Analysis and Mitigation of Sub-Synchronous Resonance using IEEE first benchmark model

Tanu Sharma[1], Kamal Kumar Sharma[2], Himanshsu Gupta[3]

[1]Student, M. Tech, EMGOI, Ambala

[2]Professor, Dept. of ECE, E-Max group of Institutions, Ambala

[3]Assistant Professor, Dept. of EE, E-Max group of Institutions, Ambala

Abstract- **Dynamic performance of turbine-generator set connected to infinite bus bar is improved for the transmission network with and without series compensation. The FACTS device (Static Var Compensator) and optimal control theory are used for the improvement in dynamic performance and mitigation of sub-synchronous resonance (SSR).The results are shown by using the response curves through Matlab Power System Block set. A well known technique i.e. Eigen value analysis is used for the analysis of SSR. Results are shown with natural damping and without natural damping. The objective of the proposed frame work is to improve the dynamic performance and prevent the system from SSR phenomenon so that there is no damage to the generator rotor shaft. The analysis is applied to the first benchmark model proposed by special IEEE Power Engineering Society task force on sub-synchronous resonance. The major subsystems incorporate are Excitation system, Mechanical system, Rotor system, Transmission line and SVC in addition to optimal controller**.

Keywords: **Sub-Synchronous Resonance (SSR), power system stabilizers (PSS), Electromagnetic Transients, Program (EMTP), particle swarm optimization(PSO)**

I.INTROUCTION

This study presents a new evolutionary method for damping of SSR oscillations in series compensated power system and increasing the stability of system with and without series compensation. The phenomenon of sub-synchronous resonance occurs mainly in series capacitor-compensated transmission systems. The first SSR problem was experienced in 1970 resulting in the failure of a turbine –generator shaft at the Mohave plant in Southern California. It was not until a second shaft failure occurred in 1971 that the real cause of the failure was recognized as sub-synchronous resonance [3]. Systems that experience SSR exhibit dynamic oscillations at frequencies below the normal system base frequency [1]. These problems are of great interest in utilities, where this phenomenon is a problem, and the computation of conditions that excite these SSR oscillations are important to those who design and operate these power systems. Until now there are so many remedies are available in the literature of the concerned problem. Definition The formal definition of SSR is provided by the IEEE [1]: Sub-synchronous resonance is 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. The definition includes any system condition that provides the opportunity for an exchange of energy at a given sub synchronous frequency. This includes what might be considered "natural" modes of oscillation that are due to the inherent system characteristics, as well as "forced" modes of oscillation that are driven by a particular device or control system. The most common example of the natural mode of sub-synchronous oscillation is due to networks that include series capacitor compensated transmission lines [1]. These lines, with their series LC combinations, have natural frequencies to that are defined by the equation (1.1)

$$\omega n = \sqrt{1/LC} = \omega 0/\sqrt{(\omega oL)(\omega oC)} = \omega 0\sqrt{XC/XL} rad/sec$$

$$OR\ fn = fo\sqrt{XC/XL}\ Hz \quad 1.1$$

or sub-synchronous resonant frequency of series compensated line is $=fo\sqrt{K}$,where ωn is the natural frequency associated with a particular line L C product, ωo is the system base frequency, and XL and Xc are the inductive and capacitive reactance, respectively. These frequencies appear to the generator rotor as modulations of the base frequency, giving both sub-synchronous and super synchronous rotor frequencies. It is the sub-synchronous frequency that may interact with one of the natural torsional modes of the turbine-generator shaft, thereby setting up the conditions for an exchange of energy at a subsynchronous frequency, with possible torsional fatigue damage to the turbine-generator shaft. This includes what might be[3] considered "natural" modes of oscillation that are due to the inherent system characteristics, as well as "forced" modes of oscillation that are driven by a particular device or control system. The most common example of the natural mode of subsynchronous oscillation is due to networks that include series capacitor compensated transmission lines. These lines, with their series LC combinations, have natural frequencies to that are defined by the equation (1.1).The different sub-synchronous frequencies for 50 Hz system are given below for different level of series compensation .

1.1 Counter Measures of SSR

The various counter measures for SSR available in the literature are following as: New lines instead of reactive series compensation, appropriate degree of reactive series compensation, Meshed system, SSR relay bypasses series compensation or trips generator, NGH scheme – resistor across series compensation, Damping controllers, Thyristor Controlled Series Capacitor, HVDC.

II. RELATED WORK

Until now different SSR mitigations and analysis techniques are proposed some of them are practicable but others cannot be used simultaneously for both stability analysis and SSR mitigations. As SSR causes damage to the turbo-generator shaft or fatigue life of shaft so in the concerned heading we are going for analysis of SSR in series or shunt compensated line.Until now there are so many remedies are available in the literature of the concerned problem.

III. PROPOSED WORK

3.1 Optimal control theory

Equation we have got from overall system model is similar to the standard equation used in the optimal control theory but not same because it does not contain the disturbance vector

i .e. $\dot{x} = Ax(t) + Bu(t) + Fw$ is standard form used in the optimal control theory

$\dot{x} = Ax(t) + Bu(t)$ 4.1

Where U (t) is control vector

X(t) is state vector

Fw is disturbance vector

For constant disturbance vector X(t) = 0

Under steady state condition

$AXss + BUss + FW = 0$ 4.2

Where subscript denotes under steady state condition

Under steady state and transient conditions the terms becomes as sum of both states defining as

Let X = X ' + Xs s

And U = U' + Us s

$\dot{x} = A(X' + Xss) + B(U' + Uss) + FW$ 4 .3

$\dot{x} = AX' + BU'$ 4 .4

If $U = -KX$

Where U is control vector and K is feedback matrix

$U' + Uss = -K(X' + Xss)$. 5

For stable system both X' and U' goes to 0 (i.e. there is no transients, means no disturbance)

$Uss = -KXss$ (For stable) 4.6

$U' = -KX'$ (For unstable) 4.7

Performance Index (PI) can be minimized to transfer the system from initial state X' (0) to

origin in infinite time X' (∞) = 0

In quadratic form

$pi = \frac{1}{2}\int_0^{\infty}(X^TQX' = U^TRU').dt$4.8

Q = Symmetric matrix (i .e $A = A^T$)

R=KI=Symmetric matrix4.9

Finding K= Feedback matrix

Using reduced order Riccati matrix equation

$A^TS + SA - SBR^{-1}B^TS + Q = 0$4.10

K= acceptable solution is that for which system remains stable

Substituting eq.4.7 in 4.4 we get

$X' = AX' + B(-KX') = (A - BK)X'$

For stability all the Eigen values of the matrix A-BK should have negative real parts.

3.2 Modeling considerations

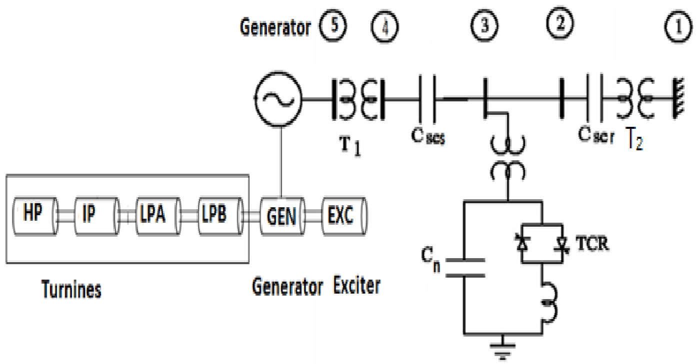
In the analysis of power system dynamic performance, modeling considerations are: Network modes, Shaft modes, Rotating masses – multi-mass representation .If the rotor is assumed to be made up of single mass. Such a representation accounts for the oscillations of the entire turbine-generator rotor with respect to other generators. The frequency of oscillations is usually in the range of 0.2 to 2 Hz. In reality a steam turbine generator rotor has a very complex mechanical structure consisting of several predominant masses (such as rotor of turbine sections ,generator rotor ,couplings and exciter rotor) connected by shaft of finite stiffness [3]. Therefore when the generator is perturbed, torsional oscillations results between different sections of the turbine generator rotor. Here the study of sub synchronous resonance phenomenon is conducted on a power system composed of a turbo generator set connected to an infinite bus through a series capacitor compensated transmission lines. The analysis is applied to first benchmark model proposed by special IEEE Power Engineering Society Task Force on sub synchronous resonance. Since we are considering a rotor with six masses, there are six modes of oscillations. The natural frequencies are given by the imaginary parts of the eigen values of the system matrix A and the damping of the system is given by the real part of the eigen values of the concerned system matrix. In general case ,a rotor with n-masses has n-1 torsional modes[3]. Their torsional modes has highest ith torsional mode frequency and its mode shape has ith polarity reversals. When power system is perturbed, its equilibrium state is distributed giving rise to interchange of energies among the masses of the mechanical system, between inductances and capacitances in the electrical system and between the electrical and mechanical system interconnected through the rotor of synchronous generator[3]. As energies are interchanged oscillations at the natural frequency of their respected subsystem are produced. For a given mechanical system there are finite numbers of modes of oscillations. For a given electrical system the numbers of modes of oscillations depends on the number of circuit configurations that can be obtained through switching [3].

The natural frequencies of the mechanical system range normally from 1.5 to 45 HZ for steam turbo generator sets, but are quite low (10 HZ or below) for those of hydro-generator sets. The inertial frequency of oscillations of the coupled electro-mechanical system is typically 1-2HZ, depending on the system's operating conditions and mechanical moment of inertia.

Since these various frequencies of oscillations are below the synchronous frequency they are termed as sub synchronous oscillations.

3.3 System under Study

The system under study consists of a generating station supplying bulk power to a large power system over a long distance transmission line. The series compensation is applied at the sending end and receiving end. The IEEE type-1 excitation is used. The damping performance of a SVS not only depends upon its structure and size but also on its location in electrical system. The power transfer capability of the system is optimal for the SVS to be located at the electrical center of the transmission line. The generating station is represented by an equivalent synchronous generator and the large power system is represented as an infinite bus. The single line diagram of the study system is shown in figure 3.1.The SVS is assumed to be of fixed capacitor thyristor controlled reactor type configuration and is connected to transmission network through a coupling transformer. The study system can be divided into four sub-systems for modeling point of view.

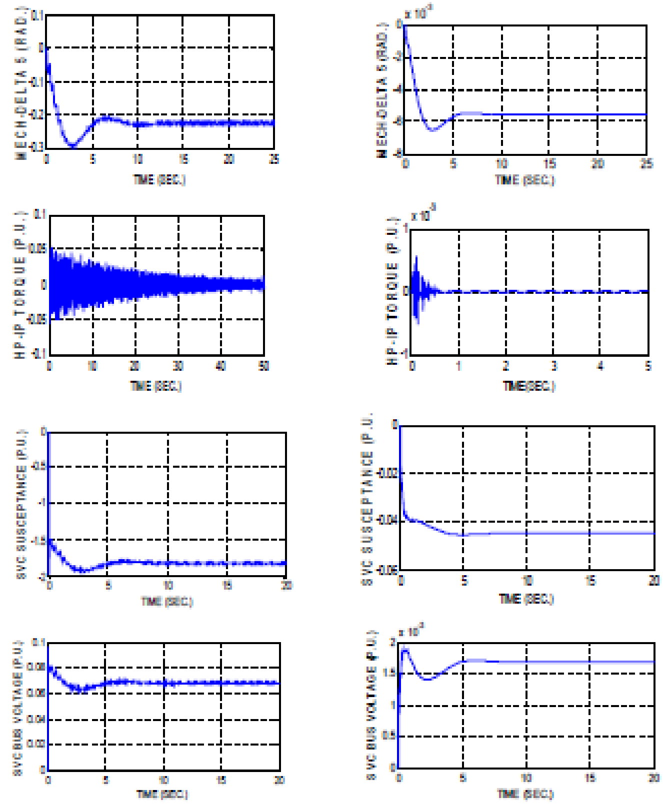


F i g .3.1 Study System

IV. DISCUSSION OF RESULT

Steady State Analysis without series compensation Load flow studies determine the voltage, current, active and reactive power, and power factor in a power system. Load flow studies are an excellent tool for system planning .A number of operating procedures can be analyzed including contingency conditions such as the loss of generator, a transmission line, a transformer, or a load . These studies will alert the user to conditions that may cause equipment overloads or poor voltage levels. Load flow studies can be used to determine the optimum size and location of capacitors for power factor improvement .Also they are used to determine system voltages under the conditions of suddenly applied or disconnected loads. The results of a load flow study are also starting points for stability studies. But here in the power system analysis the load flow study is the steady state solution of the power system network. The main information obtained here from the load flow study comprises P, Q, V and δ at operating point on each bus. The results help in determining the most effective location of the devices and their optimum ratings. They also provide the initial conditions required for dynamic studies. The system data (including transmission line, generator) as required in load flow study . Steady state performance of system at various loads, obtained from Newton Raphson method of the load flow study, is presented in Table 1 for without series compensation of the transmission line. At load Pg=600MW.

4.1 Graph without series compensation and with zero natural damping at ΔVref =10%



Time domain analysis for HP-IP Torque:

Table 4.1 Time domain analysis

HP-IP Torque Spec.	With SVS(with zero natural damping) (Time in sec.)	With SVS & Optimal Control (with zero natural damping)
Rise Time	0.00090433	$4.2337x10^{-5}$
Setting Time	Not settling in reasonable time	2.7664
Setting Min	-0.055936	-0.00052029
Setting Max	0.053361	0.00055796
Overshoot	829.77	68437
Undershoot	886.97	63910
Peak	0.055936	0.00055796
Peak time	0.08	0.12

4.2 Response Curves without series compensation and with natura damping

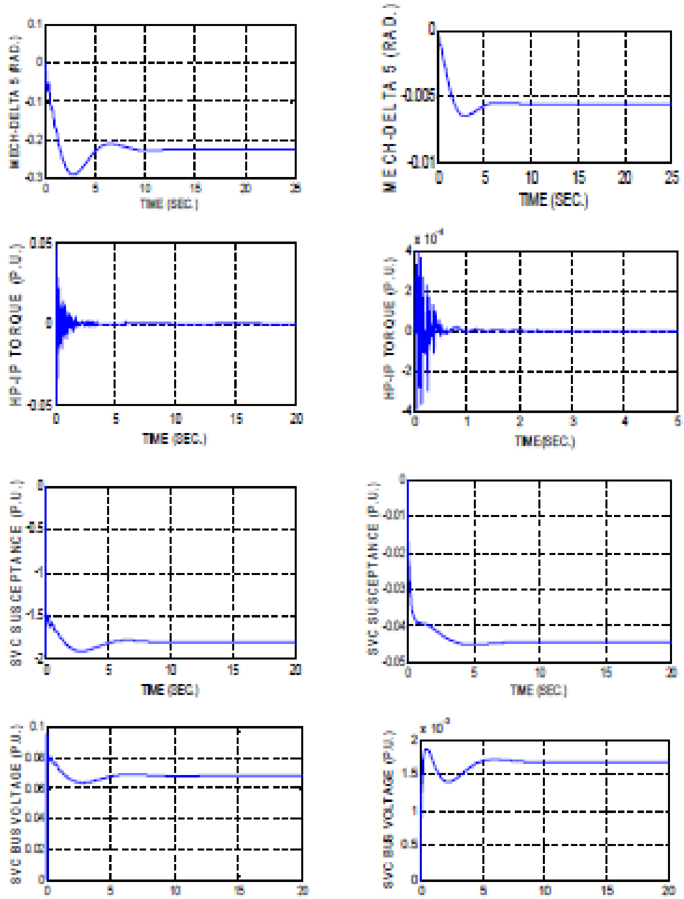


Fig 4.2 System response curves without optimal controller and with optimal controller (with natural damping)

Time domain analysis of HP-IP Torque curve for the fig. 4.2

Table 4.2: Time domain analysis

HP-IP Torque Spec.	With SVS(with natural damping) (in sec.)	With SVS & Optimal Control (with natural damping)
Rise Time	$5.3413x10^{-5}$	0.0014398
Settling Time	1.94171	0.86899
Settling Min	-0.049441	-0.00039952
Settling Max	0.047173	0.00039743
Overshoot	$1.2516x10^{8}$	$2.094x10^{5}$
Peak	0.049441	0.0003995

4.3 Response curves with 8% series compensation and with zero natural damping at ΔVref =10%

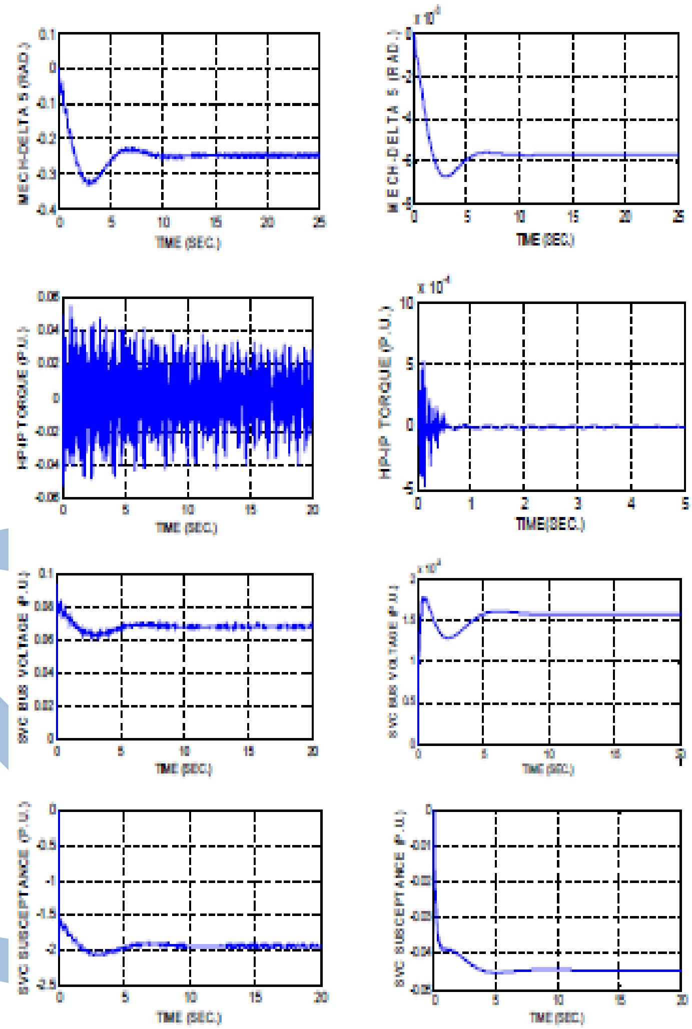


Fig.4.3 Response curves without optimal controller and with optimal controller (with zero natural damping at 8% Series compensation

Time domain analysis of response curves fig.4.3 for HP-IP Torque

Tab le 6.9 Time domain analysis

HP-IP Torque Spec.	With SVS(With zero natural damping) (In sec)	With SVS & Optimal Control (with zero natural damping)
Rise Time	0.008778	0.0073313
Settling Time	Not settling in reasonable time	2.3498
Settling Min	-0.051863	-0.0004891
Settling Max	0.054969	0.00052996
Overshoot	112.43	54420
Undershoot	200.43	59074
Peak	0.054969	0.00052996
Peak time	0.68	0.12

4.4 Graph without series compensation and with zero natural damping at ΔVref =20%

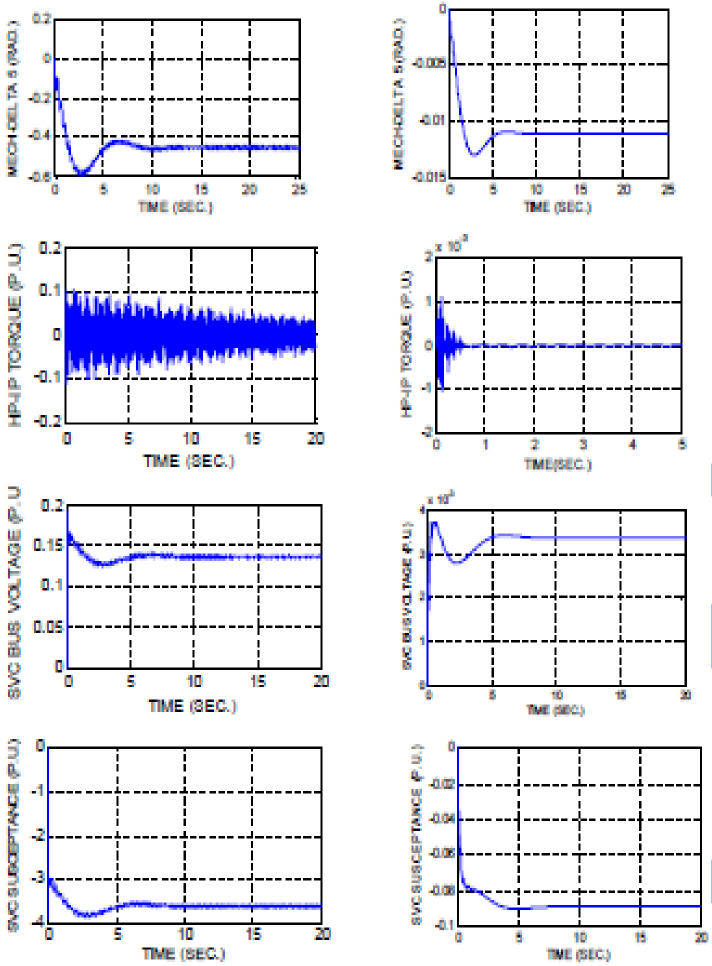


Fig 4.4 System response curves without optimal controller and with optimal controller (with zero natural damping)

Time domain analysis Table for HP-IP Torque

Table 6.4: Time domain analysis

HP-IP Torque Spec.	With SVS(with zero natural damping) (Time in sec.)	With SVS & Optimal Control (with zero natural damping)
Rise Time	0.0021486	$4.2337x10^{-5}$
Settling Time	**Not settling in reasonable time**	**2.7664**
Settling Min	-0.11187	-0.0010406
Settling Max	0.10672	0.0011159
Overshoot	291.32	68437
Undershoot	373.31	63910
Peak	**0.11187**	**0.0011159**
Peak time	0.08	0.12

V.CONCLUSION

The Eigen value analysis that the Eigen values for generator system and mechanical system are improved The eigen values and response curves are shown above for two cases i.e. Voltage deviation 10% and 20%, where (ΔVref) Change in reference Voltage is the input to the overall system as shown in system matrix. Damping of the systems enhanced using eigen value.

There are sustained oscillations or the oscillations are not damped out in a reasonable time when zero natural damping is considered as shown in torque curve between HP and IP turbine in fig.4.1 and 4.2 and fig. 4.3 & 4.4.But with optimal controller the oscillations are damped out successfully as shown in the figure drawn parallel to them. The time domain analysis is also made for the response curve of HP-IP torque for both cases i.e. without optimal controller and with optimal controller. The settling time i.e. time taken by the system to reach in steady state limit is improved which 2.3498 sec for zero natural is damping with optimal controller. The amplitude of the transient produced due to step input disturbance is reduced significantly by the optimal controller. The peak value of the transient occurs due to step input disturbance signal is decreased from 0.11187 to 0.0011159 which is about 1/100 times of the value (0.11187) without controller.

For series compensation more than 9%, the growing oscillations are produced and system goes unstable, which is not shown ,but the oscillations are damped out by the optimal controller for all the levels of series compensation. All in all the optimal controller is capable to die out oscillations in all disturbance and at all level of series compensation

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