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Simulation of IEEE First Benchmark Model for Analysis of Sub-Synchronous Resonance in Series Compensated Transmission Line Using Static Synchronous Series Compensator

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ABSTRACT

Series compensation of long transmission lines is widely used in electrical power systems in order to increase the transmission line capacity. However, for certain values of compensation, the series connected capacitors interact with the mechanical elements of the turbine-generator group leading to sub-synchronous resonance which could damage or destroy the mechanical units [1]. In this paper "The IEEE first benchmark system" is simulated using Matlab for the study of sub-synchronous resonance (SSR). The modelling and simulation of the turbine-generator group with series compensation transmission line is used for the analysis of the torsional modes, in order to determine the compensation level values that can cause the sub-synchronous resonance phenomenon. The impact of SSR on shaft torque will increase the magnitude of shaft torque which in turn produces oscillations and vibrations in the system resulting in the mechanical system failure. The oscillations due to Sub Synchronous Resonance are observed between turbine generator and various turbine shafts. FACTS device (Flexible AC transmission system) is used for reducing these oscillations or to mitigate the effect of Sub synchronous resonance phenomena. In this work, it has been shown that by insertion of SSSC the magnitude of shaft torque decreases resulting in reduced oscillation of mechanical system.

Keywords:— *Series Compensation, Sub-synchronous Resonance (SSR), Matlab Simulation Program, Synchronous Machine, First Benchmark Model, Torsional Oscillation.*

I. INTRODUCTION

Series capacitor compensation in AC transmission systems is an economical means to increase load carrying capability, control load sharing among parallel lines and enhance transient stability. However, capacitors in series with transmission lines may cause sub synchronous resonance that can lead to turbine -generator shaft failure and electrical instability at oscillation frequencies lower than the normal system frequency. Therefore, the effects of SSR must be fully understood and analyzed when planning series capacitor compensation in power systems. The main concern with SSR is the possibility of shaft damage from torsional stresses. Turbine-generator shaft failure and electrical instability at oscillation frequencies lower than the normal system frequencies result from SSR [1]. The two shaft failures at the Mohave

Generating Station in Southern Nevada led to the advancements in understanding the SSR phenomenon as well as explaining the interaction between series capacitor compensated lines and the torsion mode of steam turbine-generators [2]. Turbine-generator electromechanical interaction with series capacitors has historically been known as the phenomena of "Sub synchronous Resonance"(SSR). In this regard, this work presents a comprehensive approach towards SSR and IEEE first benchmark model.

II. Sub-Synchronous Resonance

Sub-Synchronous Resonance is an electrical power system condition where, electrical network exchanges energy with turbine generator at one or more natural frequency of combined system, below the synchronous frequency of the system [1].

Series compensation by means of capacitors is widely used in electrical systems to improve transmission capability, the stability of the power system and to compensate for voltage drops due to a high line inductance. However, if the electric network has natural frequencies smaller than the system nominal frequency, the sub-synchronous currents produce torques in the turbine-generator set up, causing that the rotor oscillates at sub-synchronous frequencies [1]. When the frequency of the sub-synchronous torques coincide with some of the frequency of the natural oscillation modes of the shaft, typical of a mass spring system, the shaft will oscillate to that natural frequency. Sometimes the oscillations are large and cause fatigue or damage to the shaft in a few seconds, affecting the power system operation.

A series compensated transmission line has a resonance frequency *given* by:

$$f_{re} = f_0 \sqrt{X_C/(X'' + X_T + X_E)} \quad \ldots\ldots \quad (1)$$

Where is the X'' sub transient reactance of the generator, is the X_T leakage reactance of the transformer. X_C and X_E are the induvtive and capacitive reactances respectively. Thus, for particular levels of series compensation it is possible that the system reaches the resonance frequency:

$$f_r = f_0 - f_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where f_m is the natural frequency of each modes

III. Types of SSR Interaction

There are three types of SSR interactions which are as.

A. Induction Generator Effect
B. Torsional Interaction
C. Transient Torque

IEEE First Benchmark Model (FBM)

IEEE FBM was created by the IEEE Working Group on Sub-synchronous Resonance in 1977 for the purpose of establishing a benchmark model which can be used as a test bench for the comparison of different methods of computer based analysis and simulation. The system consists of a single generator connected to an infinite bus through a single series compensated line [2]. The single line diagram of a Single Machine Infinite Bus system given by IEEE committee for SSR study as shown in Figure 1.

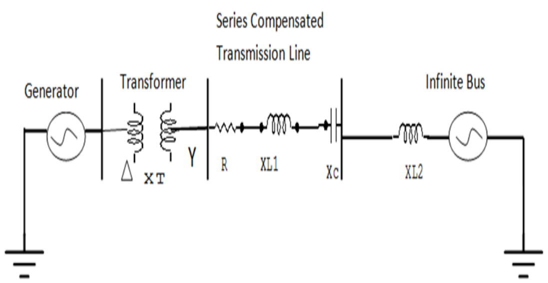

Figure 1: Single line Diagram for IEEE first benchmark system

A. Synchronous Machine Model

The synchronous machine considered is shown in Figure 2. This model shows three phase armature winding on stator i.e. a, b and c and four winding on the rotor including field winding 'f'. The damper winding is represented by equivalent damper circuit in the direct axis and quadrature axis: 1d on d-axis and 1q and 2q on q-axis.

Two equivalent rotor circuits are represented in each axis of the rotor - *F* and *D* in the *d-axis,* and G and Q in the *q-axis*, with positive current direction defined as the direction causing positive magnetization of the defined *d-* and *q-axis* direction, respectively [3]. Synchronous machine operation under balanced three-phase conditions is of particular interest for SSR analysis.

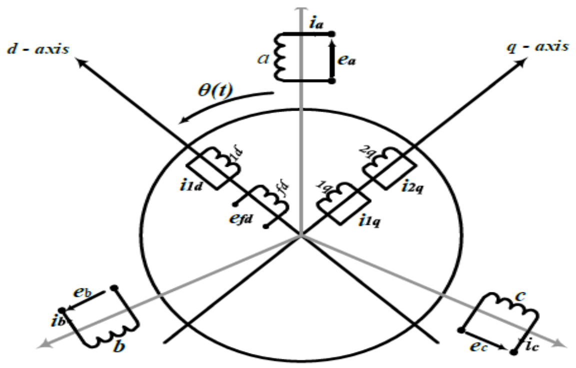

Figure 2 Schematic diagram of conventional synchronous machine

In first IEEE benchmark system circuit parameters are expressed in per unit on the generator base of 600 MVA, 22KV/50 Hz frequency.

B. Multi Mass Model of the Turbine-Generator shaft

The turbine-generator mechanical system consists of six masses; high-pressure turbine (HP), intermediate-pressure turbine (IP), low pressure turbine A (LP_A), low pressure turbine B (LP_B), an exciter (EXC), and a generator (GEN) coupled to a common shaft [3]. The turbine masses, generator rotor and exciter are considered as lumped masses connected to each other as shown in Figure 3.

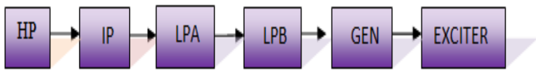

Figure 3: Mechanical structure of six mass FBM systems

IV. Modelling and Simulation

A. System without Fault

This Simulink model is an IEEE First benchmark model. It consist of a single generator (600MVA/22KV/60 Hz/3600 rpm) connected to an infinite bus and transmission line, which is series compensated without fault.

The result has been shown in Figure 5, Figure 6 and Figure 7.

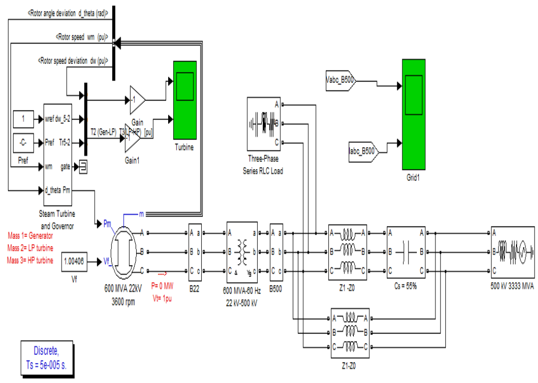

Figure 4. Matlab representation of the IEEE First benchmark mode

Obtained Results

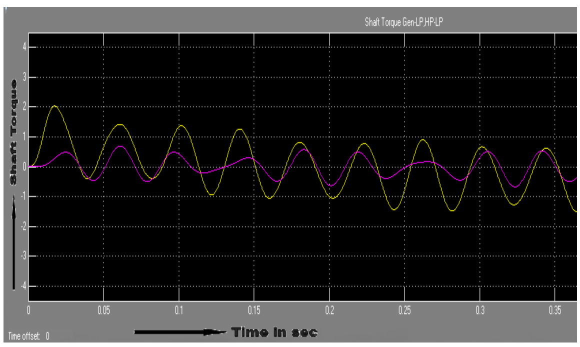

Figure 5. Shaft torque of system without fault

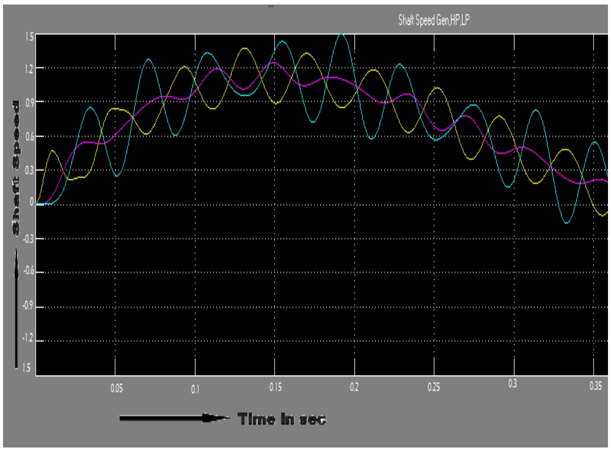

Figure 6. shaft speed of system without fault

Figure 5 and Figure 6 shows that Shaft speed and shaft torque is stable

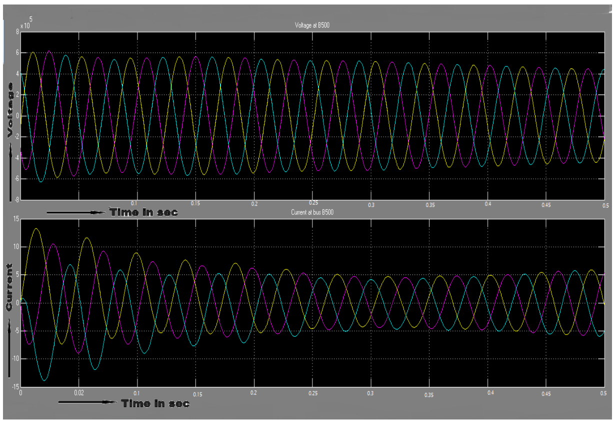

Figure 7 and Figure 8 Voltage and current of system without fault

Figure 7 and Figure 8 shows that Voltage and current of system is stable without fault. The system is stable.

System with Fault

This Simulink model is an IEEE First benchmark model used to study sub synchronous resonance. It consist of a single generator (600MVA/22KV/60 Hz/3600 rpm) connected to an infinite bus and transmission line with series compensated (three different compensation levels (35%, 55%, 75%)).The generator spring mass system consist of three masses. i.e. HP, LP, Gen which are mechanically coupled on the same shaft. A fault is applied at t=0.02sec and cleared at t=0.04sec is a three phase to ground fault. The result has been shown in Figure 10 and Figure 11.

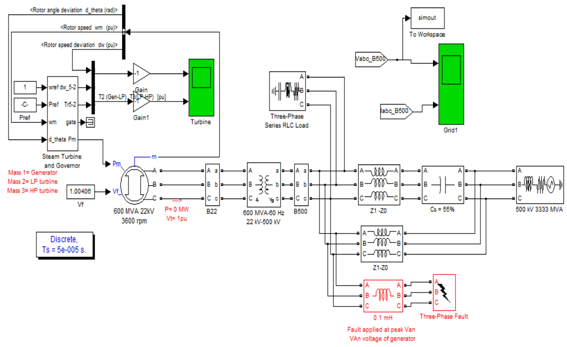

Figure 9. Matlab representation of the IEEE First benchmark mode with fault

Obtained Results

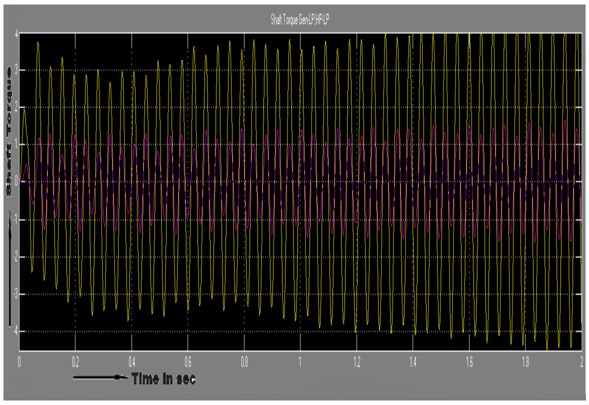

Figure 10 Shaft torque of system with three phase to ground fault

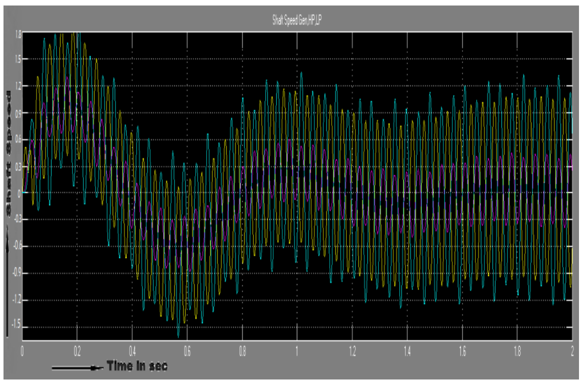

Figure 11 Shaft speed of system with three phase to ground fault

In Figure 10 shows the shaft torque of Gen-LP, HP-LP. It is observed that the shaft torque is with out of limits resulting in increases oscillation in the system. The magnitude of shaft torque increases beyond limits. It causes vibration in the system shaft. This vibration will damage the system shaft, mechanical gears, and other mechanical parts.

In Figure 11 shows the shaft speed of HP, LP, Gen. It is observed that the shaft speed is without of limits resulting in increases oscillation in the system. The magnitude of shaft speed increases beyond limits. This harm the system. In Figure 10 and Figure 11 both shows that the dynamic response of the system is unstable.

System with SSSC Model

Figure 12 Show the simulink model of the IEEE first bechmark system with SSSC (100MVA) controller to compensate the effect of SSR which is connected at the receiving side of the transmission line.

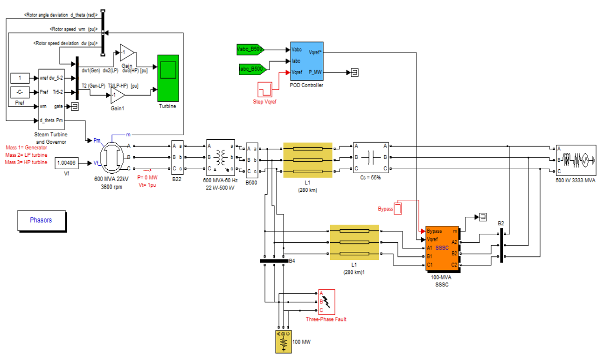

Figure 12 Matlab representation of the IEEE First benchmark mode with SSSC controller

Obtained Results

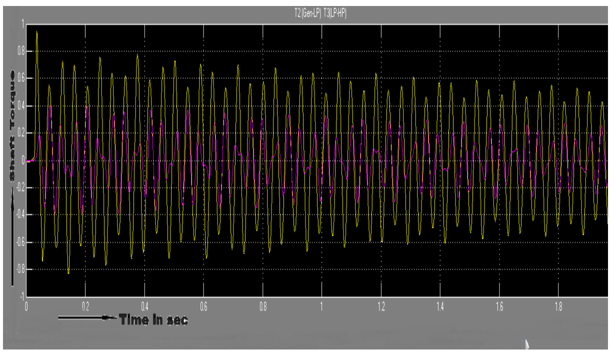

Figure 13 Shaft torque of system with three phase to ground fault

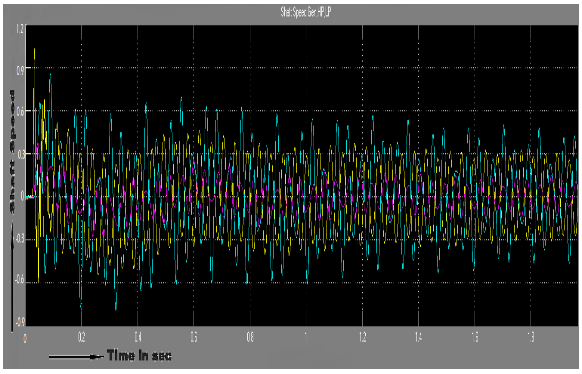

Figure 14. Shaft speed of system with three phase to ground fault

In Figure 13 shows the shaft torque of Gen-LP and HP-LP with SSSC controller. It is observed that the shaft torque is within limits resulting in reduced oscillation. This will save the system shaft, mechanical gears, and other mechanical parts.

In Figure 14 shows the shaft speed of HP, LP and Gen with SSSC controller. It is observed that the shaft speed is within limits resulting in reduced oscillation. This save the shaft of system.

In Figure 13 and Figure 14 both shows that the system dynamic response is better than Figure 10 and Figure 11. Also system settling time is 1.2sec.Torque compensate with SSSC = 3PU

V. CONCLUSION

In this paper, the **First Benchmark Model** for computer simulation of Sub synchronous resonance is simulated in MATLAB. Sub synchronous Resonance Phenomena is simulated by exciting the torsional modes with three phases to ground fault for duration of 0.02 to 0.04sec. The eigenvalue techniques and matlab – simulink has been adopted for the purpose of SSR analysis. The sub-synchronous resonance, torsional modes and compensation levels that lead to sub-synchronous resonance were determined for the power system. The SSSC controller is provided at the receiving side of the transmission system. The critical torsional mode is stabilized with good stability margin. They control the shaft speed and torque with in limit. They save the system shaft and system from damage.

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