

LOC-PSS Design for Improved Power System Stabilizer

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Abstract – A power system stabilizer (PSS) is an ancillary device used for improving stability of otherwise poorly stable power system. It helps to restore the system back to the operating point after disturbances like load changes or faulty situations are withdrawn or smoother transition from one to another operating point. Originally, power system stabilizers are installed to add damping to local oscillatory modes, which were destabilized by high gain, fast acting exciters. Its property is to provide damping torque to reduce the electromechanical oscillations introduced in the system under disturbances. In this paper, first, we analyze different types of small signal stabilities of a power system using linearized model and then, design a stabilizer for Single Machine Infinite Bus (SMIB) system. A comparison between the effect of Linear Optimal Control plus PSS (LOC-PSS) and Conventional PSS(CPSS) in terms of either power system responses or its eigen-values due to different load condition is reported. Simulation results show the LOC- PSS is robust for such nonlinear dynamic system and achieves better performance than the CPSS in damping oscillations. The effectiveness of the PSS for different load disturbances is illustrated with simulation carried out in MATLAB software.

Keywords: Power System Stabilizer, CPSS, LOC-PSS, SMIB, Heffron-Phillips, Robust Systems Control

I. Introduction

Most adaptive controllers are to predict the low frequency electromechanical oscillations resulting from poorly damped rotor oscillations. These oscillations stability becomes a very important issue as reported in [1]. The operating conditions of the power system change with time due to system's dynamic nature, thus we need to track the system stability online. To track the system, some stability indicators are estimated from the given data and updated as the new data are received.

Load changing at power system could induce low frequency oscillations. These oscillations may sustain and grow to cause loss of synchronization between generators. Power system stabilizer (PSS) has been used to damp out oscillations in recent years. However, problem with PSS is that it may not give adequate damping. In order to achieve an optimal performance against small disturbances, the coordination between PSS and Thyristor-Controlled Series Compensation (TCSC) is needed [2].

Different methods have been applied to control PSS and

Power Oscillation Dampers (PODs). Methods such as lead-lag compensation and PID controller have been studied and reported in several papers. Panda, et al [3] compares lead-lag compensation and PID controller for different disturbances. Simulation results show that lead-lag compensation gives better performance. Other studies also represent that lead lag compensation method offers better oscillations damping and system stability in power system [2], [3], [4], [5].

In this paper, a systematic approach to design PSS using Linear-Quadratic-Regulator (LQR) technique and Hinloop shaping procedure is presented for two generator infinite bus system. The analysis is made to verify the robustness of the designed controller using loop shaping procedure. To adjust the weights of the controller, Genetic Algorithm (GA) has been used. The resulting PSS can stabilize the nominal plant. The proposed work demonstrates good damping performance of the designed controller; furthermore, comparison is made between LQR based PSS and Robust PSS [6].

In order to improve the dynamic response and achieve optimal performance at any loading condition, the Linear-Quadratic-Gaussian (LQG) optimal control has been developed to be included in power system. The LQG is superior to LQR controller in terms of small settling time and less overshoot and under shoot [7].

The rest of the paper is as follows. In section 2, model of the system is described. Identification of controllers PSS is

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introduced in section 3. Finally, section 4 presents the simulation results and section 5 concludes the paper.

II. Model

The maintenance of stability in a power system is one of the most significant and essential aspect of power systems' quality. In this section, the design procedure is described. Fig.1 shows block diagram of a Single Machine Infinite Bus (SMIB) power system model. The system under study including SMIB with exciter is shown in Fig.2. The state variables are defined as:

$$X = [\Delta\omega \quad \Delta\delta \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta x_1 \quad \Delta x_2]^T$$

The nonlinear equations of the system are

$$\dot{\delta} = \omega_0 \omega$$

(1)

$$\dot{\omega} = (T_m - T_e)/M$$

(2)

$$\dot{E}'_q = \frac{1}{T_{do}} \left(E_{fd} - \frac{x_d + x_e}{x_d + x_e} E'_q + \frac{x_d + x'_d}{x_d + x_e} V \cos \delta \right)$$

(3)

$$\dot{E}_{fd} = \frac{1}{T_A} (K_A E_{ref} - K_A V_t - E_{fd})$$

(4)

$$\dot{x}_1 = -\frac{K_A K_5}{T_A} \delta - \frac{K_A K_6}{T_A} E_q - \frac{1}{T_A} x_1 - \frac{K_A}{T_A} x_2$$

(5)

$$\dot{x}_2 = -\frac{(S_E + K_E) K_F}{T_E T_F} E_{fd} + \frac{K_F}{T_E T_F} x_1 - \frac{1}{T_F} x_2$$

(6)

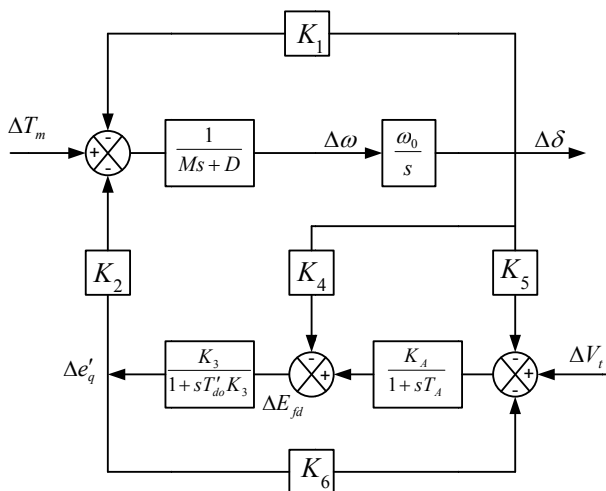


Fig.1: Linearized model of SMIB system

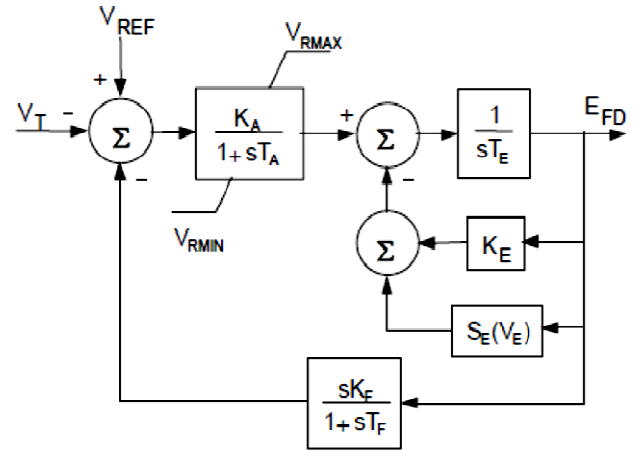


Fig.2: Excitation system model

In fig.1, constant parameters K1 to K6 represent the system parameters at a certain operation condition. The above equations can be linearized for small oscillation around an operating point and can be illustrated in block diagram as shown in fig.3. Then a SMIB system with exciter can be represented in the following state-space form:

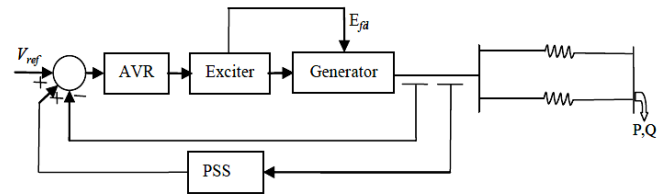


Fig.3: SIMB system with pss

$$\dot{X} = AX + Bu$$

(7)

$$y = CX$$

where

$$A = \begin{bmatrix} -\frac{D}{M} & -\frac{K_1}{M} & -\frac{K_2}{M} & 0 & 0 & 0 \\ \omega_b & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{K_4}{T'_{d0}} & -\frac{1}{T'_{d0}K_3} & \frac{1}{T'_{d0}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{S_E + K_E}{T_E} & \frac{1}{T_E} & 0 \\ 0 & -\frac{K_A K_5}{T_A} & -\frac{K_A K_6}{T_A} & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} \\ 0 & 0 & 0 & -\frac{(S_E + K_E)K_F}{T_E T_F} & \frac{K_F}{T_E T_F} & -\frac{1}{T_F} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{K_A}{T_A} \\ 0 & 0 & 0 \end{bmatrix}$$

$$u = \begin{bmatrix} \Delta T_m \\ \Delta V_{ref} \end{bmatrix} \text{ or } u = \begin{bmatrix} \Delta P_m \\ V_{ref} \end{bmatrix}$$

III. Controllers

Controller is a device fabricated in a chip form, analogue electronics, or computer that supervise and actually alters the working conditions of a considered dynamical system. This paper deals with several types of power system controllers discuss below.

The Automatic Voltage Regulator (AVR) can reduce damping torque, a limitation for generator's stability limitation and power grid. To eliminate the negative effect of AVR, one can guarantee the grid stability using a feedback from the signal of rotor speed deviations and employ it in controlling excitation voltage. This feedback is called PSS which improves the grid stability.

A. CPSS

The power system stabilizer is used to provide sufficient damping to electro-mechanical oscillation in SMIB power systems. The CPSS is used to achieve desired transient behavior and low steady state error. The input to the controllers is speed deviation $\Delta\omega$. The PSS (in fig. 4) has three components. They are: phase compensation block, signal washout block and gain block.

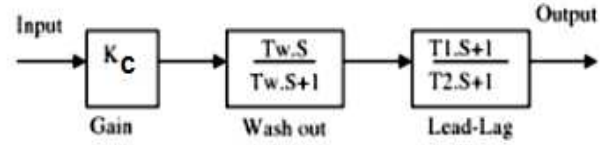


Fig. 4: Structure of Conventional CPSS controller

First, it is necessary to calculate the angle of the phase of the electrical part so that the phase compensator can perform the compensation. This starts with: [reference].

$$G_E(s) = \frac{K_A K_3 (1+sT_F)}{D(s)} \quad (8)$$

where

$$D(s) = (1 + ST_A)(K_E + ST_E)(1 + ST_F)(1 + S\hat{T}_{d0}K_3) + S_E(1 + ST_A)(1 + ST_F)(1 + S\hat{T}_{d0}K_3) + K_F K_A S(1 + S\hat{T}_{d0}K_3) + K_3 K_A K_6(1 + ST_F)$$

For the appropriate values, the angle of the phase compensator is able to perform lead-lag compensation. Thus, the phase compensator transfer function will be:

$$G_C(s) = K_C \left(\frac{1+sT_1}{1+sT_2} \right)^n \quad (9)$$

Using trial-and-error method, the optimal values of k_c can be found. With the addition of PSS three floors, A_c matrix and state vector X will be.

$$\dot{X} = \underbrace{\begin{bmatrix} A & B \\ C & D \end{bmatrix}}_{A_C} X \quad (10)$$

Where

$$X = [\Delta\omega \quad \Delta\delta \quad \Delta e'_q \quad \Delta E_{FD} \quad \Delta x_1 \quad \Delta x_2 \quad \Delta x_3 \quad \Delta x_4 \quad \Delta x_5]$$

With the addition of the new A_c matrix of stabilizer, then we need to check A_c 's eigen-values for computational reasons.

B. LOCPSS

Here, the problem is to design a stabilizer which provides a supplementary stabilizing signal in order to increase the damping torque at low frequency oscillations of the system. Our design is based on the linear quadratic power system stabilizer from the theory of linear optimal control. To formulate the problem of stabilization using linear optimal control theory, a set of state variables must be selected. Then the state equation for the Modified Heffron-Phillip's model is obtained as in [8]. In practice, the load reference point inputs are zero, due to the system's slow and inertial

mechanical nature; however, this does not impact the main results tangibly, thus, we do not consider it as a limitation.

The matrix A and B are computed using (7). Using the eigenvalues of matrix A, the system poles are obtained. Some system poles are very close to the imaginary axis and thus unstable, so frequency of the fashion show that certainly should be a mechanical system. We have designed PSS such that the stabilizer is truly away enough from the imaginary axis with the imaginary part fixed.

Q is the weighting matrix of the state variable deviations and R that of the control effort. Both Q and R, in the most cases, are chosen as diagonal matrices.

$$S = BR^{-1}B^T$$

(11)

Finally, it is necessary to form the matrix M according to the following equation and calculate the eigenvalues accordingly. The Matrix M is that of the states and quasi-states and symmetrical with respect to both the real and imaginary axes.

$$M = \begin{bmatrix} A & -S \\ -Q & -A^T \end{bmatrix} \quad (12)$$

Eigenvalues of matrix M are calculated according to the following:

$$\Lambda = \begin{bmatrix} \Lambda_- & 0 \\ 0 & \Lambda_+ \end{bmatrix} \quad (13)$$

Λ_- is eigenvalues of the matrix A and Λ_+ , eigenvalues symmetric relative to the imaginary axis, obtained from the correlation matrix which is always true. To obtain the modal matrix, we have:

$$MX = X\Lambda \quad (14)$$

Then, the eigenvectors matrix is formed from the matrix as:

$$X = \begin{bmatrix} X_I & X_{III} \\ X_{II} & X_{IV} \end{bmatrix} \quad (15)$$

The values of X_I and X_{II} are imported through MATLAB commands directly to calculate the modal matrix for our scenario. In turn, then, submatrices K and -SK are calculated. Now, the matrix A_C of the related control system can be calculated:

$$K = X_{II}^{-1}X_I^{-1}$$

(16)

$$Bu = -SKx$$

(17)

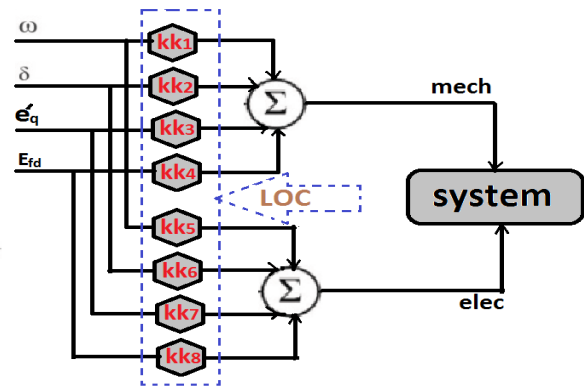
$$\dot{x} = Ax + Bu = \underbrace{(A - SK)}_{A_C}x$$

(18)

Finally eigenvalues of the matrix A_C are needed to be observed for the changes.

The LOC design selects the weighting matrices Q and R such that the performance of the closed loop system satisfies the desired requirements. A method based on modal analysis could be applied, the selected Q is incorporated with the desired eigenvalue locus. By shifting the dominant eigenvalue to the left hand side of s plane in certain damping ratio, variations of Q are handled to guarantee the better control by Riccati matrix equation solution.

The LOC scheme is shown in fig.5. Based on LOC scheme, wawill be used to find KK1, KK2, KK3, and KK4.



Fi.5:LOC base model

IV. Simulation

The dynamic stability of power system subjected to load and voltage disturbances is studied using the MATLAB program and choosing the machine parameters at nominal operating point (see Table.1).

Table.1 System Parameters

Parameter	Value	Remark
M	20.7	Inertia coefficient
D	10	Damping factor
T_A	0.02	AVR and exciter time constant
K_A	324	AVR and exciter gain
F	60	Frequency
Tdo	6.86	Open circuit direct-axis transient time constant
Xd	0.625	d-axis synchronous reactance
X'_d	0.2	Generator synchronous reactance
Xq	0.625	q-axis synchronous reactance

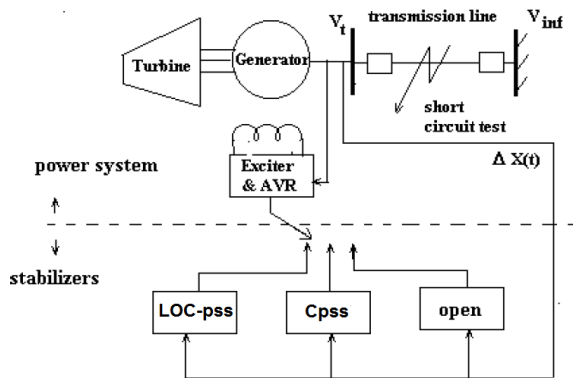


Fig.6: Schematic diagram of the power system model with different power system stabilizers

This section is devoted to the assessment of the proposed method. The power system stabilization using the proposed CPSS is evaluated by comparing the results with LOC method in different loading regimes. To this end, simulations are carried out for several general cases.

Figs7-14 show the rotor speed and angle deviation response due to 0.01 pu load and voltage disturbance with and without controllers.

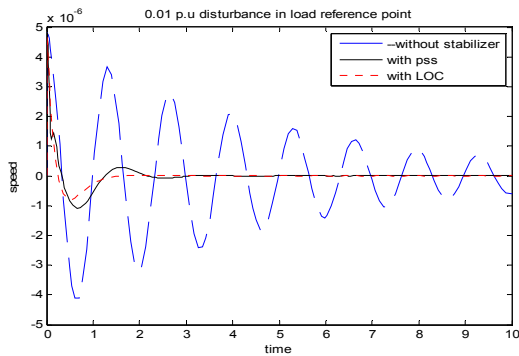


Fig.7: speed deviation responses due to 0.01 p.u load disturbances with and without controllers. At normal

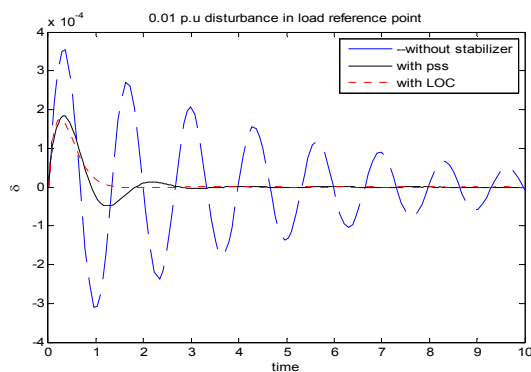


Fig.8: Angle deviation responses due to 0.01 p.u load disturbances with and without controllers. At normal

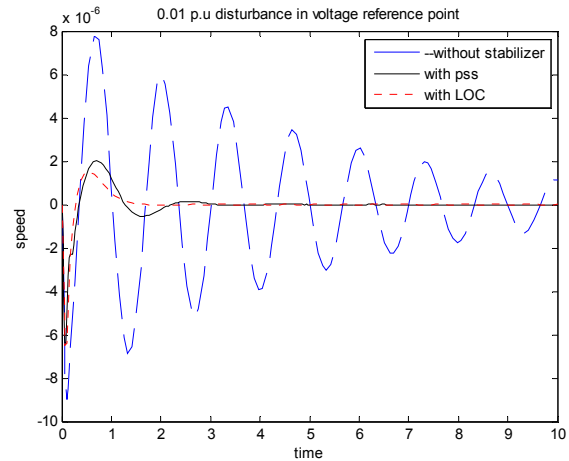


Fig.9: Speed deviation responses due to 0.01 p.u voltage disturbances with and without controllers.

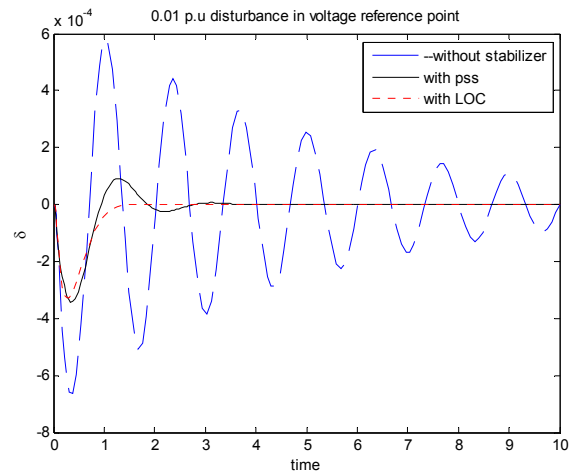


Fig.10: Angle deviation responses due to 0.01 p.u voltage disturbances with and without controllers. At normal($P=1$, $Q=0.25pu.$)

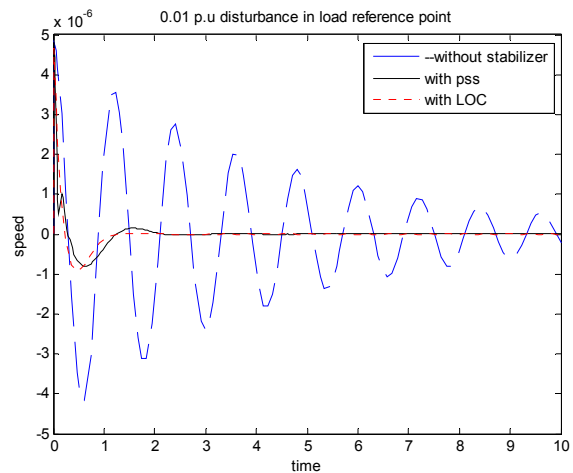


Fig.11: Speed deviation responses due to 0.1 p.u load disturbances with and without controllers. At heavy lead power factor load ($P=1$, $Q= - 0.8 pu.$)

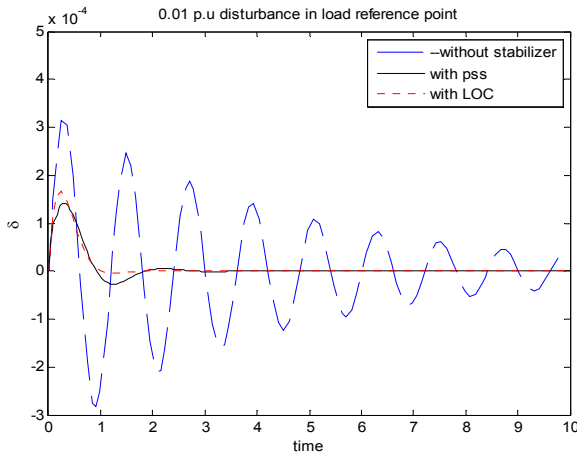


Fig.12: Angle deviation responses due to 0.01 p.u load disturbances with and without controllers. At heavy lead power factor load ($P=1, Q= - 0.8$ pu.)

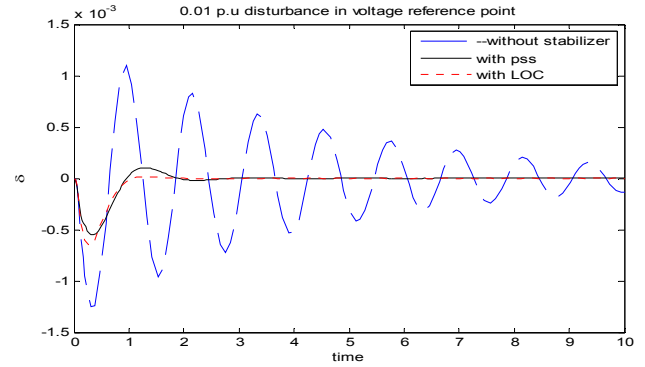


Fig.14: Angle deviation responses due to 0.01 p.u voltage disturbances with and without controllers. At heavy lead power factor load ($P=1, Q= - 0.8$ pu.)

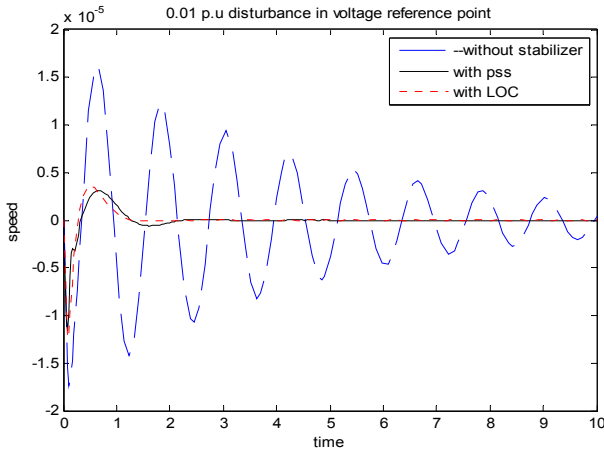


Fig.13: Speed deviation responses due to 0.01 p.u voltage disturbances with and without controllers. At heavy lead power factor load ($P=1, Q= - 0.8$ pu.)

Table.2 : Eigenvalues calculation with and without controllers of single machine power system

Operating Point (P, Q)	Without control	With CPSS control	K_c (CPSS) Optimal	With LOC-PSS control
P=0.5 , Q=0.15pu Light load	-25.3502 +43.3910i	-82.7524+42.2252i	72.3696	-208.4208-211.342i
	-25.3502-43.3910i	-82.7524 -42.2252i		-208.4208+211.342i
	-0.0086 + 4.3698i	-8.0189 +52.7797i		-29.0669 + 0.2900i
	-0.0086 - 4.3698i	-8.0189 -52.7797i		-29.0669 - 0.2900i
	-0.7443 + 1.2067i	-17.4826 + 0.0000i		-4.57814 - 0.0000i
	-0.7443 - 1.2067i	-0.9304 + 4.0298i		-4.90261 + 0.0000i
P=1 , Q=0.25pu Normal Load	-25.3981+43.4197i	-83.1042+42.5203i	42.2727	-205.8553 - 209.2577i
	-25.3981-43.4197i	-83.1042-42.5203i		-205.8553 + 209.2577i
	-0.0276+4.4908i	-7.8438+52.9552i		-30.6178 - 27.3665i
		-7.8438-52.9552i		-30.6178 + 27.3665i
		-17.4114+0.0000i	-4.5706 - 0.0000i	

	-0.0276-4.4908i	-0.9202+4.1278i		-4.9024 + 0.0000i
	-0.7329+1.2303i	-0.9202-4.1278i		
	-0.7329-1.2303i	-0.6507+1.1130i		
		-0.6507-1.1130i		
P=1 , Q=0.8pu Heavy load	-25.3742 +43.4057i	-81.9757 +41.4421i	46.8591	-206.9961 + 210.9110i
	-25.3742 -43.4057i	-81.9757 -41.4421i		-206.9961 - 210.9110i
		-8.7100+52.3036i		-32.4219 + 25.2029i
	-0.0721 + 4.0414i	-8.7100 -52.3036i		-32.4219 - 25.2029i
	-0.0721 - 4.0414i	-17.7710 + 0.0000i		-4.5745 + 0.0000i
		-0.83689 + 3.7872i		-4.9025 - 0.0000i
	-0.8012+ 1.2599i	-0.8368 - 3.7872i		
	-0.8012 - 1.2599i	-0.6954 + 1.1407i		
		-0.6954 - 1.1407i		
P=1 , Q=-0.25pu Lead PF load	-25.4388 +43.4435i	-83.6103 +43.0932i	35.9179	-203.8850 - 206.9767i
	-25.4388 -43.4435i	-83.6103 -43.0932i		-203.8850 + 206.9767i
		-7.2955+53.3065i		-29.4115 - 28.6589i
	-0.0195 + 4.7836i	-7.295 -53.3065i		-29.4115 + 28.6589i
	-0.0195 - 4.7836i	-17.2562 + 0.0000i		-4.5639 + 0.0000i
		-0.9853 + 4.3606i		-4.9023 - 0.0000i
	-0.6449 + 1.1881i	-0.9853 - 4.3606i		
	-0.6449 - 1.1881i	-0.5839 + 1.0681i		
		-0.5839 - 1.0681i		
P=1 , Q=-0.8 Lead PF and heavy load	-25.5315 +43.4983i	-84.2357+43.7337i	29.1093	-199.5962 - 202.6505i
	-25.5315 -43.4983i	-84.2357 -43.7337i		-199.5962 + 202.6505i
		-6.7702 +53.6997i		-29.0238 - 29.0523i
	-0.0693 + 5.1648i	-6.7702 -53.6997i		-29.0238 + 29.0523i
	-0.0693 - 5.1648i	-17.1274 + 0.0000i		-4.5482 + 0.0000i
		-1.0590 + 4.6706i		-4.9022 - 0.0000i
	-0.5025 + 1.0998i	-1.0590 - 4.6706i		
	-0.5025 - 1.0998i	-0.4745 + 0.9795i		
		-0.4745 - 0.9795i		

Table.2 displays the results of digital simulation of eigenvalues calculations for power system at different operation points with and without controllers. From table.2, it is clear that for the system under study, addition of stabilizers model improves stability, especially at normal, heavy and lead power factor load. The eigenvalues' results are confirmed by figures, which express the effect of stabilizers on synchronizing and damping torques, and this effect is apparent due to positive damping torques observed after adding stabilizer.

V. Conclusion

In this paper, first, the effectiveness of power system stabilizer is reviewed. Using modified Heffron Phillip's model, different types of power system stabilizers has been proposed. The proposed method has been simulated on a SMIB energy system conventional controller using complete state space model. The results of simulations in MATLAB/SIMULINK showed that in the presence of small disturbances in the system LOC-PSS is more effective as compared to the CPSS conventional controller. The LOC-PSS gives zero steady state error, smaller overshoot and

settling time as compared to CPSS. Furthermore, the simulation confirmed that the LOC-PSS can provide better performance for different types of load as compared to the CPSS. It also improves eigenvalues of the system. The synchronizing and damping torque coefficients are improved with LOC-PSS control in comparison with the system without controller.

List of symbols

T_m : Mechanical torque

T_e : Electrical torque

V_t : Terminal voltage

E_q : Inducted emf proportional to field current

E_{fd} : Generator field voltage

V_{ref} : Reference value of generator field voltage

x_e : Line reactance

V : Infinite busbar voltage

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