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Analysis and Suppression of Ssr Using Induction Machine Damping Unit *(Imdu)*

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Abstract

In the recent years, the addition of series capacitors in to the transmission lines are increasing to get better transmission efficiency . The inclusion of series capacitors incur serious problem in the entire power system .One such problem is the self excited oscillations of the capacitors. Whenever this oscillation interacts with the Generating Station there is the possibility of the occurrence of Sub-Synchronous Oscillations in the system .These oscillating frequency is in the range of about 10Hz to 40Hz . Due to the Sub-Synchronous oscillations the turbine Generator shaft may get damaged ,repeated stress over the shaft results in the shaft failure. An Induction Machine can be used as a damping unit to control this oscillations .An attempt has been made to reduce the peak torques aroused due to the addition of series capacitors in the system .The peak torques are reduced by the tight coupling of the Induction machine with the turbine- generator shaft. The results are obtained using the IEEE First Benchmark Model using MATLAB Simulation.

Keywords: Peak Torque Suppression ,Induction Machine Damping Unit (IMDU), First Benchmark Model (FBM),SubSynchronous Resonance (SSR), MATLAB

Introduction

The series compensation of line using capacitors in the transmission line results in damage of shaft in USA in 1970.The effects and results are reported in [2]. From that results it was identified as Sub-Synchronous Resonance (SSR) was the main cause for the shaft failure. There are several research work was carried on this domain to damp out the oscillations. Researchers are trying to mitigate the sub synchronous voltage and current components using power electronics devices[3]. Although the mitigation of SSR was achieved. The auxiliary devices have to be installed in between the Generating station and substation which incurs monetary losses. Some of the researchers suggest that the use of excitation controller effectively damps the oscillations , but design of controller was a tedious process. Some authors suggest that the energy stored during the torsional oscillations can be dissipated by using the Dynamic resistor bank[5]. Based on the combined active power and reactive power a controller was designed in [9].The idea of using Induction machine as a damping unit was proposed in [9][10] with the aid of many controllers. By using Induction machine alone the Sub synchronous oscillations can be damped to certain level.

A. SubSynchronous Resonance

Subsynchronous oscillation in an electric system is a condition where the exchange of energy takes place between the electrical system and the mechanical system at one or more of the natural frequencies below the synchronous frequency of the system following a disturbance from equilibrium. The equation of the resonant frequency of the electrical system (f_{er})can be stated as

$$f_{er} = f_0 \sqrt{\frac{X_c}{X'' + X_E + X_T}}$$

f_0 - system frequency in rad/s.

X_c - capacitance of the line in per unit.

X" - Transient reactance in per unit .

X_E - Transmission line Reactance in per unit.

X_T - Reactance of the transformer in per unit.

Whenever there is a disturbance from the equilibrium operating point the stator current produce rotor currents at sub synchronous frequency $f_r = f_0 - f_{er}$

If the electrical system is negatively damped , the oscillations will tend to grow.

According to [4], the FBM has the six-masses in the turbine generator shaft. These six-mass have five torsional mode frequencies. These frequencies are responsible for the torsional oscillations. The self Induction Generator effect and Torsional interaction effect causes a serious trouble in the turbine generator shaft.

Types of SSR

The current in the electrical system which has the resonant frequency component (f_{er}) was responsible for the rise of rotor current frequency(f_r). Since the rotor magnetic fields are rotating at a constant speed leads the slowly rotating sub synchronous mmf in the armature. As a result of that sub synchronous torques are produced which has a frequency component as difference of f_0 and f_{er}. There are two types of SSR have been reported since, they are

1. Self-Excitation
2. Torque amplification

A. Self-Excitation

The sub synchronous currents in the armature windings results in sub synchronous rotor torques and induce rotor currents which has sub synchronous component in it. Hence the sub synchronous armature voltage will allow the sub synchronous currents which results in self excitation. Self Excitation can be divided in to two categories . They are Torsional Interaction and Induction Generator Effect .

a) Induction Generator effect

This phenomena was influenced by the parameters of the electrical system alone . Generator armature currents at sub synchronous frequency (f_{er}) produces a rotating mmf in air gap which has a velocity of $2\pi f_{er}$.Then the mmf acts together with main field to produce sub synchronous torques which has (f_0-f_{er}) component in it .Since the rotor is rotating more faster than rotating mmf ,the resistance to the sub synchronous current when seen from the armature is negative. When this resistance surpass the addition of the armature and network impedance will results in Induction Generator Effect.

Here the attempt has been made to analyze the Induction Generator effect and the Torsional interaction separately .The Eigen value analysis for the above two phenomena was obtained using the following system model . However the digital simulation of the FBM deals with the combination of the both the effects.

b) Torsional Interaction

This phenomena includes the parameters of electrical and mechanical system. Generator rotor oscillates at a torsional frequency (f_n) induce sub synchronous frequency componenet(f_{en} =f_0-f_n) in the armature voltage .When f_{en} matches with the electrical system resonant frequency (f_{er}), the rotor oscillations will be sustained .

System Model

It consists of model of the generator , network and the model of the turbine generator shaft . Both the generator and network parameters is enough to analyse the induction generator effect of the Sub Synchronous Resonance .To analyse the torsional interaction phenomena all the three models are necessary.

a) Generator Model

The generator was modeled as it had two windings in the direct axis of the alternator and two windings on the quadrature axis of the alternator

The flux developed across the windings are given as :

$$\psi_0 = L_0 i_0$$

$$\psi_d = L_d i_d + L_{AD} i_F + L_{AD} i_D$$

$$\psi_F = L_{AD} i_d + L_F i_F + L_{AD} i_D$$

$$\psi_D = L_{AD} i_d + L_{AD} i_F + L_D i_D$$
$$\psi_q = L_q i_q + L_{AQ} i_G + L_{AQ} i_Q$$
$$\psi_G = L_{AQ} i_q + L_G i_G + L_{AQ} i_Q$$
$$\psi_Q = L_{AQ} i_q + L_{AQ} i_G + L_Q i_Q$$

where

Q and G are the windings present in the direct axis of the machine

F - field winding

D - damper winding in the quadrature axis

Based on the above flux equations the generator model was developed to study the SSR

The angular velocity of the rotating machine was give as :

$$\dot{\omega} = I_{dd}\frac{\psi_d}{2H} + I_{dF}\frac{\psi_F}{2H} + I_{dD}\frac{\psi_D}{2H} - I_{qq}\frac{\psi_q}{2H} - I_{qG}\frac{\psi_G}{2H} - I_{qQ}\frac{\psi_Q}{2H} - D\frac{\omega}{2H} + \frac{T_m}{2H}$$

b) Network model

The network model consists of the simple electric network which has a series capacitor in the transmission lines.

The voltage and current equations of the simple electric system for phase a is given as :

$$e_a = Ri_a + L\frac{di_a}{dt} + v_a$$

$$i_a = C\frac{dv_a}{dt}$$

where v_a is the voltage across the capacitor

R and L is the resistance and inductance of the transmission lines.

c) Mechanical model

The entire turbine generator shaft was modelled as a lumped mass system .The mass of each section was modelled as capacitance and the spring constant between the various sections of the turbine was modelled as inductance and the damping of the section was modelled as resistance. The differential equations of the mechanical system was given as:

$$\delta_i = \omega_i \quad \text{i=1,2,3,4,5,6}$$

$$\dot{\omega}_1 = \frac{1}{M_1}[-(D_{12})\omega_1 + D_{12}\omega_2 - K_{12}(\delta_1 - \delta_2) + T_{M1}]$$

$$\dot{\omega}_2 = \frac{1}{M_2}[D_{12}\omega_1 - (D_{12} + D_{23})\omega_2 + D_{23}\omega_3 - K_{12}(\delta_2 - \delta_1) + T_{M2}]$$

$$\dot{\omega}_3 = \frac{1}{M_3}[D_{23}\omega_2 - (D_{23} + D_{34})\omega_3 + D_{34}\omega_4 - K_{23}(\delta_3 - \delta_2) - K_{34}(\delta_3 - \delta_4) + T_{M3}]$$

$$\dot{\omega}_4 = \frac{1}{M_4}[D_{34}\omega_3 - (D_{34} + D_{45})\omega_4 + D_{45}\omega_5 - K_{34}(\delta_4 - \delta_3) - K_{45}(\delta_4 - \delta_5) + T_{M4}]$$

$$\dot{\omega}_5 = \frac{1}{M_5}[D_{45}\omega_4 - (D_{45} + D_{56})\omega_5 + D_{56}\omega_6 - K_{45}(\delta_5 - \delta_4) - K_{56}(\delta_5 - \delta_6) + T_e]$$

$$\dot{\omega}_6 = \frac{1}{M_6}[D_{56}\omega_5 - (D_{56})\omega_6 - K_{56}(\delta_6 - \delta_5)]$$

d) Induction Machine Damping Unit

The induction machine damping unit was a special type of machine designed to damp out the torsional oscillations. It damps the maximum peak torque arises in the shaft .It was designed as low power rating machine ,but it must be capable of delivering maximum energy over a short period of time .

The high energy low power induction machine was designed on the basis of the slip- torque characteristics of the induction machine . From the slip- torque characteristics it was evident that by reducing the value of rotor reactance and rotor resistance ,the maximum torque can be produced by the induction machine .

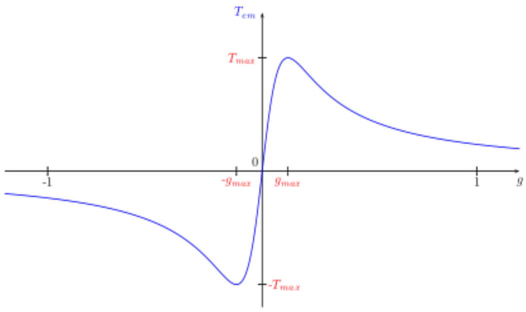

Figure 1: Slip-Torque characteristics of Induction machine

The torque developed by induction machine depends on the value of slip s. The slip was between the rotating magnetic field and the flux induced in the rotor.

Operation of IMDU

Induction machine was attached firmly to the one section of the turbine generator shaft .The induction machine was fed by the voltage generated from alternator .The addition of series capacitor in the transmission line causes sub synchronous components both in the stator windings of the alternator and also in the electromagnetic torque developed aross the alternator . This was responsible for oscillation of the shaft between the sections of shaft .

Whenever the slip of the induction machine is positive the machine acts as a motor thus tries to accelerate the shaft. Whenever the slip is negative the induction machine acts a generator which tries to decelerate the shaft.

The torque produced by the induction machine reduces the shaft twist between the LPB-GEN shaft to a certain level. The IMDU operates only when there was a deviation of speed from reference synchronous speed. It has the capability to reduce the torsional mode frequencies .Since the IMDU has negligible mass and attached firmly with the LPB section of shaft. The mass of the system remains same since it has negligible mass. The torque (T_{im})developed by Induction machine is given as :

$$T_{im} = \frac{3s}{\omega_0 r_2^{'} \{1 + (s.x_2^{'} / r_2^{'})^2\}}$$

where $s = (\omega_0 - \omega_i) / \omega_0$

ω_i - is the angular velocity corresponding to mass *i*.

Results and Discussions

Based on the equations stated in section III a state space model was developed for both the induction generator effect and the torsional interaction effect of SSR. Based on the flux equations of the generator model eigen value analysis reveals that increasing the compensation levels of the transmission lines leads to the instability of the system. On increasing the compensation flux developed between stator and rotor has a sub synchronous component in it .This flux is responsible for the induction generator effect as stated in section II.

Table 1: Eigen Value Analysis For Various Capacitance Values

Xc (in pu)	**Eigen value 1**	**Eigen value 2**	**Eigen value 3**	**Eigen value 4**	**Eigen value 5**	**Eigen value 6**
0.05	-7.03 + 477.33i	-7.03 - 477.33i	-3.67 + 276.03i	-3.67 - 276.03i	-37.50	-0.84
0.1	-7.41 + 519.18i	-7.41 - 519.18i	-2.28 + 234.37i	-2.28 - 234.37i	-39.48	-0.89
0.15	-7.66 + 551.27i	-7.66 - 551.27i	-0.86 + 202.55i	-0.86 - 202.55i	-41.76	-0.96
0.20	-7.84 + 578.33i	-7.84 - 578.33i	0.67 + 175.91i	0.67 - 175.91i	-44.36	-1.04
0.30	-8.12 + 623.71i	-8.12 - 623.71i	4.15 + 132.04i	4.15 - 132.04i	-50.56	-1.25
0.35	-8.23 + 643.52i	-8.23 - 643.52i	6.05 + 113.53i	6.05 - 113.53i	-53.98	-1.41

On analyzing the mechanical system response for the various compensation levels it is evident from Table 2 and the eigen value plot of whole system shows the excitation of torsional modes. This results in shaft oscillations at various sections of the turbine generator shaft .

Table 2: Unstable Eigen value analysis for combined system (electrical and mechanical)

State variables	NO LOAD	LOAD AT 0.9 Pu	Oscillating frequency (Hz)
Ed’	-4.43+j616.53	-4.49+j616.53	98.123
S_m	-3.01+j136.36	-3.23+j136.08	21.657
S_{LP}	0.00+j298.18	0.00+j298.18	47.456
T_{LG}	0.04+j202.74	0.02+j202.70	32.260
S_{IP}	0.13+j160.17	0.29+j160.12	25.483
T_{IL}	0.03+j127.21	0.06+j127.32	20.263
S_{HP}	-0.05+j99.72	-0.16+j99.94	15.905
δ	1.38+j9.58	1.05+j9.53	1.518

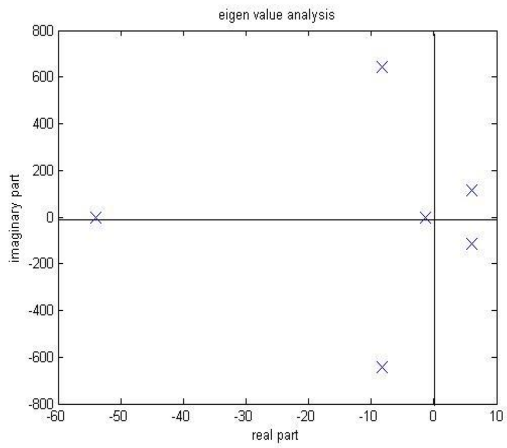

Figure 1: Eigen value plot for Induction Generator effect

From Fig 2 and 3 we can conclude that the tight coupling of the induction machine to the LPB section of the turbine generator shaft brings the system to the stable equilibrium state .

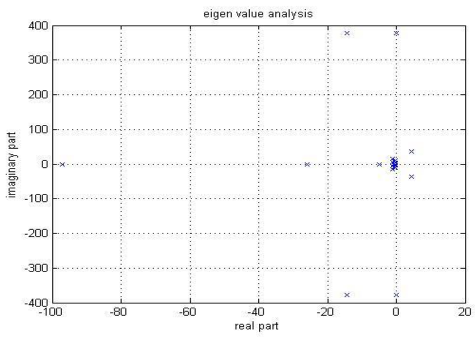

Figure 2: Eigen value plot for the combined system without Induction machine damping unit

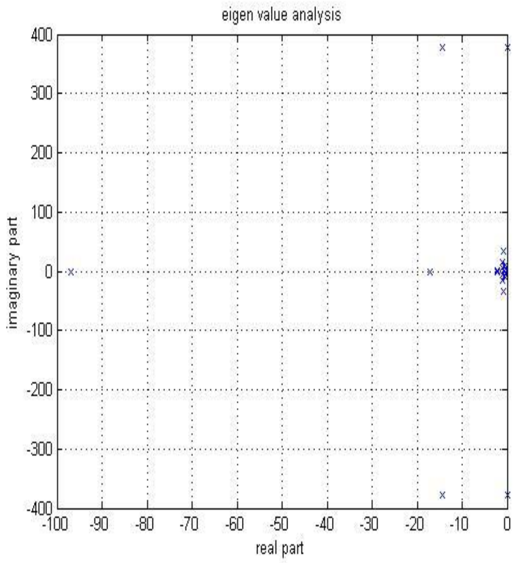

Figure 3: Eigen value plot for the system with Induction machine

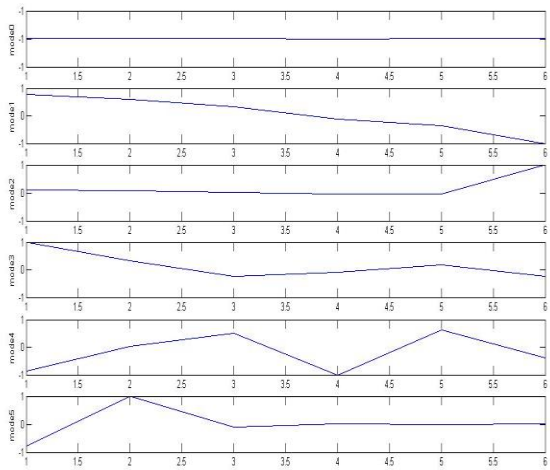

Figure 4: Torsional modes of the FBM System

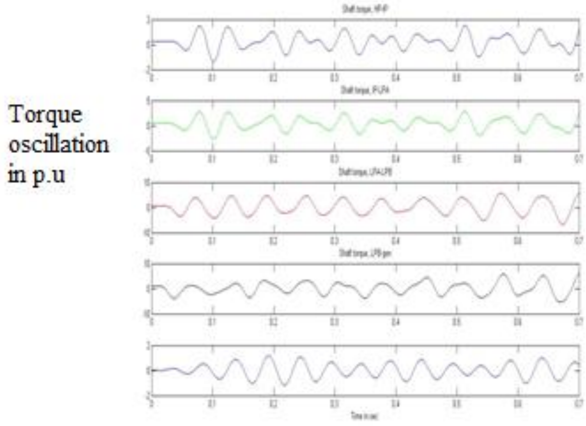

Figure 5: Torque oscillations at various sections of the Turbine-Generator shaft

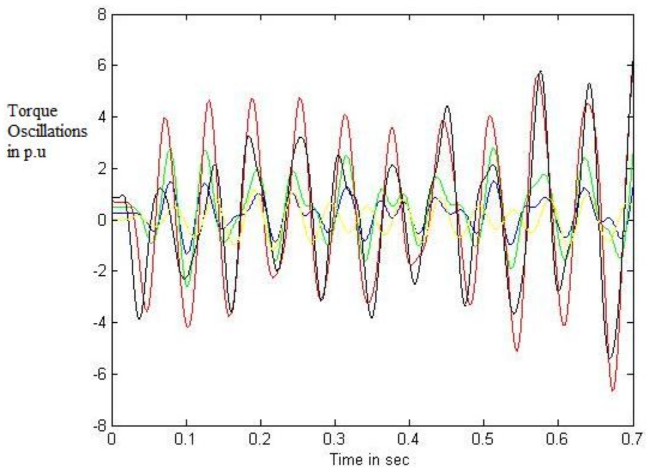

Figure 6: Oscillations of the shaft

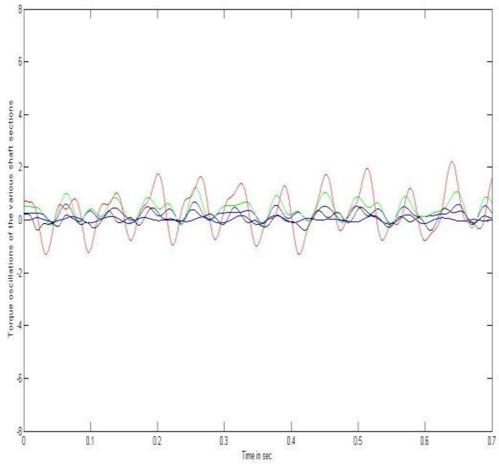

Figure 7: Oscillations of the Turbine Generator Shaft with IMDU

The time domain analysis was done in MATLAB. The turbine shaft oscillations shown in Fig 5 reveals that the shaft oscillations between the LPB and generator has maximum peak shaft torques compared to the other shaft sections. On coupling of additional mass to the LPB -Generator shaft the maximum peak torques are reduced to a certain level.

Conclusion

The eigen value analysis and time domain simulations of the First Benchmark model shows that the system state for more than 50% percent series compensation of the transmission lines will become unstable. This condition tends to SSR which will further leads to shaft failure .In order to avoid shaft failure the Induction machine damping unit was tightly coupled between the LPB section of the shaft and the generator section of the shaft . It can be concluded that addition of IMDU in the system reduces the peak shaft torques which damps the system positively.

References

[1] IEEE Subsynchronous Resonance Working Group, “Terms, definitions and symbols for subsynchronous oscillations,” IEEE Trans. Power App.Syst., vol. PAS-104, no. 6, pp. 1326–1334, Jun. 1985

[2] R.G.Farmer ,A.L.Schwalb ,"Navajo project report on subsynchronous resonance analysis and solutions " IEEE Trans. Power App. Syst vol PAS-96,no. 4 pp.1226-1232,Aug.1977

[3] N. Kakimoto and A. Phongphanphanee, “Subsynchronous resonance damping control of thyristor-controlled series capacitor,” IEEE Power Eng. Rev., vol. 22, no. 9, p. 63, Sep. 2002.

[4] IEEE Subsynchronous Resonance Task Force, “First benchmark model for computer simulation of subsynchronous resonance,”IEEE Trans. Power App. Syst., vol. PAS-96, no. 5, pp. 1565–1572, Sep. 1977.
[5] O. Wasynczuk, “Damping shaft torsional oscillations using a dynamically controlled resistor bank,” IEEE Trans. Power App. Syst., vol. PAS-100, no. 7, pp. 3340–3349, Jul. 1981.
[6] K.R.Padiyar "Power system dynamics stability and control " India : BS publications, Second edition 2008.
[7] P.Kundur "Power System Stability and Control " New York: McGraw Hill,2007
[8] B. L. Agarwal, P. M. Anderson, and J. E. Van Ness, "Subsynchronous Resonance in Power Systems ". Piscataway, NJ: IEEE Press, 1990.
[9] K. Narendra, “Damping SSR in a series compensated power system,” in Proc. IEEE Power India Conf., 2006.
[10] S. K. Gupta, A. K. Gupta, and N. Kumar, “Damping subsynchronous resonance in power systems,” Proc. Inst. Elect. Eng., Gen., Transm., Distrib., vol. 149, no. 6, pp. 679–688, Nov. 2002.
[11] S.Purushothaman and Francisco de León,"Eliminating Subsynchronous Oscillations With an Induction Machine Damping Unit (IMDU) IEEE Transactions On Power Systems, Vol. 26, No. 1,pp.225-232 February 2011.