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RESEARCH ARTICLE

Small Signal Stability Improvement by Power System Stabilizer (PSS)

Ali Vaseghi Ardekani, Alireza Toorani
Department of Electrical Engineering, Beyza Branch, Islamic Azad University, Beyza, Iran

Abstract— ***The stability of power electrical networks is a key factor for the delivery of high quality energy. A power system stabilizer (PSS) is designed to deliver a supplement excitation signal to a synchronous machine, to limit frequency oscillations. A Power System Stabilizer (PSS) is the most cost effective approach of increase the system positive damping, improve the steady-state stability margin, and suppress the low-frequency oscillation of the power system. The aim of this paper is to investigate the foundation of a PSS and its effect on the performance of a power system and its eigenvalues. According to a profile of a generator and local load simulate the system and the eigenvalues of the system without obtaining PSS. Then, the controllers designed by two different techniques, and discuss each part separately. This design methodology is implemented on a Single Machine Infinite Bus (SMIB) system. Simulation results on SMIB show the effectiveness and robustness of the proposed PSS over a range of operating conditions and system configurations.***

Keywords— ***Small signal stability; Power System Stabilizer (PSS); low frequency oscillation; power oscillation damping; Single Machine Infinite Bus (SMIB)***

I. INTRODUCTION

Due to increasing size and complexity of electric power systems there has been an increasing interest in stabilization of such large-scale power systems. In the past fixed gain controllers were effectively used for damping out the low frequency oscillations.

The occurrence of low frequency electromechanical oscillations as synchronizing power flow oscillations on transmission lines, is a direct consequence of dynamical interactions between synchronous generators when the system is subjected to perturbations [1]-[5]. This phenomenon occurs due to dynamical interactions between groups of generators (a group oscillates against another group), or between one generator (or group of generators) and the rest of the system. The first case characterizes the inter-area modes and the second one the local modes of oscillations and they normally have frequencies in the range of 0.1 to 0.7 Hz and 0.7 to 2.0 Hz, respectively [6-8].

A power system stabilizer (PSS) can provide a supplementary control signal to the excitation system and/or the speed governor system of the electric generating unit to damp these oscillations. Due to their flexibility, easy implementation, and low cost, PSSs have been extensively studied and successfully used in power systems for many years. Since a Power System Stabilizer (PSS) provides additional system damping, this controller has become an accepted solution for oscillatory instability problems and thus improves system stability [9]. In this paper, a power system stabilizer is designed to limit frequency oscillations of a power electrical network. The mathematical modeling of the single-machine infinite-bus (SMIB) installed with PSS[10].

In this article, by introducing the concepts of synchronization and damping torques, the effect of various parameters on the stability of the operating point of the system is described, followed by dynamic synchronous machine theory is discussed to compensate for phase PSS design. This paper uses PSS in helping to improve power system stability and damping to electromechanical oscillations has been assessed separately for each.

II. POWER SYSTEM MODELING FOR STUDY THE SMALL SIGNAL STABILITY

To investigate the effectiveness of using the power system stabilizer (PSS) with the automatic voltage regulator (AVR)[11], the plant model which is the single machine infinite bus (SMIB) used to evaluate the PSS is presented in figure 1.

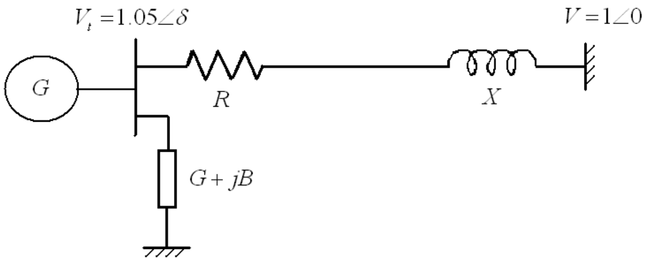

Fig. 1 A single line of example power system.

Generator data:

$$M = 9.26 \ \text{sec} \qquad D \cong 0 \qquad (1)$$
$$\tau'_{do} = 7.76 \ \text{sec} \qquad X_d = 0.973\,pu \qquad X'_d = 0.19\,pu$$
$$X_q = 0.55\,pu$$

Type-1 excitation system data:

$$K_A = 50 \qquad \tau_A = 0.05 \ \text{sec} \qquad (2)$$

Line data:

$$R = 0 \qquad X = 0.997\,pu \qquad (3)$$

Load data:

$$G = 0.249\,pu \qquad B = 0.262\,pu \qquad (4)$$

Operating point of the machine:

$$P_0 = 1\,pu \qquad Q_0 = 0.015\,pu \qquad (5)$$
$$V_{t0} = 1.05\,pu$$

Now the system is designed to be given to two different controllers and controllers based on the eigenvalues of this system will be investigated.

Small signal stability studies of the stability against small disturbances deals[12]. So at this point small range of system parameters and possible linearization around system operating point there. In most related studies, small signal stability of linear machine infinite bus are used. Modeling machine (regardless of damper windings and stator resistance and stator windings dynamics) is used[8-10]. Using this model, the analysis of stability seems quite reasonable. Ignoring damper windings and stator resistance caused some conservatism in the design of the stabilizer will also aim to examine the low frequency oscillations.

A. Model of SMIB

Third-order machine model are:

$$\upsilon_{qs} = E'_q - X'_d i_{ds} \qquad \psi_{ds} = E'_q - X'_d i_{ds} \qquad \upsilon_{qs} = \psi_{ds} \tag{6}$$

$$\upsilon_{ds} = X_q i_{qs} \qquad \psi_{qs} = -X_q i_{qs} \qquad \upsilon_{ds} = -\psi_{ds} \tag{7}$$

$$E'_{FD} = E'_q + (X_d - X'_d) i_{ds} + \frac{X'_{fd}}{\omega_b r'_{fd}} pE'_q \tag{8}$$

$$T_m - T_e = \frac{2H}{\omega_b}\frac{d\omega}{dt} \tag{9}$$

Where X'_d: d-axis transient reactance and E'_q :open circuit voltage is transient. Machine equations in linear form as follows:

$$\Delta\upsilon_{qs} = \Delta E'_q - X'_d \Delta i_{ds} \tag{10}$$

$$\Delta\upsilon_{ds} = X_q \Delta i_{qs} \tag{11}$$

$$E'_{FD} = \Delta E'_q + (X_d - X'_d)\Delta i_{ds} + \frac{X'_{fd}}{\omega_b r'_{fd}} p\Delta E'_q \tag{12}$$

In order to obtain a suitable model of the machine equations, network equations should also be written in the rotor coordinate system are linear and thus can be considered as a reference d-axis between a phase a and d and q axes components to be written as follows(figure 2):

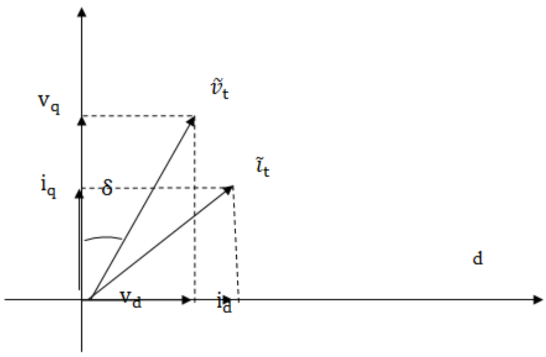

Fig. 2 A diagram phasor and relationship components d and q axies.

$$\tilde{\upsilon}_t = v_d + jv_q \tag{13}$$

$$\tilde{i}_t = i_d + ji_q \tag{14}$$

$$\tilde{i}_t = \tilde{\upsilon}_t (G + jB) + \frac{\tilde{\upsilon}_t - \tilde{\upsilon}_\infty}{R + jX} \tag{15}$$

If phasor equations to placement with d and q axis components d and q:

$$\tilde{i}_t = i_d + ji_q = (v_d + jv_q)(G + jB) + \frac{v_d + jv_q - v_\infty \sin\delta - jv_\infty \cos\delta}{R + jX} \tag{16}$$

With linearization of the above equation and placement V_d and V_q in terms of their values, the relationship between Δi_{ds} and Δi_{qs} in terms of $\Delta E'_q$ and $\Delta\delta$ is achieved and with placement the values listed in the following equations:

$$\Delta T_e = K_1 \Delta\delta + K_2 \Delta E'_q \quad (17)$$

$$\Delta \upsilon_t = K_5 \Delta\delta + K_6 \Delta E'_q \quad (18)$$

$$\Delta E'_q = (-K_4 \Delta\delta + \Delta e'_{XFD}) \frac{K_3}{1+\tau'_{do} K_3} \quad (19)$$

Coefficients K_1 to K_6 machine are dependent on machine parameters and initial conditions, and how to calculate them are given later. The third order linear model of the machine will be in figure 3[4-6]. Here it should be noted that the excitation system is modeled as a system of first order.

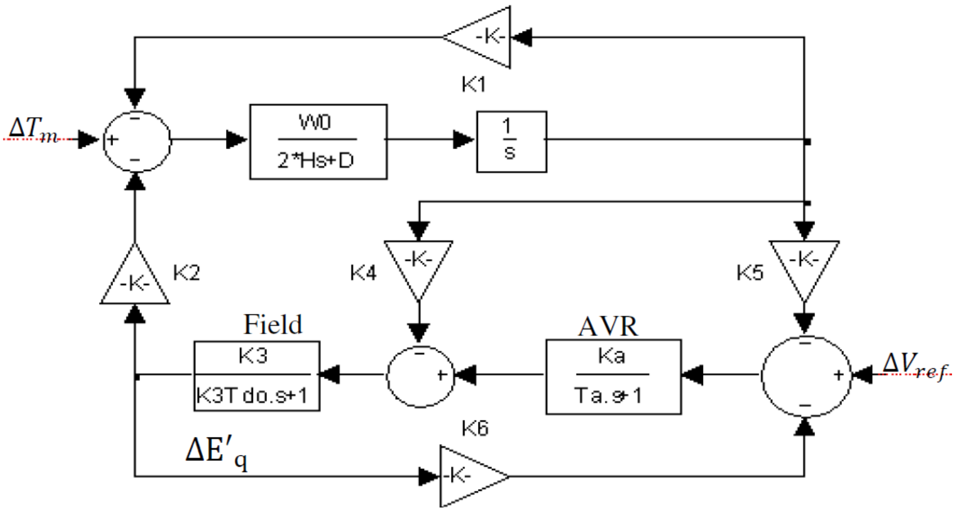

Fig. 3 Third order linearized model of machine.

This model is used in the majority of small signal stability studies.

B. *Damper and synchronization torques*

In general, the electromagnetic torque of synchronous machine can be divided to linear synchronous and damping torque split is:

$$\Delta T_e = K_s \Delta\delta + K_D \Delta\omega \quad (20)$$

$$\Delta T_m - \Delta T_e = \frac{2H}{\omega_b} \frac{d\omega}{dt} \quad (21)$$

and with the placement ΔT_e of the above equation we have:

$$\Delta T_m - K_s \Delta\delta = \frac{2H}{\omega_b} \frac{d\omega}{dt} + K_D \Delta\omega \quad (22)$$

Synchronizing and damping torque of the machine is necessary for the stability of machine and the lack of each to make the machine unstable[4]. Lack of synchronization will increase the uniform of torque angular while lack of the damping torque deficiency increases the torque angular (figure 4).

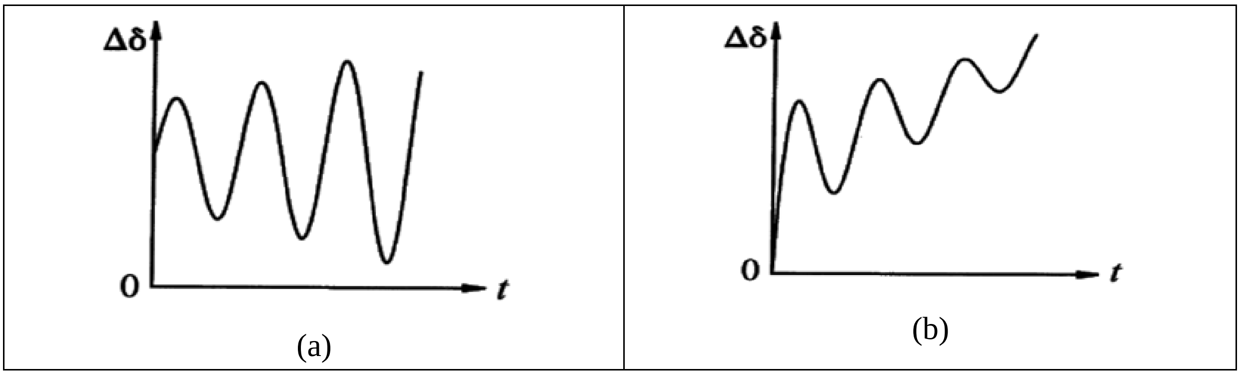

Figure 4: The effects of lack (a) the synchronization torque, (b) the damping torque

The electromagnetic torque is:

$$\Delta T_e = K_1 \Delta\delta + K_2 \Delta E'_q \tag{23}$$

$$\Delta E'_q = -\frac{K_3[K_4(1+sT_a)+K_5K_a)}{s^2 K_3 T'_{do} T_a + s(K_3 T'_{do} + T_a) + K_3 K_6 K_a} \Delta\delta \tag{24}$$

III.CHARACTERISTICS AND PERFORMANCE OF THE PSS

The controller shall be as follows:

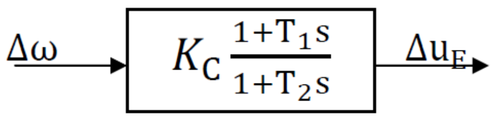

Figure 5: The forward phase controller

That $T_1 > T_2$ and Δu_E signal is input to the voltage regulator.

In addition to the PSS system only when necessary, and is based on the transient and steady-state mode, the main task of the working voltage (voltage regulation terminal of the machine) washout systems, to make a dent will be used. In order for this system to phase-shift the system does not consider the value of T is large.

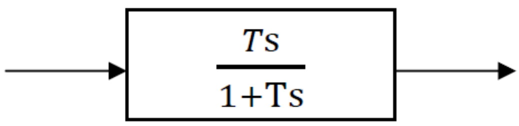

Figure 6: The washout system

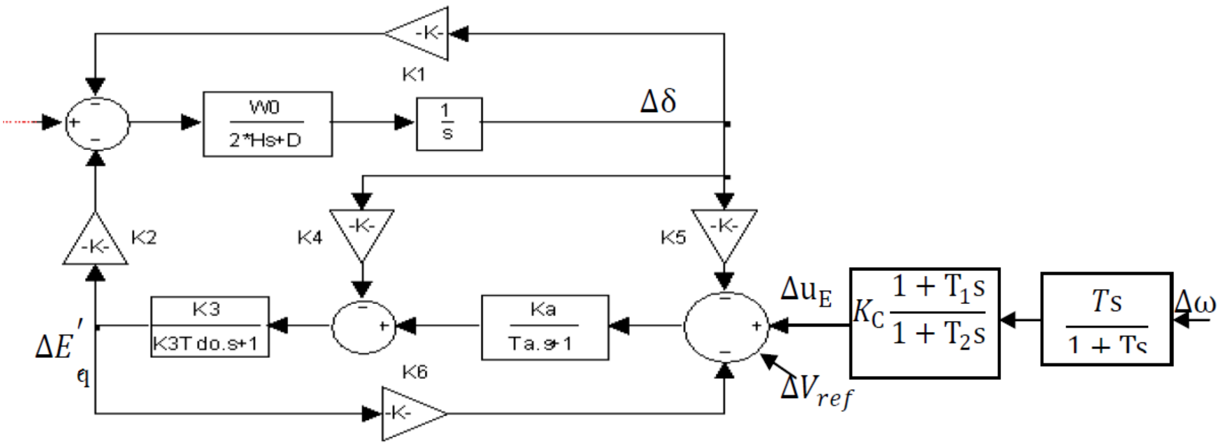

Figure 7: How to apply PSS with the system

PSS designed for a specific operating point occurs. Therefore, by changing the operating point would be desirable. PSS design of low-frequency fluctuations in frequency occurs with changes in working conditions will also change the frequency bandwidth is very low.

IV. STABILIZATION OF A SYSTEM BY PSS

A. Calculation of the initial values

Initial values will be calculated according to the following equations:

$$P_e = \mathrm{Re}(\tilde{v}_t \tilde{i}_t^*) = \mathrm{Re}[(v_d + jv_q)(i_d + ji_q)^*] = v_d i_d + v_q i_q \quad (25)$$

$$Q_e = img(\tilde{v}_t \tilde{i}_t^*) = img[(v_d + jv_q)(i_d + ji_q)^*] = v_d i_d - v_q i_q \quad (26)$$

$$v_d = X_q i_d \quad (27)$$

$$v_t^2 = v_d^2 + v_q^2 \quad (28)$$

$$v_{do} = \frac{P_e v_t}{\sqrt{P_e^2 + (Q_e + \frac{v_t^2}{X_q})^2}} \quad (29)$$

$$v_{qo} = \sqrt{v_t^2 - v_{do}^2} \quad (30)$$

$$i_{qo} = \frac{v_{do}}{X_q} \quad (31)$$

$$i_{do} = (P_e - v_{qo} i_{qo}) / v_{do} \quad (32)$$

The q-axis transient voltage can be calculated as follows:

$$E'_{qo} = v_{qo} + X\, i_{do} \quad (33)$$

The initial values for the problem would be as follows:

TABLE 1
Initial values of voltages and currents of the studied systems

$v_{do} = 0.4659pu$	$v_{qo} = 0.941pu$	$i_{qo} = 0.8471pu$
$i_{do} = 0.4354pu$	$E'_q = 1.0237pu$	

as well as the infinite bus voltage is determined as follows:

$$\tilde{v}_\infty = \tilde{v}_t - (R + jX)\tilde{i}_1 \quad (34)$$

$\tilde{i}_1$ represents the transmission line.

$$\tilde{i}_1 = \tilde{i}_t - (\nu_d + j\nu_q)(G + jB) =$$
$$0.8471 + j\,0.4354 - (0.4659 + j\,0.941)(0.249 + j\,0.262) = 0.566 + j\,0.491$$

$$\tilde{\nu}_\infty = 0.4659 + j\,0.941 - (j\,0.997)(0.566 + j\,0.491) =$$
$$0.955 + 0.3768 = 1.0267\angle 21.527 \Rightarrow$$
$$\delta_0 = 68.473^\circ, \nu_\infty = 1.0267$$

B. *Coefficient calculation of K_1 to K_6*

To calculate the coefficients K_1 to K_6 can be written:

$$\tilde{i}_t = \frac{\tilde{\nu}_t - \tilde{\nu}_\infty}{R + jX} + \tilde{\nu}_t (G + jB) \tag{35}$$

$$i_d + ji_q = (\nu_d + j\nu_q)(G + jB) + \frac{\nu_d + j\nu_q - \nu_\infty \sin\delta - j\nu_\infty \cos\delta}{R + jX}, \tag{36}$$
$$\nu_\infty \sin\delta = \nu_d - R(i_d + B\nu_q - G\nu_d) + X\,(i_q - B\nu_d - G\nu_q)$$
$$\nu_\infty \cos\delta = \nu_q - X\,(i_d + B\nu_q - G\nu_d) - R(i_q - B\nu_d - G\nu_q)$$

Placement $\nu_d = X_q I_q$ and $\nu_q = E_q' - X_d' i_d$, then linear the above equations and sort of sentences:

$$\begin{bmatrix} G + \frac{R}{R^2 + X^2} & V_\infty \frac{X\cos\delta_0 + R\sin\delta_0}{R^2 + X^2} \\ -B + \frac{X}{R^2 + X^2} & V_\infty \frac{X\sin\delta_0 - R\cos\delta_0}{R^2 + X^2} \end{bmatrix} \begin{bmatrix} \Delta E_q' \\ \Delta\delta \end{bmatrix} = \begin{bmatrix} GX_d' + \frac{RX_d'}{R^2 + X^2} & 1 - BX_q + \frac{XX_q}{R^2 + X^2} \\ 1 - BX_d' + \frac{XX_d'}{R^2 + X^2} & -GX_q + \frac{RX_q}{R^2 + X^2} \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \tag{37}$$

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \begin{bmatrix} 0.668 & 0.8687 \\ 0.1544 & 0.2392 \end{bmatrix} \begin{bmatrix} \Delta E_q' \\ \Delta\delta \end{bmatrix} \begin{bmatrix} 0.0473 & 1.4075 \\ 1.1408 & -0.13695 \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \Rightarrow \begin{bmatrix} 0.249 & 0.3778 \\ 0.741 & 0.4583 \end{bmatrix} \begin{bmatrix} \Delta E_q' \\ \Delta\delta \end{bmatrix} =$$

Electromagnetic torque in pu with air gap power is equal to:

$$\begin{bmatrix} G + \frac{R}{R^2 + X^2} & V_\infty \frac{X\cos\delta_0 + R\sin\delta_0}{R^2 + X^2} \\ -B + \frac{X}{R^2 + X^2} & V_\infty \frac{X\sin\delta_0 - R\cos\delta_0}{R^2 + X^2} \end{bmatrix} \begin{bmatrix} \Delta E_q' \\ \Delta\delta \end{bmatrix} = \begin{bmatrix} GX_d' + \frac{RX_d'}{R^2 + X^2} & 1 - BX_q + \frac{XX_q}{R^2 + X^2} \\ 1 - BX_d' + \frac{XX_d'}{R^2 + X^2} & -GX_q + \frac{RX_q}{R^2 + X^2} \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \tag{38}$$

The linearization of the above equation is obtained:

$$\Delta T_e = (X_q - X_d')(i_{qo}\Delta i_d + \Delta i_q i_{do}) + E_{qo}'\Delta i_q + \Delta E_q' i_{qo} \tag{39}$$
$$\Delta T_e = 0.5473\Delta\delta + 1.2332\Delta E_q' \tag{40}$$
$$\Delta E_{FD} = \Delta E_q' + (X_d - X_d')\Delta i_{ds} + \frac{X_{fd}'}{\omega_b r_{fd}'} p\Delta E_q' \Rightarrow \tag{41}$$
$$(1 + \tau_{do}' S)\Delta E_q' = \Delta E_{XFD}' - (X_d - X_d')\Delta i_{ds}$$
$$(\tau_{do}' = \frac{X_{fd}'}{\omega_b r_{fd}'})$$

Placement Δi_{ds} with X_d' and X_d values to be achieved:

$$\Delta E_q' = \frac{0.6565}{1 + 5.0944s}(\Delta E_{XFD}' - 0.6801\Delta\delta) \tag{42}$$
$$\nu_t^2 = \nu_d^2 + \nu_q^2 \Rightarrow \upsilon_{to}\upsilon_t = \upsilon_{do}\upsilon_d + \upsilon_{qo}\upsilon_q \tag{43}$$
$$\Delta\upsilon_t = \frac{\upsilon_{do}}{\upsilon_{to}} X_q \Delta i_q + \frac{\upsilon_{qo}}{\upsilon_{to}}(\Delta E_q' - X_d'\Delta i_d) \tag{44}$$
$$\Delta\upsilon_t = -0.0895\Delta\delta + 0.8201\Delta E_q' \tag{45}$$

TABLE 2
Values obtained for K_1 to K_6

$K_1 = 0.5473$	$K_2 = 1.2332$	$K_3 = 0.6565$
$K_4 = 0.6801$	$K_5 = -0.0895$	$K_6 = 0.8201$

C. Dampers and synchronization torques before applying PSS

Before applying PSS only with regard to the effect of AVR the electromagnetic torque equation can be written as follows:

$$\Delta E'_q = -\frac{K_3[K_4(1+sT_a)+K_5K_a)}{s^2K_3T'_{do}T_a + s(K_3T'_{do}+T_a)+K_3K_6K_a}\Delta\delta \quad , \quad \Delta T_e = K_1\Delta\delta + K_2\Delta E'_q \tag{46}$$

$$\Delta T_e = K_1\Delta\delta + K_2[-\frac{K_3[K_4(1+sT_a)+K_5K_a)}{s^2K_3T'_{do}T_a + s(K_3T'_{do}+T_a)+K_3K_6K_a}\Delta\delta]$$

$$\Delta T_m - \Delta T_e = \frac{2H}{\omega_b}\frac{d^2\delta}{dt^2} \Rightarrow \Delta T_m = \frac{2H}{\omega_b}\frac{d^2\delta}{dt^2} + \frac{D}{\omega_b}\frac{d\delta}{dt} + K_1\Delta\delta \tag{47}$$

Oscillation frequency of the system is:

$$\omega_n = \sqrt{\frac{K_1\omega_b}{2H}} = \sqrt{\frac{0.5473*120\pi}{9.26}} = 4.72(\frac{rad}{\sec}) \tag{48}$$

At this frequency, we have:

$$\Delta T_e = 0.5473\Delta\delta - \frac{0.8096[0.6801(1+0.05s)-4.475)}{0.2547s^2 + s(5.1448)+27.9197}\Delta\delta \Rightarrow \underline{s = j\omega_n = (4.72j)} \tag{49}$$

$$0.5473\Delta\delta - \frac{-3.072 + j0.13}{22.2454 + 24.2834j}\Delta\delta = 0.5473\Delta\delta -$$

$$(-0.06 + 0.07145j)\Delta\delta = \underbrace{(0.5473+0.06)}_{Synchronizing\ Torque}\Delta\delta - \underbrace{0.07145(j\Delta\delta)}_{Damping\ Torque}$$

$$\rho\Delta\delta = \omega_b * \Delta\omega \xrightarrow{Steady-State} j\Delta\delta = \frac{\omega_b}{\omega_n} * \Delta\omega \tag{50}$$

$$\Delta T_e = 0.6073\Delta\delta - 5.7069\Delta\omega \tag{51}$$

Can be seen from the above equation that the system without PSS is negative torque dampers, so you have oscillations with amplitude fluctuations in the incidence is increasing, which will ultimately lead to system instability. Instability of the system can be measured by calculating its eigenvalues.

V. EVALUATION VARIOUS MODES OF PSS BEFORE AND AFTER APPLYING

A. Eigenvalues of the system before applying PSS

In order to find the eigenvalues of the system, the system of equations must be written in state-space forms:

$$\begin{bmatrix} \dot{\Delta\omega} \\ \dot{\Delta\delta} \\ \dot{\Delta E}_{FD} \\ \dot{\Delta E}_q' \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & -\frac{K_1}{M} & 0 & -\frac{K_2}{M} \\ \omega_b & 0 & 0 & 0 \\ 0 & \frac{K_5 K_a}{T_a} & -\frac{1}{T_a} & -\frac{K_a K_6}{T_a} \\ 0 & -\frac{K_4}{T_{do}} & \frac{1}{T_{do}} & -\frac{1}{T_{do} * K_3} \end{bmatrix}}_{A} \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_{FD} \\ \Delta E_q' \end{bmatrix} \quad (52)$$

$$\underbrace{\begin{bmatrix} 0 & -0.0591 & 0 & -0.1332 \\ 377 & 0 & 0 & 0 \\ 0 & 89.4988 & -20 & -820.0923 \\ 0 & -0.0876 & 0.1289 & -0.1963 \end{bmatrix}}_{A}$$

and the eigenvalues of the system will be as follows:

TABLE 3
The various modes of the system before applying the PSS

Mechanical Mode	$0.2805 \mp j\,4.96$
Electrical Mode	$-10.3786 \mp j\,3.3374$

This can be seen from the eigenvalues of the mechanical mode is unstable. The oscillation frequency of this mode is pretty much what we got earlier as the natural frequency of the mechanical system is equal. Here the electric mode is strongly damped.

B. Eigenvalues of the system after applying PSS

The PSS system can be applied to re-calculate the eigenvalues of the system and to examine the effect of PSS.

$$\begin{bmatrix} \dot{\Delta\omega} \\ \dot{\Delta\delta} \\ \dot{\Delta E}_{FD} \\ \dot{\Delta E'}_q \\ \dot{u}_1 \\ \dot{u}_E \end{bmatrix} = \begin{bmatrix} 0 & -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & 0 \\ \omega_b & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_5 K_a}{T_a} & -\frac{1}{T_a} & -\frac{K_a K_6}{T_a} & 0 & 0 \\ 0 & -\frac{K_4}{T_{do}} & \frac{1}{T_{do}} & -\frac{1}{T_{do} K_3} & 0 & \frac{K_a}{T_a} \\ 0 & -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & -\frac{1}{T} & 0 \\ 0 & -\frac{K_c K_1 T_1}{M T_2} & 0 & -\frac{K_c K_2 T_1}{M T_2} & \frac{K_c}{T_2}(1-\frac{T_1}{T}) & -\frac{1}{T} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_{FD} \\ \Delta E_q' \\ u_1 \\ u_E \end{bmatrix} \quad (53)$$

Placement parameters, the eigenvalues of the matrix will be calculated as follows:

TABLE 4
The various modes of the system after applying the PSS

Mechanical Mode	$-1.1417 \mp j\,4.3147$
Electrical Mode	$-4.6060 \mp j\,7.5257$
Control Mode	$-10.6970 - j\,0.3372$

Thus it can be seen that PSS significantly increased torque dampers. PSS function as shown in the following diagram is $\Delta\delta - \Delta\omega$.

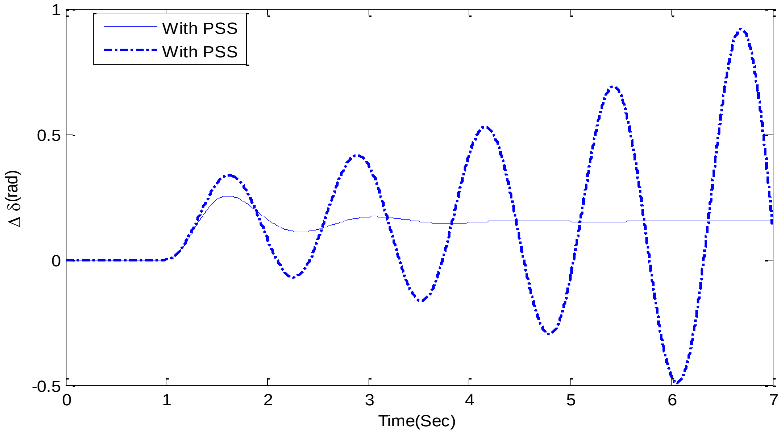

Figure 8: Showing the effect of the PSS operation

VI. CONCLUSION

This paper proposes a simple technique for design of Power System Stabilizer for damping of oscillations. PSS performance was simulated with different controllers using MATLAB software. As mentioned, the power grid disturbances caused by low-frequency oscillations in electromechanical system generator, which is both a destructive and mechanical units to be delivered to the consumer in terms of quality is problem.

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