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Enhancement of Power System Dynamic Stability by Designing a New Model of the Power System

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Abstract – Low frequency oscillations (LFOs) are load angle oscillations that have a frequency between 0.1-2.0 Hz. Power system stabilizers (PSSs) are very effective controllers in improvement of the damping of LFOs. PSSs are designed by linearized models of the power system. This paper presents a new model of the power system that has the advantages of the Single Machine Infinite Bus (SMIB) system and the multi machine power system. This model is named a single machine normal-bus (SMNB). The equations that describe the proposed model have been linearized and a lead PSS has been designed. Then, particle swarm optimization technique (PSO) is employed to search for optimum PSS parameters. To analysis performance of PSS that has been designed based on the proposed model, a few tests have been implemented. The results show that designed PSS has an excellent capability in enhancing extremely the dynamic stability of power systems and also maintain coordination between PSSs.

Keywords: Low frequency oscillation, Particle swarm optimization, Single machine normal bus, Power system stabilizer.

1. Introduction

Since 1960, low frequency oscillations have been observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1].

Two types of oscillation phenomena can occur on the present power system. One is where the oscillation of one generator at a specific power plant has an influence on the system. This type of oscillation is called local-mode oscillation and its behavior is mainly limited to the local area in the vicinity of the power plant. It has been known that the local oscillation is likely to occur when power is transmitted over long-distance transmission lines from a power plant at a remote location. This type of system can be accurately modeled using the SMIB system model [2].

The other case has been known as inter-area mode oscillation. This is the case where the low-frequency oscillation is maintained between sets of generators in an interconnected power system. The simplest type of low-frequency oscillation in the inter-area mode is between two interconnected areas. The inter-area mode oscillation has a long history. It has been observed in the tie-line connecting the large Pacific Southwest and the Pacific Northwest in the United States. It has also been observed on the tie-line connecting the northern Midwest and Canada [3, 4].

In order to avoid LFO, supplementary stabilizing signal have been proposed in the excitation systems through lead/lag power system stabilizers [5] or PI – PID PSSs [6]. The calculation of the parameters of these PSSs is based on the linearized model of the power system around a nominal operating point. PSSs are the most effective devices used to damp LFOs. For many years, conventional PSS (CPSS) have been widely used in the industry because of their simplicity [7].

Modern control theory has been applied to the PSS design in recent years. These include optimal control, adaptive control; variable structure control and H_∞ control [8].

There have been proposed two power system linear models, which are the SMIB system and the multi machine power system. These models are used for designing PSSs. The SMIB system comprises a generator, a transmission line and an infinite-bus which has been substituted instead of the rest of the power system and multi machine comprises all machines in the power system. The SMIB system is a simple model but in this model, inter-area mode oscillations are not considered. Therefore, the designed PSS (especially CPSS) according to this model lead to interfere among PSSs, because the effects of the rest of the power system have been ignored. In practice, there are different kinds of power plants connected to the power system. Hence, LFOs have different frequency. For this reason, while PSSs is being designed, it is obligatory to consider the influences of the rest of the power system. Another model of the power system (the multi machine power system) comprises all machines that deigning PSS based on it is very precise and complete. Although this model is very complex. As a result, it is essential to have a model as simple as the SMIB system and as precise as the

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multi machine power system. For reaching this purpose, this paper proposed a new model of the power system that has mentioned characteristics. According to this model, a lead PSS has been designed where its parameters have been optimized by PSO algorithm. The parameters have been optimized for nominal load when the input power of a generator has been changed suddenly and the effects of the rest of the power system that have not been modeled by a SMIB system have been applied by two inputs. The results show that designed PSS has an excellent capability in improving extremely the dynamic stability of power systems and also maintain coordination between PSSs.

2. Power System Models for Studying Low Frequency Oscillations

This section presents a brief review of the different kinds of the power system models that has been recommended for studying low frequency oscillations.

2.1 The single machine infinite bus system

Fig. 1 shows a power system that shows the SMIB system. The infinite bus depicts the thevenin equivalent of a large interconnected power system. The nonlinear equations that describe the generator and excitation system have been represented in following equations:

$$\dot{\delta} = \omega_0 \omega \tag{1}$$

$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D_m \omega) \tag{2}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}\left(E_{FD} - \frac{x_d + x_e}{x'_d + x_e}E'_q + \frac{x_d + x'_d}{x'_d + x_e}V_b \cos(\delta)\right) \tag{3}$$

$$\dot{E}_{FD} = \frac{1}{T_E}(K_E E_{ref} - K_E V_t - E_{FD}) \tag{4}$$

The above equations can be linearized for small oscillation around an operating condition [9-11] and be cast in the block diagram shown in Fig. 2. The linearized model of the power system as shown in Fig. 1 is given as follows:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{5}$$

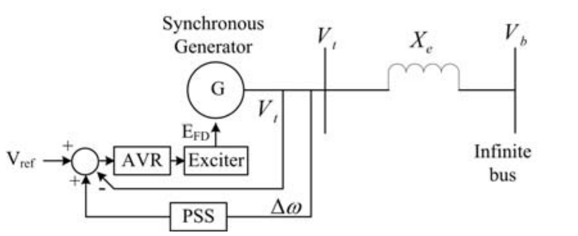

Fig. 1. The Single machine infinite bus model (SMIB)

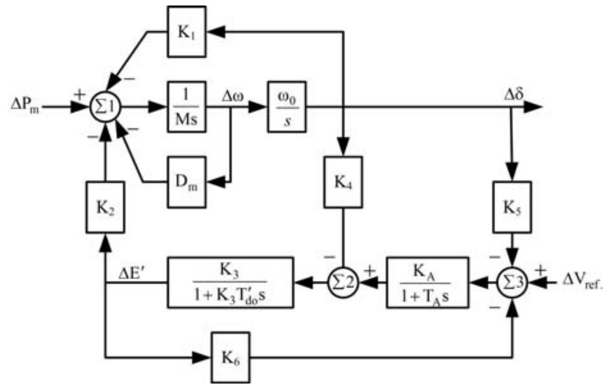

Fig. 2. Block diagram of linearized model of the Single machine infinite bus model

$$\Delta\dot{\omega} = -\frac{1}{M}(K_1\Delta\delta + K_2\Delta E'_q + D_m\Delta\omega - \Delta P_m) \tag{6}$$

$$\Delta\dot{E}'_q = -\frac{1}{T'_{do}}\left(K_4\Delta\delta + \frac{1}{K_3}\Delta E'_q - \Delta E_{FD}\right) \tag{7}$$

$$\Delta\dot{E}_{FD} = -\frac{K_A}{T_A}\left(K_5\Delta\delta + K_6\Delta E'_q + \frac{1}{K_E}\Delta E_{FD} - \Delta E_{ref}\right) \tag{8}$$

2.2 The Multi-machine power system

Reference [11] used linearized model of the SMIB for every machine in the power system and has been proposed a new model that is called the multi-machine power system. Block diagram of this model is shown in Fig. 3.

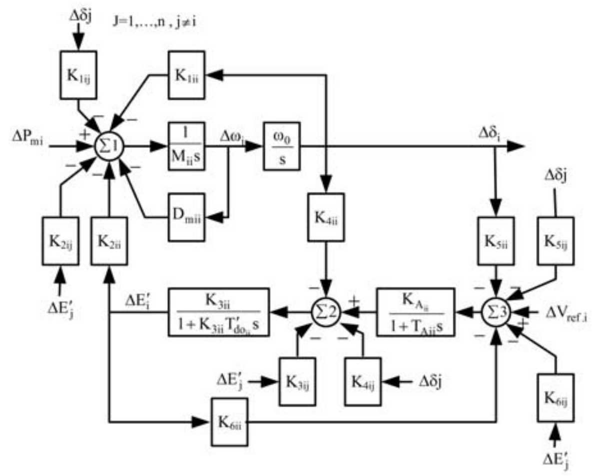

Fig. 3 Block diagram of linearized model of the multi-machine power model

3. Power System Stabilizers and Reasons for Loss of Their Coordination

Low frequency oscillations are one of the undesirable phenomena in the power systems. This phenomenon occurs when an electromechanical mode of generators is excited. In the power systems, switching, inserting loads and so on lead to excite this mode. Practically, prevention of an electromechanical mode of generators is impossible, but there is only one way to deal with it, which is increasing the low frequency oscillations damping. For achieving to this aim, It is sufficient to add D_e ($D_e > 0$) in parallel with D_m (Fig. 4). From a practical point of view, added this block means supplying a torque opposite direction of angular velocity variation that this act is done by PSSs. The basic function of PSS is added to damp the generator rotor oscillations by controlling its excitation by using auxiliary stabilizing signal(s).

Based on the Automatic Voltage Regulator (AVR) and using speed deviation, power deviation or frequency deviation as additional control signals, PSS is designed to introduce an additional torque coaxial with rotational speed deviation, so that it can be increased low-frequency oscillation damping and enhance the dynamic stability of the power system [12]. Fig. 5 shows the block diagram of the SMIB system along with classic PSS (CPSS). CPSS makes phase lead for counteracting phase lag of the electrical loop. This means that CPSS is designed so that in frequency of the electromechanical mode of the generator, its phase lead would be corresponded with the phase lag of the electrical loop. According to this design, Band width of CPSS is very narrow and only in frequency of the electromechanical mode of the generator, its phase lead be corresponded with the phase lag of the electrical loop. On the other hand, additional torque that supplying for more damping, only in that frequency would be the opposite direction of angular velocity variation. In addition, there are different kinds of power plants connected to the power system, such as fossil fuel, hydro and nuclear power plants and generators that have different characteristics. Therefore, generators have different electromechanical frequency mode relative to each other. If electromechanical mode of a generator (such as generator B- Fig. 6) in the power system is excited, it will lead to produce oscillations that transmit to other generators (such the i^{th} generator- Fig. 6) by transmission lines, but in this case produced phase lead of CPSS of the i^{th} generator is not corresponded with the phase lag of its electrical loop. Consequently, supplied torque for the increase damping will not be the opposite direction of angular velocity variation. Moreover if the frequency difference between the electromechanical mode of the i^{th} generator and oscillations that produced by generator B become too much, supplied torque will have the same direction with angular velocity variation. In this situation, CPSS lead to oscillation resonance. This condition is called interfering between PSSs. Hence, when PSSs are designed using of the SMIB system, we must expect this phenomenon. Because the SMIB model includes only a generator and other power systems are modeled with an infinite bus. Below are a few disadvantages and advantages of using the SMIB system in designing of PSSs:

- If Power system be too small, an infinite bus cannot be substituted instead of the rest of the power system. Also for modeling the infinite bus instead of the rest of the power system (if be small) needs to have much time and many calculations.
- In this model, an inter-area mode oscillation that is between two interconnected areas is not considered.
- In this model, designer can see only one electro-mechanical mode and try to damp the oscillations that are produced by this mode. For this reason, in designing

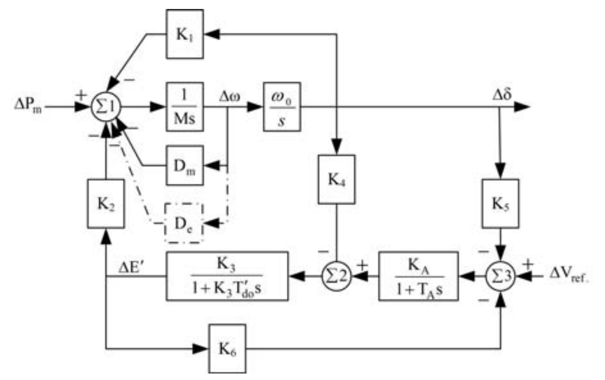

Fig. 4. Block diagram of linearized model of the SMIB system along with ideal PSS.

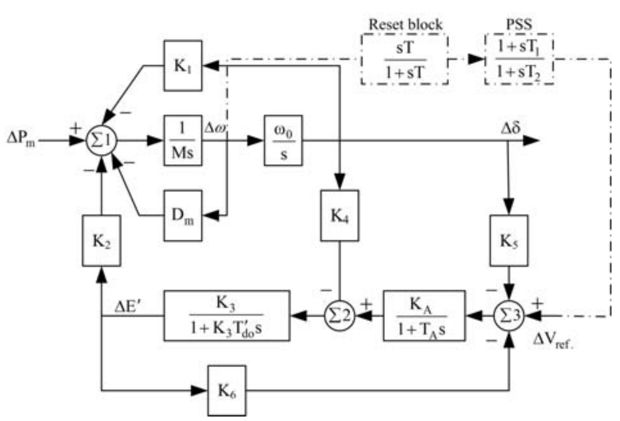

Fig. 5. Block diagram of linearized model of the SMIB bus along with CPSS.

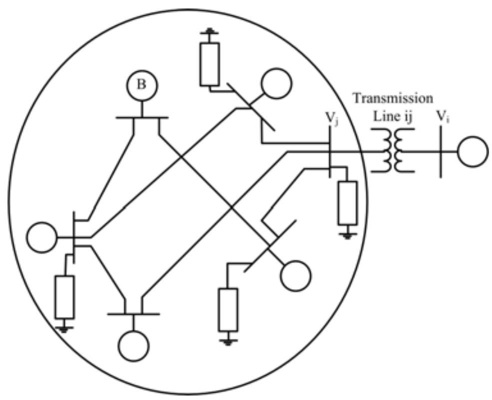

Fig. 6 Single line diagram of the multi machine power grid.

of CPSS, our attention is only to damp one frequency. But,

- This model is simple and several dynamic phenomena can be seen by it.
- This model brings good ideas in mind for designing PSSs. However, for the sake of disadvantages that mentioned earlier designing PSS based on this model lead to lack of coordination between PSSs.

As we know, there are different frequency modes in the power system. If any of these is excited, it will produce low frequency oscillations. Hence, when PSSs are designed, it is essential to be considered all the frequency modes. Accordingly, the SMIB system is not a good model for designing PSSs. However, in the multi machine power system, the power system is modeled completely and has not disadvantages of infinite bus. Although using of this model is very complex and is not recommended. As mentioned above, two models that have been described are unsuitable models for designing of PSSs. Therefore, we need a new model for this work. So, a new model which has not disadvantages of the SMIB system and the multi machine power system has been proposed and simulated. This model is a single machine normal bus (SMNB) system.

4. The Single Machine Normal Bus System

To have a precise and complete model of the power system, it is essential that all the power systems are modeled (such as the multi machine power system) or the effects of the rest of the power systems that in the SMIB system are not modeled, via one or several inputs are modeled. Consider the multi machines power system, as shown in Fig. 3, the effects of different generators on the i[th] generator are applied via K_{1ij} *to* $K_{6ij} (i \neq j)$, but as shown in Fig. 6 all influences and counteractions transmit to the i[th] generator via transmission line ij that has been attached to the power grid. It means that these effects can be considered with adding them to the bus j which is the front of the i[th] generator. Therefore, the effects of the rest of the power system can be modeled by measuring variables of the transmission ij line such as active currents and reactive currents or active powers and reactive powers or magnitude and angle (θ_j) of voltage (V_j) of the bus j. In the SMIB system, the magnitude and the angle of the infinite bus voltage is assumed constant. But from a practical point of view, the magnitude and the angle of the bus voltage which has been connected to the i[th] generator by transmission lines is oscillating for the impacts of power system oscillations. Thus, if in the SMIB system changes of these two variables are considered yields the SMNB system so that any effects of generators are not neglected. Consider the i[th] generator that shown in Fig. 6. Axis d of this model is 90 degree lag from its q axis. Relation between fi and its components in q and d axes are as following:

$$f_i = (f_{qi} - jf_{di})e^{j\delta_i} \tag{9}$$

As drawn in Fig. 7, f_i is the indicator of the voltage, the current and the flow of the i[th] generator. The power and the inductive voltage of the i[th] generator and the voltage of the i[th] bus are defined as follows:

$$P_{gi} = (\frac{V_j E'_{qi}}{x'_{di}})\sin\left(\delta_i - \theta_j\right) + \left(\frac{1}{x_{qi}} - \frac{1}{x'_{di}}\right)(\frac{V_j^2}{2})\sin 2\left(\delta_i - \theta_j\right) \tag{10}$$

$$E_{qi} = \left(\frac{x_{di}}{x'_{di}}\right)\left[E'_{qi} - V_j \cos\left(\delta_i - \theta_j\right)\right] + V_j \cos\left(\delta_i - \theta_i\right) \tag{11}$$

$$\bar{V}_i = \bar{V}_j + jx_e\left(I_{qi} - jI_{di}\right)e^{j\delta_i} \tag{12}$$

Where

$$I_{di} = \left(E'_{qi} - V_j \cos\left(\delta_i - \theta_j\right)\right) / x'_{di} \tag{13}$$

$$I_{qi} = V_j Sin\left(\delta_i - \theta_j\right) / x_{qi} \tag{14}$$

Also if Eqs. (10-12) are linearized around a certain operating point result:

$$\Delta P_{gi} = K_1\Delta\delta_i + K_2\Delta E'_{qi} + K'_1\Delta\theta_j + K'_2\Delta V_j \tag{15}$$

$$\Delta E_{qi} = K_4\Delta\delta_i + \left(1/K_3\right)\Delta E'_{qi} + K'_4\Delta\theta_j + K'_3\Delta V_j \tag{16}$$

$$\Delta V_i = K_5\Delta\delta_i + K_6\Delta E'_{qi} + K'_5\Delta\theta_j + K'_6\Delta V_j \tag{17}$$

Therefore, if Eqs. (10-12) are entered into Eqs. (1-4) and then obtained equations are linearized, block diagram of the SMNB is acquired (Fig. 8). Comparison between Figs. 2 and 9 approve that ΔV_j and $\Delta\theta_j$ are substituted instead of the rest of the power system which is not modeled in the SMIB system. It means that any kinds of oscillations with different frequencies can be applied with these inputs and then PSSs can be designed with considering the rest of the power system.

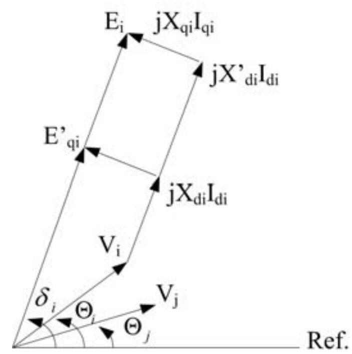

Fig. 7 Phase diagram of the i[th] generator

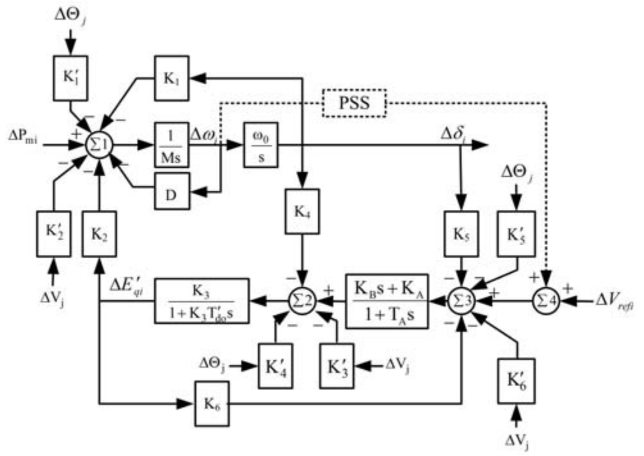

Fig. 8 Block diagram of the SMNB system.

- The advantages of this model are:
- This model is as simple as the SMIB system.
- The effects of other generators have been considered on the ith generator and has not been neglected any parts of the power system.
- In this model, the calculation of the constants such as K_1 *to* K_6 and K_1' *to* K_6' are very easy and can be calculated simultaneously without any estimations.
- Finally in this model, there is not the first disadvantage of the SMIB system.

5. The Calculation of the Constants of the SMNB System

In order to obtain the constants of the SMNB system Eqs. (10-12) should be interred in Eqs. (1-4) and then are linearized around a certain operating point. Hence, linearization of these equations around a certain operating point results in constants $K_1, K_1', K_2, K_2', K_3, K_3', K_4$ and K'_4 as follows:

$$K_1 = ((V_j^\circ E_{qi}'^\circ)/x_{di}')\cos\left(\delta_i^\circ - \theta_j^\circ\right) + \left(1/x_{qi} - 1/x_{di}'\right)V_j^{\circ 2}\cos 2\left(\delta_i^\circ - \theta_j^\circ\right) \quad (18)$$

$$K_1' = -K_1 \quad (19)$$

$$K_2 = (V_j^\circ / x_{di}')\sin\left(\delta_i^\circ - \theta_j^\circ\right) \quad (20)$$

$$K_2' = (E_{qi}'^\circ / x_{di}')\sin\left(\delta_i^\circ - \theta_j^\circ\right) + \left(1/x_{qi} - 1/x_{di}'\right)V_j^\circ \sin 2\left(\delta_i^\circ - \theta_j^\circ\right) \quad (21)$$

$$K_3 = x_{di}' / x_{di} \quad (22)$$

$$K_3' = -\left((x_{di} - x_{di}')/x_{di}'\right)\cos\left(\delta_i^\circ - \theta_j^\circ\right) \quad (23)$$

$$K_4 = \left((x_{di} - x_{di}')/x_{di}'\right)V_j^\circ \sin\left(\delta_i^\circ - \theta_j^\circ\right) \quad (24)$$

$$K_4' = -K_4 \quad (25)$$

To separate the real and the image parts of Eq. (12) for Vi yields:

$$V_{qi} = V_j \cos\left(\delta_i - \theta_j\right) + x_e I_{di} \quad (26)$$

$$V_{di} = V_j \sin\left(\delta_i - \theta_j\right) + x_e I_{qi} \quad (27)$$

If Eq. (13) and Eq. (14) are substituted into Eq. (26) and Eq. (27), yields:

$$V_{qi} = \left(\frac{\overline{x}_{di}'}{x_{di}'}\right)V_j \cos\left(\delta_i - \theta_j\right) + \left(\frac{x_e}{\overline{x}_{di}'}\right)E_i' \quad (28)$$

$$V_{di} = \left(\frac{\overline{x}_{qi}}{x_{qi}}\right)V_j \sin\left(\delta_i - \theta_j\right) \quad (29)$$

where $\overline{x}_{di}' = x_{di}' - x_e$ and $\overline{x}_{qi} = x_{qi} - x_e$.

Relation between V_i with V_{qi} and V_{di} and also ΔV_i with ΔV_{qi} and ΔV_{di} is as below:

$$V_i^2 = V_{qi}^2 + V_{di}^2 \quad (30)$$

$$\Delta V_i = \left(\frac{V_{qi}^\circ}{V_i^\circ}\right)\Delta V_{qi} + \left(\frac{V_{di}^\circ}{V_i^\circ}\right)\Delta V_{di} \quad (31)$$

To linearize Eq. (28) and Eq. (29) around a certain operating point and are substituted into Eq. (31) constants K_5, K_5', K_6 and K_6' are defined as follows:

$$K_5 = \left(\frac{V_{qi}^\circ}{V_i^\circ}\right)\left(-\frac{\overline{x}_{di}'}{x_{di}'}V_j^\circ \sin\left(\delta_i^\circ - \theta_j^\circ\right)\right) + \left(\frac{V_{di}^\circ}{V_i^\circ}\right)\left(\frac{\overline{x}_{qi}}{x_{qi}}V_j^\circ \cos\left(\delta_i^\circ - \theta_j^\circ\right)\right) \quad (32)$$

$$K_6 = \left(\frac{V_{qi}^\circ}{V_i^\circ}\left(\frac{x_e}{x_{di}'}\right)\right) \quad (33)$$

$$K_5' = -K_5 \quad (34)$$

$$K_6' = \left(\frac{V_{qi}^\circ}{V_i^\circ}\right)\left(-\frac{\overline{x}_{di}'}{x_{di}'}\cos\left(\delta_i^\circ - \theta_j^\circ\right)\right) + \left(\frac{V_{di}^\circ}{V_i^\circ}\right)\left(\frac{\overline{x}_{qi}}{x_{qi}}\sin\left(\delta_i^\circ - \theta_j^\circ\right)\right) \quad (35)$$

6. Problem Formulation

After proposing a new model of the power system for

Table 1. The parameters of the IEEE type 2 static AVR system (ST2) (Fig. 9)

Parameter	Value	Parameter	Value
T_R	0	S_{EMAX}	2.67
K_A	400	A_{EX}	0.023
T_A or T_{A1}	0.02	B_{EX}	0.9475
T_{A2}	0	E_{FDMAX}	5.020
V_{RMAX}	18.3	E_{FDMIN}	0
V_{RMIN}	-18.3	K_F	0.03
K_E	1	T_F	1
T_E	0.942	T_{F2}	0

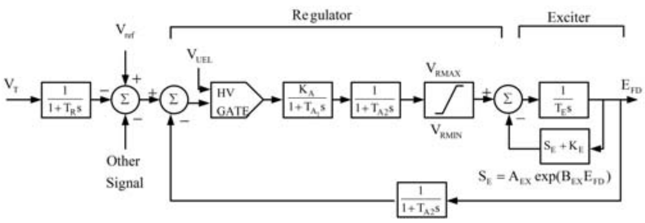

Fig. 9. The IEEE Type 2 static AVR-ompound-source rectifier exciter [14]

studying low frequency oscillations, it is time that a PSS is designed. Thus a synchronous machine with an IEEE type 2 static AVR system (AVR-ST2) (Fig. 9 and Table 1) connected to a normal bus through a transmission line has been selected to illustrate the deviation of simplified linear models of the power system for dynamic stability analysis. The excitation system that is used for designing of PSS in linearized model of power system (SMNB), a second separated mode IEEE type 2 static (ST2) excitation system [13, 14] (Table 2 and Fig. 8) is used. As shown in Fig. 10, the model consists of a generator supplying bulk power to a normal bus through a transmission line, with a PSS. The linearized model of the SMNB system that has been linearized around the certain operating point is given as follows:

$$\Delta\dot{\delta}_i = \omega_0 \Delta\omega_i \tag{36}$$

$$\Delta\dot{\omega}_i = -\frac{1}{M}\begin{pmatrix} K_1\Delta\delta_i + K_1'\Delta\theta_j + K_2\Delta E_{qi}' \\ +K_2'\Delta V_j - \Delta P_{mi} + D_{mi}\Delta\omega_i \end{pmatrix} \tag{37}$$

$$\Delta\dot{E}_{qi}' = -\frac{1}{T_{doi}'}\begin{pmatrix} K_4\Delta\delta_i + K_4'\Delta\theta_j + \frac{1}{K_3}\Delta E_{qi}' \\ +K_3'\Delta V_j - \Delta E_{FDi} \end{pmatrix} \tag{38}$$

$$\Delta\dot{E}_{FDi} = -\frac{1}{T_A}\Delta E_{FDi} - \frac{K_B s + K_A}{T_A}\begin{pmatrix} K_5\Delta\delta_i + K_5'\Delta\theta_j + K_6\Delta E_{qi}' \\ +K_6'\Delta V_j - \Delta E_{refi} + U_{PSS} \end{pmatrix} \tag{39}$$

The constants K1 to K6 and K_1' to K_6' represent the system parameters at a certain operating condition.

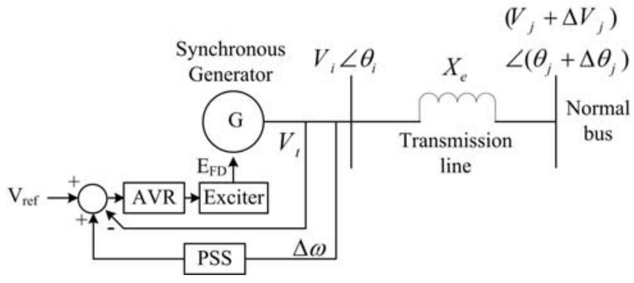

Fig. 10. The Single machine normal-bus system

Table 2. System parameters

Synchronous generator & transmission line [p. u]		Excitation system [p. u]
$X_d = 1.82$	H=5.65	$T_A = 0.030$
$X_q = 1.82$	$T_{do}' = 5$	$K_A = 60.6269$
$X_e = 0.1621$	$X'_d = 0.321$	$K_B = 0.4234$

Table 3. Various operating points

Operating point (Load)	OP1 (Heavy)	OP2 (Nominal)	OP3 (Light)
P_{gi} (pu)	1.45	0.9	0.62
Q_{gi} (pu)	0.62	0.256	0.11
V_i (pu)	1.060	1.053	1.013
θ_i (deg)	13.2	7.82	5.3
V_j (pu)	1	1.023	1
θ_j (deg)	0.00	0.00	0.00

Analytical expressions for K1 to K6 as a function of loading (P, Q) are derived in [15, 16]. Typical data for such a system are as Table 2. According to Eqs. (36-39), nominal operating point (Tables 3 and 4), 100% changes of input power for 18 cycles, $\Delta Vj = 0.05\sin(20t)$ and $\Delta\theta j = 0.02\sin(20t)$ a lead PSS as the following form is designed, which stabilizes the system while minimizing Eq. (41).

$$U = G_c(s)\Delta\omega, \qquad G_c(s) = K\frac{s+Z}{s+P} \tag{40}$$

$$fitness = \int_0^{\gamma} \gamma * (\alpha J_1 + \beta J_2)dt \tag{41}$$

The objective function that has been used in this paper is demonstrated in Eq. (41). This robust controller can be obtained by solving Eq. (41). Where $J_1 = d\omega$, $J_2 = dvi$ and $\gamma = t_{sim}$ which t_{sim} is simulation time, $d\omega$ is the angular velocity deviation, α and β are weighting parameters that in this case α is 10 and β is 1 and dvi is the terminal voltage deviation of the i^{th} generator.

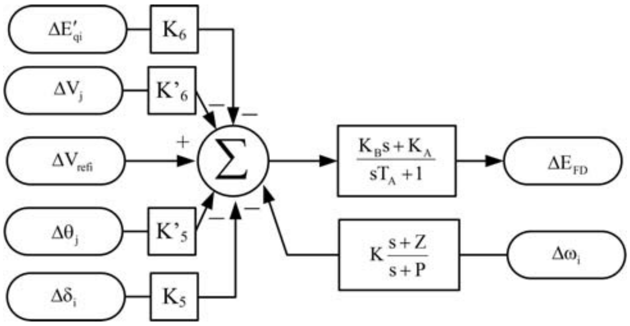

Fig. 11. PSS controller

Therefore, the design problem can be formulated as the following optimization problem (Fig. 11):

Minimize fitness subject to

$$K^{\min} < K < K^{\max}$$
$$P^{\min} < P < P^{\max}$$
$$Z^{\min} < Z < Z^{\max}$$

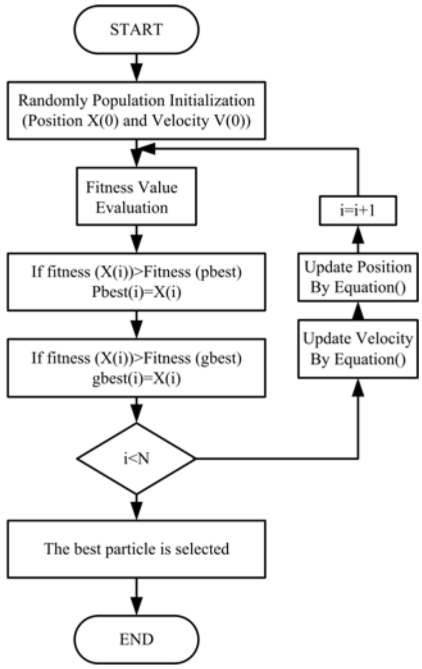

Fig. 12. Flowchart of the PSO algorithm [17]

7. PSO Algorithm

The particle swarm optimization (PSO) algorithm was first proposed by Kennedy and Eberhart [17]. Where is a novel evolutionary algorithm paradigm which imitates the movement of birds flocking or fish schooling looking for food. Each particle has a position and a velocity, representing the solution to the optimization problem and the search direction in the search space. The particle adjusts the velocity and position according to the best experiences which are called the pbest found by itself and gbest found by all its neighbors. In PSO algorithms each particle moves with an adaptable velocity within the regions of decision space and retains a memory of the best position it ever encountered. The best position ever attained by each particle of the swarm is communicated to all other particles. The updating equations of the velocity and position are given as follows [17].

$$v_i(k+1) = wv_i(k) + r_1c_1[p_i - x_i(k)] + r_2c_2[p_{gi} - x_i(k)] \quad (42)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (43)$$

Where v is the velocity and x is the position of each particle. c_1 and c_2 are positive constants referred to as acceleration constants and must be $c_1 + c_2 \le 4$, usually $c_1 = c_2 = 2$. r_1 and r_2 are random numbers between 0 and 1, w is the inertia weight, p refers to the best position found by the particle and pg refers to the best position found by its neighbors. The flowchart of PSO algorithm is shown in Fig. 12.

8. Simulation Results

Typical range of the optimized parameters is [0-500] for K, Z and P. The convergence of PSO algorithm is in Fig. 13. The optimized parameters are found via PSO algorithm are $K = 500$, $Z = 2.3302$ and $P = 81.7212$. Optimized parameters have been obtained when the input power of the ith generator and the magnitude and angle of the normal bus has been changed 100% for 18 cycles (one cycle in frequency of twenty) instantaneously, $\Delta Vj = 0.04\sin(20t)$ and $\Delta\theta j = 0.015\sin(20t)$ respectively and the normal operating point are $Pe = 0.9\ (pu)$ and $Qe = 0.256\ (pu)$ (Table 3 and 4) (the inputs (ΔVj and $\Delta\theta j$) for all tests have been applied for one cycle in their frequency). The dynamic response of the rotor angle deviation, angular velocity deviation and terminal voltage deviation are shown in Fig. 14. It is clearly seen that with inclusion of PSS, electromechanical damping characteristics of the system is improved. The parameters of PSS have been obtained using PSO based on the SMNB system. It means that this PSS must have coordination with other PSSs. On the other hand, if any low frequency oscillations reach to the i^{th} generator, PSS have to can damp them. So, it is necessary for carrying out some tests on the system to assure that designed PSS has good performance. Hence, three different kinds of tests have been implemented. First test is robustness of designed PSS opposite low frequency oscillations with different frequency. Therefore, different sine oscillations have been applied by ΔVj and $\Delta\theta j$ in second operating point (Table 4- tests 1-2 and 1-3). The dynamic responses (the rotor angle deviation, angular velocity deviation and

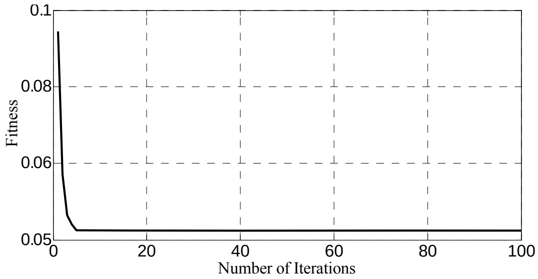

Fig. 13. Convergence of PSO algorithm

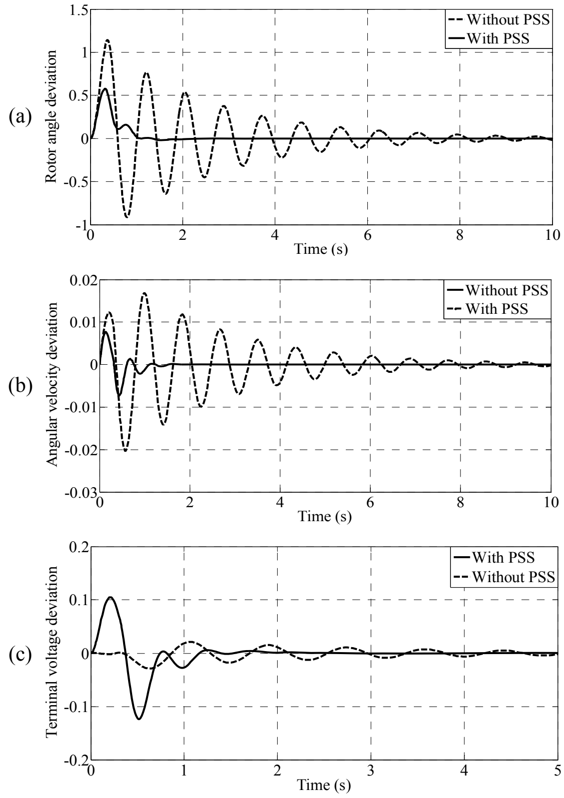

Fig. 14. System dynamic response for test 1-1. (a) rotor angle deviation (pu), (b) angular velocity deviation (pu), (c) terminal voltage deviation (pu).

terminal voltage deviation) according to these inputs are shown in Figs. 15 and 16. As shown these figures, the designed PSS gives very good damping over a range of frequencies. This means that PSS can damp any kinds of low frequency oscillations with different frequencies.

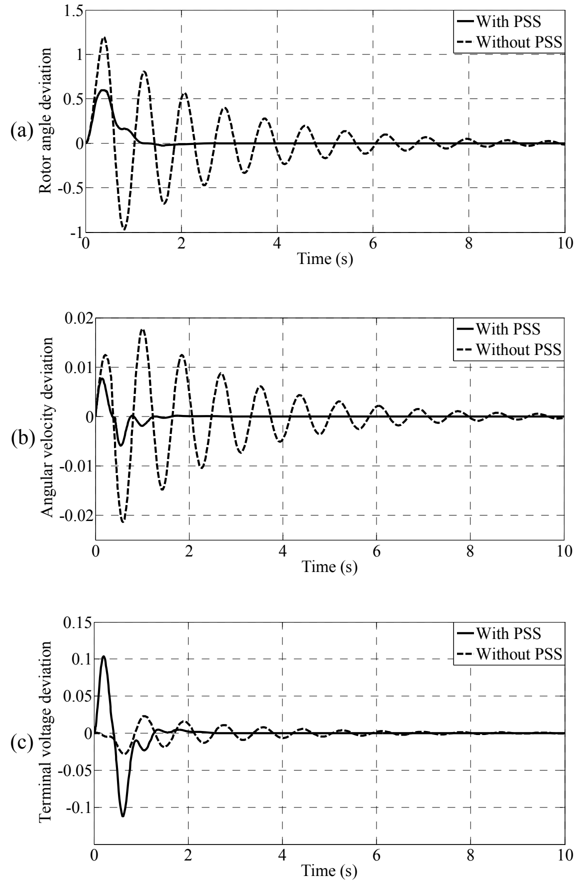

Fig. 15. System dynamic response for test 1-2. (a) rotor angle deviation (pu), (b) angular velocity deviation (pu), (c) terminal voltage deviation (pu).

Second test is robustness of designed PSS opposite disturbances and harmonics. Thus an input comprises several harmonics with different magnitudes and frequencies have been applied by ΔVj and $\Delta\theta j$ (Table 4- test 2). The dynamic responses according to this input are shown in Fig. 17. This figure shows that designed PSS has robustness opposite harmonics for damping low frequency oscillations. At last, third test is robustness of designed PSS opposite operating point changes. For this reason, two operating points (Heavy and light) have been used (Table 4- test 3). The dynamic responses according to these operating points are shown in Figs. 18 and 19. These figures show that designed PSS has good performance

Table 4. The values of Constants K_1 to K_6 and K_1' to K_6' according to operating points

Constants	OP1.Heavy	OP2.Nominal	OP3.Light	Constants	OP1.Heavy	OP2.Nominal	OP3.Light
K_1	1.8993	1.7300	1.4107	K_1'	-1.9893	-1.7210	-1.400
K_2	1.8710	1.7173	1.5278	K_2'	0.8819	0.1228	-0.1786
K_3	0.2557	0.2557	0.2467	K_3'	-1.3457	-1.8134	-2.0791
K_4	2.7553	2.4269	2.2597	K_4'	-2.7533	-2.5279	-2.2497
K_5	-0.0749	0.01773	0.0518	K_5'	0.0639	-0.0187	-0.0518
K_6	0.2145	0.2347	0.2513	K_6'	0.8220	0.8057	0.7863

Table 5. Applied tests

No. of tests	Operating points	ΔP_m and period	ΔV_j	$\Delta \theta_j$
1-1		100% , 18 cycle	0.04sin(20t)	0.015sin(20t)
1-2	2 (Nominal)	100% , 25 cycle	0.04sin(15t)	0.015sin(15t)
1-3		100%, 37 cycle	0.04sin(10t)	0.015sin(10t)
2	2 (Nominal)	100%, 37 cycle	0.015sin(5t)-0.01sin(10t)-0.01sin(2.5t)	0.015sin(5t)
		100%, 18 cycle	0.04sin(20t)	0.015sin(20t)
3	1 (Heavy), 3 (Light)	100%, 25 cycle	0.04sin(15t)	0.015sin(15t)
		100%, 37 cycle	0.04sin(10t)	0.015sin(10t)
		100%, 37 cycle	0.015sin(5t)-0.01sin(10t)-0.01sin(2.5t)	0.015sin(5t)

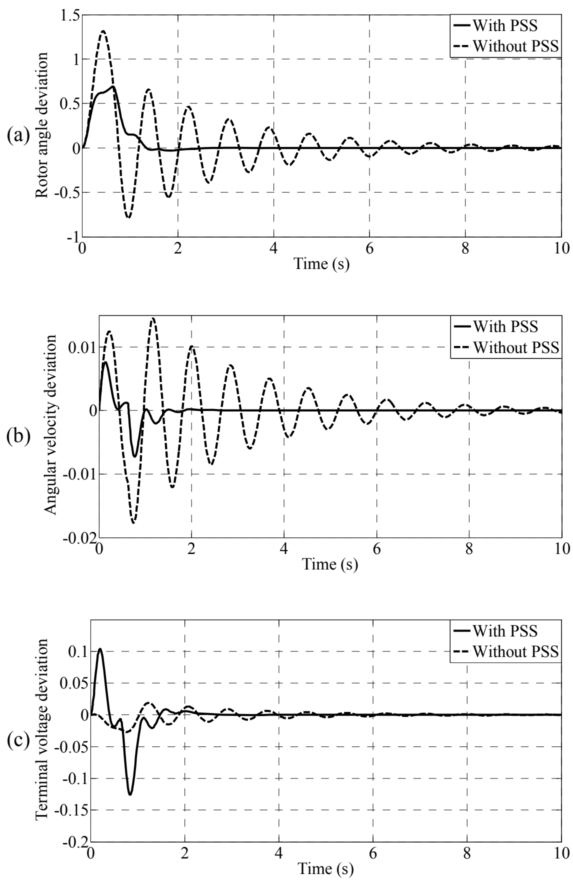

Fig. 16. System dynamic response for test 1-3. (a) rotor angle deviation (pu), (b) angular velocity deviation (pu), (c) terminal voltage deviation (pu).

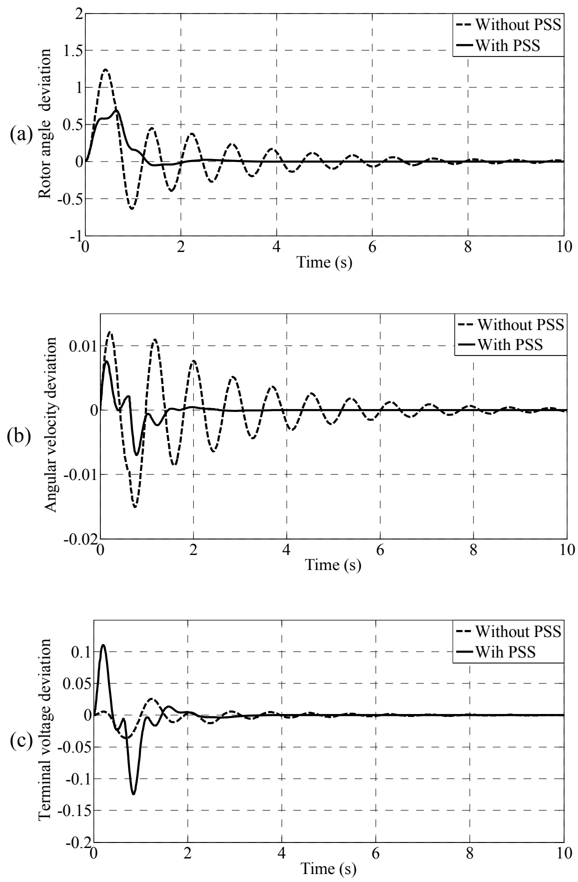

Fig. 17. System dynamic response for test 2. (a) rotor angle deviation (pu), (b) angular velocity deviation (pu), (c) terminal voltage deviation (pu).

opposite changes of operating points and can damp oscillations rapidly. According to the tests, it is clearly observed that designed PSSs based on the SMNB system, have a good performance to damp LFOs and there is not any interfering between PSSs.

9. Conclusion

This paper investigates the stability enhancement problem of the power system in order to maintaining coordination between PSSs via proposing a new model of the power system. A lead PSS has been used for analyzing this model. PSO was employed to search for optimal PSS parameters. This new model is called the single machine normal bus system. Furthermore this model improves performance of the SMIB system and the multi machine power system by regarding the rest of the power system and making simplicity respectively. The effectiveness of. the proposed model and lead PSS have been illustrated under different tests. The results show that designed PSS based on the proposed model achieve good robust performance, provide superior coordination between PSSs in comparison with SMIB model and enhance greatly the dynamic stability of the power systems.

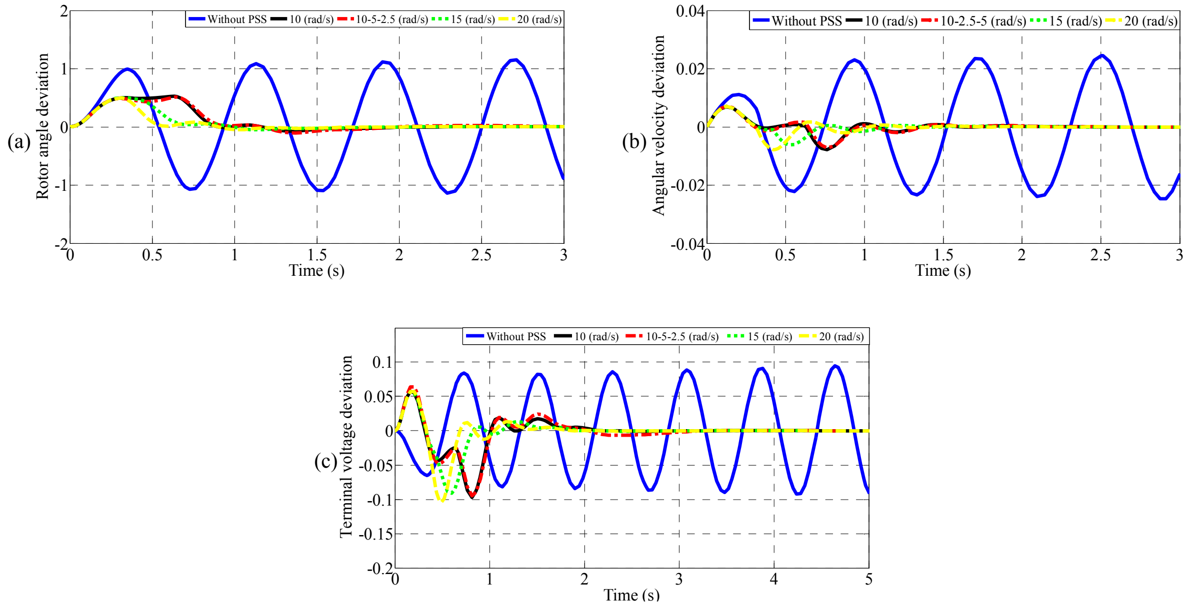

Fig. 18. System dynamic response for test 3 and first operating point (heavy load). (a) rotor angle deviation (pu), (b) angular velocity deviation (pu), (c) terminal voltage deviation (pu).

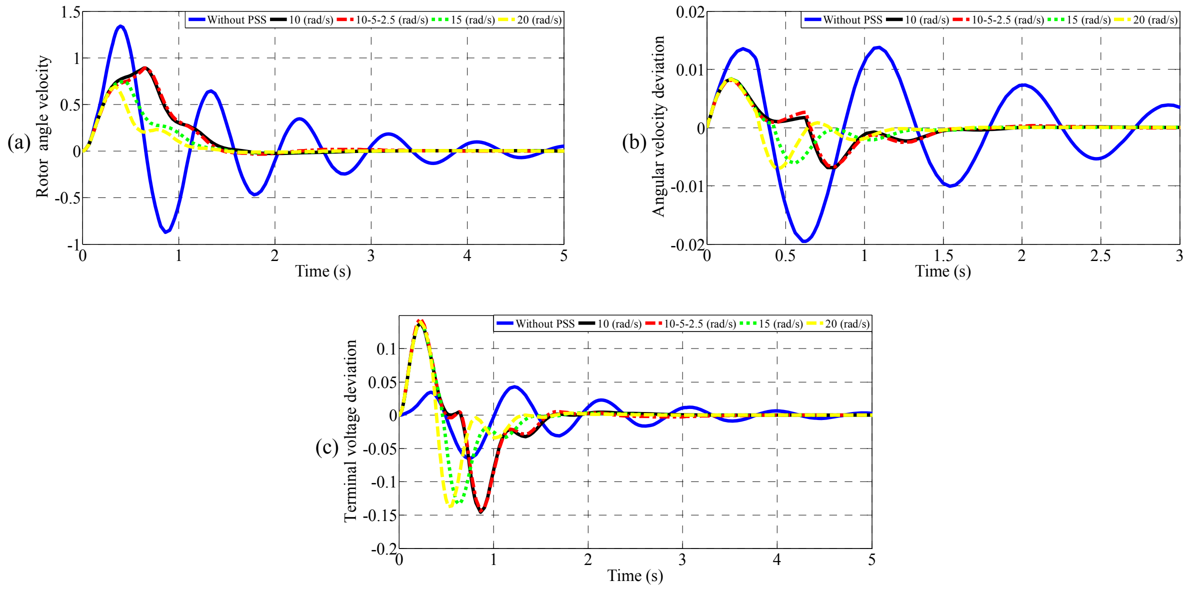

Fig. 19. System dynamic response for test 3 and third operating point (light load). (a) rotor angle deviation (pu), (b) angular velocity deviation (pu), (c) terminal voltage deviation (pu).

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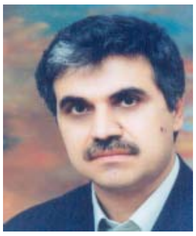

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