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Design and Analysis of a Novel Dual-Input PSS for Damping of Power System Oscillations Employing RCGA-Optimization Technique

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Abstract – *In this paper, a dual-input Power System Stabilizer (PSS) is proposed to damp the low frequency oscillations in power system. The performance of proposed dual-input PSS has been compared with single input Conventional PSS (CPSS). The Real Coded Genetic Algorithm (RCGA) optimization technique is employed to optimum tune the parameter of both the single-input and dual-input PSS in order to improve the power system stability. Having the high sufficiency to solve the very non-linear objective, the RCGA technique is exerted to solve an optimization problem. The transient performance of these devices is evaluated considering three different conditions of disturbance in single-machine infinite-bus power system. Furthermore, to more investigate the role of proposed dual-input PSS in damping the power system multi-mode oscillations, a multi-machine power system (three-machine nine-bus) is considered. The results of nonlinear simulation suggest that with proposed dual-input PSS, power system stability is considerably improved than CPSS in single-machine power system. In addition, it is revealed that with proposed dual-input PSS, undesirable inter-area and local modes of oscillations in multi machine power system are superiorly damped than CPSS.* ***Copyright © 2011 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Power System Oscillations, Conventional Power System Stabilizer, Dual-input Power System Stabilizer, Real Coded Genetic Algorithm, Single-machine Infinite-bus Power System, Multi-Machine Power System*

Nomenclature

N_{var}	Number of variables
P_n	Variable *n*
P_{hi}	Highest number in the variable range
P_{li}	Lowest number in the variable range
P_{norm}	Normalized value of variable
m	Mother chromosome
d	Father chromosome
p_{mn}	*nth* variable in the mother chromosome
P_{dn}	*nth* variable in the father chromosome
α	Parameter where crossover occurs
β	Mixing value for continuous variable crossover
σ	Standard deviation of the normal distribution
$N_n(0,1)$	Standard normal distribution
E_t	Input voltage of AVR
P_m	Mechanical power
P_e	Electrical power
ΔP_e	Changes in electromagnetic power
$\Delta\omega$	Speed deviation of rotor
t_{sim}	Time range of the simulation
N_p	Number of operating positions of disturbance
$ITAE$	Integral Time Absolute Error
F	Fitness function

I. Introduction

Low-frequency oscillations of interconnected electric power systems is one of the most important problems in power system stability [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. Thus, it is essential to such devices are equipped with power system to damp the undesired oscillations while a disturbance takes place to the power system. Commonly, a model of the controller is used to damp the electromechanical oscillations which is known as Power System Stabilizer (PSS) and is basically a classical phase compensator [2], [3]. Equipping the generator with PSS, damping the electromechanical oscillations of power system is enhanced through providing a supplementary control signal to the excitation system [4]-[6]. PSS, in fact, adds a stabilizing signal to AVR that modulates the generator excitation and compensates the negative torque of the AVR [7]. In this paper, a dual-input power system stabilizer is proposed to more reduce the power system oscillation. Usually, one of the speed deviation and incremental changes in electromagnetic power of the synchronous generator had been chosen as the input

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signal of Conventional Power System Stabilizer (CPSS). Both these signals can play a significant role in the reduction of undershoot, overshoot and settling time. Thus, since the proposed dual-input PSS receives both signals as input, it can increase the scale of transient stability improvement (fewer undershoot, fewer overshoot and fewer settling time) than CPSS.

Numbers of routine techniques have been applied to design the problems of power system controllers such as mathematical programming, gradient process for optimization and modern control theory. However, these techniques necessitate heavy computation scale with slow convergence.

In addition, the process is sensitive to be trapped in local minima and the obtained response may not be optimal [8]. The progressive methods develop a technique to search for the optimum solutions via some sort of directed random search processes [9]. A suitable trait of the evolutionary methods is that they search for solutions without prior problem perception. In recent years, researchers apply various ingenious computation techniques to solve the different optimization problems of electrical engineering.

Simulated Annealing (SA) algorithm has been used to optimum tune the parameters of PSS and Flexible AC Transmission System (FACTS) based stabilizer in order to damp the electromechanical modes of oscillations, enhance the power system stability and improve the system voltage profile [10]. The optimal location of a static synchronous compensator (STATCOM) and optimization of static synchronous series compensator (SSSC)-based damping controller parameters using the Particle Swarm Optimization (PSO) techniques have been obtained to improve the power system stability [8], [11]. Furthermore, GAs has been used to design the FACTS controllers [12]-[16] and optimum location of FACTS device [17]-[20] to enhance power system stability.

The high performance of GA technique 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 proposed dual-input PSS and CPSS in order to enhance the power system stability. Damping of power system oscillations has been thoroughly investigated by means of these devices under three different positions of disturbance in the single-machine, infinite-bus power system. Furthermore, power system multi-mode oscillations improvement is studied using these devices for multi-machine power system.

Finally, non-linear simulation results show that dual-input PSS enhances the transient stability strongly more than CPSS. The results of non-linear simulation in both the single-machine infinite-bus and multi machine power systems approved the transient performance of proposed dual-input PSS.

II. Description of the Implemented Real Coded Genetic Algorithm Technique

Genetic Algorithm is a kind of random search optimization technique based on the mechanism of natural generation selection. 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 described as below:

II.1. Initialization

To commence the RCGA optimization process, initial population shall be specified. An initial population can randomly be generated or obtain from other methods [18]. The length limitation of variables should determine for optimization problem:

$$p = \left(p_{hi} - p_{lo}\right) p_{norm} + p_{lo} \tag{1}$$

II.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. 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:

$$chromosome\ \left(variables\right) = \left[P_1, P_2, \ldots, P_{Nvar}\right] \tag{2}$$

$$cost = f\left(chromosome\right) = f\left(P_1, P_2, \ldots, P_{Nvar}\right) \tag{3}$$

II.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 [21].

II.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.

II.4.1. Crossover

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

$$\alpha = roundup\{random * N\,var\} \tag{4}$$

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

$$parent\,1 = [p_{m1} p_{m2} \cdots p_{m\alpha} \cdots p_{mN\,var}] \tag{5}$$

$$parent\,2 = [p_{d1} p_{d2} \cdots p_{d\alpha} \cdots p_{dN\,var}] \tag{6}$$

Then the selected variables are combined to form new variables that will appear in the children:

$$p_{new1} = p_{m\alpha} - \beta [p_{m\alpha} - p_{d\alpha}] \tag{7}$$

$$p_{new2} = p_{d\alpha} + \beta [p_{m\alpha} - p_{d\alpha}] \tag{8}$$

where, β is also a random value between 0 and 1. The final step is to complete the crossover with the rest of the chromosome as before:

$$offspring\_1 = [p_{m1} p_{m2} \cdots p_{new1} \cdots p_{dN\,var}] \tag{9}$$

$$ofspring\_2 = [p_{d1} p_{d2} \cdots p_{new2} \cdots p_{mN\,var}] \tag{10}$$

II.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:

$$p_n' = p_n + \sigma N_n(0,1) \tag{11}$$

II.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.

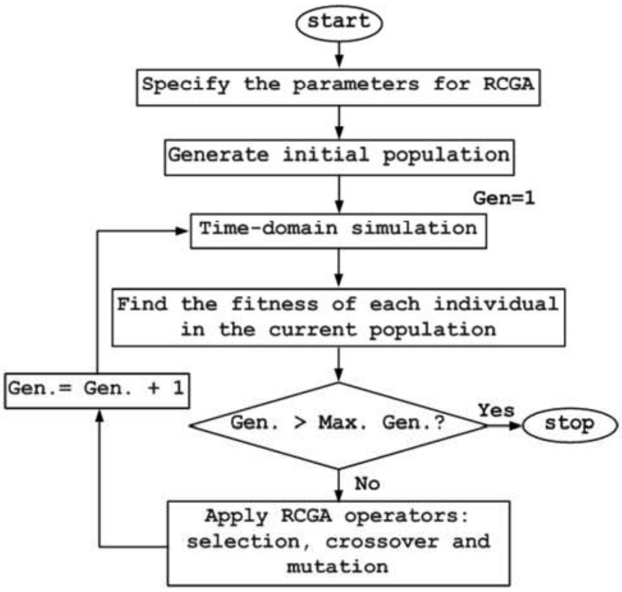

Fig. 1. Flowchart of the RCGA optimization technique

III. 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. 2. It is almost similar to the power system used in [22]. The generator is equipped with Hydraulic Turbine and Governor (HTG). To appraise the transient performance of the proposed dual-input PSS and CPSS, they are added to the excitation system separately and RCGA process carried out on them. Speed deviation of generator is chosen as the input signal of the CPSS. In addition, speed deviation of generator and incremental change in electromagnetic power are considered as the input signals of the proposed dual-input PSS. All of the other relevant parameters are provided in Appendix A.

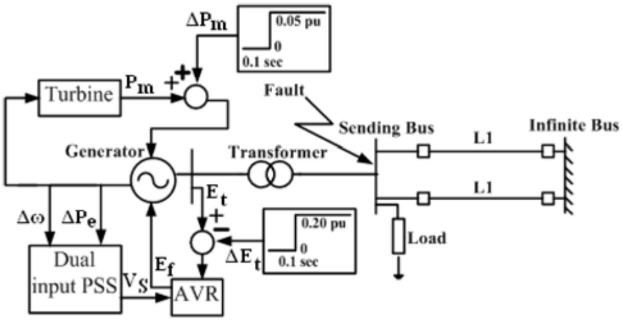

Fig. 2. Single-machine, infinite-bus power system

III.1. Conventional Power System Stabilizer Model

CPSS includes a transfer function comprise of an amplification block, a washout block, lead-lag block, sensor time constant and limiter block [7], [8]. The PSS input signal can be either speed deviation of generator or incremental change in electromagnetic power. The structure of the CPSS controller is presented in Fig. 3. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range 1–20 seconds [7]. The values of T_{WP} and sensor time constant are considered 10s and 15ms respectively. The parameters of the power system stabilizer which should determine by RCGA technique, including: gain of K_P and the time constants of T_{1P} and T_{2P}.

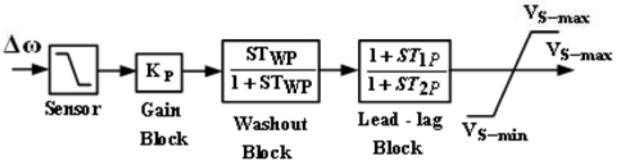

Fig. 3. Structure of the conventional power system stabilizer

III.2. Dual-input Power System Stabilizer Model

The proposed dual-input PSS consists of two amplification blocks, two wash out blocks, two sensor time constants, three limiter blocks and a compensator block.

In this study, the values of T_W, T_P, K_W, K_P and sensor time constant are considered 100ms, 5ms, 0.10, 10 and 15ms, respectively. The compensator block provides the proper phase and gain characteristic for output-signal of proposed dual-input PSS 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, [7]. Both the speed deviation and incremental change in electromagnetic power of the synchronous generator are considered as input signals of proposed dual-input PSS. The structure of the proposed dual-input PSS controller is presented in Fig. 4.

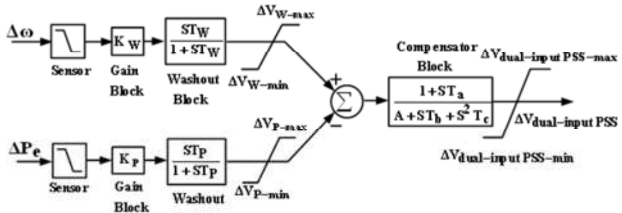

Fig. 4. Structure of the proposed dual-input power system stabilizer

III.3. Optimum Tune the Parameters of Proposed Dual-input PSS and CPSS

In this study, RCGA optimization technique is applied to optimize the parameters of proposed dual-input PSS and CPSS in order to improve the power system stability. To enhance the transient performance of these devices (fewer settling time, fewer overshoot and fewer undershoot), the total fitness function is determined as Equation (13):

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| \cdot t \cdot dt \tag{12}$$

$$F = \sum_{i=1}^{N_p} J_i \tag{13}$$

The time-domain simulation of the non-linear system model is performed for the simulation period. It is aimed to minimize this fitness function in order to improve the system response in terms of the settling time, overshoots and undershoot. The problem constraints are the parameters of proposed dual-input PSS and CPSS, which must be bounded. Therefore, the design problem can be formulated as the following optimization problem:

$$Minimize\ F \tag{14}$$

subject to:

$$\begin{array}{ll} K_{Pi}^{min} \le K_{Pi} \le K_{Pi}^{max} & A_i^{min} \le A_i \le A_i^{max} \\ T_{1Pi}^{min} \le T_{1Pi} \le T_{1Pi}^{max} & T_{ai}^{min} \le T_{ai} \le T_{ai}^{max} \\ T_{2Pi}^{min} \le T_{2Pi} \le T_{2Pi}^{max} & T_{bi}^{min} \le T_{bi} \le T_{bi}^{max} \\ i = 1-3 & T_{ci}^{min} \le T_{ci} \le T_{ci}^{max} \end{array} \tag{15}$$

Genetic Algorithm is employed to solve the optimization problem and obtain the optimal set of proposed dual-input PSS and CPSS parameters. The flowchart of the optimization based on optimum tune parameters of these devices is described in Fig. 5.

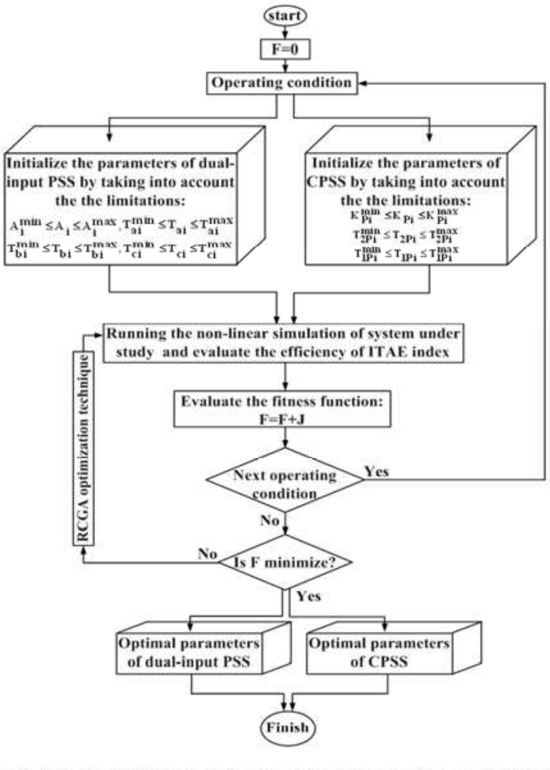

Fig. 5. Flowchart of the optimization technique based on optimum tune parameters of dual-input PSS and CPSS

IV. Simulation Results

To assess the transient performance of proposed dual-input PSS and CPSS, three different conditions of disturbance are considered which are described in following states.

In all three conditions, system status is nominal loading condition ($P_e = 0.7^{pu}$ and $\delta_0 = 42.2^\circ$). CPSS parameters in [23] are considered as non-optimization status.

Assessing the objective function presented in Equation (13), optimization of proposed dual-input PSS and CPSS parameters with considering three different conditions of disturbances are carried out. Optimal parameters of proposed dual-input PSS and CPSS are presented in Table I.

TABLE I
OPTIMAL PARAMETER SETTINGS OF THE PROPOSED DUAL-INPUT PSS AND CPSS

Proposed dual-input PSS				CPSS		
T_a	T_b	T_c	A	K_P	T_{1P}	T_{2P}
255.281	4.948	0.334	480.745	3.311	1.308	0.112

The following section results approve that parameters obtained and tabulated here have optimal performing rather than conventional parameters.

IV.1. Three Phase Short Circuit

A 3-phase fault occurs in the middle of one of parallel transmission lines at t = 0.1s, then it is cleared after 0.242s.

However, no change happens in excitation voltage and mechanical power. As mentioned above, RCGA optimization technique is employed to optimum tune the parameters of these devices in order to evaluate the transient performance of proposed dual-input PSS and CPSS.

The system responses under 3-phase short circuit are displayed in Figs. 6-8. These figures confirm that the proposed dual-input PSS is robust than CPSS in enhancing the damping of low-frequency oscillations. Consequently, employing proposed dual-input PSS, the power system stability is more increased as compared to CPSS.

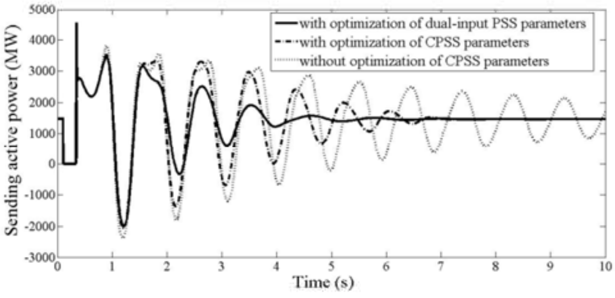

Fig. 6. Sending active power response for 3-ph fault at sending bus

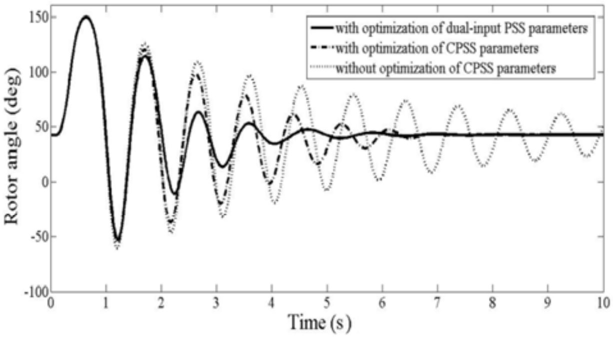

Fig. 7. Rotor angle response for 3-ph fault at sending bus

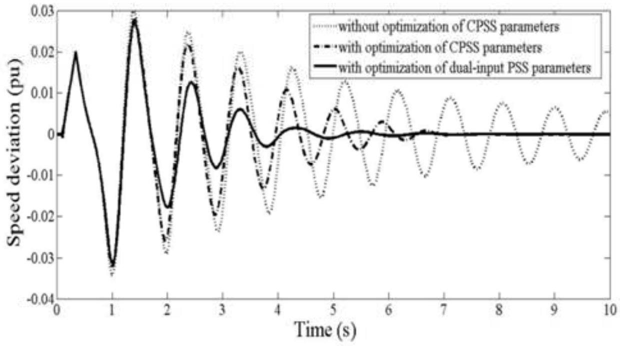

Fig. 8. Speed deviation response for 3-ph fault at sending bus

IV.2. Change in Input Voltage of AVR

To evaluate the transient performance of proposed dual-input 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. System response is displayed in Fig. 9. It is revealed that power system stability is further improved in presence of proposed dual input PSS.

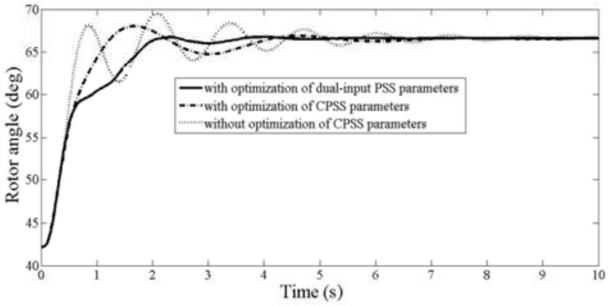

Fig. 9. Rotor angle response for step change of 0.2pu in ΔE_t

IV.3. Change in Mechanical Power

In this state, mechanical power is altered to 1.05pu at t=0.1s, which lasts to the end of the simulation time. System response under change in mechanical power is displayed in Fig. 10. As described before, the power system stability is further improved with proposed dual input PSS.

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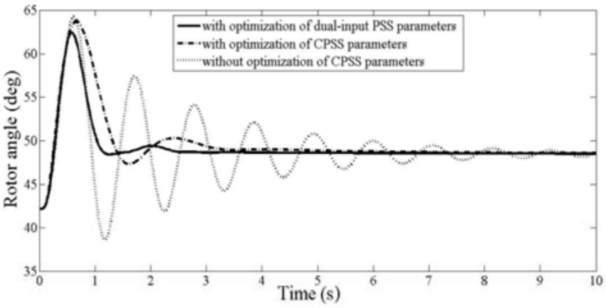

Fig. 10. Power angle response for step change of 0.05pu in ΔP_m

V. Three-Machine, Two-Area Power System

V.1. System Model

Single line diagram of three-machine, two-area power system model is shown in Fig. 11. This system has been simulated using MATLAB/SIMULINK environment. It is almost similar to the power system used in [21] [24], [25].

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 dual-input PSSs and CPSSs individually are added to it. All of the other relevant parameters are provided in Appendix B.

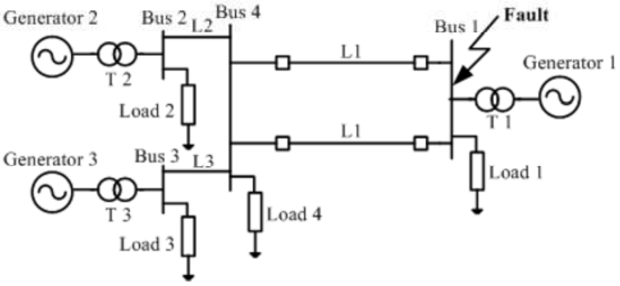

Fig. 11. Single-line diagram of the three-machine, two-area power system

The objective functions J is determined as:

$$J = \int_{t=0}^{t=t_{sim}} \left(|\omega_1 - \omega_2| + |\omega_3 - \omega_2| + |\omega_3 - \omega_1| \right) t dt \quad (16)$$

where ω_1, ω_2 and ω_3 are the rotor speed of generators G_1, G_2 and G_3, respectively, and t_{sim} is the time that simulation runs, as well as J is Integral Time Absolute Error (ITAE) of the speed signal deviation.

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 [24].

V.2. Simulation Results

To evaluate the transient performance of proposed dual-input PSS and CPSS, a 3-phase fault considered at bus-1 at t=0.1s and it is cleared after 0.149s. As described above, RCGA optimization technique is employed to optimum tune the parameters of these devices and to approve the transient performance of proposed dual-input PSS than CPSS. These parameters are presented in Table II.

TABLE II
OPTIMAL PARAMETER SETTINGS OF THE PROPOSED DUAL-INPUT PSSS AND CPSSS

Proposed dual-input PSS1				CPSS1		
T_{a1}	T_{b1}	T_{c1}	A_1	K_{P1}	T_{1P1}	T_{2P1}
149.867	62.186	0.688	195.171	1.277	0.608	0.862
Proposed dual-input PSS2				CPSS2		
T_{a2}	T_{b2}	T_{c2}	A_2	K_{P2}	T_{1P2}	T_{2P2}
55.337	90.995	1.425	549.555	1.017	1.424	1.725
Proposed dual-input PSS3				CPSS3		
T_{a3}	T_{b3}	T_{c3}	A_3	K_{P3}	T_{1P3}	T_{2P3}
84.524	50.683	1.538	536.084	1.552	0.727	0.483

The system response under this disturbance is presented in Figures 12-14. The power system stability by using of the proposed dual-input PSS is more enhanced as compared to CPSS, and these plots approve this acclaim.

The variations of the inter-area modes of oscillations, presented in Figs. 12 and 13. Also, local mode of oscillations is shown in Fig. 14.

Obviously without employing the proposed dual-input PSS, both inter-area and local modes of oscillations are more oscillatory compared to employing proposed dual-input PSS.

Finally, power system stability using proposed dual-input PSS is significantly enhanced.

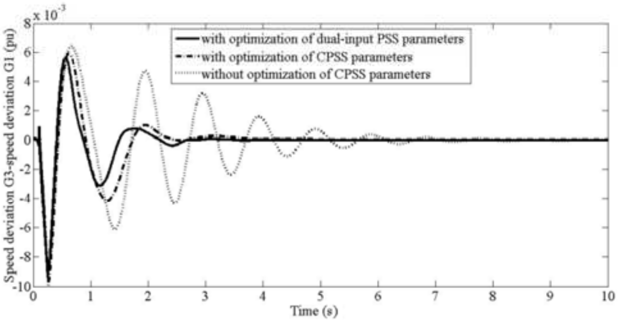

Fig. 12. Inter-area mode of oscillation under 3-ph fault in transmission line

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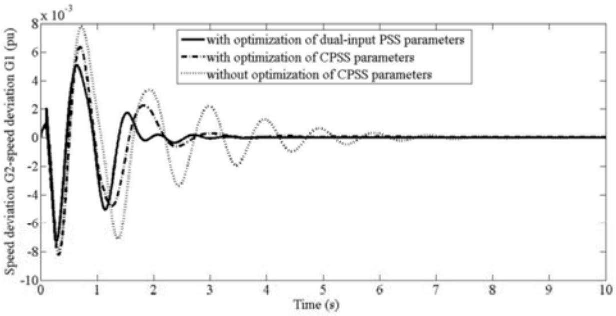

Fig. 13. Inter-area mode of oscillation under 3-ph fault in transmission line

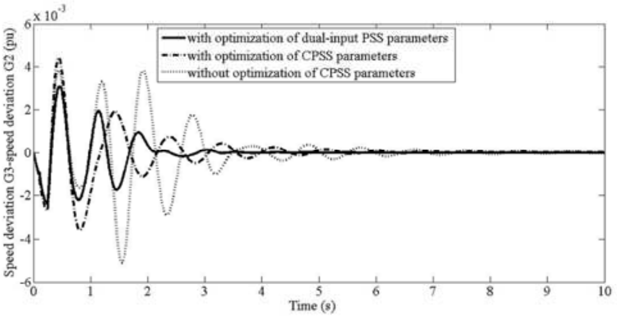

Fig. 14. Local mode of oscillation under 3-ph fault in transmission line

VI. Conclusion

In this paper, a new dual-input PSS is proposed to diminish the power system oscillations. This device can play an important role to enhance the power system stability by injecting a proper signal to excitation system. Furthermore, to approve the transient performance of proposed dual-input PSS, it is compared with CPSS. Initially, it is considered as a single-machine, infinite -bus power system to appraise the transient performance of these devices. RCGA-optimization technique is employed to obtain the optimal parameters of these devices in order to enhance the power system stability. Furthermore, the transient performance of these devices is evaluated in spite of occurring three different condition of disturbance in this system. Secondly, a multi-machine power system is considered to more investigate the role of proposed dual-input PSS for damping of power system multi-mode oscillations. Finally, the results of nonlinear simulation indicate that by using the proposed dual-input PSS power system stability is improved better than CPSS in both the single-machine, infinite bus and multi-machine power systems. So, the transient performance of proposed dual-input PSS is approved.

Appendix

A. Single-machine infinite-bus power system

Generator: S_B=2100 MVA, H=3.7 s, V_B=13.8 kV ,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,T_d=0.01s, β=0 T_w=2.67s V_{gmax}=0.1p.u./s, R_p=0.05, K_p=1.163, K_i= 0.105

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.

*Load*1 = 7500MW+ 1500 MVAR, Load2 = Load3 = 25 MW, Load4 = 250 MW.

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