = 25 \mu\text{F}$ . To obtain this figure, it was assumed that the generator was an ideal voltage source. These capacitors correspond to 1 and 0.47 p.u. of series compensation at turn-off angle equal to 90o. The first case allows a wider compensation range. This figure shows that the variation of power as function of the turn-off angle ( $\Delta P/\Delta\gamma$ ) may be smaller or larger proposed control for damping power oscillations. Depending on the operating point and the size of the GCSC capacitor. When a GCSC is used for power flow control it should have a wider control capability. However, when it is used for power oscillation damping it can be smaller as it will be shown later.

- **Power Flow Control Characteristics**

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**Figure 6: Turn-off Angle Generator Based on Line Current Frequency Detector**

- **Simulation Results and Discussions**

The simulation of the system in Figure 1 with the GCSC and the aforementioned control method was started with an ideal voltage source, the ideal voltage source was substituted by the synchronous generator driven by the turbine.

**Table 2: Comparison of Cases of GCSC**

Case	$X_{fc}(p.u)$	$X(\gamma)(p.u)$
1G2C	0.318	0.152
1G1C	0.236	0.236
2G1C	0.152	0.318

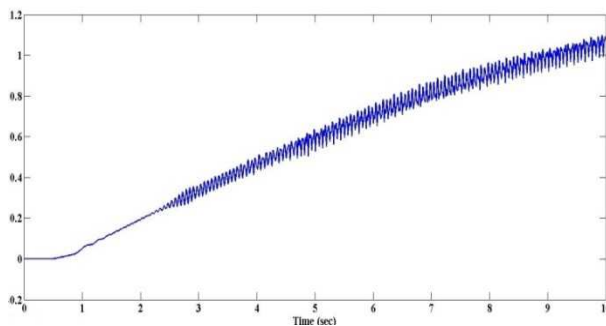
Some simulation studies were done to verify the performance of the GCSC to mitigate SSR in the system shown in Figure 4. The single fixed capacitor in Figure 4 was substituted by the GCSC shown in Figure 1 associated with a fixed capacitor. The sum of the fixed capacitor reactance ( $X_{C \text{ fixed}}$ ) plus the equivalent GCSC reactance for a given fixed turn-off angle ( $X_{GCSC}$ ) was made equal to the value of reactance that excites SSR at torsional mode 1 presented in Table 2. The idea was exactly to excite the SSR in this mode 1. With the objective to show that the GCSC is able to damp power oscillation even without specific controller the following simulation was done.

A GCSC and a fixed capacitor were used as series compensation of the line shown in Figure 4. The GCSC was operated with turn-off angle  $\gamma$  equal to  $113.5^\circ$  (in steady state) producing a capacitive compensation reactance of 0.152 p.u. The fixed capacitor was adjusted to provide 0.318 p.u. of series compensation. Therefore, the total series compensation was made equal to 0.47 pu of capacitive reactance, which should make the system highly oscillatory at torsional mode 1 (oscillation frequency = 15.746 Hz). Figure 6 shows the electric torque of the generator for this case of simulation.

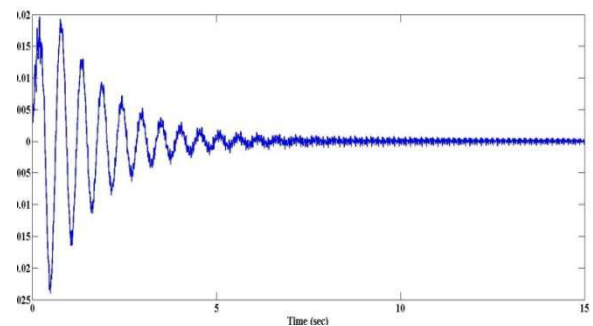
The simulation is started with an ideal voltage source at the generator side. At  $t=0.5$  s a three phase fault is created at infinite bus terminal for 0.3s duration. This result was shown in [5] and demonstrates that the GCSC can mitigate SSR even without control system when mode 1 is excited.

Figure 7 Shows the speed variations of turbine generator set due to fault which has excited the mode 1 of SSR. Figure 8 shows that due to proper control of series capacitor voltage through GCSC has controlled the effect of SSR and quickly returned the speed to rated value. Figure 9 and Figure 10 show the speed deviation of the rotor without and with GCSC connection. Figure 11 shows the power oscillations in Electric power due to SSR without GCSC and Figure 12 depicts that the SSR has been efficiently damped out with GCSC and the power oscillations are decreased.

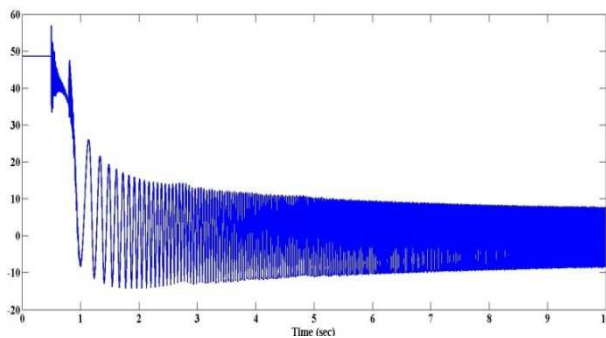
Figure 13 and Figure 14 shows the variations of mechanical stresses on Gen-LPB section without and with GCSC. Figure 15 and Figure 16 shows the variations of mechanical stresses on LPB-LPA section without and with GCSC. Figure 17 and Figure 18 shows the variations of mechanical stresses on LPA-IP section without and with GCSC. Figure 19 and Figure 20 show the mechanical stresses on IP-HP section without and with GCSC respectively. From Figure 13 to Figure 20 it is quite evident that the mechanical stresses on the turbine couplings exceed the maximum stress limit of  $45 \times 10^7 \text{ N/m}^2$  under SSR. Whereas, the operation of GCSC has successfully damped out the torsional oscillations.



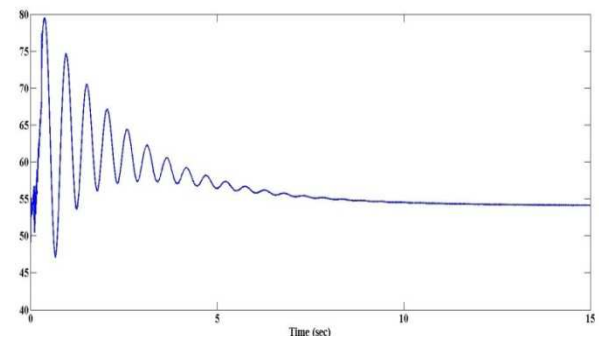
**Figure 7: Speed Deviation without GCSC**



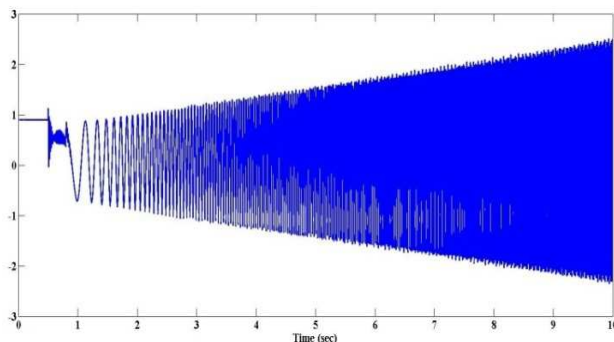
**Figure 8: Speed Deviation with GCSC**



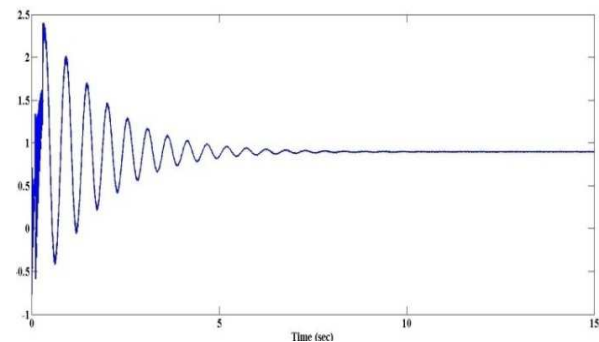
**Figure 9: Load Angle (Deg) without GCSC**



**Figure 10: Load Angle (Deg) with GCSC**



**Figure 11: Electric Power without GCSC**



**Figure 12: Electric Power with GCSC**



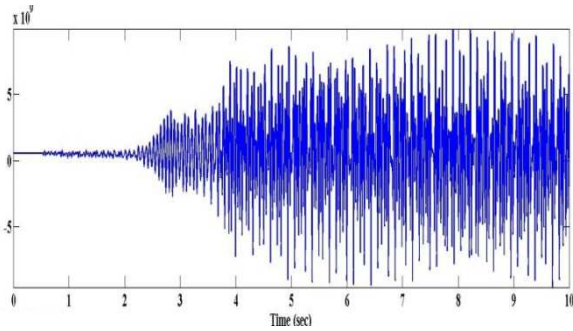


Figure 13: Stress in Gen-LPB Section without GCSC

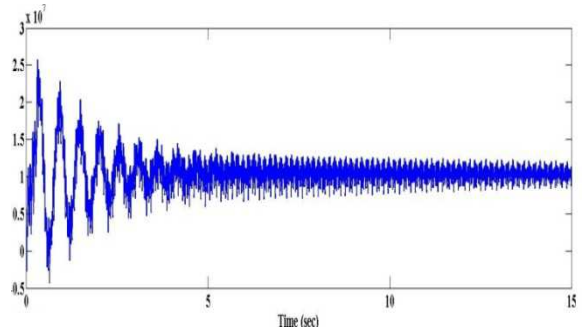


Figure 14: Stress in Gen-LPB Section with GCSC

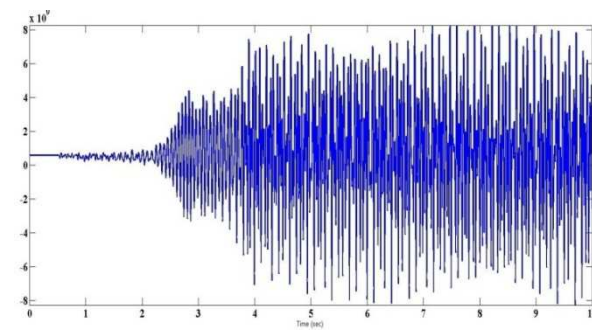


Figure 15: Stress in LPB-LPA Section without GCSC

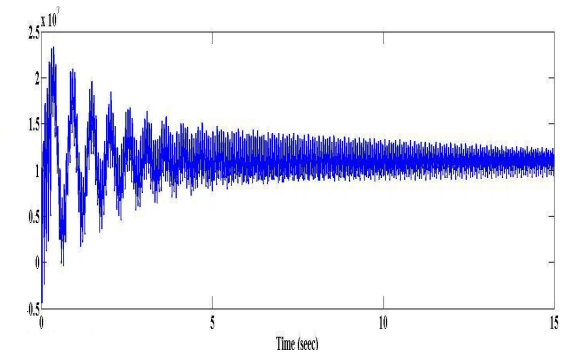


Figure 16: Stress in LPB-LPA Section with GCSC

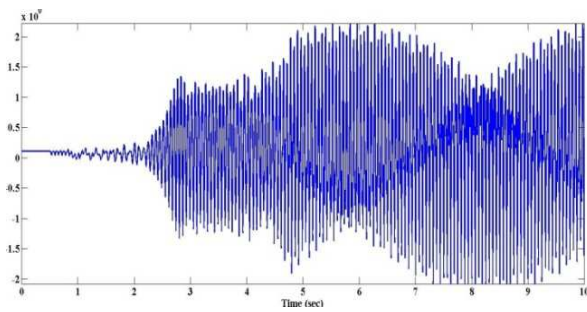


Figure 17: Stress in LPB-IP Section without GCSC

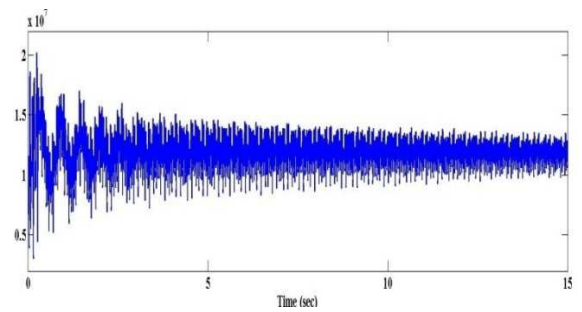


Figure 18: Stress in LPB-IP Section with GCSC

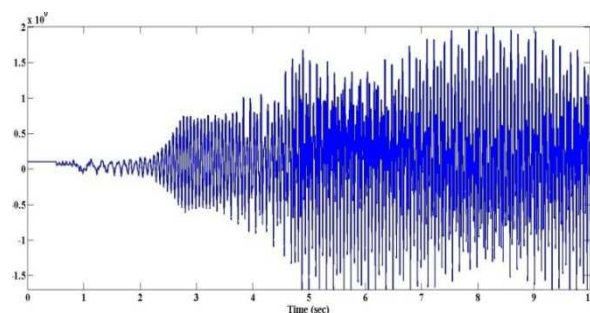


Figure 19: Stress in IP-HP Section without GCSC

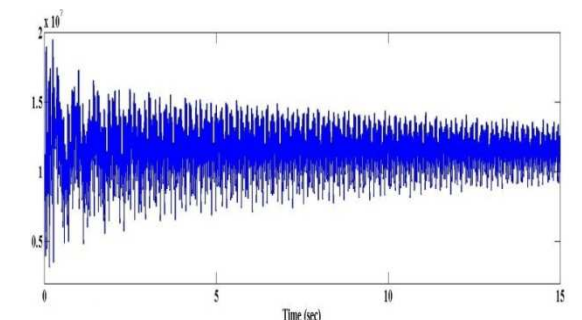


Figure 20: Stress in IP-HP Section with GCSC

## CONCLUSIONS

In this paper, it is shown that by using GCSC with controlled capacitor the stresses due to torsional sub synchronous oscillations can be damped. If stresses are above endurance limit of  $45 \times 10^7$  N/m<sup>2</sup>, then shaft may get damaged. Table 3 shows the comparison between the stresses, at different coupling sections of the T G shaft without and

with GCSC. Due to the application of GCSC system becomes stable and stresses are reduced up to 80 to 95%, which are below the endurance limit.

**Table 3: Comparison of Stresses with and without GCSC**

Sections	Stress in N/m <sup>2</sup> without GCSC	Stress in N/m <sup>2</sup> with GCSC
HP and IP	150x10 <sup>7</sup>	4.0x10 <sup>6</sup>
IP and LPA	200x10 <sup>7</sup>	7.5x10 <sup>6</sup>
LPA and LPB	700x10 <sup>7</sup>	6.0x10 <sup>7</sup>
LPB and GEN	1000x10 <sup>7</sup>	8.5x10 <sup>7</sup>

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## AUTHOR'S DETAILS



Mr. J Ankamma Rao received the B.E. degree in Electrical & Electronics Engineering from Andhra University, Visakhapatnam, A. P, India, 2007 & M. Tech. degree in Integrated Power System from Visvesvaraya National Institute of Technology, Nagpur, India, in 2012. Currently, he is an Assistant Professor in Samara University, Samara, Afar Region, Ethiopia. His research areas are power system protection and FACTS.



Mr. Srinivas STP received the B. Tech. degree in Electrical & Electronics Engineering from Jawaharlal Nehru Technological University, Kakinada, India, 2009 & M. Tech. degree in in Power Systems from Visvesvaraya National Institute of Technology, Nagpur, in 2012. Currently, he is an Assistant Professor in QIS College of Engineering and Technology, Ongole, India. His research areas are power system Analysis, Dynamics and FACTS.



Dr. B. Venkata Prasanth received the B. Tech. degree in Electrical & Electronics Engineering from *Sri Krishnadevaraya University* & M. Tech. degree in Electrical Power Systems from Jawaharlal Nehru Technological University, Ananthapur, India. He received his Ph.D. degree in Electrical & Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad, India. He has got a teaching experience of more than 14 years. Currently, he is working as Professor & Head in QIS College of Engineering and Technology, Ongole, India in the Dept. of Electrical & Electronics Engineering. He has published a number of papers in various national & international journals & conferences. He is also guiding a number of research scholars in various topics of electrical engineering. His research interests include application of intelligent controllers to power system control design, power system restructuring, power system economics & optimization.

