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Abstract - Series compensation has been successfully employed for many years in electric power networks. Series capacitor compensation has a tendency to act as a negative damping on torsional vibrations of nearby turbine generator units. However, their presence in the system may lead to the Sub-synchronous resonance (SSR) phenomenon especially for the nearby generating plants that have a direct or a near radial connection to series capacitor compensated line. In an attempt to analyze the SSR phenomenon, analysis has been done on Second Benchmark model system using both frequency analysis and eigenvalue techniques with three phase fault for different compensation levels. This analysis has been carried out using Matlab control system toolbox.

Keywords*- Subsynchronous resonance, Eigen values, Torsional oscillations ,Booster Transformer..*

I. INTRODUCTION

Series capacitors have been used extensively since a long time as an effective means of increasing the power transfer capability of long transmission lines. Series capacitors introduce a capacitive reactance in series with the inherent inductive reactance of a transmission line, thereby reducing the effective inductive reactance. Series capacitors significantly increase transient and steady-state stability limits, in addition to reactive power and voltage control. One transmission project, consisting of 1000 miles of 500 kV transmission lines, estimates that the application of series capacitors reduced the project cost by 25%. Until 1971, it was generally believed that up to 70% series compensation could be used in any transmission line with little or no concern. However, in 1971 it was learned that series capacitors can create an adverse interaction between the series compensated electrical system and the spring-mass mechanical system of the turbine-generators. This effect is called *sub synchronous resonance* (SSR). Since it is the result of a resonant condition and it has a natural frequency below the fundamental frequency of the power system.

II. SSR PHENOMENON

For the discussion of SSR a simple system, consisting of turbine-generator connected to a single series compensated transmission line as shown in Fig 1 is considered. The turbine-generator has only two masses connected by a shaft acting as a torsional spring. There are damping elements between the two masses and each mass has a damping element.

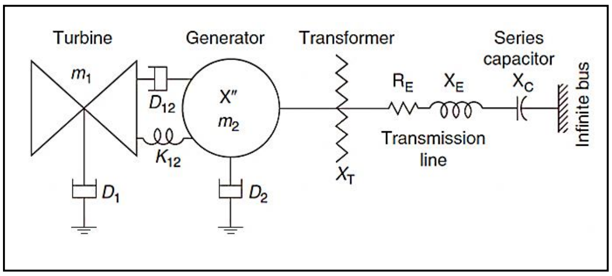

Fig.1 System Under study

The electrical system has a single resonant frequency, f_{er}, and the mechanical spring-mass system has a single natural frequency, f_n.

The electrical system may be a complex grid with many series compensated lines resulting in numerous resonance frequencies f_{er1}, f_{er2}, f_{er3}, etc. Likewise, the turbine-generator may have several masses connected by shafts (springs), resulting in several natural torsional frequencies (torsional modes) f_{n1}, f_{n2}, f_{n3}, etc. Hence, the system is adequate to present the physical principles of SSR. For any electric system disturbance, there will be armature current flow in the three phases of the generator at frequency f_{er}. The positive sequence component of these currents will produce a rotating magnetic field at an angular electrical speed of $2\ f_{er}$. Currents are induced in the rotor winding due to the relative speed of this rotating field and the speed of the rotor. The armature magnetic field, rotating at an angular frequency of f_{er}, interacts with the rotor's dc field, rotating at an angular frequency of f_o, to develop an electromagnetic torque component on the generator rotor at an angular frequency of f_o-f_{er}. This torque component contributes to torsional interaction [1]. The effect of SSR is analyzed using these torsional oscillations

III. SYSTEM CONFIGURATION

The system considered in the present work is the IEEE second benchmark model [5] with additional booster transformer block [Appendix-I]. The single line diagram is shown in Figure 2. A single generator of 600 MVA, 22kV is connected to infinite bus bar through a transformer and two transmission lines. The line is series compensated for 55% transmission line reactance. The transient disturbance considered for torque amplification study is achieved through a three-phase to ground fault, applied at t = 0.02 sec and cleared after 0.017 sec. The spring-mass system is composed of three masses viz. the generator, low-pressure turbine and high-pressure turbine. The model is built and simulated using Power System block-set conjunction with Simulink. The block-set uses the Matlab computation engine to simulate and analyze the interaction of the electrical network with the mechanical part of the system. Both the electrical network and the spring-mass system are represented in Matlab in their differential equations. This model is liberalized about an operating point (Bus1) and arranged in state space for analysis and simulation purposes [1,7].

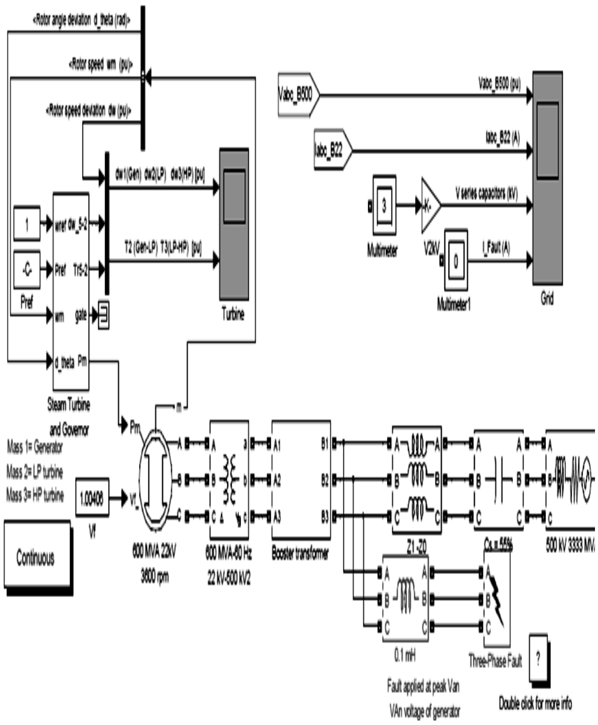

Fig 2: Matlab Simulink model for analyzing the sub synchronous resonance effect.

A booster transformer is added to the block and subsynchronous resonance is investigated by varying the boosting effect of the transformer. Further, the frequency analysis and Eigen value analysis are performed and results are discussed.

IV. TORQUE AMPLIFICATION AND SPEED DEVIATION

Table Showing The Speed Deviation And Torque For Different Compensation Levels					
Capacitive compensation 55%			Fault at 0.2 sec Cleared after 0.17 sec		
Speed Deviations			Compensation	Torque In P.U	
0.01807	0.0175	0.0560	10 %	5.2015	5.4431
0.01576	0.0149	0.0462	20 %	4.5728	4.5607
0.01438	0.0122	0.0389	30 %	4.2045	3.6877
0.01351	0.0102	0.0318	40 %	3.6526	3.1033

Table 1: Speed deviations of generator- LP and HP turbine.

The IEEE benchmark system with booster transformer is simulated for a three phase fault occurred at 0.02 sec and speed deviations and torque at different levels of compensation are tabulated in table 1. The speed deviations are reduced as the level of compensation increases. The torque output is also reduced as the compensation is increased.

V. EIGENVALUE ANALYSIS

Eigenvalue analysis for SSR is a direct approach for torsional interaction and induction generator effect since Eigen values can be analyzed by linear methods. Following approach has been employed.

1. Modeling of power system by its positive sequence model.
2. Modeling of the generator electrical network parameters
3. Modeling of the turbine-generator spring-mass system with zero damping.
4. Calculating the eigenvalues of the interconnected systems.

The real component of eigenvalues that corresponds to the sub-synchronous modes of the turbine generator spring-mass system shows the severity of torsional interaction. The real component of eigenvalues that correspond to only electric system resonant frequencies shows the severity of the induction generator effects problem.

The eigenvalues to be analyzed for torsional interaction can be identified by comparing the imaginary part of each eigenvalue with the modal frequencies of the spring-mass system. The corresponding real part of the eigenvalue is a quantitative indication of the damping for that mode. If the eigenvalue has a negative real part, positive damping is indicated. If it has a positive real part, negative damping is indicated.

VI. SUBSYNCHRONOUS RESONANCE ANALYSIS

FREQUENCY ANALYSIS:

The existence of the subsynchronous mode in the proposed system can be identified by frequency domain calculation of network impedance at bus 1. The impedance of the network as function of frequency is computed for 55% series compensation levels and booster transformer. The network's frequency spectrum is shown in Fig 3.

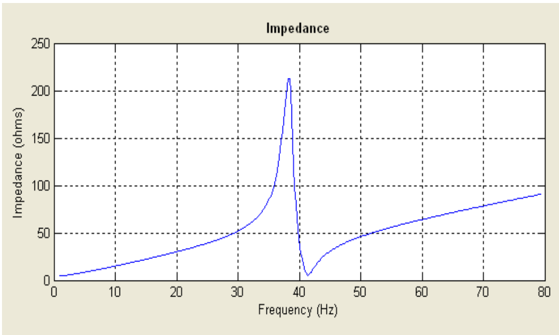

Fig 3: Impedance diagram of the system with booster transformer.

The resonant frequency occurs at 37.5 Hz. The natural frequencies (f_{er}) due to parallel resonance are clearly identified for a particular compensation. In the simulation, the value of capacitive reactance is of 0.55 per unit. This gives the total system impedance of 0.0052 + *j0.0243 per* unit. The value of 0.0297 per unit capacitive reactance corresponds to 55% compensation of the 0.0540 per unit inductive reactance of the transmission line. The practical upper limit for series compensation of long transmission lines is up to 70 %. Using the given value of capacitance, the resonant frequency of the transmission line is computed as follows:

$$\omega_0 = \frac{1}{\sqrt{LC}} = \sqrt{\frac{X_c}{X_l}} = 0.7416\, p.u. = 232.98 \text{ rad/s.}$$

The zero sequence impedances are not required for the computations. This corresponds to a frequency of f = 37.07 Hz. which is clearly in the range of frequencies that may give rise to a subsynchronous resonance with the turbine-generator shaft.In terms of Eigen value computations, we can expect eigenvalues with complex pairs in the neighborhood of $\omega = 2\Pi f \pm \omega_0$.

EIGENVALUE ANALYSIS

There is a need to verify severity of sub synchronous conditions which can be accurately accomplished using eigenvalue analysis. This can be performed using Matlab control system toolbox.

Once the state space model of the system is obtained, based on its set of linearized differential equations, the eigenvalues and eigenvectors can be readily calculated using Power System Blockset which provides the state space model for the network and spring mass system individually.

The Eigenvalue of the electrical network with booster transformer is shown in table 2. The imaginary part indicates the frequencies of the oscillatory modes, while the real part represents the damping factor of these modes. For stable conditions all eigenvalues should in the left of imaginary axis.

S.No	Eigen No.	Real part $[s^{-1}]$	Imaginary Part Frequency (rad/s)
1	1,2	-2.49800	240
2			
3	3,4	-2.29517	236
4			
5	5,6	-0.8083	149
6			
7	7,8	-0.0013	0
8			
9	9	-6.5713	0
10	10	-6.0474	0
11	11	-2.1177	0

Table 2: Eigen values of the system with booster transformer.

S.No	Eigen No.	Real part $[s^{-1}]$	Imaginary Part Frequency (rad/s)
1	1,2	-2.6381	243
2			
3	3,4	-2.382	238
4			
5	5,6	-0.8486	150
6			
7	7,8	-0.0023	0
8			
9	9	-6.92055	0
10	10	-6.3038	0
11	11	-2.1620	0

Table 3: Eigen values of the system with out booster transformer.

The analysis has also been done without the booster transformer and the eigen values are indicated in Table 3

The real part magnitude of corresponding resonant frequencies are minimised. The frequency magnitude is also decreased with insertion of booster transformer.

VII. TIME DOMAIN SIMULATION

Time domain simulation is most useful to study torque amplification, where maximum turbine-generator shaft stress for predicting fatigue life expenditure of the shaft and the risk of dynamic conditions can be determined.

VIII. RESULTS AND DISCUSSIONS

Figure 4 and 5 shows the effect of series compensation level on the magnitude of the torque oscillation between generator and low-pressure turbine and low pressure and high-pressure turbine. For every case of shunt compensation the fault clearing time is 0.017 sec. The decrease in maximum magnitude of the torques of the two shaft segments, Gen-LP and LP-HP is evidenced when the shunt compensation level is changed from 10% to 40% with booster transformer.

The fault clearing time has significant effect on the magnitudes of torque oscillations. Figure 4 shows the oscillation of the torques, the percentage speed deviations. The fault clearing time is 0.017 sec for 55% level of series compensation.

Fig. 5 shows that the variation of voltage, current and capacitor voltage for different levels of compensation. From fig. 4 it is clear that as the compensation is altered by varying the shunt inductor inductance of booster transformer, there is a significant decrease in the magnitude of the speed deviation and torque. The peak variations are tabulated in table 1. The torque amplification due to series capacitor is reduced by increasing the shunt compensation.

Table 3 shows the variation of power and torque of the system considered for different compensation level. The power transfer capability is slightly reduced as shunt compensation is increased. The voltage magnitude and current magnitudes have no significant change.

The negative real part indicates the positive damping whereas the positive real part indicates the negative damping [7]. From the table it is observed that the damping coefficient is positive by which the system is "damped" and the oscillations will gradually die out which can be observed in Fig 4 and 5 These figures shows the phenomenon for the 55% of compensation on system model #1.The peak values of all these signals correspond to max speed deviation and torque.

Sl. No.	Variable	10% compensation	20% compensation	30% compensation	40% compensation
1	Bus Type	P & V generator	P & V generator	P & V generator	P & V generator
2	Van phase	-29.59°	-29.60°	-29.60°	-29.61°
3	Vab	1.019 pu 0.41°	1.019 pu 0.40°	1.019 pu 0.40°	1.019 pu 0.39°
4	Vbc	1.019 pu -119.59°	1.019 pu -119.60°	1.019 pu -119.60°	1.019 pu -119.61°
5	Vca	1.019 pu 120.41°	1.019 pu 120.40°	1.019 pu 120.40°	1.019 pu 120.39°
6	Ia	38.746 A -120.13°	38.746 A -120.13°	38.746 A -120.13°	38.746 A -120.13°
7	Ib	38.746 A 119.87°	38.746 A 119.87°	38.746 A 119.87°	38.746 A 119.87°
8	Ic	38.746 A -0.13°	38.746 A -0.13°	38.746 A -0.13°	38.746 A -0.13°
9	P	-14268 W	-14022 W	-13794 W	-13683 W
10	Q	1.5039e+006 Vars	1.5039e+006 Vars	1.5039e+006 Vars	1.5039e+006 Vars
11	Pmec	-14252 W	-14006 W	-13778 W	-13667 W
12	Torque	-37.805 N.m	-37.151 N.m	-36.547 N.m	-36.252 N.m

Table 2: Power flow and torque for different compensation.

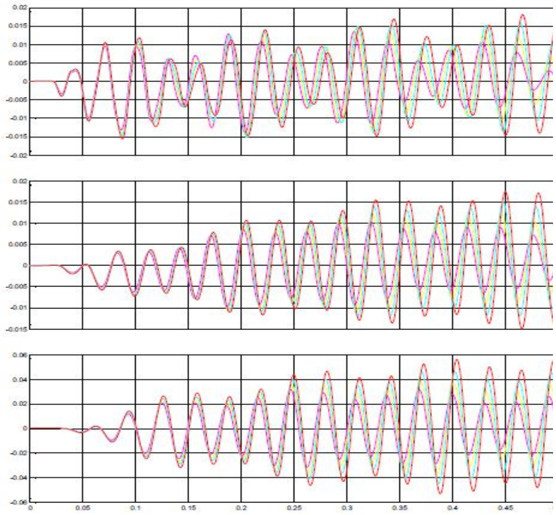

Fig 4: waveforms for the variation speed deviation and torque

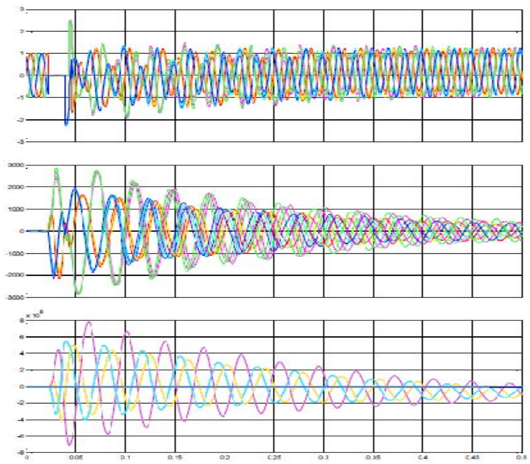

Fig 5: Transient response of the system

CONCLUSION

Sub synchronous resonance effect is studied using IEEE Second Benchmark system with booster transformer and the results have been investigated. It is observed that series compensation produces Subsynchronous resonance, during fault conditions. This effect is counteracted with the help of booster transformer which acts as shunt compensation. The fault condition is created using MATLAB and the behavior of the system is studied using the speed and torque deviations. It is concluded that there is a significant decrease in torsional oscillations and speed deviations.

The study under Eigen values approach is analyzed and concluded that the system considered is well stable and damped for 55% of series compensation. Different compensation levels by varying the booster transformer have been investigated and the results obtained have proved that system is stable as compensation is increased. Due to shunt compensation there is significant decrease in magnitude of torsional oscillations which are caused by series compensation.

APPENDIX-I

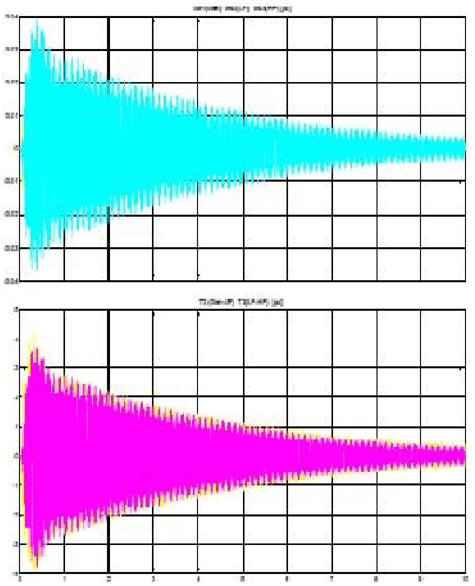

Fig A-1speed and torque variation with booster transformer

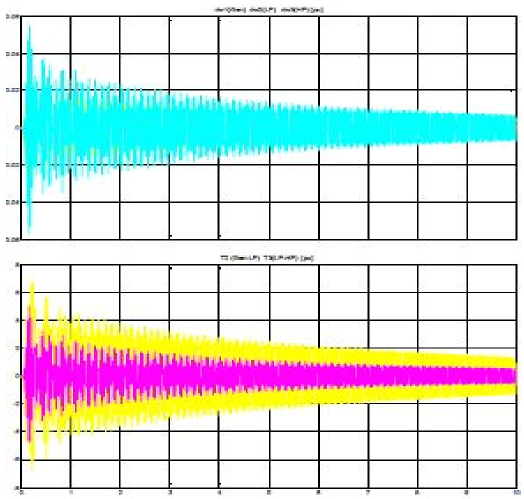

Fig A-2.Speed and torque variation with only inductive compensation

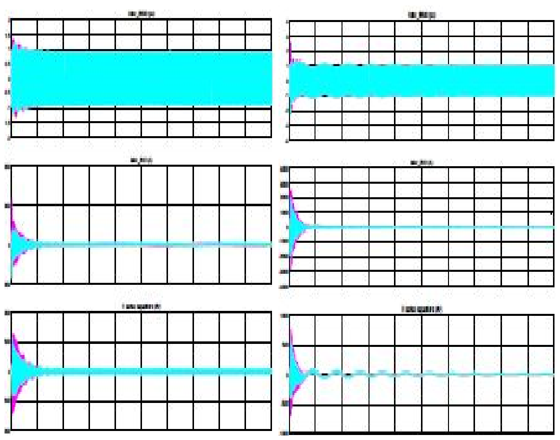

Fig A-3 transient response with 30 % compensation

This appendix shows the advantage of using booster transformer over the simple inductive compensation. The torque and speed deviation are more when only shunt inductive compensation is used. Fig ‘s A-1 and A-2 shows the variation of speed and torque change and it is observed that the max speed change is less than ± 4% for the system with only booster transformer where as it is almost 6 % with simple inductive compensation. The torque oscillations have a maximum peak of 4 p.u for the system employing booster transformer, whereas for the system with simple inductive compensation is nearly 6.5 p.u.

A booster transformer can be considered as a variable inductor that may affect the natural frequency of the transmission line. When this happens, interactions with the generators may be present, with SSR occurrence.

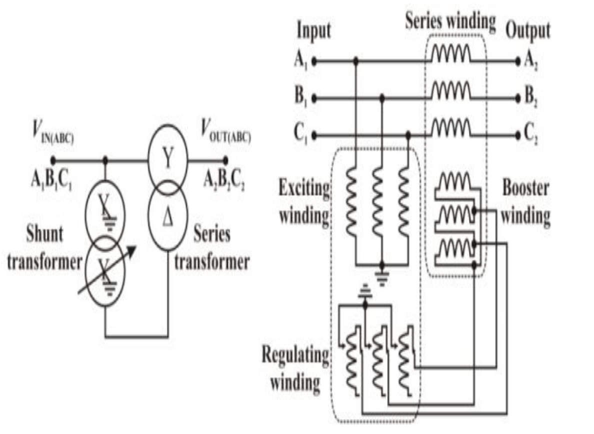

Fig A-4. Booster transformer modeling.

BIBILIOGRAPHY

[1] Subsynchronous resonance in power systems by p.m Anderson, b. l. agrawal, j. e. van ness.

[2] Electric power engineering handbook second edition edited by Leonard l. grigsby

[3] Power system dynamics stability and control second edition k. r. padiyar

[4] Second benchmark model for computer simulation of subsynchronous resonance ieee transactions on power apparatus and systems, vol. pas-104, no. 5, may 1985.

[5] First benchmark model for computer simulation of subsynchronous resonance ieee transactions on power apparatus and systems, vol. pas-96, no. 5, September/October 1977.

[6] Reader's guide to subsynchronous resonance ieee committee report subsynchronous resonance working group of the system dynamic performance subcommittee.

[7] Subsynchronous resonance damping in interconnected power systemsnadiayousif, majid al-dabbagh electrical energy and control systems school of electrical and computer engineering, rmit university – city campus.

[8] Terms, definitions and symbols for subsynchronous oscillations ieee subsynchronous resonance working group of the system dynamic performance subcommittee power system engineering committee