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SYNCHRONOUS GENERATOR EQUIPPED WITH POWER SYSTEM STABILIZER FOR POWER OSCILLATION DAMPING

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ABSTRACT

The increasing magnitude and difficulty of interconnected power systems due to competitive energy markets, economy and population development have created the need to operate the power systems close to their capacity limits. This leads sometimes to stability problems or poor dynamic behaviours like power oscillations. These oscillations can cause a reduction of the system components lifetime, expensive operations of the electrical grids and in the worst case, risks of partial system collapses. On the other hand, in the synchronous generator, the damping that the field and damper windings provide to the rotor oscillations is weakened due to excitation control system action. The reason for this is that in the rotor circuits appear additional currents induced by the voltage regulation and those currents oppose to the currents induced by the rotor speed deviations. Therefore, an additional stabilizing signal was needed and the Power System Stabilizer (PSS) was developed with this aim. The PSS is a feedback controller, part of the control system for a synchronous generator, which provides an additional signal that is added to the input summing point at the Automatic Voltage Regulator AVR. The PSS main function is to damp generator rotor oscillations. By adding the stabilizing signal the PSS is expected to produce an electric torque component that counteracts the mechanical dynamics. The produced electric torque component should be in phase with the deviations of the generator rotor speed in order to be able to damp the oscillations. The simulation of the proposed model was carried out using specialized power system analysis toolbox (PSAT).

Keywords: synchronous generator, power system stabilizer, low frequency oscillations, power system stability, PSAT.

1. INTRODUCTION

Low frequency oscillations in the range of 0.2 to 3 Hz are inherent to power systems. They appear when there are power exchanges between large areas of interconnected power systems or when power is transferred over long distances under medium to heavy conditions. The use of fast acting high gain Automatic Voltage Regulator (AVR), although improves the transient stability, has a detrimental effect on the small-signal stability. For the last four decades, low frequency oscillations arising from the lack of sufficient damping in the system have been frequently encountered in power systems. The recent introduction of the deregulation and the unbundling of generation, transmission and distribution as well as the large amount of Distributed Generation connected to the power system have exacerbated the problem of low-frequency oscillations.

For many years, Power System Stabilizers (PSSs) have been used to add damping to electromechanical oscillations. Conventional Power System Stabilizers (CPSSs) have been widely accepted by the power utilities due to their simplicity, moreover they are the most cost effective damping control. Traditionally, CPSSs were designed using classical control techniques such as root-locus, phase compensation, eigenvalue analysis, etc. These stabilizers are mainly designed around the nominal operating condition.

A traditional function of the excitation system is to regulate generator voltage and thereby help control system voltage [1]. The power system stabilizer (PSS) is a supplementary controller, which is often applied as part of the excitation control system. Grid codes and regulatory agencies are increasingly specifying PSS controls for new generation and retrofit on existing units. The basic function of the PSS is to apply a signal to the excitation system, creating electrical torques that damp out power oscillations.

Although the primary function of the PSS is to supply positive damping torque contributions, experience indicates that it can impact the generator power system transient performance under certain conditions. Dynamic instability is related to the high loading of modern electrical power systems, to the design of lower-cost synchronous generators and especially to the use of high-gain and quick-acting excitation systems. To improve the damping of electromechanical oscillations when necessary, such systems should be designed to allow proper processing of stabilization signals, usually derived from the machine rotor-speed or electrical power [2].

Over the years, these inherent oscillations have received a great deal of attention. Since the development of interconnection between synchronous generators and the introduction of deregulation of power systems, these oscillations have become apparent especially during and after small and large disturbances. Several factors contribute to the rise of these oscillations. These oscillations are commonly known as electromechanical modes. The use of automatic controls, necessary to maintain the stability during transient faults have adverse effects on the system damping due to their negative feedback nature. For instance, the rapid Automatic Voltage Regulator (AVR) and fast acting excitation system tend to reduce the damping torque component on the rotor which is necessary to damp oscillations.

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2. POWER SYSTEM STABILITY

A. Basic concepts

Power system stability is the ability of the system, for a given initial operating condition, to regain a normal state of equilibrium after being subjected to a disturbance. Stability is a condition of equilibrium between opposing forces. Instability results when a disturbance leads to a sustained imbalance between the opposing forces. The power system is a highly nonlinear system that operates in a constantly changing environment. Loads, generator outputs, topology, and key operating parameters change continually. When subjected to a transient disturbance, the stability of the system depends on the nature of the disturbance as well as the initial operating condition. The disturbance may be small or large. Small disturbances in the form of load changes occur continually, and the system adjusts to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully meet the load demand. It must also be able to survive numerous disturbances of a severe nature, such as a short - circuit on a transmission line or loss of a large generator.

Traditionally, the stability problem has been one of maintaining synchronous operation. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism [16]. This aspect of stability is influenced by the dynamics of generator rotor angles and power-angle relationships. Instability may also be encountered without the loss of synchronism.

B. Classification of power system stability

Power System Stability, its classification, and problems associated with it have been addressed by many CIGRE and IEEE publications. The CIGRE study committee and IEEE power systems dynamic performance committee defines power system stability as:"Power system stability is the ability of an electrical power system, for given operating conditions, to regain its state of operating equilibrium after being subjected to a physical disturbance, with the system variables bounded, so that the entire system remains intact and the service remains uninterrupted" [6]. Figure 1 shows the overall picture of the stability problem.

Rotor angle stability deals with the ability to keep/regain synchronism after being subject to a disturbance in an interconnected power system. In normal system operation, all synchronous machines rotate at the same electrical speed 2πf. The mechanical and electromagnetic torques acting on the rotating masses of each generator balance each other and the phase angle differences between the internal e.m.f.'s of the various machines are constant and it remain in synchronism.

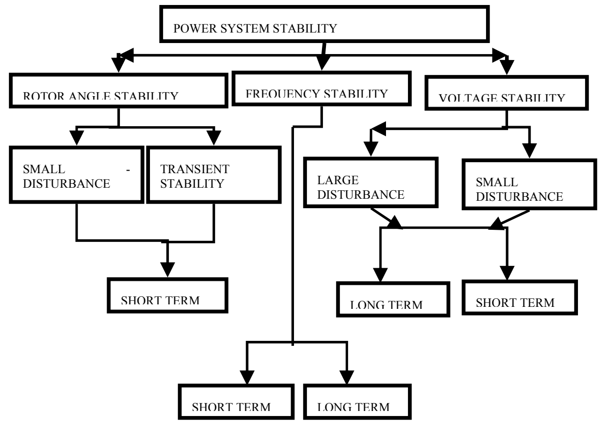

Figure-1. Classification of power system stability.

Frequency stability is concerned with the ability of a power system to maintain steady frequency within a nominal range following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to restore balance between system generation and load, with minimum loss of load.

Voltage stability is concerned with the ability of a power system to maintain steady voltages at all buses in the system under normal operating conditions, and after being subjected to a disturbance. Instability that may result occurs in the form of a progressive fall or rise of voltage of some buses. The possible outcome of voltage instability is loss of load in the area where voltages reach unacceptably low values, or a loss of integrity of the power system.

Small-disturbance (or small-signal) angle stability deals with the ability of the system to keep synchronism after being subject to small disturbances. Small disturbances are those for which the system equations can be linearized around an equilibrium point. Small disturbances are always present in fact it is a necessary condition for operating of a power system and it depends on operating point and system parameters. A small disturbance, the variation in electromagnetic torque can be decomposed into synchronizing torque and damping torque. A decrease in synchronizing torque will eventually lead to aperiodic instability (machine going out of step) and a decrease in damping torque will eventually lead to oscillatory instability (growing oscillations) [15].

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Stability depends on both the initial operating state of the system and the severity of the disturbance. Usually, the system is altered so that the post-disturbance steady-state operation differs from that prior to the disturbance.

C. Need for classification

Power system stability is a single problem; however, it is impractical to deal with it as such. Instability of the power system can take different forms and is influenced by a wide range of factors. Analysis of stability problems, including identifying essential factors that contribute to instability and devising methods of improving stable operation is greatly facilitated by classification of stability into appropriate categories. These are based on the following considerations.

- The physical nature of the resulting instability related to the main system parameter in which instability can be observed.
- The size of the disturbance considered indicates the most appropriate method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to determine stability.

3. PSS MODELLING

A. PSS model

The basic function of a power system stabilizer is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal. To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations [3]. It is well established that fast acting exciters with high gain AVR can contribute to oscillatory instability in power systems. This type of instability is characterized by low frequency (0.2 to 2.0 Hz) oscillations which can persist (or even grow in magnitude) for no apparent reason. This type of instability can endanger system security and limit power transfer. The basic block diagram of PSS is shown in Figure-2.

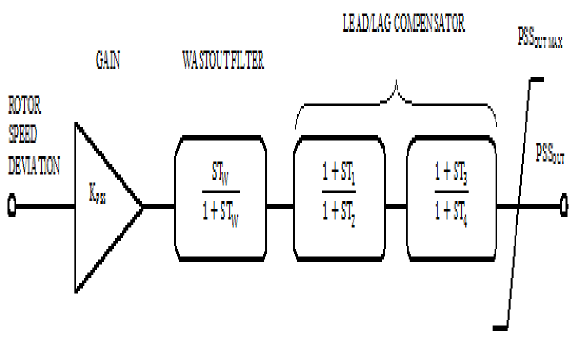

Figure-2. Basic block diagram of PSS.

Transfer function of PSS can be expressed in following equation (1)

$$PSS_{OUT} = K_{PSS} * \frac{ST_W}{1+ST_W} * \frac{1+ST_1}{1+ST_2} * \frac{1+ST_3}{1+ST_4} \quad (1)$$

The PSS consist of stabilizer gain K_{PSS} (block used to determine how much amount of damping introduced by PSS), a washout filter with time constant T_W=10 s and two phase compensator blocks with time constant T_1, T_2, T_3 and T_4. The washout block ensures that the PSS output is zero in the steady state condition.

Using various input parameters such as speed, electrical power, rotor frequency several PSS models have been designed. Among those some are depicted below.

1) **Speed as input:** A power system stabilizer utilizing shaft speed as an input must compensate for the lags in the transfer function to produce a component of torque in phase with speed changes so as to increase damping of the rotor oscillations.
2) **Power as input:** The use of accelerating power as an input signal to the power system stabilizer has received considerable attention due to its low level torsional interaction. By utilizing heavily filtered speed signal the effects of mechanical power changes can be minimized. The power as input is mostly suitable for closed loop characteristic of electrical power feedback.
3) **Frequency as input:** The sensitivity of the frequency signal to the rotor input increases in comparison to speed as input as the external transmission system becomes weaker which tend to offset the reduction in gain from stabilizer output to electrical torque , that is apparent from the input signal sensitivity factor concept.

B. Eigenvalues and stability analysis

Once the state space system for the power system is written in the general form, the stability of the system can be calculated and analyzed. The analysis performed follows traditional root-locus (or root-loci) methods [4]. First, the eigenvalues λi are calculated for the A-matrix, which are the non-trivial solutions of the equation

$$A\Phi = \lambda\Phi \quad (2)$$

Where Φ is an nx1 vector. Rearranging (2) to solve for λ yields

$$\det(A - \lambda I) = 0 \quad (3)$$

The n solutions of (3) are the eigenvalues ($\lambda 1$, $\lambda 2$, ..., λn) of the nxn matrix **A**. These eigenvalues may be real or complex, and are of the form $\sigma \pm jw$. If **A** is real, the complex eigenvalues always occur in conjugate pairs.

The stability of the operating point (δo, ωo) may be analyzed by studying the eigenvalues. The operating point is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable. If any of the eigenvalues appear on or to the right of this axis, the corresponding modes are said to be unstable, as is the system. This stability is confirmed by looking at the time dependent characteristic of the oscillatory modes corresponding to each eigenvalue λi, given by $e^{t\lambda i}$. The latter shows that a real eigenvalue

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corresponds to a non oscillatory mode. If the real eigenvalue is negative, the mode decays over time. The magnitude is related to the time of decay: the larger the magnitude, the quicker the decay. If the real eigenvalue is positive, the mode is said to have aperiodic instability.

4. SIMULATION STUDY

The power system models in this paper were built using the specialized Power Systems Analysis Toolbox, PSAT a software application developed for MATLAB, which performs both the numerical simulation and linearized Eigen structure analysis [7].

A. Case 1

Simulation models of Figure-1 and Figure-2 examine the transient stability of a thermal generating station consisting of four 555 MVA, 24 KV, 50 HZ units supplying power to an infinite bus through two transmission circuits. Figure-3 shows the performance of synchronous generator without PSS during fault condition and Figure-4 shows the performance of synchronous generator with PSS during fault condition.

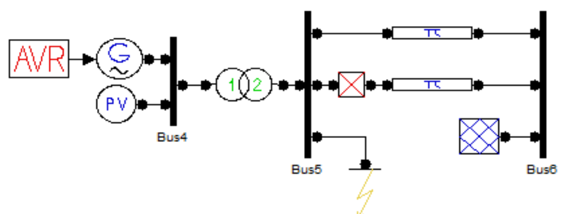

Figure-3. Performance of synchronous generator without PSS during fault condition.

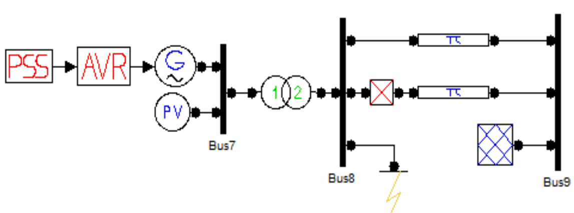

Figure-4. Performance of synchronous generator with PSS during fault condition.

Time domain analysis and Eigen value analysis of Figure-3 shown in given below. Time domain analysis plotted between rotor speed deviation vs time period.

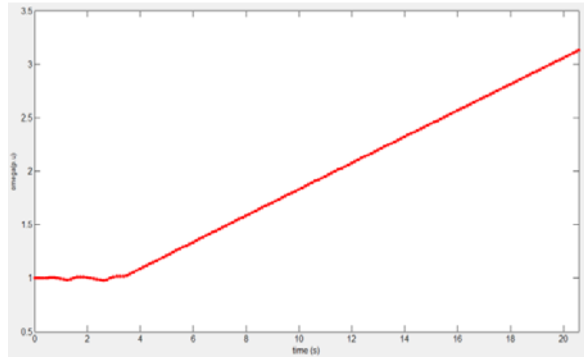

Figure-5. During fault condition rotor speed deviation of synchronous generator without PSS.

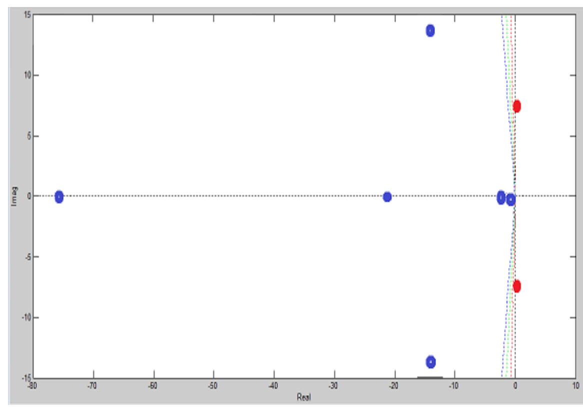

Figure-6. Eigenvalues analysis result without PSS (S-domain).

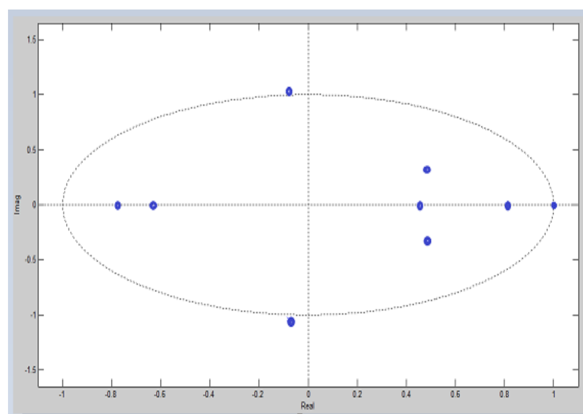

Figure-7. Eigenvalues analysis result without PSS (Z-domain).

Figure-6 and Figure-7 shows the eigenvalues analysis of Figure-3. This two figure illustrate the two eigenvalues are greater than zero in S-domain and outside of the unity circle in Z-domain. So the system was unstable when the system does not having PSS. Statistics of eigenvalues report of Figure-3 was given in below Table-1.

Table-1. Eigenvalues report statistics without PSS.

Dynamic order	9
Buses	3
Positive Eigens	2
Negative Eigens	7
Complex Pairs	2
Zero Eigens	0

Time domain analysis and eigen value analysis of Figure-4 shown in Figures 8-10. Time domain analysis plotted between rotor speed deviation vs time period.

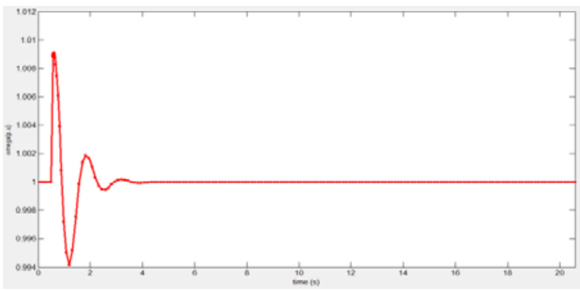

Figure-8. During fault condition rotor speed deviation of synchronous generator with PSS.

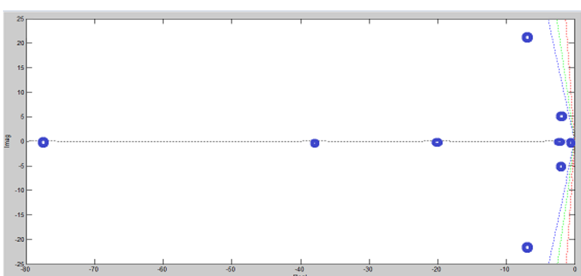

Figure-9. Eigenvalues analysis result with PSS (S-domain).

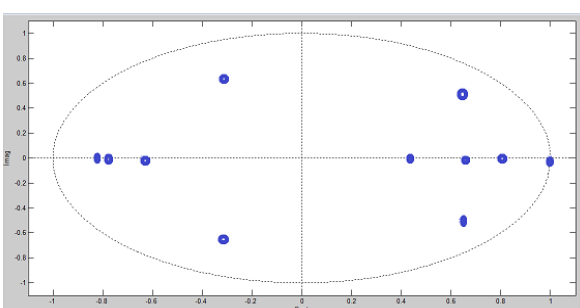

Figure-10. Eigenvalues analysis result with PSS (Z-domain).

Figure-9 and Figure-10 shows the eigenvalues analysis of Figure-4. These two figures illustrate that all the eigenvalues are less than zero in S-domain and all the eigenvalues are inside of the unity circle in Z-domain. So the system was stable with PSS. Statistics of eigenvalues report of Figure-4 was given in below Table-2.

Table-2. Eigenvalues report statistics with PSS.

Dynamic order	12
Buses	3
Positive Eigens	0
Negative Eigens	12
Complex Pairs	2
Zero Eigens	0

B. Case 2

Simulation model of Figure-11 examine the stability analysis of IEEE 14 bus system. This system consists of 5 synchronous generators but PSS installed only for generator 1 alone. But the whole system will be observable and controllable.

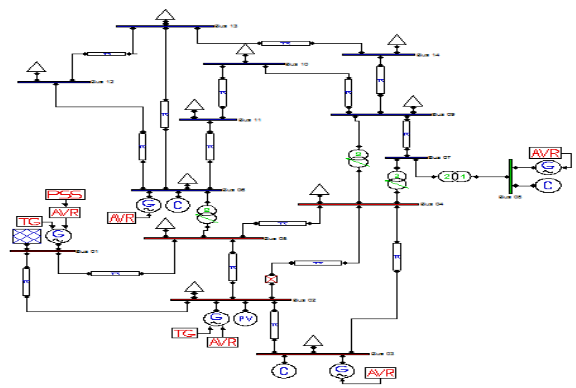

Figure-11. Stability analysis of IEEE 14 bus system.

Figure-12 and Figure-13 shows the time domain analysis of IEEE 14 bus system without and with power system stabilizer under normal operating condition. Graph plotted between time vs rotor speed of the synchronous generator.

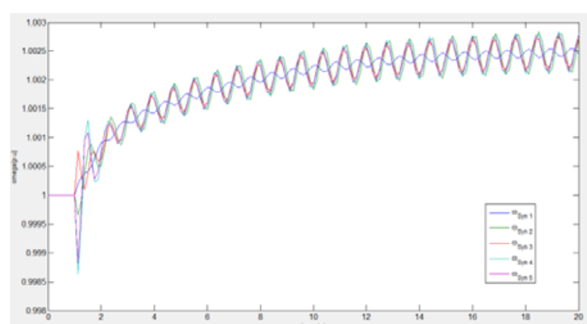

Figure-12. Time domain analysis of IEEE 14 bus system without load condition (without PSS).

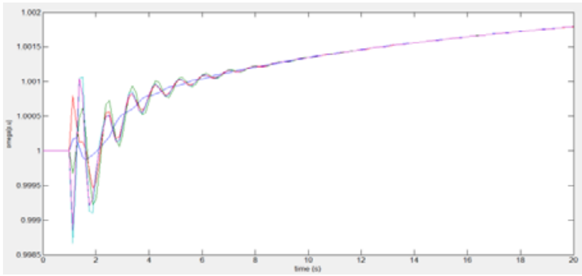

Figure-13. Time domain analysis of IEEE 14 bus system without load condition (with PSS).

Figure-14 and Figure-15 shows the time domain analysis of IEEE 14 bus system without and with power system stabilizer during 40% load condition. Graph plotted between time vs rotor speed of the synchronous generator.

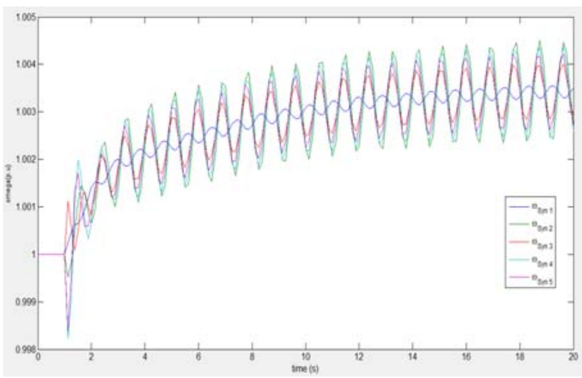

Figure-14. Time domain analysis of IEEE 14 bus system with load condition (without PSS).

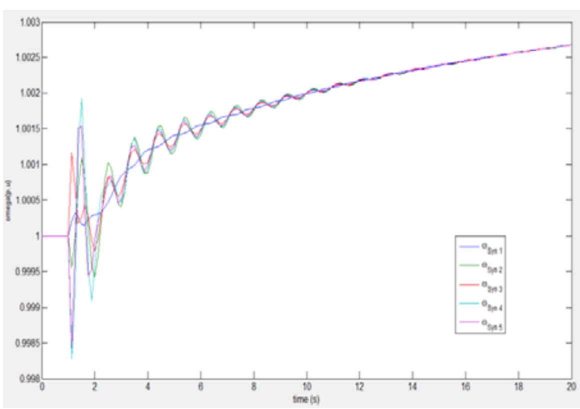

Figure-15. Time domain analysis of IEEE 14 bus system with load condition (with PSS).

5. CONCLUSIONS

Power system stabilizer used to damp out oscillation in the test system and also come back the system to the stable condition after the disturbance. So the performance of PSS analyzed by using the above simulation models. In case 1 simulation models both the time domain analysis and Eigen value analysis were done. Time domain analysis graphically shows the oscillations is damped out after the installation of PSS. Eigen value analysis used to analyze the stability of the system. This was done by both s-domain and z-domain. In s-domain when all the Eigen values are negative the system said to be stable and in z-domain when all the Eigen values are inside of the unity circle the system said to be stable. So the above simulation clearly shows the oscillation was damped out after the installation of PSS. In case 2 simulation model, the stability of IEEE 14 bus system analyzed by using time domain analysis. This analysis graphically shows the oscillation was damped out after the contribution of PSS. The future work aims at tuning the proposed system by firefly algorithm for reducing oscillation time period.

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