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Assessment of Sub-Synchronous Resonance, Compensation Levels of Turbine-Synchronous Generator Group

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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. 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.

Keywords:*—Series Compensation, Sub-synchronous Resonance (SSR), 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.

2. 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:

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

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

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

Where f_m is the natural frequency of each mode of mechanical units.

Sub-synchronous resonance is addressed in three categories, i.e., Induction Generator Effect, Torsional Interaction, and Transient Torque [1]. In all cases, sub-synchronous resonance is due to the interaction of a series capacitor with turbine-generator

III. 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

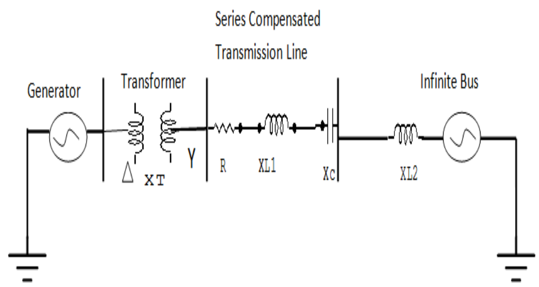

Figure 1: Single line Diagram for IEEE first benchmark system

IV. RATINGS OF THE SYNCHRONOUS MACHINE, TRANSMISSION LINE AND THE TURBINE-GENERATOR GROUP

The parameters used correspond to a 600 MVA and 22KV system and 50Hz. The parameters and rating of the synchronous generator, transformer, transmission line and infinite bus are shown in Table 1. The inertia and spring constants of each axis section of the turbine-generator group are shown in Table 2.

A. Rating of Synchronous Generator-

Rated MVA = 600 MVA

Rated Voltage =22KV

Rated Frequency = 50Hz

Rated Speed = 3600rpm

Table 1. Parameters of the Synchronous Generator

Mass	Inertia Con-stant (H)	Torque Frac-tion	Shaft Section	Spring Constant K in p.u T/ rad.
HP	0.0929	0.28	**HP-IP**	19.303
IP	0.1556	0.24	**IP-LP_A**	34.929
LP_A	0.8587	0.24	**LP_A-LP_B**	52.038
LP_B	0.8842	0.24	**LP_B-Gen**	70.858
Gen	0.8684	0.24	**Gen-Exe**	2.82
Ex-citer	0.0342	-		

B. Rating of Transformer-

Rated MVA = 600 MVA

Rated Voltage =22/500KV

Rated Frequency = 50Hz

Delta/star ground

C. Rating of Infinite Bus

Rated MVA = 3333 MVA

Rated Voltage =500KV

Rated Frequency = 50Hz

Table 2. Inertia and Spring Constants of the Turbine-Generator Group

Pa-rame ter	pu value	Parameter	pu value
R	0.02	**r_D**	1.54
X_T	0.14	**X_D**	0.0055
X_L	0.50	**r_Q**	3.1
X_d	1.79	**X_Q**	0.095
X_q	1.71	**r_G**	0.326
X_d''	0.135	**X_G**	5.3
X_q''	0.200	**X_{AD}**	1.66
r_a	0	**X_{AQ}**	1.58
X_a	0.13	**X_d'**	0.169
r_f	0.53	**X_q'**	0.228
X_f	0.062	**$X_{syst.}$**	0.50

The obtained natural frequency for each mode of mechanical unit are shown in Table 1

Using the natural frequencies of the mechanical system given in Table(3), it is possible to calculate the series compensation levels that lead the system to sub-synchronous resonance, this is exciting one or various of the five torsional modes of the turbine-generator shaft. The sub-synchronous frequency are calculated by-

$$f_{er} = f_0 - f_m \quad \text{....................(3)}$$

Where f_0 is base electrical frequency of system. Then, the natural frequency of the compensated transmission line that excites the first torsional mode of the mechanical system is:

$$f_{er} = 50 - 14.34 = 35.66 \text{ Hz}$$

The natural frequency of the transmission line in terms of the reactances is:

$$f_{er} = f_0 \sqrt{\frac{X_C}{X_{Ltotal}}} \qquad \text{.................................... (4)}$$

where is X_C the capacitive reactance of the series compensator, X_{Ltotal} is the total inductive reactance of the line, defined by $X_{Ltotal} = X_{transf} + X_{line} + X''$; X'' is the average value of the and *d* axes sub-transient reactances.

$$X'' = ((X_d'' + X_q''))/2 \qquad \text{..................(5)}$$

The capacitive reactance is –

$$X_C = X_{Ltotal} \left(\frac{f_{er}}{f_0}\right)^2 \qquad \text{.................................(6)}$$

The compensation level % -

$$\frac{X_C}{X_{Ltotal}} * 100 \qquad \text{...(7)}$$

Table 3 Natural Frequency of the Turbine-Generator Group

Mode	Natural Frequency
0	0
1	14.34
2	18.45
3	23.32
4	29.47
5	43.32

The modal shapes obtained are shown in Figure 2. The modal shapes indicate in graphic form the relative rotational displacements for each one of the masses when they rotated at their natural frequency. The modal shapes are numbered according to the natural frequency and sign changes of the corresponding modal shape.

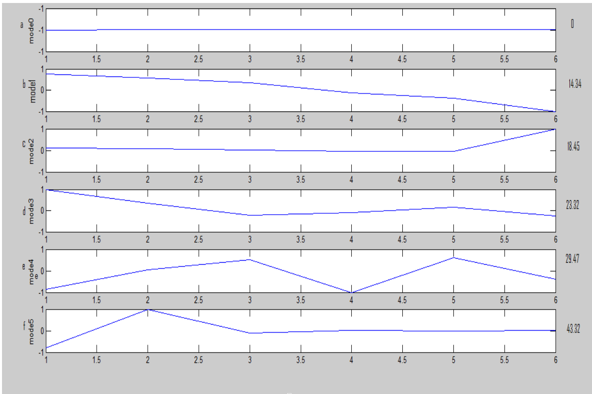

Figure 2. Modal Shapes of the Turbine-Generator

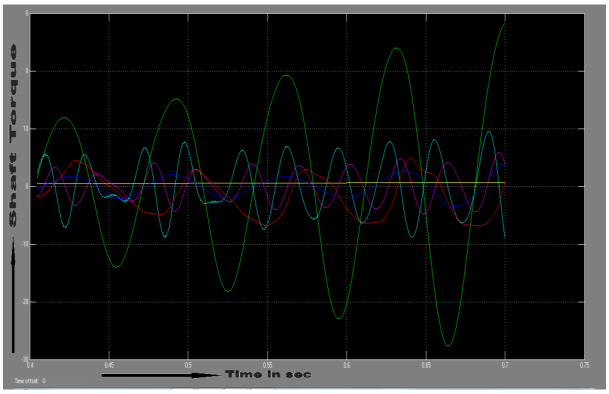

Figure 3. Shaft Torque of the rotor of the system

From Table 3, Figure 2, and Figure 3. Shows the natural frequency, modes shapes and shaft torque of the rotor of a system. We are considering a rotor with five masses; there are five modes of oscillation. The natural frequencies are 14.34 Hz, 18.45 Hz, 23.32 Hz, 29.47 Hz, and 43.32Hz. The relative rotational displacements of the individual masses for each mode of oscillation are given by eigenvector of the corresponding eign value.

The reference mode is shown in Figure 2. The other five modes represent the torsional modes of oscillation. The first torsional mode has a natural frequency of 14.34 Hz. It has one polarity reversal in the shape are shown in Figure 2. The polarities of eigenvector elements associated with rotors of the generator and the LPA section are opposite to those associated with rotors of the LPB, IP and HP sections. This indicates that the generator and the LPA rotors oscillate against the three rotors when this mode is excited.

The second torsional mode has a natural frequency of 18.45 Hz. It has two polarity reversals in the shape are shown in Figure 2. The third torsional mode has a natural frequency of 23.32Hz. It has three polarity reversals in the shape are shown in Figure 2. The fourth torsional mode has a natural frequency of 29.47Hz. It has four polarity reversals in the shape are shown in Figure 2e. as so on. The shaft torque of rotor of a system is shown in Figure 3. The impact of this modes on shaft torque where the magnitude of shaft torque is increase and produce oscillations and vibrations in the system and the mechanical system becomes failure.

The obtained eigenvalues for each modes are shown in Table 4.

Table 4. Eigenvalues of the Turbine-Generator Shaft

Mode	HP	IP	LP_A	LP_B	Gen	Exciter
0	-1.00e+000	-1.00e+000	-1.00e+000	-1.00e+000	-1.00e+000	-1.00e+000
1	7.7700e-001	5.836e-001	3.4238e-001	-1.1168e-001	-3.7308e-001	1.000e+001
2	1.0989e-001	6.4643e-002	1.5003e-002	-3.9497e-002	-3.7354e-002	1.000ee+000
3	1.000e+000	3.4216e-001	-2.2972e-001	-9.5435e-002	1.6597e-001	-2.5248e-001
4	-8.6379e-001	4.3687e-002	5.0271e-001	-1.000e+000	6.2049e-001	-3.7677e-001
5	-7.8741e-001	1.000e+001	-1.1328e-001	2.113e-002	-4.4608e-003	9.4527e-004

Table 5. Sub-Synchronous Frequencies and Compensation Level which Excite the Five Torsional Swings of System

Modes	Sub-synchronous Frequency(Hz)	Xc (pu)	Compensation Level (%)
1	35.66	0.44125	88.25
2	31.55	0.345404	69.0808
3	26.68	0.2847	56.94
4	20.53	0.14625	29.25
5	6.68	0.015483	3.096

5. 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 have 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 to avoid this compensation values. 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.

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