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Real-Coded Genetic Algorithm for Robust Power System Stabilizer Design

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***Abstract*—**Power system stabilizers (PSS) are now routinely used in the industry to damp out power system oscillations. In this paper, real-coded genetic algorithm (RCGA) optimization technique is applied to design robust power system stabilizer for both single-machine infinite-bus (SMIB) and multi-machine power system. The design problem of the proposed controller is formulated as an optimization problem and RCGA is employed to search for optimal controller parameters. By minimizing the time-domain based objective function, in which the deviation in the oscillatory rotor speed of the generator is involved; stability performance of the system is improved. The non-linear simulation results are presented under wide range of operating conditions; disturbances at different locations as well as for various fault clearing sequences to show the effectiveness and robustness of the proposed controller and their ability to provide efficient damping of low frequency oscillations.

***Keywords*—**Particle swarm optimization, power system stabilizer, low frequency oscillations, power system stability.

I. Introduction

LOW frequency oscillations are 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]. Power system stabilizers (PSS) are now routinely used in the industry to damp out oscillations. An appropriate selection of PSS parameters results in satisfactory performance during system disturbances [2].

The problem of PSS parameter tuning is a complex exercise. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers namely: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory [3]. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal [4]. Most of the proposals on PSS parameter tuning are based on small disturbance analysis that required linearization of the system involved. However, linear methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for tuning the PSS in that the controller tuned to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances. In order to overcome the above short comings, this paper uses three-phase non-linear models of power system components and to optimally tune the PSS parameters.

Also, the controller should provide some degree of robustness to the variations loading conditions, and configurations as the machine parameters change with operating conditions. A set of controller parameters which stabilize the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations [5].

The evolutionary methods constitute an approach to search for the optimum solutions via some form of directed random search process. A relevant characteristic of the evolutionary methods is that they search for solutions without previous problem knowledge. Recently, Genetic Algorithm (GA) appeared as a promising evolutionary technique for handling the optimization problems [6]. GA has been popular in academia and the industry mainly because of its intuitiveness, ease of implementation, and the ability to effectively solve highly nonlinear, mixed integer optimisation problems that are typical of complex engineering systems. In view of the above, this paper proposes to use GA optimization technique for the design of robust PSS.

A comprehensive assessment of the effects of PSS-based damping controller for both single-machine infinite-bus (SMIB) and multi-machine power system has been carried out in this paper. The design problem of the proposed controller is transformed into an optimization problem. The design objective is to improve the stability the power system, subjected to severe disturbances. GA based optimal tuning algorithm is used to optimally tune the parameters of the PSS. The proposed controller has been applied and tested under wide range of operating conditions; disturbances at different locations as well as for various fault clearing sequences to show the effectiveness and robustness of the proposed

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controller and their ability to provide efficient damping of low frequency oscillations.

This paper is organized as follows. In Section II, the power systems under study are presented. The proposed controller structure and problem formulation is described in Section III. A short overview of GA is presented in Section IV. Simulation results are provided and discussed in Section V and conclusions are given in Section VI.

II. Power Systems Under Study

The SMIB power system shown in Fig. 1and the multi-machine system shown in Fig. 2 are considered in this study for the design of robust PSS. The SMIB system comprises a generator connected to an infinite bus through a step-up transformer followed by a double circuit transmission line. In the figure T represents the transformer; V_T and V_B are the generator terminal and infinite bus voltage respectively; I is the line current and P_L is the real power flow in the transmission lines. The generator is equipped with hydraulic turbine & governor (HTG), excitation system and a power system stabilizer. The multi-machine system consists of three generators divided in to two subsystems and are connected via an intertie. Following a disturbance, the two subsystems swing against each other resulting in instability. To improve the reliability the line is sectionalized. In Fig. 2, G_1, G_2 and G_3 represent the generators; T/F_1 - T/F_3 represent the transformers and L_1, L_2 and L_3 represent the line sections respectively. The generators are equipped with hydraulic turbine & governor (HTG), excitation system and power system stabilizer. All the relevant parameters are given in appendix.

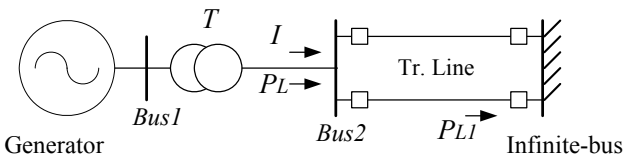


Fig. 1 Single-machine infinite-bus power system

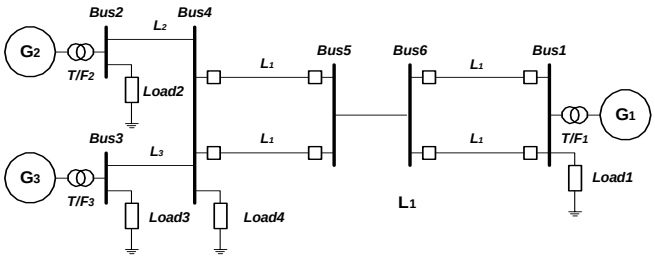


Fig. 2 Multi-machine power system

III. The Proposed Approach

A. Structure of Power System Stabilizer

The structure of PSS, to modulate the excitation voltage is shown in Fig. 3. The structure consists of a sensor, a gain block with gain K_P, a signal washout block and two-stage phase compensation blocks as shown in Fig. 3. The input signal of the proposed controller is the speed deviation (Δω), and the output is the stabilizing signal V_S which is added to the reference excitation system voltage. The signal washout block serves as a high-pass filter, with the time constant T_W, high enough to allow signals associated with oscillations in input signal to pass unchanged. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range of 1 to 20 seconds [1]. The phase compensation block (time constants T_1, T_2 and T_3, T_4) provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

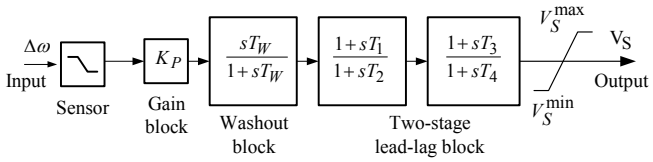


Fig. 3 Structure of power system stabilizer

B. Problem Formulation

In case of above lead-lag structured PSS, the sensor and the washout time constants are usually specified. In the present study, a sensor time constant T_{SN} = 15 ms and washout time constant T_W=10s are used. The controller gain K_P and the time constants T_1, T_2, T_3 and T_4 are to be determined.

It is worth mentioning that the proposed controllers are designed to minimize the power system oscillations after a large disturbance so as to improve the power system stability. These oscillations are reflected in the deviations in power angle, rotor speed and line power. Minimization of any one or all of the above deviations could be chosen as the objective. In the present study, an integral time absolute error of the speed deviations is taken as the objective function for SMIB power system. For multi-machine power system an integral time absolute error of the speed signals corresponding to the local and inter-area modes of oscillations is taken as the objective function.

The objective functions are expressed as:

For SMIB system:

$$J = \int_{t=0}^{t=t_{sim}} [\ |\Delta\omega|\ ] \cdot t.dt \qquad (1)$$

For multi-machine system:

$$J = \int_{t=0}^{t=t_{sim}} (\sum \Delta\omega_L + \sum \Delta\omega_I) \cdot t \cdot dt \qquad (2)$$

Where, $\Delta\omega$ denotes the speed deviation of SMIB system generator; $\Delta\omega_L$ and $\Delta\omega_I$ are the speed deviations of inter-area and local modes of oscillations respectively and t_{sim} is the time range of the simulation. In the present three-machine study, the local mode $\Delta\omega_L$ is (ω_2- ω_3), and the inter-area mode $\Delta\omega_I$ is [(ω_2- ω_1) + (ω_3- ω_1)], where ω_1 , ω_2 and ω_3 are the speed deviations of machines, 1 2 and 3 respectively.

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For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots.

IV. Overview of Genetic algorithm (GA)

The Genetic algorithm (GA) has been used to solve difficult engineering problems that are complex and difficult to solve by conventional optimization methods. GA maintains and manipulates a population of solutions and implements a survival of the fittest strategy in their search for better solutions. The fittest individuals of any population tend to reproduce and survive to the next generation thus improving successive generations. The inferior individuals can also survive and reproduce.

Implementation of GA requires the determination of six fundamental issues: chromosome representation, selection function, the genetic operators, initialization, termination and evaluation function. Brief descriptions about these issues are provided in the following sections.

A. Chromosome representation

Chromosome representation scheme determines how the problem is structured in the GA and also determines the genetic operators that are used. Each individual or chromosome is made up of a sequence of genes. Various types of representations of an individual or chromosome are: binary digits, floating point numbers, integers, real values, matrices, etc. Generally natural representations are more efficient and produce better solutions. Real-coded representation is more efficient in terms of CPU time and offers higher precision with more consistent results.

B. Selection function

To produce successive generations, selection of individuals plays a very significant role in a genetic algorithm. The selection function determines which of the individuals will survive and move on to the next generation. A probabilistic selection is performed based upon the individual's fitness such that the superior individuals have more chance of being selected. There are several schemes for the selection process: roulette wheel selection and its extensions, scaling techniques, tournament, normal geometric, elitist models and ranking methods.

The selection approach assigns a probability of selection P_j to each individuals based on its fitness value. In the present study, normalized geometric selection function has been used. In normalized geometric ranking, the probability of selecting an individual P_i is defined as:

$$Pi = q'(1-q)^{r-1} \tag{3}$$

$$q' = \frac{q}{1-(1-q)^{P}} \tag{4}$$

where,

q = probability of selecting the best individual
r = rank of the individual (with best equals 1)
P = population size

C. Genetic operators

The basic search mechanism of the GA is provided by the genetic operators. There are two basic types of operators: crossover and mutation. These operators are used to produce new solutions based on existing solutions in the population. Crossover takes two individuals to be parents and produces two new individuals while mutation alters one individual to produce a single new solution. The following genetic operators are usually employed: simple crossover, arithmetic crossover and heuristic crossover as crossover operator and uniform mutation, non-uniform mutation, multi-non-uniform mutation, boundary mutation as mutation operator. Arithmetic crossover and non-uniform mutation are employed in the present study as genetic operators. Crossover generates a random number r from a uniform distribution from 1 to m and creates two new individuals by using equations:

$$x_i' = \begin{Bmatrix} x_i, if\ i < r \\ y_i\ otherwise \end{Bmatrix} \tag{5}$$

$$y_i' = \begin{Bmatrix} y_i, if\ i < r \\ x_i\ otherwise \end{Bmatrix} \tag{6}$$

Arithmetic crossover produces two complimentary linear combinations of the parents, where r = U (0, 1):

$$\bar{X}' = r\bar{X} + (1-r)\bar{Y} \tag{7}$$

$$\bar{Y}' = r\bar{Y} + (1-r)\bar{X} \tag{8}$$

Non-uniform mutation randomly selects one variable j and sets it equal to an non-uniform random number.

$$x_i' = \begin{Bmatrix} x_i + (b_i - x_i) f(G) & if\ r_1 < 0.5, \\ x_i + (x_i + a_i) f(G) & if\ r_1 \geq 0.5, \\ x_i, \quad otherwise & \end{Bmatrix} \tag{9}$$

where,

$$f(G) = (r_2 (1 - \frac{G}{G_{\max}}))^b \tag{10}$$

r_1, r_2 = uniform random nos. between 0 to 1.
G = current generation.
G_{max} = maximum no. of generations.
b = shape parameter.

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D. Initialization, termination and evaluation function

An initial population is needed to start the genetic algorithm procedure. The initial population can be randomly generated or can be taken from other methods.

The GA moves from generation to generation until a stopping criterion is met. The stopping criterion could be maximum number of generations, population convergence criteria, lack of improvement in the best solution over a specified number of generations or target value for the objective function.

Evaluation functions or objective functions of many forms can be used in a GA so that the function can map the population into a partially ordered set. The computational flowchart of the GA optimization process employed in the present study is given in Fig. 4.

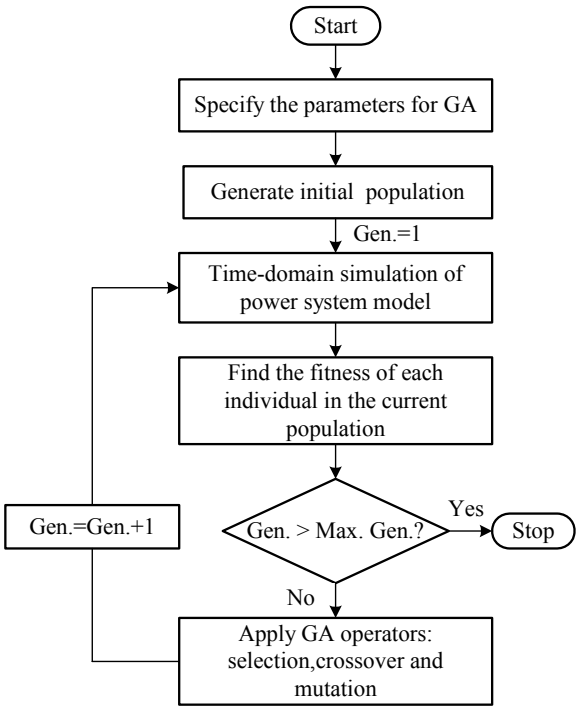


Fig. 4 Flowchart of genetic algorithm

V. Results and Discussions

The SimPowerSystems (SPS) toolbox is used for all simulations and PSS design. SPS is a MATLAB-based modern design tool that allows scientists and engineers to rapidly and easily build models to simulate power systems using Simulink environment. The SPS's main library, *powerlib*, contains models of typical power equipment such as machines, governors, excitation systems, transformers, and transmission lines. The library also contains the Powergui block that opens a graphical user interface for the steady-state analysis of electrical circuits. The Load Flow and Machine Initialization option of the Powergui block performs the load flow and the machines initialization [7].

In power system stability study, the fast oscillation modes resulting from the interaction of linear R, L, C elements and distributed parameter lines are of no interest. These oscillation modes, which are usually located above the fundamental frequency of 50 Hz or 60 Hz, do not interfere with the slow machine modes and regulator time constants. The phasor solution method is used here where these fast modes are ignored by replacing the network's differential equations by a set of algebraic equations. The state-space model of the network is replaced by a transfer function evaluated at the fundamental frequency and relating inputs (current injected by machines into the network) and outputs (voltages at machine terminals). The phasor solution method uses a reduced state-space model consisting of slow states of machines, turbines, and regulators, thus dramatically reducing the required simulation time. In view of the above, the phasor solution method is used in the present study.

A. Single-Machine Infinite-Bus Power System

In order to optimally tune the parameters of the PSS, as well as to assess its performance and robustness under wide range of operating conditions with various fault disturbances and fault clearing sequences, the test system depicted in Fig. 1 is considered at the first instant. The model of the example power system shown in Fig. 1 is developed using SPS blockset. The system consists of a of 2100 MVA, 13.8 kV, 60Hz hydraulic generating unit, connected to a 300 km long double-circuit transmission line through a 3-phase 13.8/500 kV step-up transformer and a 100 MVA SSSC. The generator is equipped with Hydraulic Turbine & Governor (HTG) and Excitation system. All the relevant parameters are given in appendix.

B. Application of GA

For the purpose of optimization of equation (1), RCGA is employed. The objective function is evaluated for each individual by simulating the example power system, considering a severe disturbance. For objective function calculation, a 3-phase short-circuit fault in one of the parallel transmission lines is considered. For the implementation of GA normal geometric selection is employed which is a ranking selection function based on the normalised geometric distribution. Arithmetic crossover takes two parents and performs an interpolation along the line formed by the two parents. Non uniform mutation changes one of the parameters of the parent based on a non-uniform probability distribution. This Gaussian distribution starts wide, and narrows to a point distribution as the current generation approaches the maximum generation. The optimization was performed with the total number of generations set to 100. Table I shows the optimal values of PSS parameters obtained by the GA for SMIB system. The convergence rate of objective function J with the number of generations is shown in Fig. 5.

TABLE I
OPTIMIZED PSS PARAMETERS FOR SMIB SYSTEM

K_P	T_1	T_2	T_3	T_4
48.0988	0.0585	0.022	3.6177	4.8472

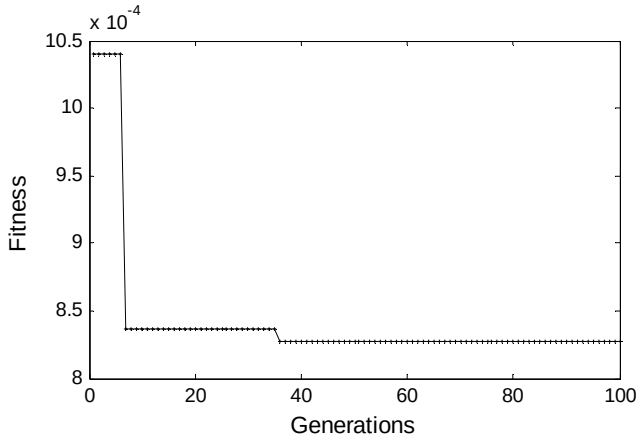


Fig. 5 Convergence of fitness value for SMIB power system

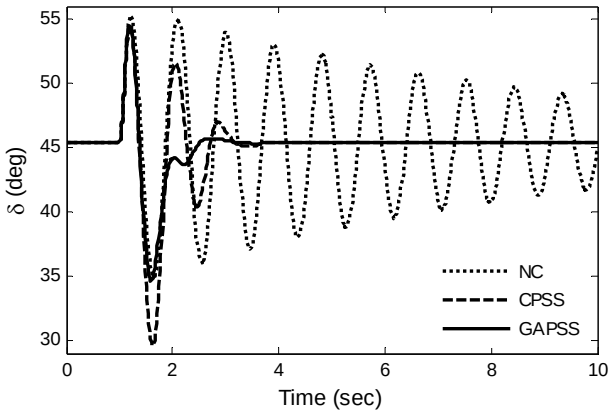


Fig. 7 Power angle response of for 3-cycle 3-phase fault at middle of transmission line with nominal loading condition

C. Simulation Results for SMIB Power System

To assess the effectiveness and robustness of the proposed controller, simulation studies are carried out for various fault disturbances and fault clearing sequences. The behavior of the proposed controller under transient conditions is verified by applying various types of disturbances under different operating conditions. In all the Figs., the response without control (no control) is shown with dotted line with legend NC; the response with conventionally designed power system stabilizer [1] is shown with dashed lines with legend CPSS and the response with proposed RCGA optimized PSS is shown with solid line with legend GPSS respectively. The following cases are considered:

Case I: Nominal loading:

A 3-cycle 3-phase fault is applied at the middle of one transmission line at nominal loading condition (P_e = 0.75 pu, $\delta_0 = 45.36^0$). The fault is cleared by tripping of the faulty line and the line is reclosed after 3-cycles. The original system is restored after the line reclosure. The system response for the above contingency is shown in Figs. 6-8. It is clear from these Figs. that, the system is poorly damped without control under this disturbance.

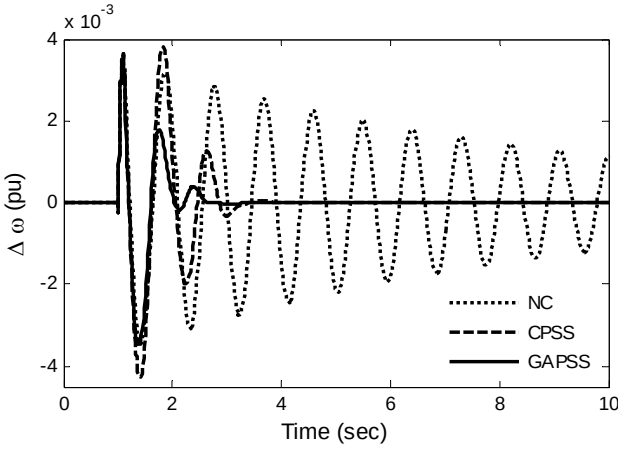


Fig. 6 Speed deviation response of for 3-cycle 3-phase fault at middle of transmission line with nominal loading condition

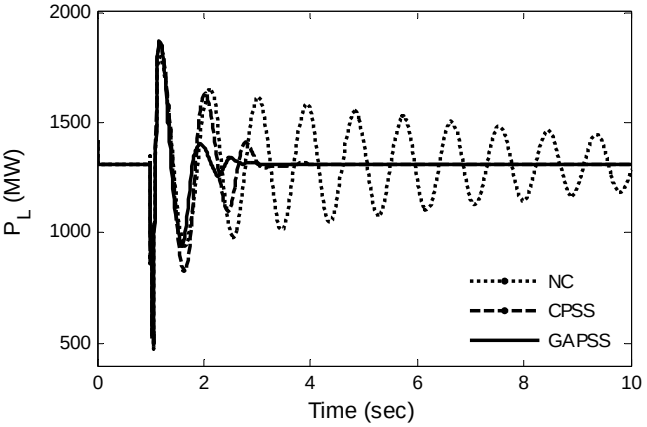


Fig. 8 Tie-line power flow response of for 3-cycle 3-phase fault at middle of transmission line with nominal loading condition

Power system oscillations are effectively suppressed with the application of conventional power system stabilizer. It is also clear from Figs. that, the proposed RCGA optimized PSS out perform the conventional PSS from dynamic performance point of view. The power system oscillations are quickly damped out with the application of proposed GPSS.

Case II: Heavy loading:

To test the robustness of the controller to operating condition and fault clearing sequence, the generator loading is changed to heavy loading condition (P_e = 1.0 pu, $\delta_0 = 60.72^0$), and a 3-cycle, 3-phase fault is applied at Bus2. The fault is cleared by opening both the lines. The lines are reclosed after 3-cycles and original system is restored. The system response for the above severe disturbance is shown in Figs. 9-10. It can be clearly seen from these Figs. that, for the given operating condition and contingency, the system is unstable without control. Stability of the system is maintained and power system oscillations are effectively damped out with the application of conventional PSS. The proposed PSS provides the best performance and outperform the conventional PSS by minimizing the transient errors and quickly stabilizes the system.

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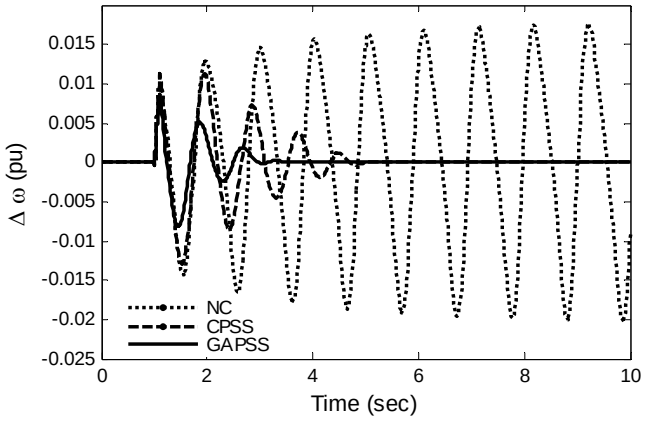


Fig. 9 Speed deviation response of for 3-cycle 3-phase fault at Bus2 with heavy loading condition

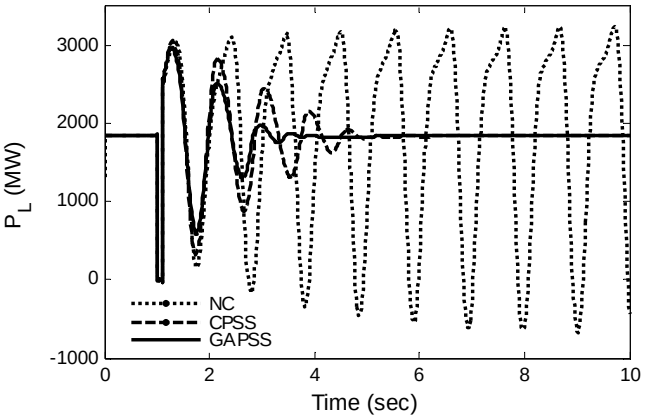


Fig. 10 Tie-line power flow response of for 3-cycle 3-phase fault at Bus2 with heavy loading condition

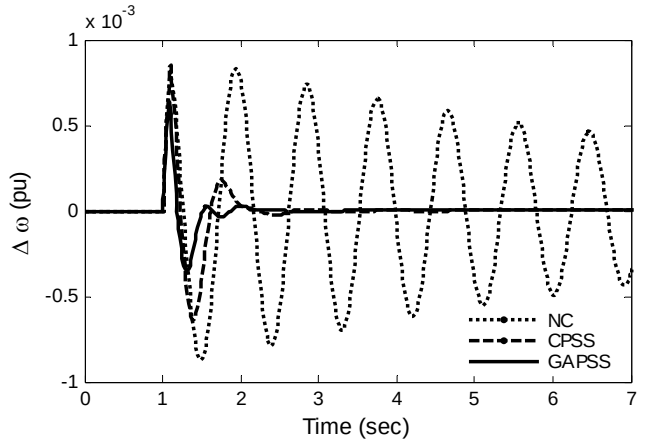


Fig. 11 Speed deviation response of for 100 ms load rejection at Bus2

Case III: Small disturbance:

In order to examine the effectiveness of the proposed controller under small disturbance, the load at Bus2 is disconnected at t = 1 sec for 100 ms (This simulates a small disturbance). Fig. 11 shows the system speed deviation response for the above contingency. It is clear from Fig. 11 that, the system is poorly damped without control under this small disturbance. It is also evident from Fig. 11 that the proposed PSS is robust to type of disturbance and provides efficient damping to power system oscillations even under small disturbance. The dynamic performance of the proposed GPSS is also superior to that of conventional CPSS.

D. Multi-Machine Power System

The proposed approach of designing and optimizing the parameters of PSS is also extended to a multi-machine power system shown in Fig. 2. It is similar to the power systems used in references [8-9]. The system consists of three generators divided in to two subsystems and are connected via an intertie. Following a disturbance, the two subsystems swing against each other resulting in instability. The relevant data for the system is given in appendix A.

Load flow is performed with machine 1 as swing bus and machines 2 and 3 as a PV generation buss. The initial operating conditions used are:

Machine 1 generation: Pe_1 = 3480.6 MW (0.8287 pu); Qe_1 = 2577.2 MVAR (0.6136 pu)

Machine 2 generation: Pe_2 = 1280 MW (0.6095pu); Qe_2 = 444.27 MVAR (0.2116 pu)

Machine 3 generation: Pe_3 = 880 MW (0.419pu); Qe_3 = 256.33 MVAR (0.1221 pu)

The same approach as explained for SMIB case is followed to optimize the three power system stabilizers assumed to be installed for three generators. Convergence rate of objective function J with the number of generations is shown in Fig. 12. The optimized values of the PSSs are shown in Table II.

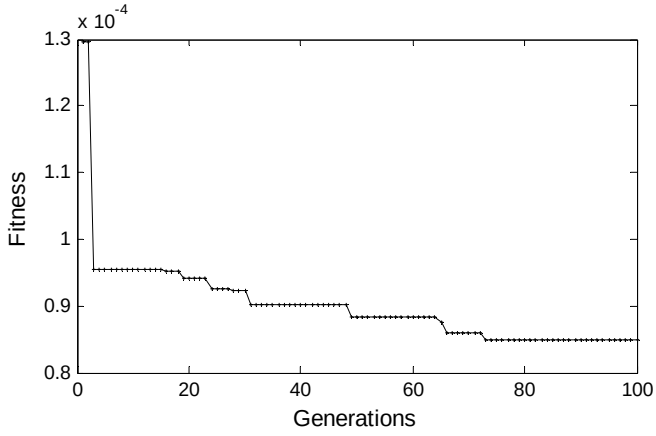


Fig. 12 Convergence of fitness value for multi-machine system

TABLE II
OPTIMIZED PSS PARAMETERS FOR MULTI-MACHINE SYSTEM

Parameters	PSS-1	PSS-1	PSS-1
K_P	31.8276	40.5438	34.2573
T_1	0.0778	0.0205	0.0727
T_2	0.0444	0.0283	0.0564
T_3	3.6471	3.8237	3.1789
T_4	5.5578	5.7608	5.9391

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E. Simulation Results for Multi-Machine System

Simulation studies are carried out and presented under different contingencies. The responses of the system when the RCGA optimized PSSs are present, is shown with solid line with legend GAPSSs. The uncontrolled response is shown with dotted line with legend NC. Following cases are considered:

Case I: Three-phase fault disturbance:

A 3-cycle, 3-phase fault is applied at one of the line sections between Bus1 and Bus6 near Bus6 at t = 1 s. The fault is cleared by opening the faulty line and the line is reclosed after 3-cycles. The original system is restored after the fault clearance. Figs. 13-16 show the variations of the inter-area and local mode of oscillation and the tie-line power flow against time for the above severe disturbance. From these Figs. it can be seen that, inter-area modes of oscillations are highly oscillatory in the absence of control and the proposed controller significantly improves the power system stability by damping these oscillations. Further, the proposed controller is also effective in suppressing the local mode of oscillations.

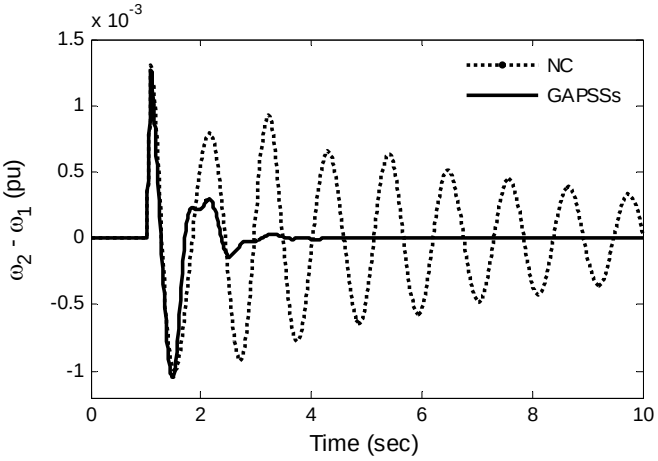


Fig. 13 Inter-are mode of oscillation for three-phase fault disturbance

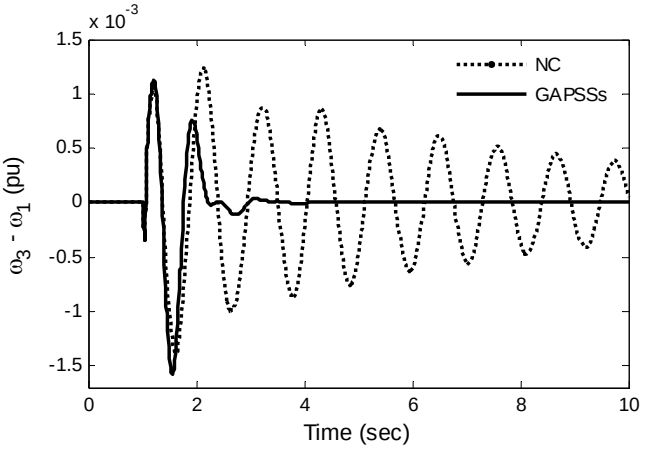


Fig. 14 Inter-are mode of oscillation for three-phase fault disturbance

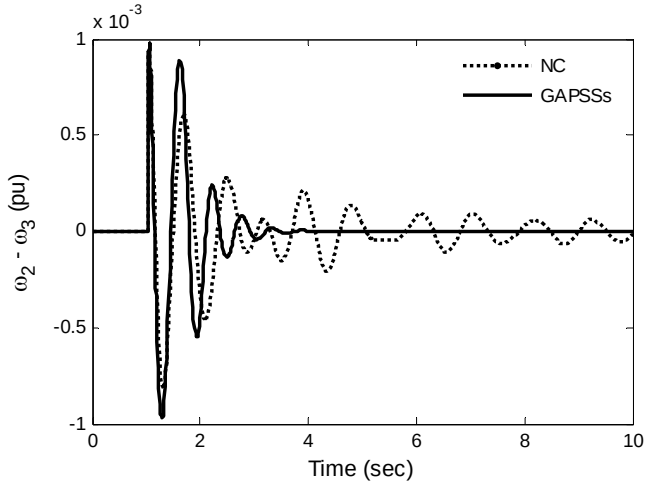


Fig. 15 Local mode of oscillation for three-phase fault disturbance

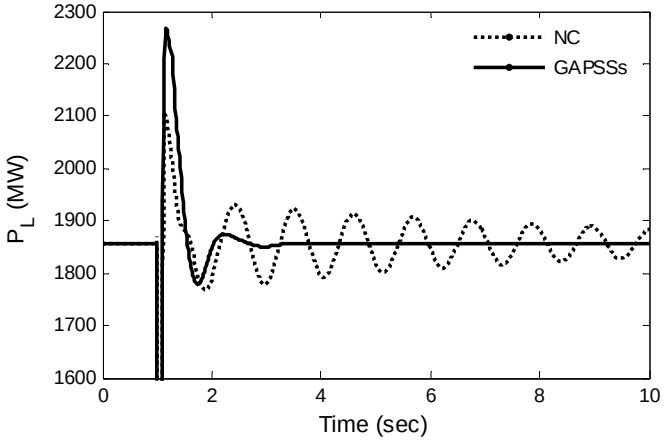


Fig. 16 Tie-line power flow for three-phase fault disturbance

Case II: Small disturbance:

In order to examine the effectiveness of the proposed controller under small disturbance, the load at Bus4 is disconnected at t = 1 s for 100 ms. Figs. 18-19 show the

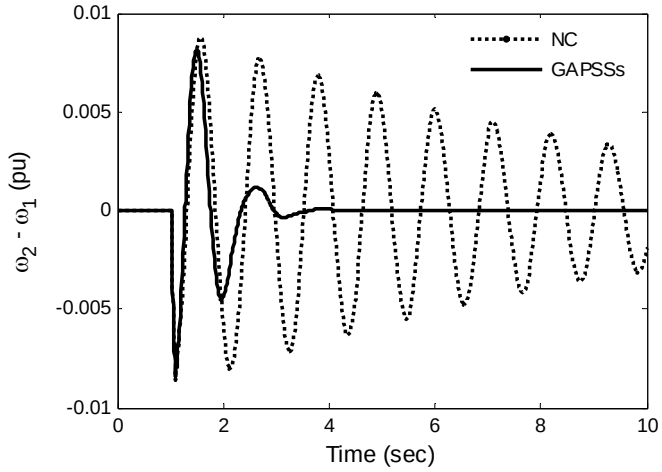


Fig. 17 Inter-are mode of oscillation for small disturbance

variations of the inter-area and local modes of oscillations against time, and the tie-line power flow from which it is clear that the proposed controllers damps the modal oscillations effectively even for small disturbance.

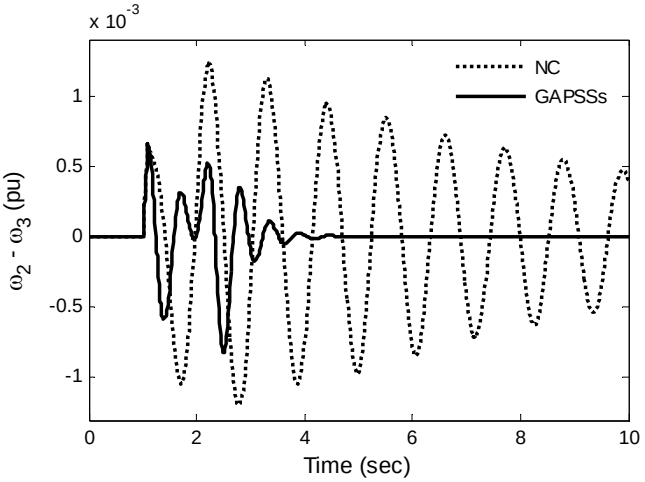


Fig. 18 Local mode of oscillation for small disturbance

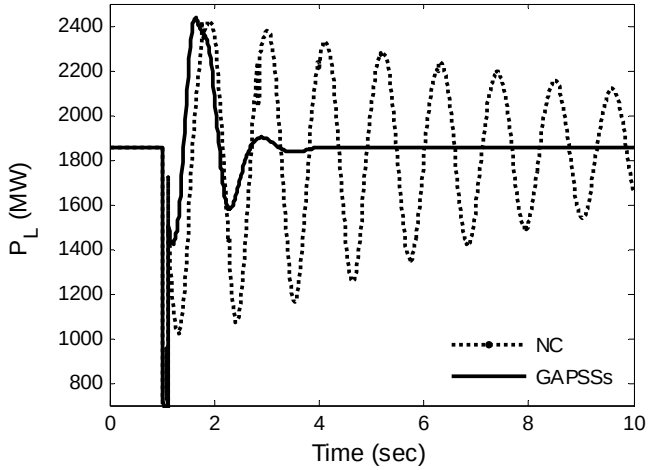


Fig. 19 Tie-line power flow for small disturbance

VI. Conclusion

In this paper, power system stability enhancement by power system stabilizer is presented. For the proposed controller design problem, a non-liner simulation-based objective function to increase the system damping was developed. Then, the real coded genetic algorithm optimization technique is implemented to search for the optimal controller parameters. The effectiveness of the proposed controller, for power system stability improvement, is demonstrated for both single-machine infinite-bus and multi-machine power system subjected to various disturbances. The dynamic performance of proposed PSS has also been compared with a conventionally designed PSS to show its superiority. The non-linear simulation results presented under wide range of operating conditions; disturbances at different locations as well as for various fault clearing sequences, show the effectiveness and robustness of the proposed RCGA optimized PSS controller and their ability to provide efficient damping of low frequency oscillations.

Appendix

A complete list of parameters used appears in the default options of SimPowerSystems in the User's Manual [15]. All data are in pu unless specified otherwise.

Single-machine Infinite Bus Power System:

Generator: S_B = 2100 MVA, H =3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544 e -3, X_d =1.305, X_d'= 0.296, X_d'' = 0.252, X_q = 0.474, X_q' = 0.243, X_q'' = 0.18, T_d =1.01 s, T_d'= 0.053 s, T_{qo}'' = 0.1 s.

Load at Bus2: 250MW

Transformer: 2100 MVA, 13.8/500 kV, 60 Hz, R_1 =R_2= 0.002, L_1 = 0,$L2$=0.12, D_1/Y_g connection, R_m = 500, L_m = 500

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

Conventional power system stabilizer

Sensor time constant =15 ms, T_W= 10 s, T_1=0.05 s, T_2=0.02 s T_3=3 s, T_4=5.4 s, Output limits of V_S = ± 0.15

Three-machine Power System:

Generators: S_{B1} = 4200 MVA, S_{B2} = S_{B3} = 2100 MVA, H =3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544 e -3, X_d =1.305, X_d'= 0.296, X_d'' = 0.252, X_q = 0.474, X_q' = 0.243, X_q'' = 0.18, T_d = 1.01 s, T_d' = 0.053 s, T_{qo}'' = 0.1 s.

Loads: Load1=7500MW+1500MVAR, Load2=Load3=25MW, Load4=250MW

Transformers: S_{BT1}=2100MVA, S_{BT2}= S_{BT2}=2100MVA, 13.8/500 kV, f = 60 Hz, R_1 =R_2= 0.002, L_1 = 0, L_2=0.12, $D1/Y_g$ connection, R_m = 500, L_m = 500

Transmission lines: 3-Ph, 60 Hz, Line lengths: $L1$ = 175 km, $L2$=50 km, $L3$=100 km, 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} = - 0.1 pu/s, V_{gmax} = 0.1 pu/s, R_p = 0.05, K_p = 1.163, K_i = 0.105, K_d = 0, T_d = 0.01 s,β =0, T_w = 2.67 s

Excitation System: T_{LP} = 0.02 s, K_a =200, T_a = 0.001 s, K_e =1, T_e =0, T_b = 0, T_c =0, K_f= 0.001, T_f = 0.1 s, E_{fmin} = 0, E_{fmax} = 7, K_p = 0

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