Simulation of IEEE FIRST BANCHMARK Model for SSR Studies

K. G. Prajapati[1] A. M. Upadhyay[2]
[1]M. E. [Electrical] Student [2]Associate Professor
[1, 2]Department of Electrical Engineering
[1, 2] S. S. E. C., Bhavnagar, Gujarat, India

Abstract—The benchmark model for the study of Subsynchronous resonance is presented by IEEE Subsynchronous Resonance task force. Here, the IEEE First Benchmark system for Subsynchronous resonance is simulated using MATLAB for comparison. The oscillations due to SSR are observed between turbine-generator and between various turbine shafts. This paper mainly focuses on the use of highly versatile software MATLAB for analysis of Subsynchronous Resonance in power systems.

Key words: SSR, Synchronous Machine, Transient torque, Multimass model.

I. INTRODUCTION

Electrical power generation involves interaction between the electrical and mechanical energies coupled through the generator. It follows that any change in the electric power system results in a corresponding reaction/response from the mechanical system and vice versa. Slow-changing load translates to a slow-changing mechanical torque on the rotor shaft, which in turn, is matched by a slow-changing rotor angle to new steady-state angle between the rotor and the stator along with adjustment in the mechanical power input to the rotor through the turbines. Major disturbances such as faults and fault clearing result in large transient torques on the mechanical system and corresponding transient twisting of the rotor shaft couplings between tandem turbines and generator [1].

Worldwide series capacitors have been extensively used for improving power transmission. While it has been known that series capacitors can cause self-excited oscillations at low frequencies (due to low X/R ratio) or at Subsynchronous frequencies (due to induction generator effect), the problem of self excited torsional frequency oscillations (due to torsional oscillations) was first experienced at Mohave power station in U.S.A. in December 1970 and October 1971 [2]. The problem of self excitation due to torsional interaction is a serious problem and led to detailed analysis and study.

II. TYPES OF SSR INTERACTIONS

There are three types of SSR interactions which are Induction Generator Effect, Torsional Interaction Effect and Transient Torque Effect.

Induction generator effect is caused by self excitation of the electrical system. Torsional interaction occurs when the induced subsynchronous torque in the generator is close to one of the torsional natural modes of the turbine generator shaft[3]. Transient torques are those that result from system disturbances. System disturbances cause sudden changes in the network parameters, resulting in sudden changes in currents that will tend to oscillate at the natural frequencies of the network. Also, this can cause shaft damage as experienced at Mohave generating station in U.S.A. [3].

Digital programs like Electromagnetic Transient Programs (EMTP) and Simulator like RTDS (Real Time Digital Simulator) are available to perform the studies of Subsynchronous Resonance. SIMULINK®, developed by MathWorks, is a data flow graphical programming language tool for modeling, simulating and analyzing multi domain dynamic systems. With the use of above software, the First Benchmark model[4] is developed and simulated.

III. THE IEEE FIRST BENCHMARK MODEL

The single line diagram of a Single Machine Infinite Bus system given by IEEE committee for SSR study is shown in fig. 1[4].

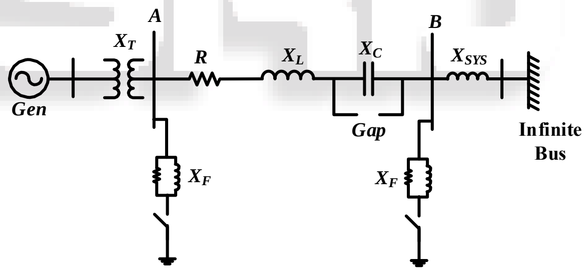

Fig. 1: Single Line Diagram for First Benchmark Model for SSR Study.

The circuit parameters are expressed in per unit on the generator MVA rating at 60Hz. Reactances are proportional to frequency, resistances are constant. The infinite bus is a 3-phase 60 Hz voltage source with zero impedance at all frequencies. Two fault locations (A and B) are designated. This network is used for both transient and self-excitation studies.

IV. SYSTEM MODELING

First, individual mathematical models describing the synchronous generator, turbine-generator mechanical system, and electrical network are presented. Then, all the equations are combined in a standard form for the analysis.

A. Synchronous Machine Modeling

For SSR analysis, experience has shown that reasonable results may be obtained by defining two rotor circuits on two different axes that are in space quadrature - the familiar *d* and *q*-axes. A conventional synchronous machine schematic diagram is shown in Fig. 2. The model shows three-phase armature windings on the stator (*a, b,* and *c*). The rotor of the machine carries the field f_d winding and damper windings. The damper windings are represented by equivalent damper circuits in the direct axis (*d*-axis) and quadrature axis (*q*-axis): *1d* on *d*-axis, and *1q* and *2q* on *q*-axis.

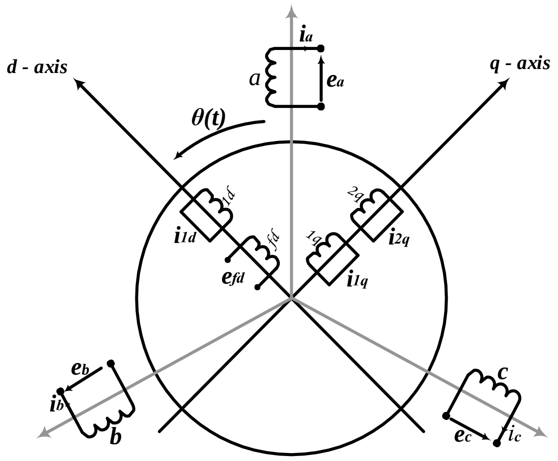

Fig. 2 : Schematic diagram of a conventional synchronous machine.

a,b,c : Stator windings

e_a,e_b,e_c : Stator three-phase winding voltages.

i_a,i_b,i_c : Stator three-phase winding currents.

f_d : Field winding.

f_{ed} : Field voltage.

1d : *d* – axis damper winding.

1q : First *q* – axis damper winding.

2q : Second *q* – axis damper winding.

$\theta(t)$: The electrical angle (in rad) by which *d* – axis leads magnetic axis of phase a winding.

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. Synchronous machine operation under balanced three-phase conditions is of particular interest for SSR analysis. The synchronous machine voltage equations in normalized form can be written as follows.

$$\begin{bmatrix} v_d \\ -v_F \\ -v_D \\ v_q \\ -v_G \\ -v_Q \end{bmatrix} = \left[\begin{array}{ccc|ccc} r_a & & & & & \\ & r_F & & & & \\ & & r_D & & & \\ \hline & & & r_a & & \\ & & & & r_G & \\ & & & & & r_Q \end{array}\right] \begin{bmatrix} i_d \\ i_F \\ i_D \\ i_q \\ i_G \\ i_Q \end{bmatrix} - \left[\frac{1}{\omega_B}\right] \begin{bmatrix} p\psi_d \\ p\psi_F \\ p\psi_D \\ p\psi_q \\ p\psi_G \\ p\psi_Q \end{bmatrix} + \left[\begin{array}{c} -\omega\psi_q \\ 0 \\ 0 \\ \hline +\omega\psi_d \\ 0 \\ 0 \end{array}\right] \text{pu}$$

The machine circuit equations given are usually expressed schematically by the *d* and *q* equivalent circuits as shown in Fig. 3

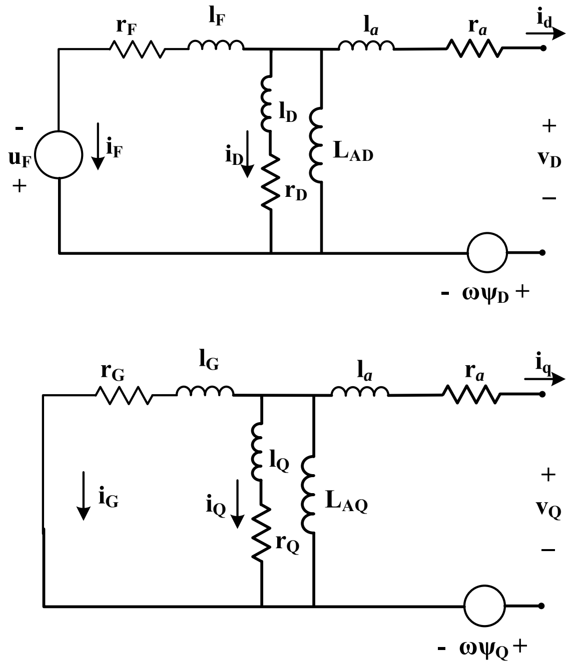

Fig. 3 :Equivalent circuit of machine from the voltage equations

The Synchronous Machine block is given in MATLAB Simpowersystems Library. The model takes into account the dynamics of the *stator*, *field,* and *damper* windings. The equivalent circuit of the model is represented in the rotor reference frame (*qd* frame). All parameters and electrical quantities are viewed from the rotor.

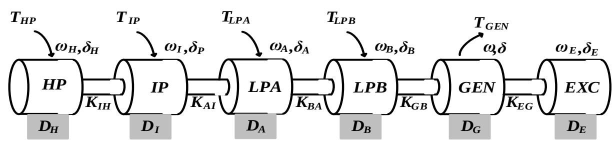

Fig. 4: Mechanical structure of six mass FBM system

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 (LPA) and low pressure turbine B (LPB), an exciter (EXC), and a generator (GEN) coupled to a common shaft as shown in Fig.4. The turbine masses, generator rotor and exciter are considered as lumped masses (rigid body) connected to each other via massless springs.

From Fig.4, the torques acting on the generator mass are:

Generator:

Input torque $T_{GENin} = K_{GB}(\Delta\delta_B - \Delta\delta)$

Output torque $T_{GENout} = \Delta T_e - K_{EG}(\Delta\delta - \Delta\delta_E)$

Damping $T_{GENDamping} = D_G \Delta\omega$

Similarly, for the low pressure turbine B, the forces acting are:

Low pressure turbine B:

Input torque $T_{LPBin} = \Delta T_{LPB} + K_{BA}(\Delta\delta_A - \Delta\delta_B)$

Output $T_{LPBout} = K_{GB}(\Delta\delta_B - \Delta\delta)$

Damping $T_{LPBDamping} = D_B \Delta\omega_B$

Similarly all other masses torque equations can be derived. The Steam Turbine and Governor block in MATLAB Simpower systems library implements a complete tandem-compound steam prime mover, including a speed governing system, a four-stage steam turbine, and a shaft with up to four masses. The shaft models a four-mass system, which is coupled to the mass in the Synchronous Machine model for a total of five masses. The exciter mass is omitted and a static excitation system is used. Machine's mass is labeled as mass #2. The mass in the Steam Turbine and Governor block, which is closest to the machine's mass, is mass #3, while the mass farthest from the machine is mass #6. The shaft is characterized by mass inertias H, damping factors D, and rigidity coefficients K.

V. SIMULATIONS AND RESULTS

The MATLAB Simpowersystems library components such as multimass model of steam turbine and governor system, Synchronous machine, exciter, a lumped parameter transmission line and infinite source are connected as in fig.1. and the circuit model is prepared in MATLAB SIMULINK®. The system is simulated for the same operating condition as in[4]. For the transient case, three phase fault is applied at bus B in fig.1 for duration of 75 msec from 0.01 seconds to 0.075 seconds(4.5 cycles). Fault reactance is 0.04 p.u. and it is adjusted to produce a capacitor transient voltage approaching the lower gap setting.

Generator power output Po	0.9 pu
Generator power factorPF	0.9 pu (lagging)
Capacitor reactance	0.371 pu
Capacitor bypass voltage	(not used)
Capacitor reinsertion voltage	(not used)

Table. 1: Transient Case Description

Capacitor voltage, Generator current, Generator Electrical Torque and Shaft Torque of LPA-LPB are plotted for the time duration of 0.5 sec.

Fig.5*(a)*.shows the variation of voltage across the capacitor in per unit. The Capacitor voltage is varying up to 1 p.u. and it is settling down to a constant value after 0.3 seconds. Fig.5*(b)*. shows the variation of the machine current of phase A in per unit. From the graph, it is seen that the machine phase current is oscillatory. Electrical torque of the synchronous generator is shown Fig.5*(c)*. It is clear that the torque is not constant after application of fault at bus B. That shows the electrical transmission network resonant frequency matches one of the natural modes of the multimass turbine.

The torque on the shaft between the LPA-LPB turbine masses is shown in fig.5*(d)*. There are oscillations of frequency warring from 15Hz to 45Hz (subsynchronous).

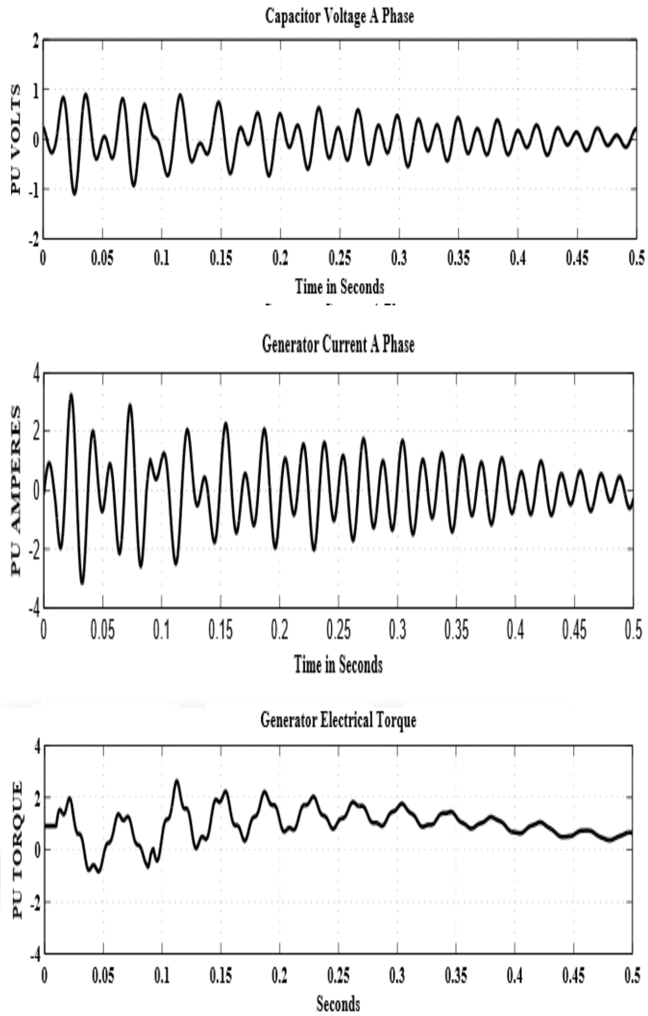

Fig. 5: Response Curves For Transient Case

Extending the simulation for 5 seconds for the same operating condition and applying three phase fault at bus-B in fig.1 after 50 cycles and clearing after 4.5 cycles the torque oscillations are as shown in fig.6. The oscillations are growing rapidly. Fig.7 is FFT analysis window of the torque on the shaft section LPA-LPB. It is clear from the fig. that three torsional modes 16 Hz, 25 Hz, and 32 Hz are excited.

VI. CONCLUSION

By exciting the turbine torsional modes with three phase fault Subsynchronous Resonance Phenomena is simulated. The simulation is carried out for the same operating condition as in [4]. Comparing with the reference results except for the self-excitation case, the results obtained (fig.5) are closely matching. The results are slight different because of the difference in modeling of the components and method of solving the non-linear equations. Also with the FFT analysis tool of Power GUI the excited torsional modes can be observed. The MATLAB model for SSR can be used for the analysis of the various strategies of SSR mitigation.

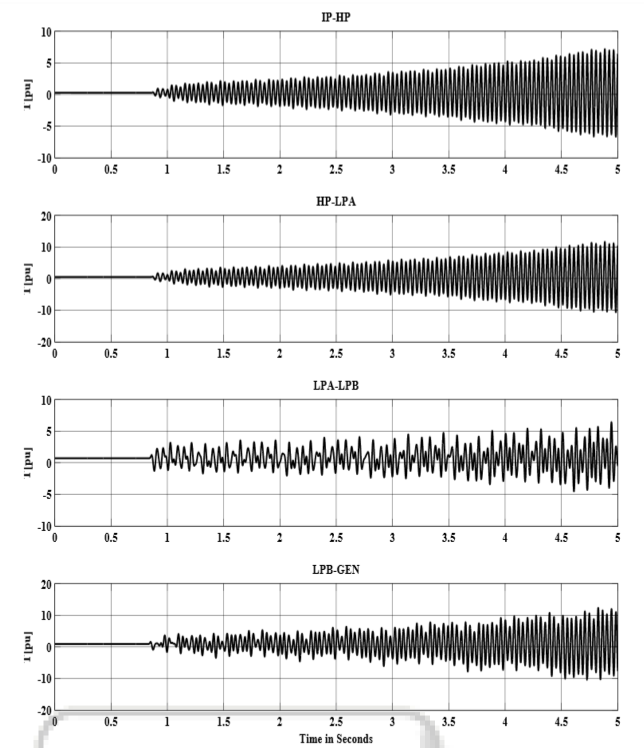

Fig. 7: FFT Analysis Of The LPA-LPB Section Torque Shown In Fig. 6

APPENDIX

The network parameters of the system are as follows:

A. *Generator Parameters*

Power Factor: 0.9 lagging

$X_a = 0.13$ pu	$X_d = 1.79$ pu
X_d= 0.169 pu	$X_l = 0.135$ pu
$X_q = 1.71$ pu	X_q= 0.228 pu
X_q pu	Ra=0.002 pu
$T_{d0} = 4.3$ s	$T_{d0} = 0.032$ s
T_{q0} s	T_{q0} s

B. *Mechanical Parameters:*

Mass	Inertia(Seconds)	Torque Fraction
HP	0.0929	0.30
IP	0.1556	0.26
LPA	0.8587	0.22
LPB	0.8842	0.22
GEN	0.8686	

Shaft	Spring Constant (pu)
HP - IP	7277
IP - LPA	13168
LPA-LPB	19618
LPB-GEN	26713

C. *Transformer Parameters:*

Rated MVA: 892.4

Voltage Rating: 26/539 kV

Delta / Star grounded

R = 0.00792 pu

X = 0.14 pu

$X_0 = 0.14$ pu

D. *Transmission line parameters:*

R = 0.02 pu

X = 0.50 pu

E. *Series capacitor:*

C = 0.371 pu

F. *Infinite Bus*

Voltage: 500 kV RMS L-L

Phase angle: 0°

G. *Fault Impedance*

Reactance: 0.04 pu

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