SIMULATION OF FIRST BENCHMARK MODEL FOR ANALYSIS OF SUBSYNCHRONOUS RESONANCE IN POWER SYSTEMS USING SEQUEL

Mr.J.SREERANGANAYAKULU
Assistant Professor,
SITAMS,
Chittoor - 517127.

N.Chinna Alluraiah
Assistant Professor,
SITAMS,
Chittoor-517127.

Abstract: This paper mainly focuses on the use of upcoming and indigenous software SEQUEL for analysis of Subsynchronous Resonance phenomena in power systems. Here, the IEEE First Benchmark system for Subsynchronous resonance is simulated using SEQUEL for comparison. The oscillations due to SSR are observed between turbine-generator and between various turbine shafts.

Keywords: SEQUEL, Self Excitation, Induction generator effect, Torsional interaction, Transient torque, Multimass model.

Introduction:

Worldwide series capacitors have been extensively used for improving power factor and thereby the 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 [1]. The problem of self excitation due to torsional interaction is a serious problem and led to detailed analysis and study.

The IEEE SSR working group defines **Subsynchronous Resonance** (SSR) as an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system [2].

There are two aspects of the SSR problem [1]. These are
1. **Self excitation** (Steady state SSR) and
2. **Transient torque** (Transient SSR)

Subsynchronous frequency currents entering the generator terminals produce the synchronous frequency teminal voltage components. These voltage components may sustain the currents to produce the effect that is termed as **self excitation**. There are two types of self excitation, one involving only rotor electrical dynamics and the other involving both rotor electrical and mechanical dynamics. First one is the **induction generator effect** while the second one is called **torsional interaction**. Here, the torsional interaction effect is more significant when compared to induction generator effect. 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. An indigenous up coming software **SEQUEL** (A Solver for circuit EQuations with User-defined ELements) has been developed by IIT Bombay for the simulation of the power electronic systems and power systems. With the use of above software, the First Benchmark model is developed and simulated.

First Benchmark system for Subsynchronous Resonance:

A single line diagram of the First Benchmark model given by IEEE committee for the study of Subsynchronous Resonance is as shown in figure 1.
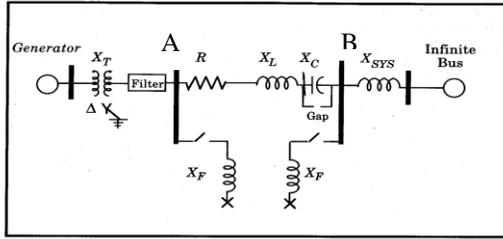
Fig 1: *Network for First Benchmark Model for SSR*

compensated transmission line connecting a

Synchronous machine model

Simple models of synchronous generators are not adequate for accurate description of the power results in time-invariant machine equations which are easier to handle. So, we consider a Synchronous machine in the Park reference frame (i.e. rotor reference frame) with one damper winding in D-axis and two in the
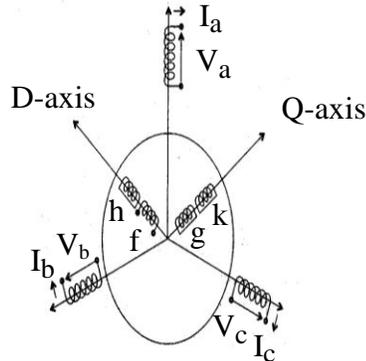Q-axis is considered as depicted in Figure 2.

Figure 2: *Synchronous machine model*

This model shows a three phase armature windings (a, b and c) on the stator and four windings on the rotor including field winding 'f'. The amortisseur (or damper) circuits in the salient pole machine or the eddy-current effects in the rotor are represented by a set of coils with constant parameters. Three damper coils, 'h' in the d-axis and g, k on the q-axis are shown in the Figure 4. Their dynamics can be described by six simultaneous differential equations using d, q, o in place of a, b, c (neglecting the 'o' axis differential equation). The seventh equation is the electromechanical torque equation. In a synchronous machine, the

synchronous generator to a large system. Here, the circuit parameters are expressed in per unit on the generator base of 892.4 MVA, 60 Hz frequency. Reactances are proportional to frequency and resistances are constant. This system configuration corresponds to the Navajo Project's 892.4 MVA, 500 kV transmission systems. This model is flexible for addition of new test cases (if any). Here, two fault locations (A and B) are designated, and there is provision for inclusion of a filter. The network parameters are provided in appendix.

system dynamics. So the detailed synchronous machine model [1] developed from the basic equations using phase variables and application of Park's transformation is chosen. Park's transformation
stator frequency is locked to the rotor speed to avoid instability.

Equivalent circuit of Synchronous machine

There are two equivalent circuits corresponding to the two axes d and q. These are as shown in the Figure 3. On the d-axis there are three coupled coils namely, armature d-coil, field winding f, and damper winding h. By the application of per unit system, all the quantities get referred to the armature side.

All the reactances are expressed in per unit. 'la' is the armature leakage reactance. 'lf' and 'ld' can be viewed as the leakage inductances of the field and the d-axis damper windings respectively. L_{AD} represents the per unit mutual inductance (between the field and damper windings). Coming to equivalent circuit on q-axis, both damper windings are short circuited as shown in figure 2.
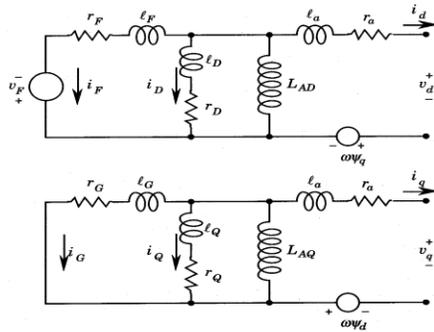
Figure 3: *The d and q axis per unit equivalent circuits of synchronous machine.*

$$[R_S] = \begin{bmatrix} Ra & 0 & 0 \\ 0 & Ra & 0 \\ 0 & 0 & Ra \end{bmatrix}$$

$$[Rr] = \begin{bmatrix} R_f & 0 & 0 & 0 \\ 0 & R_h & 0 & 0 \\ 0 & 0 & R_g & 0 \\ 0 & 0 & 0 & R_k \end{bmatrix}$$

The transformed voltage equations (Park's transformation) in the D and Q axis windings such as vd, vq, vfd etc. are shown in below.

v_d = ra * id − ω_r * lq * iq - ωr * lkq * ikq + ld * id + lmd * (ifd+ihd)

v_q = ω_r * ld * id + ra * iq − ω_r * lfd * ifd − ω_r * lhd * ihd + lq * iq+ lmq * (igq+ikq)

v_{fd} = rfd * ifd + lmd * id + lfd * ifd + lfh * ihd

0 = - rhd * ihd + lmd * id + lfh * ifd + lhd * ihd

0 = - rgq * igq + lmq * iq + lgq * igq +lgk * ikq

0 = - rkq * ikq + lmq * iq + lgk* igq + lkq * ikq

The machine Torque equations are given by

Tem=3/2*P/2(Lmd*iqs*ifd+(Ld-Lq)*iqs*ids+Lmd*iqs*ihd-Lmq*ids*igq-Lmq*ids*ikq)

2/P (J d2θm/dt2+D*dθm/dt) =Tm-Te

The voltage equations for the stator and rotor coils are as given below:

- dψ / dt − [R$_S$] i$_S$ = v$_S$
- dψ / dt - [R$_r$] i$_r$ = v$_r$

Where, v^t_S = [v$_a$ v$_b$ v$_c$], v^t_r = [-v$_f$ 0 0 0]

and

Multi-mass model of the Turbine - Generator Shaft

There are different models involved in SEQUEL for the construction of the mechanical **multi-mass model**. These are six masses consisting of four different levels namely Generator, High Pressure (HP), Low Pressure (LPA and LPB), Intermediate Pressure (IP) and an Exciter. All these six masses are coupled to the same shaft.

Mechanical multi-mass system with different masses namely HP, IP, LPA, LPB turbines, Generator and an exciter connected to the same shaft is shown in figure 4 below.
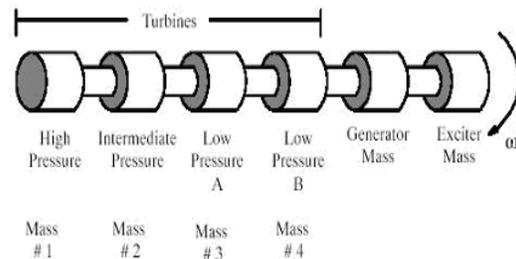

Figure 4: *Block Diagram of the mechanical multi-mass system*

This is a mechanical system which has several rotors corresponding to different stages of steam turbines, generator and rotating exciter. These are connected by shaft sections which are not rigid and act as springs. That is, when an external torque is applied to one end of the shaft it twists. The torque transmitted by the shaft can be assumed to be directly proportional to the difference between the angular positions of the shaft at the two ends.

The torsional system consisting of six masses is shown in the figure 5. This figure
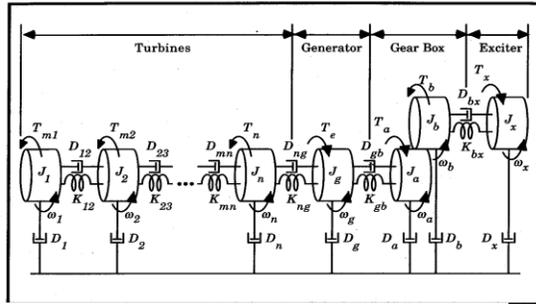

Figure 5: *Lumped Spring-Mass Model of a Turbine-Generator shaft*

The system, when considered in isolation, has resonant frequencies of oscillation termed as torsional modes (10 to 45 Hz). When a transient electrical torque is applied (at the generator mass) the response of the torsional system depends on the frequencies contained in the torque transient. If one of the frequencies in the applied torque is close to one of the torsional frequencies, the oscillations in the generator rotor (with respect to a synchronously rotating reference) have significant amplitudes and result in emfs generated in the stator windings. These emfs also are at sub and super synchronous frequencies and the subsynchronous frequency component tends to sustain the armature currents (and the rotor oscillations).

The various components of torque associated with the generator rotor are as follows:

Input torque $\quad = T_{12} = K_{12}(\delta_2 - \delta_1)$

Output torque $\quad = T_e$

Damping torque $\quad = D_1(\Delta\omega_1)$

Accelerating torque $\quad = T_a = T_{12} - T_e - D_1\Delta\omega_1$

The equations of the complete rotor system shown in figure 5 are as follows:

GEN: $2 H_1 d(\Delta\omega_1)/dt = K_{12}(\delta_2 - \delta_1) - T_e -$

$\quad D_1(\Delta\omega_1)$

$\quad d\delta_1/dt = (\Delta\omega_1)\omega_0$

shows a mechanical multi-mass system of mass, spring and dash pots.

LP_A : $2H_2 d(\Delta\omega_2)/dt = T_{LPA} + K_{23}(\delta_3 - \delta_2) -$

$\quad K_{12}(\delta_2 - \delta_1) - D_2(\Delta\omega_2)$

$\quad d\delta_2/dt = (\Delta\omega_2)\omega_0$

LP_B : $2H_3 d(\Delta\omega_3)/dt = T_{LPB} + K_{34}(\delta_4 - \delta_3) -$

$\quad K_{23}(\delta_3 - \delta_2) - D_3(\Delta\omega_3)$

$\quad d\delta_3/dt = (\Delta\omega_3)\omega_0$

IP : $2H_4 d(\Delta\omega_4)/dt = T_{IP} + K_{45}(\delta_5 - \delta_4) -$

$\quad K_{34}(\delta_4 - \delta_3) - D_4(\Delta\omega_4)$

$\quad d\delta_4/dt = (\Delta\omega_4)\omega_0$

HP : $2H_5 d(\Delta\omega_5)/dt = T_{HP} + K_{45}(\delta_5 - \delta_4) -$

$\quad D_5(\Delta\omega_5)$

$\quad d\delta_5/dt = (\Delta\omega_5)\omega_0$

EXC: $2H_6 d(\Delta\omega_6)/dt = T_{EXC} + K_{56}(\delta_6 - \delta_5) -$

$\quad D_6(\Delta\omega_6)$

$\quad d\delta_6/dt = (\Delta\omega_6)\omega_0$

Simulations and Results:

The SEQUEL library components such as multimass model (Synchronous machine, Turbines and exciter), transmission line and infinite source are connected as in figure 1. and the circuit file is made in SEQUEL. The system is simulated for the same operating condition as in reference [3]. For the transient case, phase to ground fault is applied at bus B in figure 3 for duration of 75 msec from 0.1 seconds to 0.175 seconds. In the reference paper, fault reactance is 0.04 p.u. and it is adjusted to produce a capacitor transient voltage approaching the lower gap setting. But in SEQUEL the fault reactance could not be modeled and fault resistance is modeled. Capacitor voltage, Generator current, Generator Electrical Torque, Shaft Torque of LPA-LPB and GEN-EXC are plotted for the

same time duration as in the reference paper for comparison.

Figure 6 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.
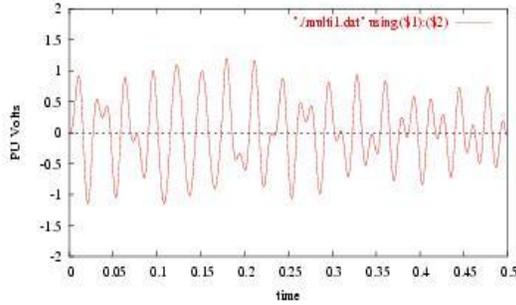

Fig 6: *variation of voltage across capacitor*
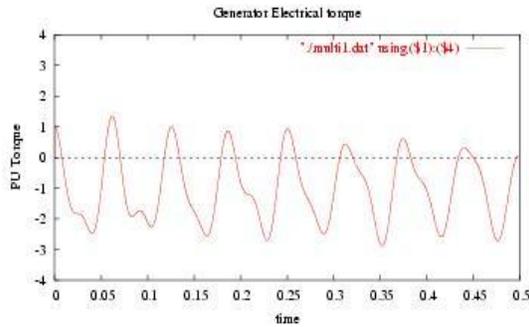
oscillations between generator and the turbine shafts.

The figure 9 shows the shaft torque between the low pressure turbines LPA and LPB. From the graph, it is seen that the shaft torque oscillates due to SSR phenomena.
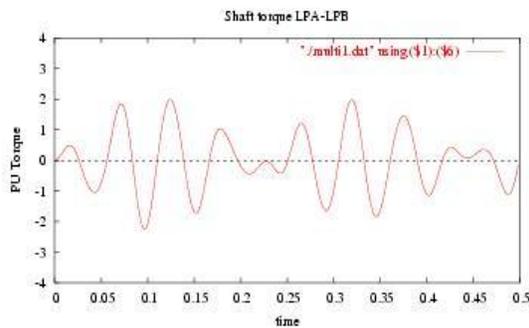

Figure 9: *Shaft Torque between LPA and LPB*

Figure 7 shows the variation of the machine current in per unit. From the graph, it is seen that the machine phase current is oscillatory.
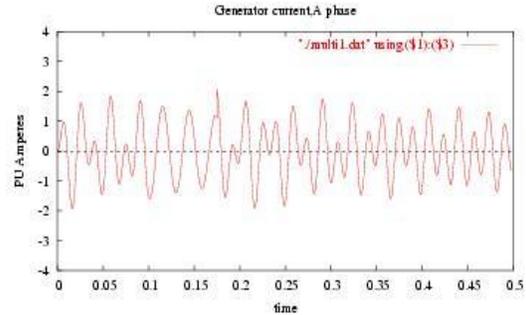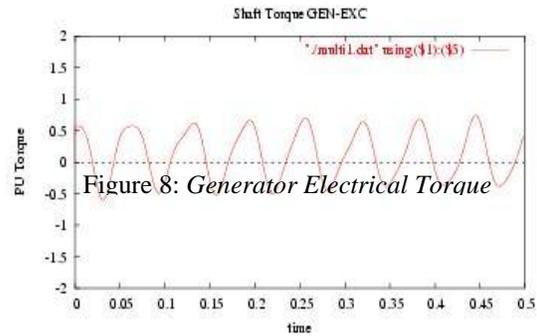

Fig 7: *Variation of machine current in phase a*
The figure 8 shows the variation of generator electrical torque T_{GEN} due to the SSR

The figure 10 shows the shaft torque in GENERATOR-EXCITER. This result shows that this system is not going to self-excitation mode within 0.5 seconds as in the reference paper. The results of the reference paper are given in figure 11.

Figure 8: *Generator Electrical Torque*

Figure 10: *Shaft Torque between Generator and Exciter*

A slight shift in these waveforms is also observed if these waveforms are compared closely with the reference results. It is due to the point of switching on the fault which is not yet implemented in SEQUEL due to time limitation. As it is known that the results from two different softwares differ slightly due to the simulation time step and the method of solving the non-linear equations.

As an attempt is made to develop the electrical components from the basic equations instead of using the component modeled readily available, the results from the SEQUEL and the reference paper are found to be closely matching.
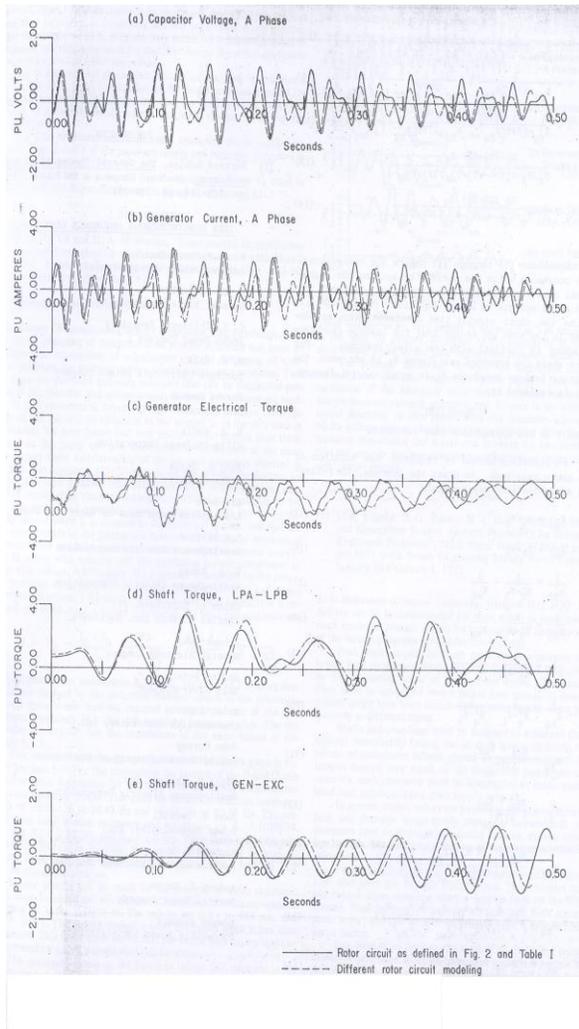
committee [3]. Further refinement in the SEQUEL models can be carried out as a future work to get exactly the same results as in IEEE committee report.

Appendix

The network parameters of the synchronous machine working as generator are as follows:

a. Generator parameters:
Rated MVA: 892.4
Rated voltage: 26.0 kV
Power Factor: 0.9
$Xa = 0.13$ pu; $Xd = 1.79$ pu
$Xd' = 0.169$ pu; $Xl = 0.135$ pu
$Xq = 1.71$ pu; $Xq' = 0.228$ pu
$Xq'' = 0.2$ pu; $Ra = 0.002$ pu
$Td_0' = 4.3$ s; $Td_0'' = 0.032$ s
$Tq_0' = 0.85$ s; $Tq_0'' = 0.05$ s

b. Mechanical Parameters:

Mass	Inertia (Secs)
HP	0.0929
IP	0.1556
LPA	0.8587
LPB	0.8842
GEN	0.8686
EXC	0.0342

Shaft	Spring Constant (p.u.)	Turbine Torque (p.u.)
HP-IP	7277	0.3
IP-LPA	13168	0.26
LPA-LPB	19618	0.22
LPB-GEN	26713	0.22
GEN-EXC	1064	0.22

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:
$R = 3.9344$ Ω
$X = 162.97$ Ω

e. Series capacitor:
$C = 21.977$ μF

f. Infinite Bus:
Voltage: 477.8 kV RMS L-L
Phase angle: 3.8 lagging

Figure 11: *Transient Response of IEEE First Benchmark Model given by IEEE committee*

Conclusion

In this paper, the First Benchmark Model for computer simulation of Subsynchronous resonance is simulated in SEQUEL (Solver for circuit Equations with User defined Elements). The simulation is carried out for same operating condition as in [3]. Subsynchronous Resonance Phenomena is simulated by exciting the torsional modes with three phase to ground fault for duration of four and half cycles. The results obtained are closely matching with the reference results except for the self-excitation case. The slight difference in the results is attributed to the difference in modeling of the components and method of solving the non-linear equations. These results are in full agreement with those given by the IEEE

Series impedance: 19.5206 Ω
g. Fault Impedance:

Resistance: 4830.0 Ω
Reactance: 13.00 Ω

References:
1. K.R. Padiyar, "*Power System Dynamics Stability and Control*", Indian Institute of Science, Bangalore, 1996.
2. P.M. Anderson, B.L. Agrawal, J.E. Van Ness,"*Subsynchronous Resonance in Power Systems*", IEEE Press, New York, 1990.
3. IEEE SSR Working Group, "*First Benchmark Model for Computer Simulation of Subsynchronous Resonance*", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, no. 5, September/October 1977.
4. M.H. and M.K. Donnelly "*Thyristor-Based Damping of Turbine-Generator Shaft Torsional Oscillations Resulting From Power System Disturbances and Subsynchronous Resonance: A Review*", Montana State
University, Bozeman, MT 59717, R. Adapa, Electric Power Research Institute, Palo Alto, CA 94303, 1990.
5. Mahesh B. Patil, "**SEQUEL** *Users' Manual*", Indian Institute of Technology, Bombay.
6. "**RTDS** *Users' Manual Set*", Central Power Research Institute, Bangalore.
7. O.Wasynczuk, "*Damping Subsynchronous Resonance using Reactive Power Control*", IEEE Transactions on Power Apparatus and Systems, Vol. PAS100, No. 3, March 1981.
8. O.Wasynczuk, "*Damping of shaft torsional oscillations using a dynamically controlled resistor bank*", IEEE transactions on power apparatus and systems, vol 100, no. 7, 1981.
9. K.R.Padiyar, "Power System Dynamics and Stability", McGraw-Hill, 1990.