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Damping of SSR using SSSC with hysteresis current control

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***Abstract*— The main objective of this paper is to present a more detailed investigation on the capability of SSSC to electromechanical oscillation. This investigation was done based on the IEEE First Benchmark Model where the electrical and mechanical systems were modeled in MATLAB. For the analysis presented in this paper SSSC is used to damp out torsional oscillations**.

***Index Terms*— SSSC,Subsynchronous,SSR**

I. INTRODUCTION

The single line diagram of the IEEE First Benchmark model with series compensated transmission line is shown in Figure 3.1.The generator is represented by the d- and q-axis equivalent circuit with one damper winding and field winding on the d-axis & two damper windings on q-axis. The mechanical system comprises six masses, i.e. the high pressure turbine (HP), the intermediate pressure turbine (IP), two low pressure turbines- LPA and LPB, the generator (GEN), & the exciter (EXC) as shown in Figure 3.1. Mechanical damping is assumed to be zero for all masses to represent the worst damping conditions. The generator is equipped with a static excitation system. From the structure of this mass spring system; there exist three torsional modes (mode-1, mode-2 and mode-3) and one electromechanical mode (mode-0) in the system. These four modes are called SSR modes or torsional modes since their natural frequencies are all less than synchronous frequency or power frequency. The inherent natural frequencies for mode 0, 1, 2 and 3 are 1.1026 Hz, 15.9358 Hz, 23.1469 Hz and 25.6135 Hz respectively. SSR modes stand for number of twists on the shaft. For example mode 0 signifies that the three masses oscillate in unison without a shaft twist, mode-1 has one shaft twist and mode-2 has two shaft twists and so on.

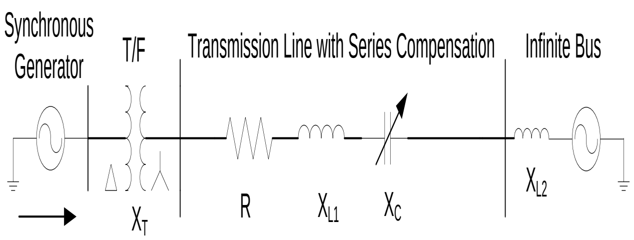

Fig.1 Single Line IEEE FBM Model for SSR Damping Studies

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The mechanical system consists of rotors of generators exciters and turbine shaft can be viewed as mass spring damper system. Consider a generator having a rotor with four masses HP, IP, LPA, LPB and GEN. The first mode is the system mode. There are 'n-1' (n is number of masses) torsional mode having frequency 24 and 29 Hz. These frequencies can be obtained as an imaginary part of eigen value of system matrix 'A' $\{\dot{X} = AX + BU\}$. Relative rotational displacements of individual masses for each mode of oscillation are given by eigen vector of corresponding eigen value.

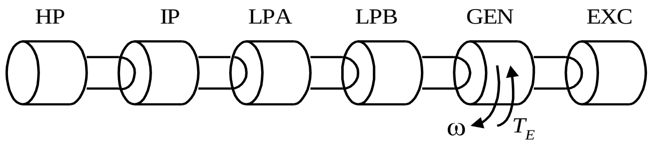

Figure 2 Five Mass Representation of the Mechanical System

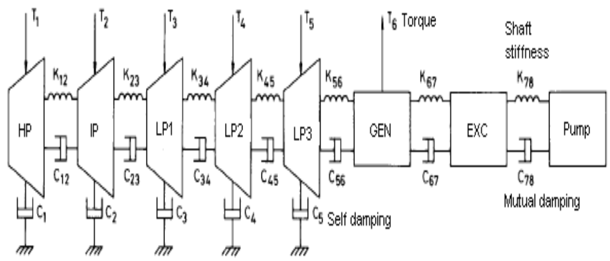

Figure 3 Lumped Inertia Mechanical Model of Steam Turbine Generator

The mechanical model of the steam turbine generator is a multiple lumped inertia system in fig.3.3, the turbine discs and electrical machines are modeled by lumped inertias connected by the shafts, which are represented, by inertia less torsional springs of equivalent stiffness. Mechanical damping is included in the form of viscous dampers associated with the steam damping on individual turbine discs and the shaft damping between discs. The turbine generators mechanical parameters are given in below. The torsional equations of motion for the model are described in first order differential form

i.e. $p[\theta] = [A] [\theta] + [T]$

Where

$p = \{d/dt\}$ is the vector of angle twist.

[T] is the externally applied torques and

[A] is the state coefficient matrix, which includes the damping and stiffness terms**.** The explicit form of the matrix [A] may be derived from the equation of motion for each individual inertia.

The rotor of a T-G unit is a very complex mechanical system. It may exceed 150 feet in total length and weigh several hundred tons. The rotor system contains rotor forgings of varying sizes each with machined shaft sections and couplings that may either be integral or shrunk and keyed to the rotor. Turbine sections contain a number of discs, which may also be integral or attached to the rotor. There are also a number of smaller components including turbine blades, rotor coils, retaining rings, blowers, pumps and excitation system components that are included in the completed assembly. This system possesses an infinite number of modes or torsional vibration, some containing very complex mode shapes. The analysis of the mechanical response of this system to a transient event requires an analytical model in which, depending on the purpose of the analysis to do.

The mechanical system comprises five masses, i.e. the HP, IP, LPA, LPB, and GEN, which are mechanically coupled on the same shaft. From the structure of this model mass spring system, their exists five torsional modes (mode '1',mode '2',mode '3', mode '4' and mode '5') and one electromagnetic mode (mode '0') in the system. These six-modes are called SSR modes or torsional modes since there natural frequencies are all less than synchronous frequency or power frequency (50Hz).The inherent natural frequencies for mode 0, 1, 2, 3, 4 and 5 are 1.1026 Hz, 15.9358 Hz, 23.1469 Hz, 25.6135, 32.2935 and 47.4563 Hz respectively.

The SSR mode i (i= 0, 1, 2, 3, 4 and 5) stands for the number of twists on the shaft. For example mode '0' signifies the four masses oscillate in unison without a shaft twist, mode '1' has one shaft twist, mode '2' has two shaft twists, etc so on. All turbine torques proportional, with each contributing fraction. The fractions for HP, IP and LP are 60%, 20% and 20% respectively.

On the other hand, the electrical modal of the studies system comprises the GEN connected to load through step up transformer and two parallel transmission lines, one of which is series compensated. The value of X_c/X_L of the compensated line in fig.3.1 defines the series compensation ratio. The capacitive reactance X_c can be varied and Xc/X_L is ranged from 10% to 90%.

II. STATIC SYNCHRONOUS SERIES COMPENSATOR

Fig 4.3 shows a voltage source inverter connected in series via a transformer to a transmission line. A source of energy is needed to provide the DC voltage across capacitor and supply the losses of VSI.

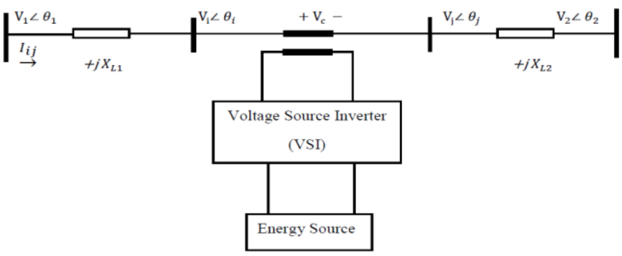

Figure 4. The basic configuration of SSSC

In principle, an SSSC is capable of interchange of active and reactive energy with the power system. However if only reactive power compensation is intended, the size of energy source could be quite small. The injected voltage could be controlled in magnitude and phase if sufficient energy source is provided. For the reactive power compensator function, only the magnitude of the voltage is controllable since the vector of the inserted voltage is perpendicular to the line current. In this case the series injected voltage can either lead or lag the line current by 90°. This means that the SSSC can be smoothly controlled at any value leading or lagging within the operating range of VSI. Thus the behavior of an SSSC can be similar to a controllable series capacitor and a controllable series reactor. The basic difference is that the voltage injected by SSSC is not related to the line current and can be independently controlled. The importance of this characteristic is that an SSSC is effective for both low and high loading.

A. Analysis of SSR

The analysis of SSR with SSSC is carried out based on damping torque analysis, eigen value analysis and transient simulation.

B. Damping Torque Analysis:

Damping torque analysis is a frequency domain method which can be used to screen the system conditions that give rise to potential SSR problems. The significance of this approach is that it enables the planners to decide upon a suitable countermeasure for the mitigation of the detrimental effects of SSR. Damping torque method gives a quick check to determine the torsional mode stability. The system is assumed to be stable if the net damping torque at any of the torsional mode frequency is positive.

The interaction between the electrical and mechanical system can be represented by the block diagram shown in Fig.5

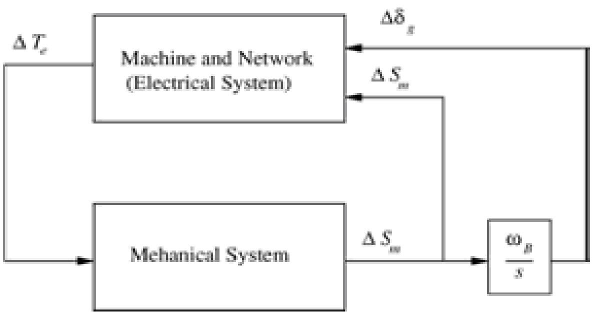

Figure 5. Interaction between Mechanical and Electrical System

At any given oscillation frequency of the generator rotor, the component of electrical torque (ΔT_e) in phase with the rotor speed (ΔS_m) is termed as damping torque. The expression for damping torque coefficient (T_{de}) by the external transmission network. Although it is possible to consider the detailed model of the generator in the computation of damping torque, it is convenient to model the generator with classical model (constant voltage source (E^1) behind a transient reactance (X_d^1)) if the objective is to study mainly the torsional interactions. This assumption is equivalent to neglecting induction generator effect (IGE) and does not have a significant effect on the prediction of torsional mode stability. The stability of mode 0 (corresponding to low frequency oscillations) is obviously dependent on the generator model considered. Here, detailed generator model is required.

The electrical torque (ΔT_e) as a function of the change in per unit rotor speed (ΔS_m) can be derived from the knowledge of the impedance functions. At the generator internal bus the following equation applies.

$$\begin{bmatrix}\Delta I_{gD}(j\omega)\\ \Delta I_{gQ}(j\omega)\end{bmatrix} = \begin{bmatrix}Y_{DD}(j\omega) & Y_{QQ}(j\omega)\\ Y_{QD}(j\omega) & Y_{QQ}(j\omega)\end{bmatrix}\begin{bmatrix}\Delta E_{gD}(j\omega)\\ \Delta E_{gQ}(j\omega)\end{bmatrix} \quad (4.4)$$

The expression for the damping torque can be written as

$$T_{de}(\omega) = f\frac{(\Delta T_e(j\omega))}{(\Delta S_m(j\omega))} \quad (1)$$

and can be expressed as

$$T_{de}(\omega)\left[Y_{QD}(j\omega)\frac{\omega_0}{j\omega} + Y_{QQ}(j\omega)\right](E')^2 \quad (2)$$

When the mechanical damping is zero, the instability of *i*th torsional mode frequency ω_i is determined from the criterion $T_{de}(\omega_i) < 0$ and the decrement factor σ_i can be approximately expressed as

$$\sigma_i = -\frac{T_{dc}(\omega_i)}{4H_{mi}} \quad (3)$$

where H_{mi} is the modal inertia for the *i*th mode.

III. CONTROL SCHEME

The SSSC consists of a voltage source inverter and a coupling transformer. The control scheme is implemented to generate the gate pulses which are given to the 24 pulse voltage source inverter. The control scheme implemented is shown in Fig 6. The line voltage and current are sensed and from that measurement actual active power P_{act} and reactive power Q_{act} are calculated. These P_{act} and Q_{act} work as a feedback for the closed loop control system. The desired active and reactive power P_{ref} and Q_{ref} are compared with the P_{act} and Q_{act} respectively to generate error signals E_p and E_q. These error signals are processed in the controller.

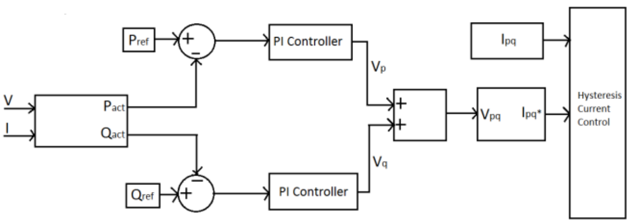

Figure 6 Block diagram of control scheme implemented to generate gate pulses

The outputs of the controllers V_p and V_q are used to generate three-phase reference voltages (V_{pqa}^*, V_{pqb}^*, V_{pqc}^*) injected in the line through insertion transformer. The three-phase reference currents (I_{pqa}^*, I_{pqb}^*, I_{pqc}^*) are calculated by knowing the impedance of insertion transformer (Z_e). These currents (I_{pqa}^*, I_{pqb}^*, I_{pqc}^*) are compared with the three-phase currents (I_{pqa}, I_{pqb}, I_{pqc}) measured at the output of the inverter.
The PWM current controller based on hysteresis control is used to generate the gate pulses for the inverter switches. According to the switching signals, inverter generates the three-phase voltages (V_{pqa}, V_{pqb}, V_{pqc}) at its output terminals and these voltages are injected in the series with the transmission line. This injected voltage insures that P_{act} remains same as P_{ref} and Q_{act} remains same as Q_{ref}.

IV. SIMULATION RESULTS

The system shown below is an IEEE first benchmark model used to study sub synchronous resonance and particularly stress calculation on a series compensated power system. It consists of a single generator (892.4 MVA, 500 KV, 50 Hz, 3000 rpm) connected a load via a series compensated transmission line. The sub synchronous mode introduced by the compensation capacitor after a disturbance has been applied and cleared excites the oscillatory torsional modes of the multi-mass shaft can be observed. The simulation model is shown in fig.7

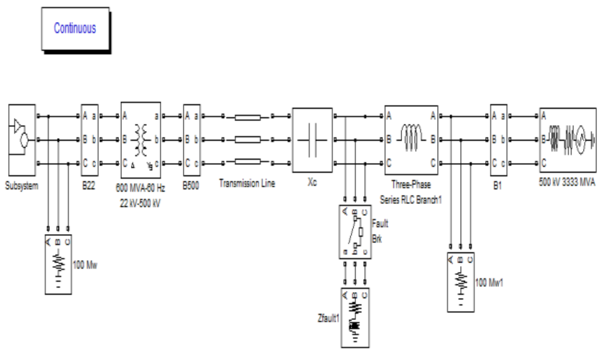

Figure. 7 IEEE First Benchmark on Sub Synchronous Resonance System

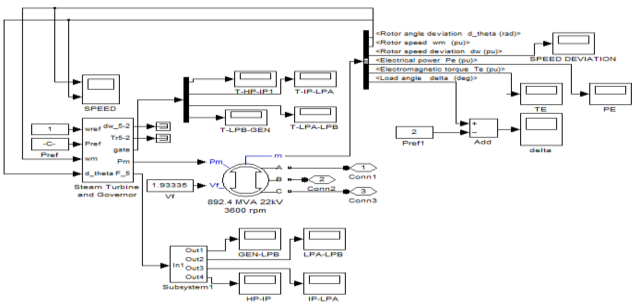

Figure 8 Subsystem Steam Turbine Generating Station

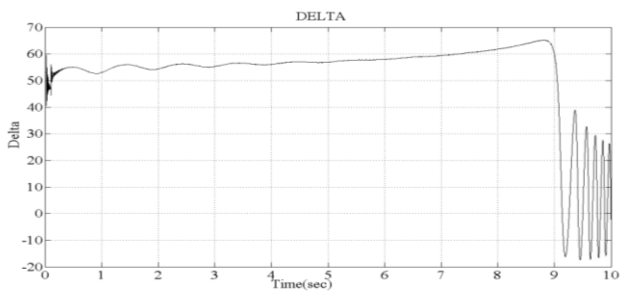

Figure 9. Rotor Angle

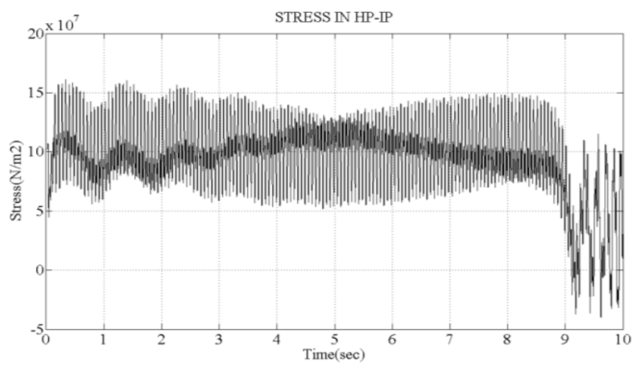

Figure 10. Stresses between HP-IP

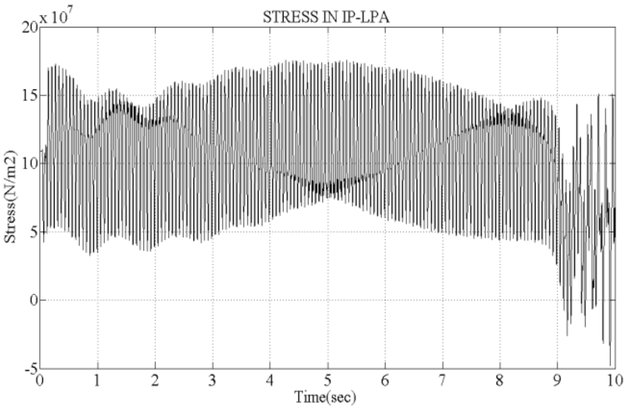

Figure 11. Stresses between IP-LPA

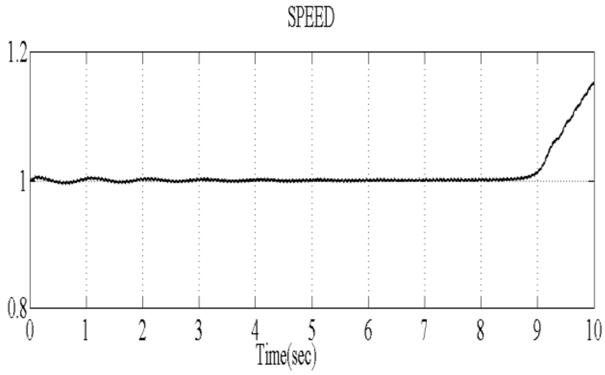

Figure 12. Rotor Speed

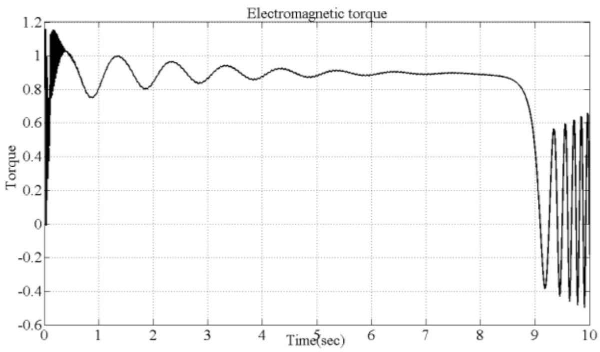

Figure 13.Electromagnetic Torque

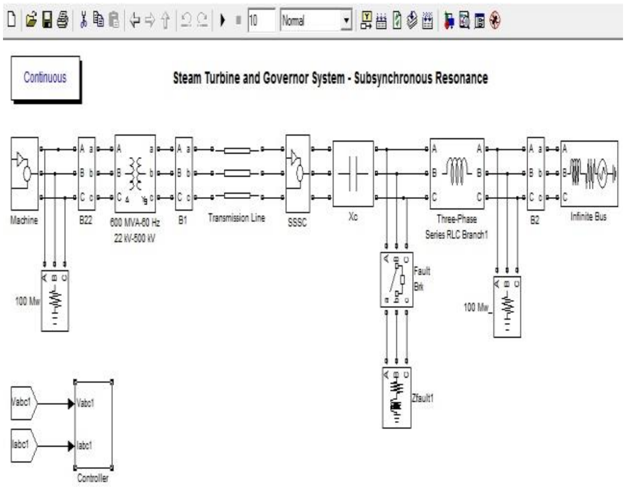

Figure. 14 Sub Synchronous Resonance System with SSSC

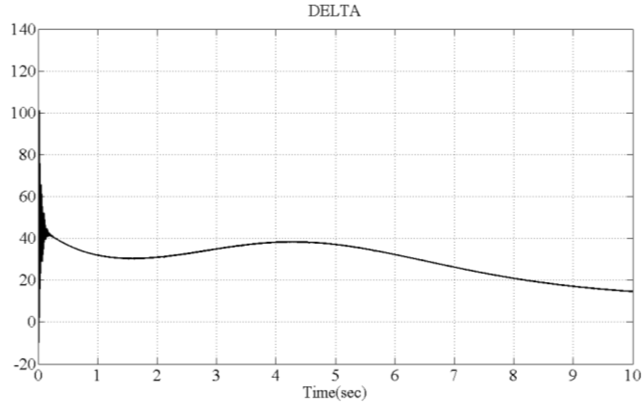

Figure 15. Rotor Angle

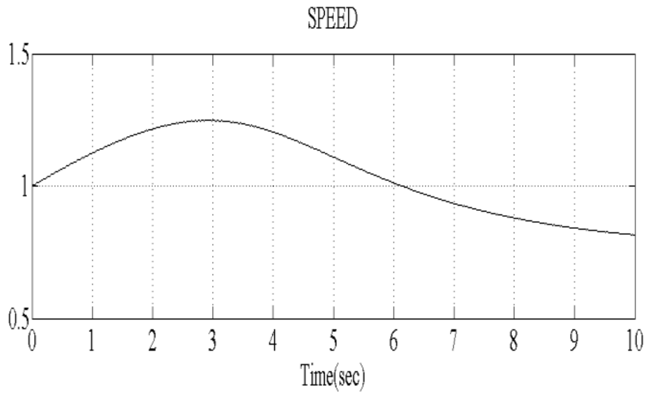

Figure 16.Rotor Speed

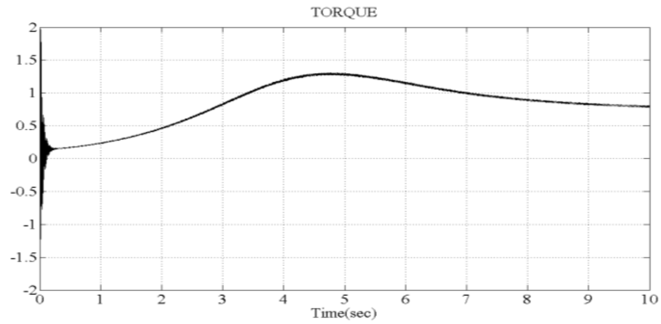

Figure 17. Electromagnetic Torque

CONCLUSION

In this Project, new concepts of application of Static Synchronous Series Compensator (SSSC), for stabilizing torsional oscillations have been proposed. If stresses are above endurance limit of $45x10^7$ N/m^2, then shaft may be damaged.

Table I shows the comparison between the stresses, at different coupling sections of the T-G shaft without and with SSSC. Due to the application of SSSC system becomes stable and stresses are reduced up to 80 to 95%,, which are below the endurance limit.

TABLE I

Comparison of Stresses

Sections	Stress in N/m^2 without UPFC	Stress in N/m^2 with UPFC
HP and IP	$15x10^7$	$10x10^7$
IP and LPA	$18x10^7$	$11x10^7$
LPA and LPB	$80x10^7$	$4x10^7$
LPB and GEN	$90x10^7$	$5x10^7$

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