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Design and Scrutiny of Maiden PSS for Alleviation of Power System Oscillations Using RCGA and PSO Techniques

A. D. Falehi†

Abstract – In this paper, a novel and robust Power System Stabilizer (PSS) is proposed as an effective approach to improve stability in electric power systems. The dynamic performance of proposed PSS has been thoroughly compared with Conventional PSS (CPSS). Both the Real Coded Genetic Algorithm (RCGA) and Particle Swarm Optimization (PSO) techniques are applied to optimum tune the parameter of both the proposed PSS and CPSS in order to damp-out power system oscillations. Due to the high sufficiency of both the RCGA and PSO techniques to solve the very non-linear objective, they have been employed for solution of the optimization problem. In order to verify the dynamic performance of these devices, different conditions of disturbance are taken into account in Single Machine Infinite Bus (SMIB) power system. Moreover, to ensure the robustness of proposed PSS in damping the power system multi-mode oscillations, a Multi Machine (MM) power system under various disturbances are considered as a test system. The results of nonlinear simulation strongly suggest that the proposed PSS significantly enhances the power system dynamic stability in both of the SMIB and MM power system as compared to CPSS.

Keywords: Dynamic stability, Proposed PSS, CPSS, RCGA, PSO, SMIB System, MM system

1. Introduction

Dynamic stability of power system is one of the most important and critical issues in electric power systems [1]. If sufficient damping is not available, while a disturbance occurs in power system, the oscillations could be increased and continued for minutes to cause loss of synchronism [2]. Thus, it is essential that the power systems equip with such devices to damp the power system oscillations. Commonly, a lead-lag structure of the controller has been applied to damp the electromechanical oscillations which is known as Power System Stabilizer (PSS) and is basically a classical phase compensator [3, 4]. In essence, the PSS provides a component of electrical torque in phase with speed variations on the rotor [5]. Equipping the generator with PSS, Alleviating the electromechanical oscillations of power system has been increased via providing a supplementary control signal to the excitation system [6-8]. Fundamentally, PSS injects a stabilizing signal to Automatic Voltage Regulator (AVR) that modulates the generator excitation and compensates the negative torque of the AVR [9]. A maiden attempt has been made to attain a new robust PSS in order to further enhance the damping of oscillations in electric power systems. Generally, one of the speed deviation and incremental changes in output power of generator has been chosen as the input signal of Stabilizers. In this study, speed deviation of generator is determined as input signal of both the proposed PSS and Conventional PSS (CPSS). A number of conventional techniques namely: pole placement method [10, 11], eigenvalues sensitivities [12, 13] and residue compensation [14] have been implemented so as to tuning the controllers' parameters. Unfortunately, such conventional methods are time consuming as their computation burden is so heavy, and also have slow convergence. In addition, process is sensitive to be trapped in local minima and the obtained response may not be optimal [15].

The progressive methods develop a technique to search for the optimum solutions via some sort of directed random search processes [16]. A suitable trait of the evolutionary methods is that they search for solutions without prior problem perception. In recent years, a number of various ingenious computation techniques namely: Simulated Annealing (SA) algorithm, Evolutionary Programming (EP), Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO) have been employed by scholars to solve the different optimization problems of electrical engineering. The high performance of both the PSO and GA techniques to solve the non-linear objectives has been approved in many literatures. In this paper, RCGA optimization technique is chosen to solve the optimization problem and optimum tune the parameters of both the proposed PSS and CPSS in order to damp-out oscillations. Power system dynamic stability enhancement has been thoroughly evaluated by both these devices under different positions of disturbance in the SMIB power system. To verify the robust dynamic performance of proposed PSS in damping of power system multi-mode (local area and inter area) oscillations, a MM power system under several various disturbance has been considered.

Ultimately, the non-linear simulation results of SMIB

† Corresponding author: Department of Electrical Engineering, Izeh Branch, Islamic Azad University, Izeh, IRAN. (falehi87@gmail.com)
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and MM power system unveil the effectiveness and robustness of proposed PSS in order to enhance the power system dynamic stability as compared to CPSS.

2. Description of the Implemented RCGA and PSO Techniques

2.1 RCGA technique

Genetic Algorithm is a kind of the heuristic random search method based on the mechanics of natural selection and survival of the fittest in found in biological organisms. Due to GAs are usually more flexible and robust than other methods, they have been successfully used in power system planning. GA maintains and controls a population of solutions and enhances performance of fitness function in their search for better solutions. Reproducing the generation and keeping the best individuals for next generation, the best gens will be obtained. The RCGA optimization process can be represented as below:

2.1.1 Initialization

To commence the RCGA optimization process, initial population shall be specified. An initial population can randomly be generated or obtained from other methods [17]. The length limitation of variables should determine for optimization problem.

$$p = (p_{hi} - p_{lo})p_{norm} + p_{lo} \qquad (1)$$

Where p_{lo} p_{hi} and p_{norm} are highest number in the variable range, lowest number in the variable range and normalized value of the variable, respectively.

2.1.2 Objective function

Each individual represents a possible solution to optimize the fitness function. The fitness for each individual in the population is evaluated by taking objective function. By eliminating the worst individuals, a new population is created, while the most highly fit members in a population are selected to pass information to the next generation.

$$chromosome\ (\mathrm{var}iables) = [P_1, P_2, ..., P_{N\,\mathrm{var}}] \qquad (2)$$

$$\cos t = f(chromosome) = f(P_1, P_2, ..., P_{N\,\mathrm{var}}) \qquad (3)$$

Where, N_{var} is total number of different variables.

2.1.3 Selection function

The selection function attempts to implement pressure on the population like natural biological systems. The selection function decides which of the individuals can survive and transfer genetic characteristic to the next generation. The selection function specifies which individuals are selected for crossover. Several methods exist that parents are chosen according to efficiency of their fitness. In this paper, roulette wheel selection method is considered and is described in details in [18].

2.1.4 Genetic operator

There are two main operators in GA optimization process which are basic search mechanism of the GA techniques: crossover and mutation. They are used to create new population based on acquirement the best solution.

2.1.4.1 Crossover

Crossover is the nucleus of genetic operation, which helps to gain the new regions in the search space. Conceptually, pairs of individuals are selected randomly from the population and fit of each pair is allowed to mate. Thus, parameter where crossover occurs expressed as:

$$\alpha = roundup\{random * N\,\mathrm{var}\} \qquad (4)$$

Each pair of mates creates a child bearing some mix of the two parents.

$$parent\,1 = [p_{m1}p_{m2} \cdots p_{m\alpha} \cdots p_{mN\,\mathrm{var}}] \qquad (5)$$

$$parent\,2 = [p_{d1}p_{d2} \cdots p_{d\alpha} \cdots p_{dN\,\mathrm{var}}] \qquad (6)$$

Where, m and d subscripts discriminate between the mom and the dad parent. Then the selected variables are combined to new form variables that will appear in children

$$p_{new1} = p_{m\alpha} - \beta\,[p_{m\alpha} - p_{d\alpha}] \qquad (7)$$

$$p_{new2} = p_{d\alpha} + \beta\,[p_{m\alpha} - p_{d\alpha}] \qquad (8)$$

Where, β is also a random value between 0 and 1. The final step is combination of crossover with the rest chromosome:

$$offspring\_1 = [p_{m1}p_{m2} \cdots p_{new1} \cdots p_{dN\,\mathrm{var}}] \qquad (9)$$

$$ofspring\_2 = [p_{d1}p_{d2} \cdots p_{new2} \cdots p_{mN\,\mathrm{var}}] \qquad (10)$$

2.1.4.2 Mutation

The mutation process is used to avoid missing significant information at a special situation in the decisions. Mutation is usually considered as an auxiliary operator to extend the search space and cause release from a local optimum when used cautiously with the selection and crossover systems. With added a normally distributed random number to the variable, uniform mutation will be obtained:

$$p_n' = p_n + \sigma N_n(0,1) \quad (11)$$

Where, σ = standard deviation of the normal distribution

$N_n(0,1)$ = standard normal distribution (mean = 0 and variance = 1)

2.1.5 Stopping criterion

The stopping scale can be considered as: the maximum number of generation, population convergence criteria, lack of improvement in the best solution over a specified number of generations or target value for the objective function. With ending of generation the best individuals will be obtained. Flowchart of the RCGA optimization technique process is presented in Fig. 1.

2.2 PSO technique

PSO is a stochastic global optimization method, which has been motivated by the behavior of organisms, such as fish schooling and bird flocking [19]. PSO has the flexibility than other heuristic algorithms to control the balance between the global and local configuration of the search space. This unique feature of PSO vanquishes the premature convergence problem and enhances the search capability. Also unlike the traditional methods, the solution quality of this technique does not depend on the initial population.In the current research, the process of PSO technique can be summarized as follows [20, 21]:

1) Initial positions of *pbest* (personal best of agent i) and *gbest* are (group best) varied. However, using the different direction of *pbest* and *gbest*, all agents piecemeal receive near-by the global optimum.

2) Adjustment of the agent position is perceived by the position and velocity information. However, the method can be used to the separate problem applying grids for XY position and its velocity.

3) Didn't have any incompatibilities in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer non-linear optimization problems with continuous and district state variables easily and naturally.

4) The above statement is based on using only XY axis (two dimensional spaces). Thus, this method can be easily employed for n-dimensional problem.

The modified velocity and position of each particle can be calculated using the current velocity and the distances from $pbest_{j,g}$ to $gbest_g$ are presented as follows [22]

$$\upsilon_{j,g}^{(t+1)} = w \times \upsilon_{j,g}^{(t)} + c_1 + r_1 \times (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 + r_2 \times (gbest_g - x_{j,g}^{(t)}) \quad (12)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + \upsilon_{j,g}^{(t+1)}, \ j = 1,2,...n | \ g = 1,2,...,m \quad (13)$$

$$\upsilon_g^{min} \le \upsilon_{j,g}^{(t)} \le \upsilon_g^{max} \quad (14)$$

Where *n* is the number of particles in the swarm; *m* is the number of components for the vectors υ_j and x_j, t is the number of generation (iteration); $\upsilon^{(t)}_{j,g}$ is the *gth* component of the velocity of particle *j* at iteration *t*.

c_1 and c_2 are two positive constants, called cognitive $\upsilon^{(t)}_{j,g}$ and social parameters respectively. r_1 and r_2 are random numbers, uniformly distributed in (0, 1). $x^{(t)}_{j,g}$ is the *gth* component of the position of particle *j* at iteration *t*; $pbest_j$ is the *pbest* of particle *j*; *gbest* is the *gbest* of the group.

w is the inertia weight, which produces a balance between global and local explorations requiring less iteration on average to find a suitably optimal solution. It is determined as follows:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (15)$$

Where w_{max} is the initial weight, w_{min} is the final weight, *iter* is the current iteration number, $iter_{max}$ is the maximum iteration number. The *jth* particle in the swarm is represented by a d-dimensional vector $x_j=[x_{j,1}, x_{j,2},..., x_{j,d}]$ and its rate of velocity is symbolized by another d-dimensional vector $v_j=[v_{j,1}, v_{j,2},..., v_{j,d}]$. The best previous position of the *jth* particle is represented by $pbest_j=[pbest_{j,1}, pbest_{j,2},..., pbest_{j,d}]$. The index of best particle among all of the particles in the population is represented by the $gbest_g$. In PSO, each particle moves in the search space for seeking the best global minimum (or maximum).

The velocity update in a PSO comprises of three parts; namely cognitive, momentum and social parts. The performance of PSO depends upon the balance among these parts. The parameters c_1 and c_2 determine the relative pull of *pbest* and *gbest* and the parameters r_1 and r_2 help in stochastically varying these pulls.

2.3 Conventional power system stabilizer model

Basically, CPSS consists of an amplification block, a washout block, two lead-lag blocks, sensor time constant and limiter block [9, 15]. The PSS input signal can be either speed deviation of generator or incremental change in electromagnetic power. The structure of the CPSS controller is exhibited in Fig. 1. The time constants of T_{2P}, T_{4P} are usually predefined. In this study, $T_{2P} = T_{4P} = 0.3$s is taken into account. Also, the value of sensor time constant is considered 15ms. The parameters of the power system stabilizer which should determine by both the RCGA and PSO techniques, including: K_P, T_W, T_{1P} and T_{3P}.

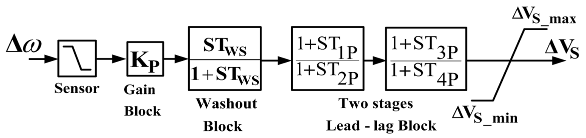

Fig. 1. Structure of the CPSS

2.4 Proposed power system stabilizer model

The proposed PSS consists of an integral block, a derivative block, a sensor time constants, a limiter blocks and a compensator block. The value of sensor time constant is considered 15ms. The proposed PSS provides the proper phase and gain characteristic for injecting the AVR input in order to damp the power system oscillations. The amount of poles in compensator block must be lesser than zeroes in the investigating the damping of low frequency oscillations [2]. The structure of the proposed PSS controller is given in Fig. 2. The parameters of the power system stabilizer which should determine by both the RCGA and PSO techniques, including: of K_I, K_D, T_c and A.

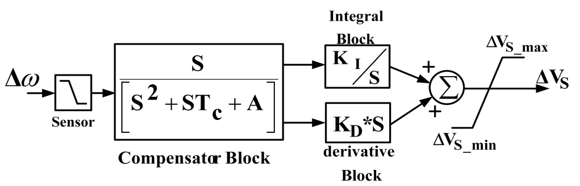

Fig. 2. Structure of the Proposed PSS

3. Single / Multi Machine Power System

To prove the robust dynamic performance of proposed PSS, both the single and multi-machine power system have been considered for this study.

3.1 Single machine, Infinite bus power system

The SMIB power system has been simulated in MATLAB/SIMULINK environment. Single line diagram of this power system model is shown in Fig. 3. It is almost similar to the power system used in [20, 24]. The generator is equipped with Hydraulic Turbine and Governor (HTG). To appraise the transient performance of the proposed PSS and CPSS, they are exerted to the excitation system separately and RCGA/PSO process carried out on their parameters. All of the other relevant parameters are provided in Appendix A.

3.2 Three-Machine, Two-Area power system

Single line diagram of three-machine, two-area power system model is shown in Fig. 4. This system like the SMIB power system has been simulated using MATLAB/SIMULINK environment. It is almost similar to the power system used in [18, 25, 26]. This system includes three generators and each one equipped with Hydraulic Turbine and Governor (HTG) and excitation. Also, the excitation system furnished with both types of PSS which PSSs and CPSSs individually are added to it. All of the other relevant parameters are provided in Appendix B.

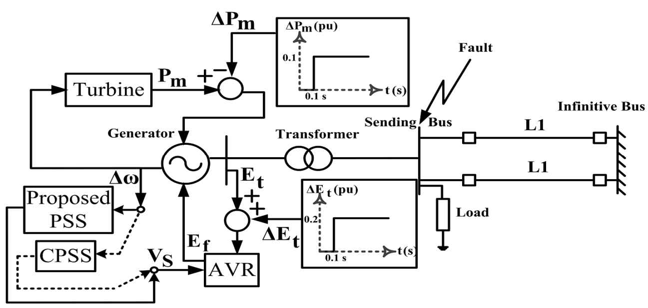

Fig. 3. Single-machine, infinite-bus power system

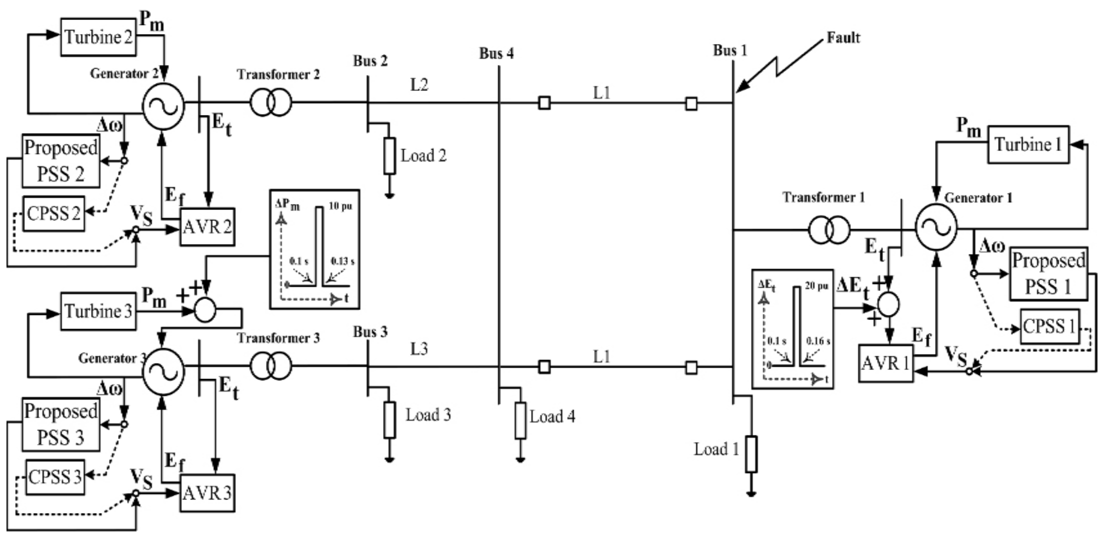

Fig. 4. Single-line diagram of the three machine system

3.3 Optimum tune the parameters of proposed PSS and CPSS

In order to enhance the dynamic stability of power system, RCGA and PSO techniques are implemented to optimum tune the parameters of proposed PSS and CPSS, as well as to achieve the optimization target. To appraise the dynamic performance (fewer settling time, fewer overshoot and fewer undershoot) of these devices despite occurrence of different disturbance, the total fitness function is specified with Eq. (18) [27]:

For SMIB power system

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| .t.dt \tag{16}$$

For MM power system

$$J = \int_{t=0}^{t=t_{sim}} \left(|\omega_1 - \omega_2| + |\omega_3 - \omega_2| + |\omega_3 - \omega_1| \right).t.dt \tag{17}$$

$$F = \sum_{i=1}^{N_p} J_i \tag{18}$$

Where, $\Delta\omega$ is the speed deviation in per unit and t_{sim} is the time range of the simulation and Np is the total number of operating positions of disturbance which the optimization is performed. ω1, ω2 and ω3 are the rotor speed of generators G1, G2 and G3, respectively. The oscillations between the generators G2 and G3 are local mode of oscillations. And also the oscillations between the generators G2 and G1 or between G1 and G3 are inter-area mode of oscillations in presented power system. Generally, the oscillation frequencies of inter-area and local-area modes are 0.2-0.8 Hz and 0.8-1.5 Hz respectively [25]. The time-domain simulation of the non-linear system model is performed for the simulation period. It is aimed to minimize the fitness function in order to improve the system response in terms of the settling time, overshoots and undershoot.

According to aforesaid explanations, both the RCGA and PSO techniques are engaged to achieve the optimization target. The flowchart of the optimization based on optimum tune parameters of these devices is described in Fig. 5.

4. Simulation Results

4.1 Single-Machine infinite bus power system

To appraise the effectiveness and robustness of proposed PSS, three different conditions of disturbance have been taken into account, which are illustrated in following states. In all three conditions, system status is situated at nominal loading condition ($P_e = 0.7^{pu}$ and $\delta_0 = 42.2^\circ$). By evaluating the objective function which is presented in Eq. (18), optimization of proposed PSS and CPSS parameters with considering three different conditions of disturbances are carried out. Optimal parameters of proposed PSS and CPSS are given in Table 1.

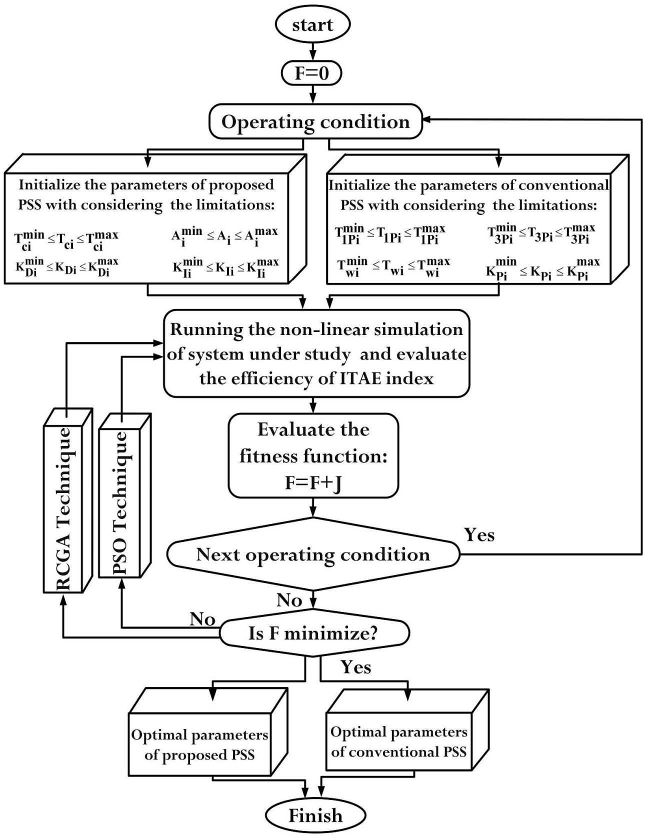

Fig. 5. Flowchart of the proposed optimization technique based optimum tune parameters of proposed PSS and CPSS

Table 1. Optimal parameter settings of both PSSs

Proposed PSS				CPSS			
RCGA Technique							
K_I	K_D	T_c	A	K_P	T_{1P}	T_{3P}	T_{WP}
12.21	918.37	699.16	44.67	1.89	0.15	0.18	4.68
PSO Technique							
K_I	K_D	T_c	A	K_P	T_{1P}	T_{3P}	T_{WP}
12.46	906.43	691.47	43.73	1.93	0.17	0.23	4.93

Following sections results which are the resultant of Table. 1 approve the robust dynamic performance of proposed PSS as compared to CPSS.

4.1.1 Three phase short circuit

A 3-phase fault occurs in the sending bus at t = 0.1s that is cleared at 0.3s. However, no change happens in excitation voltage and mechanical power. Figs. 6 and 7 depict the root locus curves with and without presence of proposed PSS. Likewise, the system responses under 3-

phase short circuit are displayed in Figs. 8-10. These figures prove that the proposed PSS is highly effective to damp the power system oscillations as compared to CPSS.

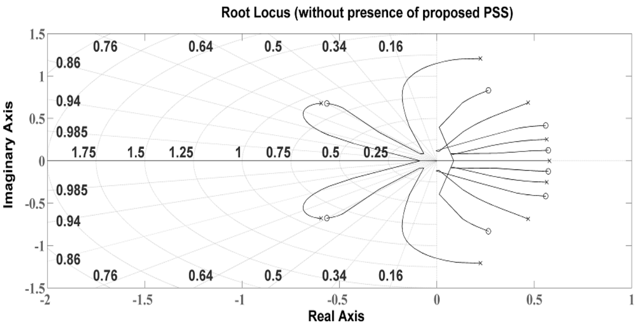

Fig. 6. System root locus without presence of proposed PSS

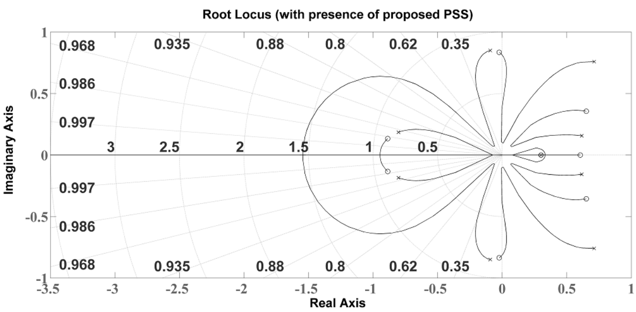

Fig. 7. System root locus with presence of proposed PSS

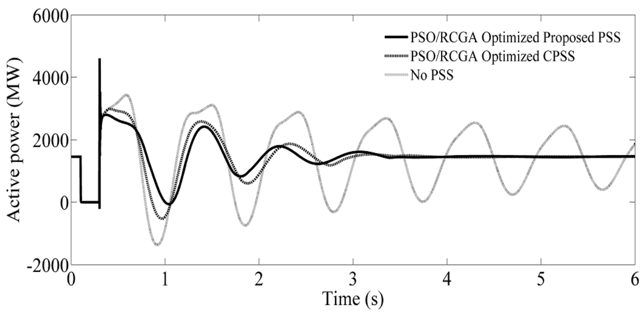

Fig. 8. Sending active power for 3-ph fault at sending bus

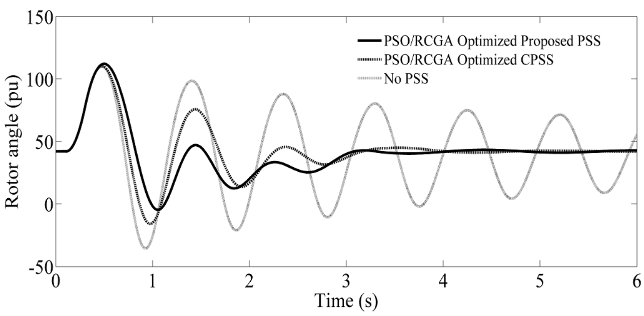

Fig. 9. Rotor angle for 3-ph fault at sending bus

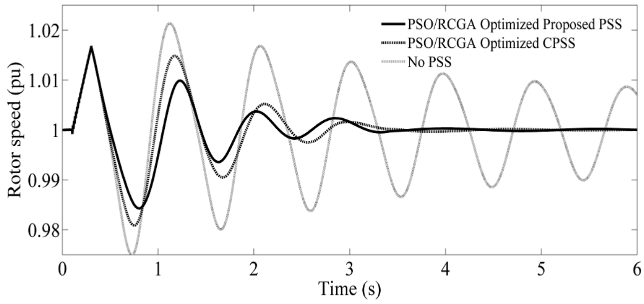

Fig. 10. Rotor speed for 3-ph fault at sending bus

4.1.2 Step change in input voltage of AVR

To verify the dynamic performance of proposed PSS and its sufficiency, a step change of 0.2pu is considered in ΔE_t at t=0.1s (while there is no change in mechanical power without any fault occurrence in power system) which lasts to the end of the simulation time. The system response which is shown in Fig. 11 demonstrates the robustness and effectiveness of proposed PSS to damp system oscillations.

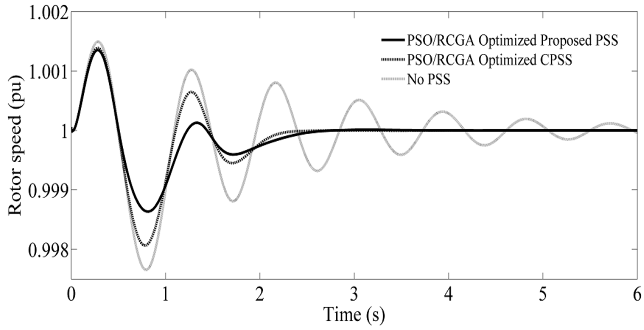

Fig. 11. Rotor speed for step 0.2pu change of in ΔE_t

4.1.3 Step change in mechanical power

In this state, mechanical power is altered to 0.9pu at t=0.1s, which lasts to the end of the simulation time. The system response under this disturbance can be seen in Fig. 12. As expected, the proposed PSS significantly enhances the dynamic stability of power system.

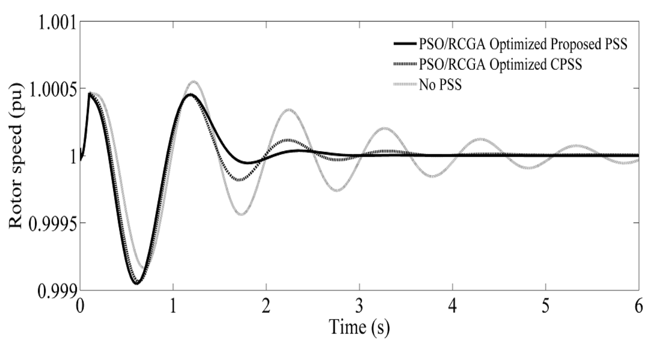

Fig. 12. Rotor speed for step change of 0.1pu in ΔP_m

4.2 Three-Machine, Two-Area power system

In this section, three different conditions of disturbance have been considered to demonstrate the robust dynamic performance of proposed PSS. PSO and RCGA techniques have been applied to optimally tune the parameters of these devices in order to diminish the oscillations in power system. By evaluating the objective function which is presented in Eq. (18), optimization of proposed PSS and CPSS parameters with considering three different conditions of disturbances are carried out. These parameters are presented in Table 2.

Table 2. Optimal parameter settings of both PSSs

Proposed PSS_1				CPSS_1			
RCGA Technique							
$K_{I,1}$	$K_{D,1}$	$T_{c,1}$	$A_{,1}$	$K_{P,1}$	$T_{1P,1}$	$T_{3P,1}$	$T_{WP,1}$
29.86	970.32	755.31	750.15	7.75	0.38	0.20	3.18
Proposed PSS_2				CPSS_2			
$K_{I,2}$	$K_{D,2}$	$T_{c,2}$	$A_{,2}$	$K_{P,2}$	$T_{1P,2}$	$T_{3P,2}$	$T_{WP,2}$
59.70	47.99	890.82	521.93	29.70	0.22	0.17	2.74
Proposed PSS_3				CPSS_3			
$K_{I,3}$	$K_{D,3}$	$T_{c,3}$	$A_{,3}$	$K_{P,3}$	$T_{1P,3}$	$T_{3P,3}$	$T_{WP,3}$
6.87	235.57	274.20	853.76	7.10	0.24	0.37	3.64
Proposed PSS_1				CPSS_1			
PSO Technique							
$K_{I,1}$	$K_{D,1}$	$T_{c,1}$	$A_{,1}$	$K_{P,1}$	$T_{1P,1}$	$T_{3P,1}$	$T_{WP,1}$
28.53	967.03	761.68	762.84	7.97	0.63	0.25	3.32
Proposed PSS_2				CPSS_2			
$K_{I,2}$	$K_{D,2}$	$T_{c,2}$	$A_{,2}$	$K_{P,2}$	$T_{1P,2}$	$T_{3P,2}$	$T_{WP,2}$
61.26	48.09	883.70	521.93	28.39	0.31	0.24	2.52
Proposed PSS_3				CPSS_3			
$K_{I,3}$	$K_{D,3}$	$T_{c,3}$	$A_{,3}$	$K_{P,3}$	$T_{1P,3}$	$T_{3P,3}$	$T_{WP,3}$
6.73	240.20	269.38	846.93	7.37	0.29	0.42	3.89

Following section results like the SMIB system results approve the robust dynamic performance of proposed PSS.

4.2.1 Three Phase Short Circuit

Dynamic performance of both the proposed PSS and CPSS is appraised with considering a 3-phase fault at bus-1 at t=0.1s which is cleared after 0.29s. The system responses are displayed in Figs. 13 and 14. According to the aforesaid explanations and what is expected, the proposed PSS remarkably damps both the enter-area and local-area modes of oscillation in electric power system.

4.2.2 Impulse Change in Input Voltage of AVR

To assess the effectiveness and robustness of proposed PSS, an impulse change of 20pu is considered in ΔE_t of unit 1 at t=0.1s which lasts to 0.06 sec later. The system responses are shown in Figs. 15 and 16. As can be seen, the power system multi mode oscillations have been strikingly reduced by proposed PSS.

4.2.3 Impulse change in mechanical power

By injecting an impulse change of 10pu in mechanical power of generator 3 at t=0.1s, the dynamic performance of both the proposed PSS and CPSS have been evaluated and compared. This disturbance is cleared after 0.03 sec. The system responses under this disturbance are presented in Fig. 17 and 18. As expected, the power system stability with presence of proposed PSS have been significantly enhanced as compared to CPSS.

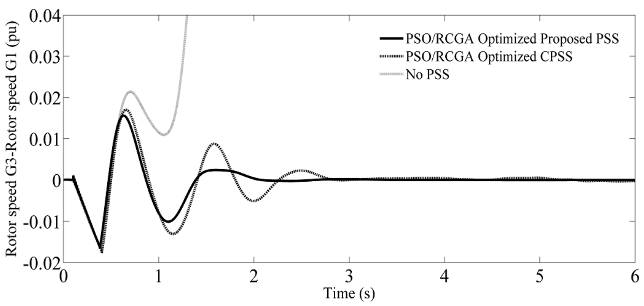

Fig. 13. Inter-area mode of oscillations

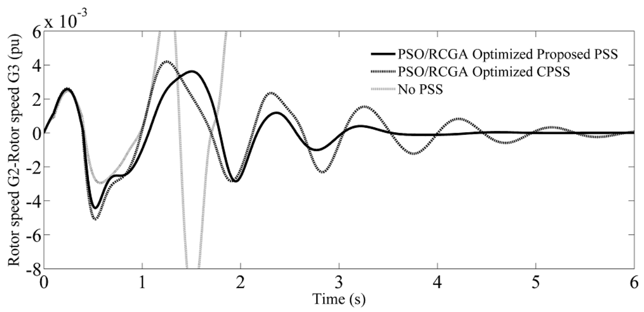

Fig. 14. Local mode of oscillations

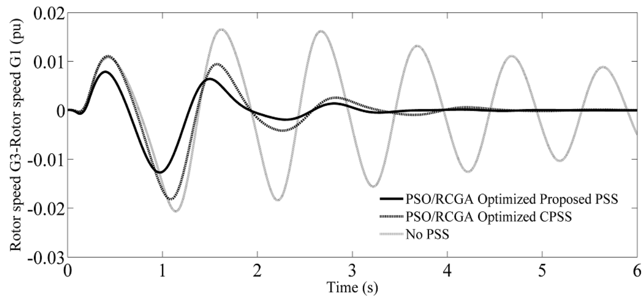

Fig. 15. Inter-area mode of oscillations

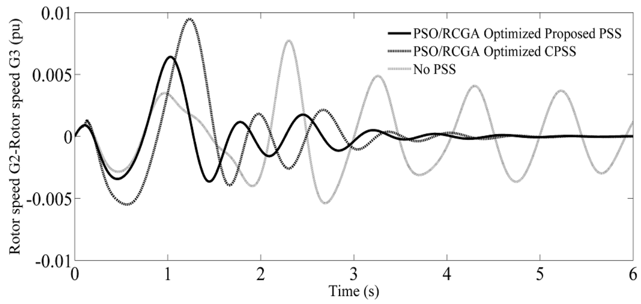

Fig. 16. Local mode of oscillation

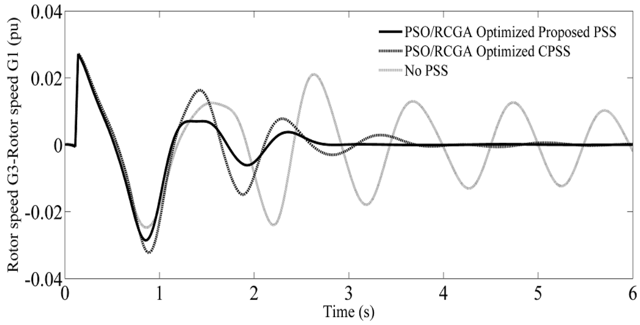

Fig. 17. Inter-area mode of oscillations

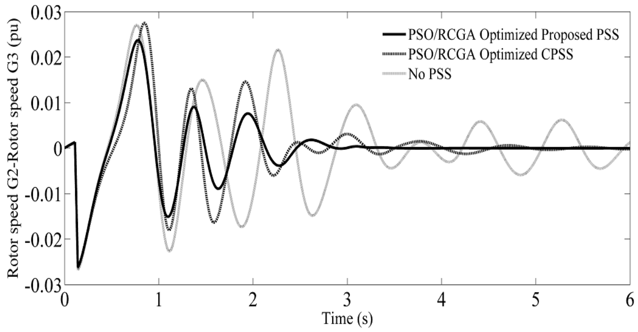

Fig. 18. Local mode of oscillations

5. Conclusion

In this paper, a novel and robust PSS is proposed to damp-out the oscillations in electric power system. This device plays an important role to enhance the power system damping effect by injecting a proper signal to the excitation system of generator. It has been thoroughly compared with CPSS to demonstrate the dynamic performance of proposed PSS. An effective and efficient approach based on RCGA and PSO techniques is implemented to optimally tune the parameters of both these devices in order to enhance the power system dynamic stability. The effectiveness and robustness of the proposed PSS have been perfectly and carefully appraised by taking into account three different conditions of disturbance in both the SMIB and MM power systems. The results of nonlinear simulation reveal that the dynamic performance of proposed PSS is much more efficient and robust than CPSS in damping of the power system oscillations in both the SMIB and MM power systems.

6. Appendix

A. Single-machine infinite-bus power system

Generator: S_B=2100MVA, H=3.7s, V_B=13.8kV, R_S= 2.8544e-3, f=60 Hz, X_d =1.305p.u., X'_d =0.296p.u X''_d = 0.252p.u., X_q =0.474p.u., X'_q =0.243 p.u., X''_q =0.18 p.u., T_d =1.01 s, T'_d =0.053 s, T''_{qo} =0.1 s.

Load at Bus-2: 250 MW.

Transformer: 2100 MVA, 13.8/500 kV, 60 Hz, R_1=R_2 = 0.002 p.u., L_1= 0, L_2= 0.12 p.u., D_1/Y_g connection, R_m=500 p.u., L_m= 500 p.u.

Transmission line: 3-Ph, 60 Hz, Length=300 km each, R_1 =0 .02546 Ω/km, R_0 = 0.3864 Ω/km, L_1 = 0.9337e-3 H/km, L_0=4.1264e-3 H/km, C_1=12.74e-9 F/km, C_0=7.751e-9 F/km.

Hydraulic Turbine and Governor: K_a=3.33, T_a= 0.07, G_{min}=0.01, G_{max}=0.97518, V_{gmin}=-0.1p.u./s, Td=0.01s, β=0 T_w=2.67s V_{gmax}=0.1p.u./s, R_p=0.05, K_p=1.163, K_i= 0.10

B. Multi-machine power system

Generators: S_{B1}=4200 MVA, S_{B2}=S_{B3}=2100 MVA, f= 60 Hz, V_B=13.8kV, X_d = 1.305, X'_d = 0.296; X''_d = 0.252 p.u, X_q =0.474p.u., X'_q =0.243, X''_q =0.18p.u., T_d=1.01s T'_d =0.053s; T''_{qo} =0.1 s, R_S =2.8544e-3, H=3.7s, p=32

Transformers: S_{B1} = 4200 MVA, S_{B2} = S_{B3} = 2100 MVA, D1/Yg, V_1 = 13.8 kV, V_2 = 500 kV, R_1=R_2= 0.002 p.u., L_1=0, L_2=0.12 p.u., R_m=500 p.u, L_m=500p.u..

Transmission lines: 3-Ph, R_1=0.02546 Ω/km, R_0= 0.3864 Ω/km, L_1=0.9337 e-3 H/km, L_0=4.1264 e-3 H/km, C_1=12.74 e-9 F/km, C_0 = 7.751 e-9 F/km, L_1 = 350 km, L_2 = 50 km, L_3 = 100 km. ***Load1:*** 7500MW+ 1500 MVAR, ***Load2 = Load3:*** 25 MW, ***Load4:*** 250 MW

References

[1] J. Shi, L. H. Herron and A. Kalam, Optimization of Fuzzy Controllers as Real-time Power System Stabilizers, Engng. Applic. Artif. Lntell, Vol. 7, No. 5, October 1994, pp. 545-558.

[2] A. D. Falehi, M. Rostami, "Design and Analysis of a Novel Dual-input PSS for damping of power system oscillations Employing RCGA-Optimization Technique, International Review of Electrical Engineering", 6 (2011), No. 2, 938-945.

[3] Zbigniew Lubosuy, dual input quasi-optimal PSS for generating unit with static excitation system, Power Plants and Power Systems Control, Kananaskis, Canada, 25-28 June 2006, pp. 267-283.

[4] T.R.Jyothsna and K.Vaisakh, Design of a Decen-tralized Non-linear Controller for Transient Stability Improvement under Symmetrical and Unsymmetrical Fault Condition: A comparative analysis with SSSC, IEEE Power Systems Conference and Exposition, Seattle, March 2009, pp. 1-8.

[5] F. P. deMello, T. F. Laskowski, Concepts of power systemdynamic stability, IEEE Trans. Power Apparatus Syst. PAS-94 (1975) 827-833.

[6] V. Mukherjee and S. P. Ghoshal, Application of capacitive energy storage for transient performance improvement of power system, Electric Power

Systems Research, Vol. 79, No. 2, pp. 282-294, 2009.
[7] D.K. Chaturvedi and O.P. Malik, Generalized neuron-based PSS and adaptive PSS, Control Engineering Practice, Vol. 13, No. 12, pp.1507-1514, 2005.
[8] A.M. El-Zonkoly, A.A. Khalil and N.M. Ahmied, Optimal tuning of lead-lag and fuzzy logic power system stabilizers using particle swarm optimization, Expert Systems with Applications, Vol. 36, No. 2, March 2009, pp. 2097-2106.
[9] P. Kunder, "Power System Stability and Control", New York: McGraw, Hill, 2001
[10] P. Shrikant Rao and I. Sen, "Robust pole placement stabilizer design using linear matrix inequalities," IEEE Trans. on Power Systems, Vol. 15, No. 1, pp. 3035-3046, February 2000.
[11] M.A. Abido, "Pole placement technique for PSS and TCSC-based stabilizer design using simulated annealing," Int. J. Electric Power Syst. Res., Vol. 22, No. 8, pp. 543-554, 2000.
[12] B.C. Pal, "Robust pole placement versus root-locus approach in the context of damping interarea oscillations in power systems," IEE Proceedings on Generation, Transmission and Distribution, Vol. 49, No. 6, pp. 739-745, 2002.
[13] L. Rouco, F.L. Pagola, "An eigenvalue sensitivity approach to location and controller design of controllable series capacitor for damping power system oscillations," IEEE Transactions on Power Systems, Vol. 12, No. 4. pp. 1660-1666, 1997.
[14] M. E. About-Ela, A. A. Sallam, J. D. McCalley and A. A. Fouad, "Damping controller design for power system oscillations using global signals, IEEE Trans on Power Syst, Vol. 11, pp. 767-773, 1996.
[15] Sidhartha Panda and Narayana Prasad Padhy, Optimal location and controller design of STATCOM for power system stability improvement using PSO, Journal of the Franklin Institute, Vol. 345, No. 2, pp. 166-181, 2008.
[16] R. L. Haupt and S. E. Haupt, Practical Genetic Algorithms, New York: Wiley, 2004.
[17] Sidhartha Panda and Ramnarayan N. Patel, Improving power system transient stability with an off-center location of shunt FACTS devices, Journal of Electrical Engineering, Vol. 57, No. 6, 2006, pp. 365-368.
[18] D. E. Goldberg, Genetic algorithms in search, optimization and Machine learning, Reading, Mass.: Addison-Wesley, 1989.
[19] G.I. Rashed, H.I. Shaheen, X.Z. Duan, S.J. Cheng, "Evo-lutionary optimization techniques for optimal location and parameter setting of TCSC under single line contingency" Applied Mathematics and Computation, Vol. 205, 2008, pp. 133-147.
[20] Y.J. Liu, X.X. He, "Modeling identification of power plant thermal process based on PSO algorithm," in: American Control Conference, 2005, pp. 4484-4489.
[21] J. Kennedy, R. Eberhart, Swarm Intelligence, 1st ed., Academic press, San Diego, CA, 2001.
[22] A. D. Falehi, "Simultaneous Coordinated Design of TCSC Based Damping Controller and AVR Based on PSO Technique" International Journal of Engineering, PRZEGLĄD ELEKTROTECHNICZNY (Electrical Review), Vol. 88, No. 5, pp. 136-140, 2012.
[23] A. D. Falehi, A. Dankoob, S. Amirkhan, H. Mehrjardi, Coordinated Design of STATCOM-Based Damping Controller and Dual-Input PSS to Improve Transient Stability of Power System, International Review of Electrical Engineering, Vol. 6, No. 3, June 2011.
[24] A. D. Falehi, M. Rostami, H. Mehrjardi, "Transient Stability Analysis of Power System by Coordinated PSS-AVR Design Based on PSO Technique" International Journal of Engineering, Vol. 3, No. 5, pp. 178-184, 2011.
[25] S. Panda, Multi-objective evolutionary algorithm for SSSC-based controller design, Electric Power Systems Research, Vol. 79, No. 6, pp. 937-944, 2009.
[26] S. Mishra, P.K. Dash, P.K. Hota and M. Tripathy, Genetically optimized neuro-fuzzy IPFC for damping modal oscillations of power system, IEEE Transaction on Power System, Vol. 17, No. 4, pp. 1140-1147, 2002.
[27] A. D. Falehi, M. Rostami, A Robust Approach Based on RCGA-Optimization Technique to Enhance Power System Stability by Coordinated Design of PSS and AVR, International Review of Electrical Engineering, Vol. 6, No. 1, February 2011, pp. 371-378.

Ali Darvish Falehi was born in IRAN, in 1985. He received the M.Sc degree from the Shahed University, Tehran, Iran, in 2010. Ali has published more than 10 ISI papers like IREE, JEET, TUBITAK and PE. He currently is IEEE member in region 8. His interests include FACTS, D-FACTS, PSS, AGC, Fuzzy Controllers, Power System Stability, Power Quality, and Optimization Techniques.