Enhancement of Low Frequency Oscillation Damping in Multi-machine Power System using Power System Stabilizer

Wai Myat Thu and Kyaw Myo Lin

***Abstract*—Low frequency oscillations are potential to occur in the exchange of regional power flow under normal operation, especially in the operation of an interconnected power system. The Power System Stabilizer (PSS) has been installed in the automatic voltage regulator to avoid poor damping of low frequency oscillations. The main objective of this paper is to examine the application of power system stabilizer for improving the damping of low frequency oscillations of a power system. In this paper, the method of eigenvalue analysis is utilized to perform the study of the low-frequency oscillations with an emphasis on the dominant oscillation mode. Detailed dynamic model of IEEE 39 Bus test system is studied for illustration of the application of PSS in oscillation damping improvement and the simulation analysis is established by Power System Analysis Toolbox (PSAT) in this paper. The performances of PSS to improve in damping low frequency oscillatory modes have been demonstrated and the simulation results have shown the enhancement of oscillatory stability of the test system.**

***Keywords*—Damping Controller, Eigenvalue Analysis, Low Frequency Oscillation, Oscillatory Stability, PSS**

I. INTRODUCTION

In modern power systems, apart from a large number of generators and associated controllers, there are many types of load, ranging from a simple resistive load to more complicated loads with electronic controllers. The influx of more and more controllers and loads, increase the complexity and nonlinearity of power systems. The change in electromagnetic torque of synchronous machine following a perturbation or disturbance can be resolved into two components – (i) a synchronizing torque component in phase with rotor angle deviation and (ii) a damping torque component in phase with speed deviation [1]. Lack of sufficient synchronizing torque results in "aperiodic" or non-oscillatory instability, whereas lack of damping torque results in low frequency oscillations.

The root cause of electrical power oscillations are fast acting exciters with high gain AVR and the unbalance between power demand and available power at a period of time [2].

Low frequency oscillations are generator rotor angle oscillations having a frequency between 0.1-2.0 Hz and can be classified as local and inter-area mode. Local modes are associated with the swinging of units at a generating station with respect to the rest of the power system. Oscillations occurred only to the small part of the power system. Typically, the frequency range of local mode is 1-2 Hz. Inter-area modes are associated with swinging of many machines in one part of the system against machines in other parts. It generally occurs in weak interconnected power systems through long tie lines. Typically, frequency range of inter-area mode is 0.1-1 Hz [3].

The desired additional damping is provided by a supplementary control loop known as Power System Stabilizer (PSS) [4]. This paper presents results of oscillatory stability enhancement of a multi-machine power system, considering the Power System Stabilizers (PSS) as additional source of damping to low-frequency oscillations. The rest of paper is organized as follows: Section II introduces the basic theory of power system model and eigenvalue analysis concepts used throughout this paper. A brief description of power system with PSS and design parameter of PSS is discussed in Section III. Section IV illustrate the test system of the dynamically challenging unstable the 10-machine New-England Power System (IEEE 39-Bus). In section V, the simulation results for the test system are presented and discussed. Finally, conclusions are drawn in section VI.

II. BASIC BACKGROUND

Low frequency oscillation study requires dynamic modeling of most of the power system components. Once the mathematical model is available different methodologies can be applied to study the system oscillatory behaviour in low frequency range. Eigenvalues analysis is used among the utilities to get a complete understanding of system oscillatory phenomena and to find the low frequency oscillation mode of power system [5].

A. Eigenvalue Analysis

Eigenvalue of a power system model have been derived and evaluated in an analysis of the system stability. Low frequency

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oscillation modes of the system can be determined by system eigenvalues at an operating point. The relative participation of state variables and their contribution in certain oscillation mode are given by the corresponding elements in the right and left eigenvectors. The behavior of a normal power system can be described by a set of first order nonlinear ordinary differential equations and a group of nonlinear algebraic equations. It can be written in the following form by using differential algebraic equation:

$$\begin{aligned} \dot{x} &= f(x,w,u) \\ 0 &= g(x,w,u) \\ y &= h(x,w,u) \end{aligned} \tag{1}$$

where, x is vector of state variables, such as rotor angle and speed of generators. The column vector w is the vector of bus voltages. u, y are the input and output vector of variables respectively. Although power system is a nonlinear, it can be linearized around the equilibrium point as given in (2).

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \tag{2}$$

where, Δx , Δy , and Δu express state, output, and input vector, respectively; A, B, C, and D express the state, control or input, output, and feed forward matrices, respectively.

The eigenvalues, λ of A matrix can be obtained by solving the root of the following characteristic equation:

$$\det(A - \lambda I) = 0 \tag{3}$$

where, I is unit matrix. The complex eigenvalues always occur in conjugate pairs, as shown in (4);

$$\lambda_i = \sigma_i \pm j\omega_i \tag{4}$$

In order for the system to be stable or oscillation free, all the eigenvalues should be located in the open left half plane [6]. This means that real part of the eigenvalues should be negative and damping ratio should be positive. If at least one of the eigenvalues has positive real part, the system is said to be unstable. More specifically, in oscillatory unstable cases, a pair of complex eigenvalues will appear with positive real part.

B. Damping Ratio and Oscillation Frequency

As for any obtained eigenvalues, the damping ratio, ζ_i and oscillation frequency of each, f_i can be defined as follows:

$$\zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{5}$$

$$f_i = \frac{\omega_i}{2\pi} \tag{6}$$

The above parameters can be used to evaluate the damping effects of the power system stabilizers on the power oscillation. It is obvious that the higher damping ratio and the lower oscillation frequency, the damping effects to enhance the stability of the power system for the solution with power system stabilizers to damp the power oscillation [7].

III. POWER SYSTEM STABILIZER (PSS)

The basic function of PSS is to improve damping to the generator rotor oscillations by controlling its excitation by using auxiliary stabilizing signal(s) such as speed deviation, power deviation or frequency deviation. The speed and frequency inputs have been widely used. The PSS is designed to introduce an electrical torque in phase with the rotor speed variations, so that it can increase oscillation damping and enhance the dynamic stability of power system [8].

A. Structure of PSS

A power system stabilizer must compensate for the lags in transfer function of the excitation system, the generator, and the power system to increase damping of the rotor oscillations. PSS has five major elements. These are signal sensor or low pass filter, washout filter, phase compensation, gain and limiter [9]. The major elements of PSS are shown in Fig. 1.

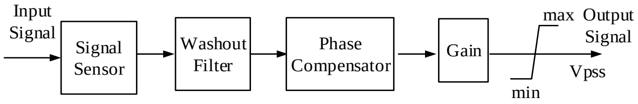

Fig. 1 General power system stabilizer model

B. Power System Model with PSS

In order to improve small-signal oscillations, a PSS is incorporated in power system. Among three type of single input PSS, a speed input PSS has been applied in this section. The basic block diagram of a speed input single-stage PSS, which acts through excitation system, is depicted in in Fig 2.

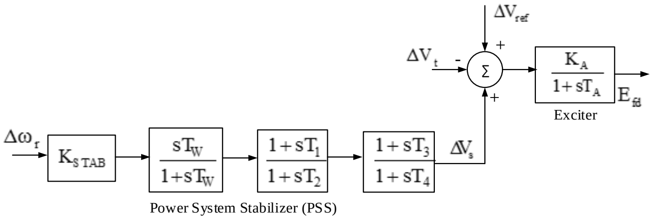

Fig. 2 PSS basic structure and supplementary signal to exciter

In this model, the rotor speed deviation has been used as an input signal for the additional damping control of the excitation system of the synchronous machines. The gain of PSS, K_{STAB} is adjusted to obtain the desired damping for unstable or poorly damped modes; a washout block is defined by the time constant, T_W, it works as a filter for low-frequencies; the time constants T_1, T_2, T_3 and T_4 define two blocks lead-lag of the input signal [10].

Generally, the gain of the PSS is set to one-third of the instability gain for speed and power input or the value corresponding to the maximum damping of rotor oscillations. For local mode oscillations in the range of 0.8 to 2.0 Hz, a washout time constant, T_W of about 1 s is satisfactory. For inter-area modes, T_W of 10 s or higher is desirable [12].

IV. TEST SYSTEM UNDER STUDY

The test is carried out based on the IEEE 39 Bus system, which is commonly known as "the 10-machine New-England" Power System whose diagram is shown in Fig. 3. This is a most widely used test system for validating several control designs. The data for the system are taken from [13]. This model contains 10-machines, 39-bus, 46-transmission line and the 19-loads which are modeled as constant active and reactive power loads. It has totaling loads of 6150.1 MW and 1233.9 Mvar.

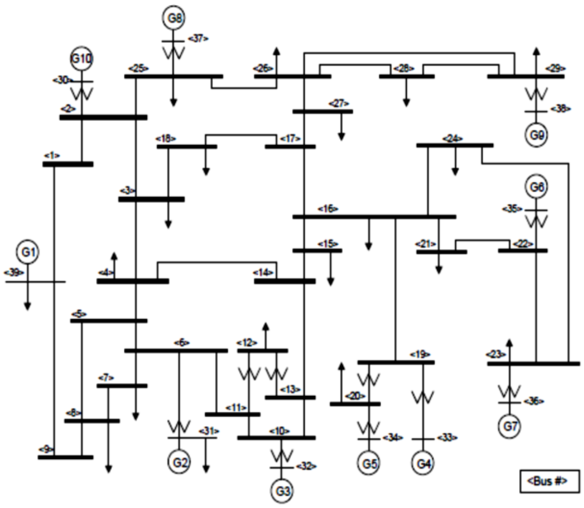

Fig. 3 The 10-machine New-England test system

To analyze the test system, power system analysis toolbox (PSAT), educational free and open source software [14] is employed as a simulation tool and the dynamic analysis routine of PSAT is utilized for simulation. The generators of test system are modeled by the fourth order model while the governor and AVR of the generators are defined as type 1 and type 2, respectively. These models are not mentioned in this section and can be studied in the PSAT manual [15].

V. SIMULATION RESULTS AND DISCUSSION

For the low frequency oscillation, the small signal stability of the system under study is investigated by the method of eigenvalue analysis for finding the damping ratio, frequency, and dominant mode of oscillation. Time domain simulations will then be conducted to verify the effectiveness of installing PSSs on rotor speed deviation, generator excitation voltage and generator output power, respectively.

A. Damping Improvement of PSS with Eigenvalue Analysis

In this eigenvalue evaluation, eigenvalue analysis routine of PSAT is used to identify the dominant oscillation modes, which are located near the imaginary axis, can be recognized. Through analyzing eigenvalues, characteristics of system dynamic states are understood and the eigenvalue plot for test system without PSS is shown in Fig. 4.

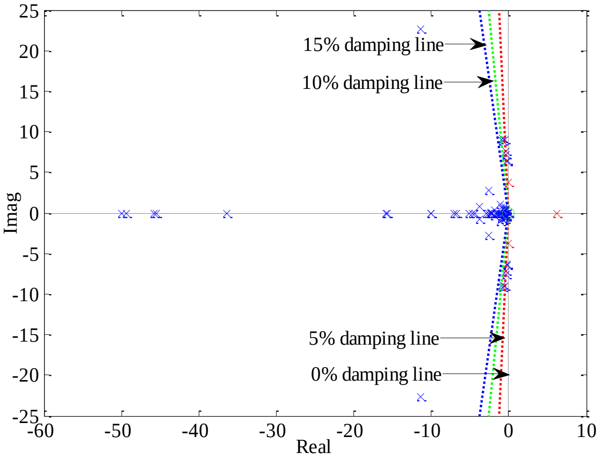

Fig. 4 Dominant eigenvalues of the test system without PSS

In above Fig, some paired complex eigenvalues located outside the 5 % damping line and three complex pairs of eigenvalues located in the right half plane which indicates that systems is unstable. It can be seen in that there is some instability for the inter-area mode and local mode. There are 22 complex pairs among those eigenvalues for the test system without PSS. These complex pairs at low frequency less than 2 Hz were observed as critical mode. From Fig.4, an eigenvalue analysis of the system before the PSS installing showed that it exhibits 7 electromechanical oscillation modes, and 4 of these modes present damping ratio lower than 5% in operating conditions. The calculated eigenvalues, whose dominate oscillation modes, damping coefficient and the natural frequency of oscillation associated with them are shown in Table I.

TABLE I
DOMINANT OSCILLATION MODES (WITHOUT PSS)

Mode	Eigenvalues	Frequency(Hz)	Damping Ratio
1	0.01058±j3.8097	0.60633	-0.0028
2	-0.18589±j6.3219	1.0066	0.0294
3	-0.22856±j6.4615	1.029	0.0354
4	-0.37147±j7.1377	1.1375	0.052
5	-0.30897±j7.6368	1.2164	0.0404
6	-0.54281±j9.0846	1.4484	0.0596
7	-0.7324±j9.1376	1.459	0.0799

It can be observed from table that for the system without PSSs, there are 7 modes of low frequency oscillations with the very weak damping ratios, which is the disadvantage to the normal operation of the multi-machine test system. Dominant eigenvalue analysis results for the test system with different stabilizer arrangement are shown in Fig. 5.

In Fig. 5, all eigenvalues are in the negative real half of the complex plane, has been well known for a stable system. The introduction of PSS has pull out the critical eigenvalue to the open left half plane by adding more damping on it. It can be seen that the desired small-signal stability margins of 5% and 10% are both satisfied when using these PSS. The eigenvalue analysis for the linearized model of the multi-machine test system with 10-PSSs has been performed.

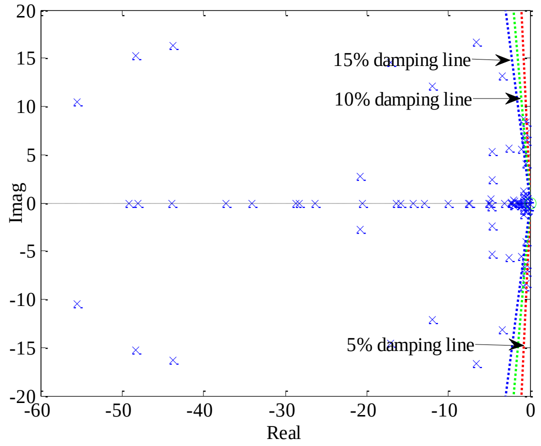

Fig. 5 Dominant eigenvalues of the test system without PSS

Table II provides the eigenvalues, the oscillation modes, their corresponding frequencies less than 2 Hz and damping ratios for the test system with PSS.

TABLE II
DOMINANT OSCILLATION MODES (WITH PSS)

Mode	Eigenvalues	Frequency(Hz)	Damping Ratio
1	-0.46701±j4.0075	0.64213	0.1158
2	-1.0672±j5.5527	0.8991	0.1887
3	-2.5718±j5.6728	0.9913	0.4129
4	-0.41618±j6.3724	1.0164	0.0658
5	-0.60333±j6.7573	1.0797	0.0889
6	-0.50942±j7.2213	1.1522	0.0704
7	-0.70615±j8.7487	1.3969	0.0805

Comparing with Table I, it can be easily seen that with the implement of PSSs installation, the damping ratios for both the inter-area and the local modes are greater than 0.05 and 0.1, which indicate the better stabilization effects of PSS on low frequency oscillation mode.

B. Performance of PSS on Generator Rotor Speed

The nonlinear simulation on the multi-machine test system has been performed by setting the 3-phase fault nearby Bus-24, with the aid of PSAT time domain simulation routine. Fig. 6 and 7 show the dynamic responses of the test system for such large disturbance.

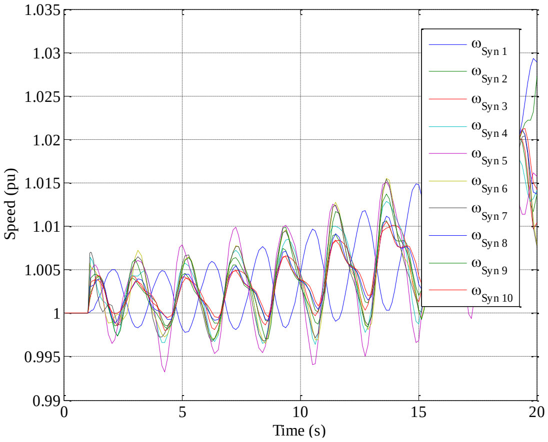

Fig. 6 Speed response of generators with without PSS

In Fig. 6, it can be seen that the system without PSSs exists the serious power oscillations, which is directly reflected by the instability of machine speed. The rotor speed of generators are oscillated and gradually increased. Especially, Gen-5 is most oscillatory when compared with other units. With the implementation of PSSs, the different responses of speed between before and after installing PSS are shown in Fig. 7.

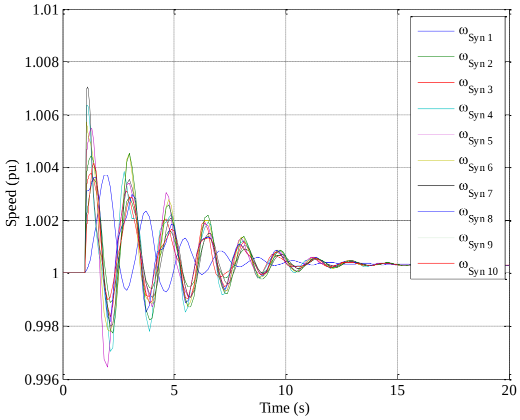

Fig. 7 Speed response of generators with PSS

The speed response with PSS is damped within 4 s. Fig. 7 clearly depict that installation PSS in multi-machine power system, is a very effective way to damp out the low frequency oscillations and lead to enhance electromechanical damping traits of the system.

C. Impact of PSS on Generator Excitation Voltage

To study the impact of PSS, the excitation voltage of generating units should be traced. Fig. 8 illustrates the excitation voltage of generator without PSS.

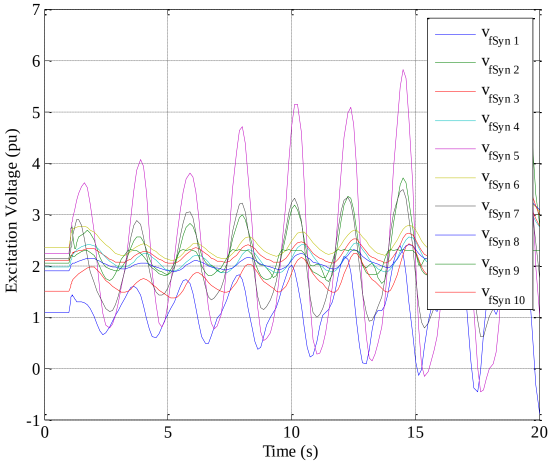

Fig. 8 Response of excitation voltage without PSS

From the simulation result of Fig. 8, it can be mentioned that, excitation voltage at Gen-5 is significantly fluctuated before installing PSS. It can be mentioned that the necessity of installing a PSS into the stability dominant generator Gen-5 and the system becomes transiently unstable upon the application for 3 phase fault. On the other hand, the transient oscillations in excitation voltage of generators are effectively suppressed with PSS as shown in Fig. 9.

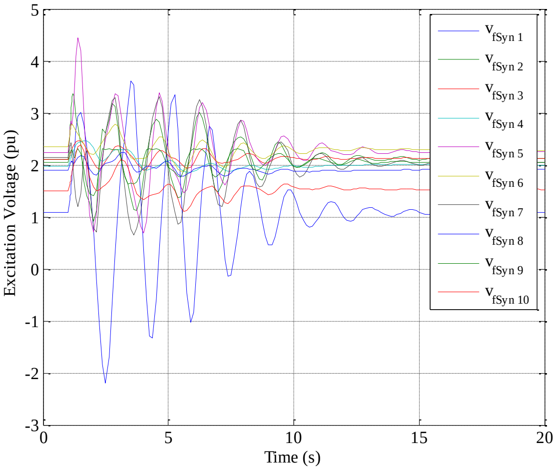

Fig. 9 Response of excitation voltage with PSS

After PSS is equipped with each respective dominant generator, the oscillation of excitation voltage in Gen-5 is increased in damping to be acceptable range which is shown in Fig. 9. The oscillations of excitation voltage are damped at start from 10s when PSSs are equipped.

D.Effect of PSS on Generator Output Power

Fig. 10 and Fig. 11 show the response of output power of generators equipped without and with PSS. Simulation results of not installing PSSs are shown in Fig. 10, and results of installing the PSSs are shown in Fig. 11. It can be clearly seen that, the design of PSS parameters needs to regulate or adjust against the dynamics of the entire power system.

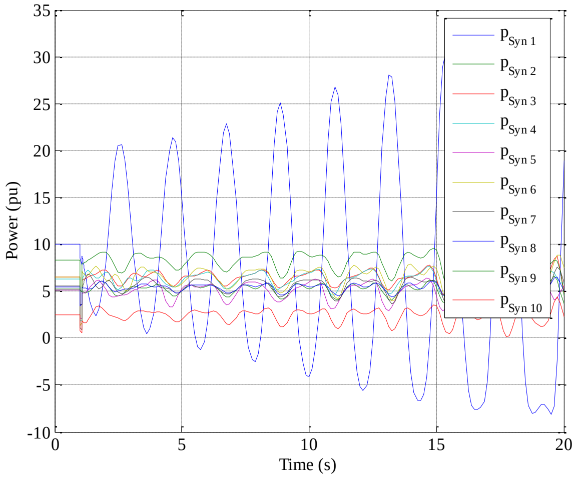

Fig. 10 Power output response of generators without PSS

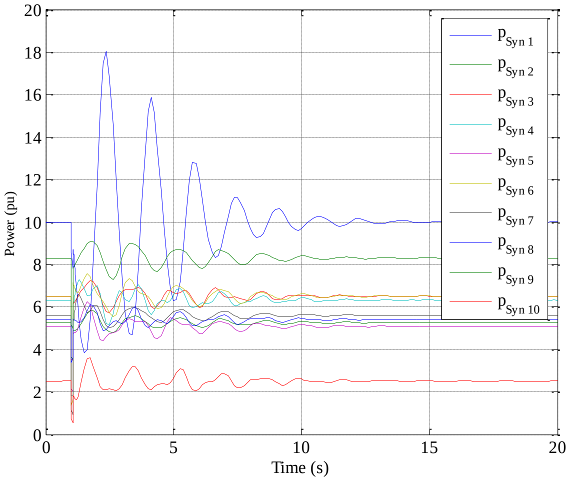

Fig. 11 Power output response of generators with PSS

By comparison of these results, the low-frequency oscillation of the electrical output of generator Gen-1 is damped at 10 s (shown in Fig. 11) by installing the designed PSS into the dominant one. Therefore, the low-frequency oscillation is removed from all outputs which can be seen in Fig. 11. In the confirmation, the low-frequency dominant PSSs with different parameters setting have been equipped in the generators. The results indicate that the design of PSS needs to consider the system configurations, the designed PSS succeeded in enhancing the power system stability.

VI. CONCLUSIONS

This paper presented the performance of the PSS controllers for the damping of low-frequency oscillations in IEEE 39-Bus power system. The method of eigenvalue analysis has been utilized to analyze the damping oscillation and performance of PSS. The PSS controllers using the variations of angular speed ($\Delta\omega$) input signal have been installed in order to introduce damping. The installations of PSS at the given machines provided to achieve power system stability performance including oscillation stability performance and transient stability performance. The results illustrated the enhancement of oscillation damping with the application of PSSs in the well-known 10-machine equivalent of the unstable network. Through simulations on the test system, it is concluded the efficiency of PSS to promote damping of electric power system oscillation.

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